CABINET

MINISTERIAL BRIEF

Environment, Planning and Sustainable Development Directorate

To:	Minister for Climate Change, Environment, Energy and Water	**Tracking No.: 25/222**
Date:	24/04/2025	
From:	Executive Group Manager, Climate Change, Energy, Environment and Water	
Subject:	Exposure Draft Lodgement of 'Options for restoring Lake Tuggeranong', a draft of the 'Healthy Waterways Plan for Lake Tuggeranong'	
Critical Date:	12/05/2025	
Critical Reason:	To allow all directorates to review the draft submission and provide comments.	

- DDG, Environment, Water and Emissions Reduction 27/04/25

Recommendations

That you agree to lodge the draft Cabinet Submission at Attachment 1 and associated documents for exposure circulation.

Agreed / Not Agreed / Please Discuss

Suzanne Orr MLA 18/05/25

Minister's Feedback

Background

1. Since 2014, the ACT Government has invested heavily to investigate and address persistent water quality issues in Lake Tuggeranong through Healthy Waterways Program Stages 1 and 2 (around $44 million investment in Tuggeranong).

2. In 2023-24 Budget the Government committed to developing catchment plans that would consolidate learnings from the program and present options to Government to address water quality in four urban lakes and ponds, and in the Naas/Gudgenby rural catchment (2023-24 Business Case *EPSDD C02 – Expanding Healthy Waterways – Consolidating Gains*).

    a. The Naas/Gudgenby catchment plan was delivered in 2023 and is informing investment under the Restoring the Upper Murrumbidgee River Program, a joint program between the Commonwealth and ACT Governments.

    b. The Lake Tuggeranong plan is the first of the urban plans to be developed, to be followed by Lake Burley Griffin (Q4 2026), Lake Ginninderra (Q2 2027) and Yerrabi Pond (Q2 2027).

3. For this term, the Government priority (208) is to **Develop and deliver a 10-year plan for a healthier Lake Tuggeranong.**

4. Options for restoring Lake Tuggeranong (the draft Plan) is a draft of the Healthy Waterways Plan for Lake Tuggeranong (the final Plan), which will be finalised following public consultation and consideration by Cabinet.

5. The submission seeks Cabinet approval to take the draft Plan to community consultation to inform the development of the final Plan.

6.

Issues

<u>Options to reduce nutrient (phosphorus) pollution</u>

7. Through the Healthy Waterways program and its productive collaboration with researchers from the University of Canberra, we now know that algal blooms are being driven by excessive amounts of phosphorus entering the lake through stormwater inflows.

8. Modelling has been used to:

    a. Model water quality and quantity for the Tuggeranong catchment (<u>Attachment G</u>)

    b. Develop an in-lake model to set the target phosphorus reduction amount (<u>Attachment H</u>)

    c. Assess the cost-effectiveness ($/kg phosphorus reduced) of different mitigation options (<u>Attachment I</u>).

9. According to water quality models, seven of the recently built water quality assets are intercepting only 13% of the nutrient pollution destined for Lake Tuggeranong. This demonstrates that water quality assets are necessary to intercept unavoidable pollution, but on their own won't remove enough phosphorus to solve the problem. The draft Plan identifies and assesses a range of other ways to reduce phosphorus which can be used to improve on the reductions achieved by water quality assets.

10. Modelling indicates that measures to prevent phosphorus entering stormwater in the first place are more cost-effective than removing it through water quality infrastructure like wetlands. Increasing the frequency of street sweeping is the most cost-effective of all the options assessed.

11. No individual management options are a 'silver bullet'. Multiple options will need to be implemented to achieve a meaningful decrease in the incidence of algal blooms in Lake Tuggeranong.

12. The draft Plan provides two indicative scenarios for investment: one based only on cost-effectiveness, and one including more costly options like wetlands which provide broader benefits like improving biodiversity and amenity.

What can be achieved in Lake Tuggeranong

13. In managing Lake Tuggeranong we want to reduce the amount of phosphorus in the lake by 700kg/year as that will, based on our modelling, allow the lake to be suitable for contact based activities on average in three out of four years (Attachment H).

Next steps to finalise the Plan

14. Following Cabinet and agency feedback and community consultation on the options, the Healthy Waterways Team will create a final version of the Plan

15. The final version of the Plan will be brought to Cabinet at the first available opportunity in 2026 and published on the EPSDD website as soon as practicable after Cabinet consideration.

16. Business cases will then be developed to implement the Plan.

Financial Implications

17. Improving water quality in Lake Tuggeranong will require significant investment by Government over the longer term, estimated at $105-$144 million over 30 years (Attachment I).

18. You supported a business case for ERC's consideration in the 2025-26 budget *Improving Lake Tuggeranong* (EPSDD E16). The business case requests funding for $2.6 million for one year only: for 'no-regrets' options to start to implement the recommendations in the draft Plan, including retaining staff required to do necessary planning.

19. You may consider bringing forward a more substantial business case to the 2026-27 budget. That business case would provide costings for a detailed plan of implementation, informed by community and Government feedback on the approach proposed in this draft Plan.

Consultation

Internal

20. The Office of Water - Water Information Services Team provided extensive modelling to underpin the draft Plan, including three supporting technical reports detailing methodologies (Attachments G, H, I) that will be published on EPSDD's website alongside the draft Plan.

21. The EPSDD Communications and Engagement team developed the Communications and Engagement Strategy (Attachment D), an At-a-glance Snapshot of the draft Plan and the proposed community consultation (Attachment E).

Cross Directorate

22. The Healthy Waterways Team met with CMTEDD (Finance and Budget Group) on 5 March 2025 to discuss the Cabinet Submission and associated 2025-26 Business Case. The Group encouraged finalisation of the Plan to support future business case development and sought clarity on any funding overlap with the Water Efficiency Business Case. This information was provided 18 March, confirming no overlap.

23. The Healthy Waterways Team worked closely with TCCS in developing the draft Plan:

    a. With Roads ACT to carry out the street sweeping trial. Roads ACT also provided estimated costs of street sweeping to be included in cost modelling.

    b. ACT Sport and Recreation provided input on sports field fertiliser management practices.

    c. Place Management provided estimated costs for the mitigation option around improving open space mowing to reduce the impact of grass clippings.

    d. With ACT NoWaste, discussing the potential for street sweeping trucks and green bins to have Healthy Waterways messaging on them.

24. The ACT Chief Health Officer provided advice on current understanding of the potential links between cyanobacteria (from blue-green algae) and motor neurone disease.

External

25. The draft Plan has been reviewed by two expert reviewers, Prof Fiona Dyer (University of Canberra) and Prof Tim Fletcher (University of Melbourne).

26. From mid-2023 the Healthy Waterways team delivered presentations on the research findings and proposed direction of the draft Plan to the Tuggeranong Community

Council, ACT and Region Catchment Management Coordination Group, and Upper Murrumbidgee Catchment Network.

27. Initial First Nations input on the draft Plan was through an Aboriginal Water Assessment, facilitated by the Office of Water's Ngunnawal Water Policy Officer. This will be augmented through a facilitated process with consultant Paul Knight, as part of an Office of Water project to strengthen engagement with First Nations on water issues. Mr Knight will facilitate conversations with Ngunnawal Traditional Custodians and other Aboriginal and Torres Strait Islander people with connections to the lands and waters of the ACT and Region.

Work Health and Safety

28. Nil.

Benefits/Sensitivities

29. Improving the water quality in the lake will have wellbeing benefits in the environment and climate domain, as well as economic benefits. The Wellbeing Impact Assessment is at Attachment C.

Inclusion of cost estimates in the draft Plan

30. The plan includes the estimated costs of different mitigation options, and the estimated cost to implement the Plan over 30 years. Including the figures in this public facing document transparently conveys to the community the level and timeframe of investment needed to fix the problem.

Potential use of algicides

31. The draft Plan notes that in the future treatment options such as algicides (chemical treatment to kill algae) may be required to control severe blooms. There may be community opposition to their use because of environmental impacts.

    a. The draft Plan proposes further investigations to assess the effectiveness and potential environmental impacts of using algicides to control algal blooms in Lake Tuggeranong.

    b. As these investigations are yet to occur, community consultation on the draft Plan will not include consulting on potential algicide use.

Blue-green algae and motor neurone disease

32. The draft Plan discusses potential health risks associated with blue-green algae and motor neurone disease. There's a growing body of evidence on the issue and it has had media attention. In 2023, the NSW Government announced $2 million for urgent research into motor neurone disease and its connection with blue-green algae, including in the Riverina irrigation district where the incidence is seven times the national average (Media release).

33. A causal link and level of exposure risk has not yet been conclusively established by the scientific community. However, if aerosolized exposure to bloom-affected lake water is considered as a risk, as suggested in the draft Plan, this presents an elevated health risk for Tuggeranong residents living by the lake or using the lake surrounds, not just those who use it for primary and secondary contact activities.

34. The Government should consider whether to include this in the draft Plan, noting that this is a matter discussed by members of the community and the press.

Communications, media and engagement implications

35. The draft Plan presents information about the underpinning science and modelling that may be too detailed for many in the community. However, it's important to include this information to convey the problem and solutions accurately, to provide confidence in the findings and conclusions, and to set community expectations about what is realistically achievable for Lake Tuggeranong and expected timeframes for change.

36. The Communications and engagement strategy (Attachment D) has been developed to provide community with the opportunity to have their say and allows for an eight- week consultation period.

37. Communications consultants will be engaged to help facilitate engagement with the community, and with First Nations.

38. An 'At a glance snapshot' document will form part of the communications materials, giving Community a snapshot of what the consultation is about and how they can participate (Attachment E).

Signatory Name:	Kieran Lawton	Phone:	Via Teams
Action Officer:	Ralph Ogden & Katie Miller	Phone:	Personal information

Attachments

1 – Draft Cabinet submission
- A – Table of Comments
- B – Open Access Assessment: Cabinet Decision and Wellbeing Impact Assessment summary
- C – Wellbeing Impact Assessment
- D – Communications and Engagement Strategy
- E – 'At a Glance' snapshot
- F – Options for Restoring Lake Tuggeranong (draft Plan)
- G – Technical Report #1 – Dey et al (2024) Lake Tuggeranong Catchment Model Calibration Report
- H - Technical report #2 – Kahn and Dey (2024) Report supplement – Lake Tuggeranong In-Lake model
- I - Technical report #3– Booksmythe et al (2024) Lake Tuggeranong Catchment Management Options Assessment Report

ACT Government

CABINET SUBMISSION

Cabinet number	25/222
Title	**Healthy Waterways Plan for Lake Tuggeranong**
Meeting Type	Cabinet
Minister	Suzanne Orr MLA Minister for Climate Change, Environment, Energy & Water
Co-Sponsoring Minister/s	N/A
ERC date	Tuesday, 8 July 2025
Cabinet date	Wednesday, 30 July 2025

Status	EXPOSURE DRAFT	
Relationship to previous decisions	2023/24 ERC EPSDD C02 – Expanding Healthy Waterways – Consolidating Gains	
Submission type	Agree to public consultation	
Purpose	To approve release of 'Options for Restoring Lake Tuggeranong' (draft Plan) for public consultation	
Category	Category 2 - Cabinet Business/Government business/Community Engagement	
Financial Impact	No	
Treasury Agreement	Yes	28/04/2025
	Date of Treasury agreement:	13/05/2025
Legislative change	No - change to legislation not required	
PCO/JACS Human Rights	N/A	Click here to enter a date.
	N/A	Click here to enter a date.
Regulatory impact	No	Click here to enter text
Wellbeing Impact Assessment	Yes	
Primary Wellbeing Domain	Environment and climate	
Closing the Gap - Priority Reforms	Not in Scope for Closing the Gap Priority Reform	

Minister's signature_____ Date __/___/_____

RECOMMENDATIONS

1) I recommend Cabinet agree:

   a. To release the report 'Options for Restoring Lake Tuggeranong' (the draft Plan) (Attachment F) and the 'At a glance snapshot' (Attachment E) for public consultation using the Communications Strategy outlined in Attachment D, and

   b. that the Minister for Climate Change, Environment, Energy and Water finalise any minor amendments to the draft Plan prior to releasing for public consultation.

   c. Supporting communications materials will be approved by the Minister for Climate Change, Environment, Energy and Water.

2) I recommend Cabinet note:

   a. The final 'Healthy Waterways Plan for Lake Tuggeranong' (the final Plan) will be brought to Cabinet following the public consultation, likely early 2026.

   b. The final Plan will deliver on a 2024 election commitment to *'develop and deliver a 10-year plan for a healthier Lake Tuggeranong'*.

   c. The draft Plan is underpinned by three comprehensive technical reports detailing modelling and other analyses. These will be made publicly available on the EPSDD website at the time of the draft Plan's public release (Attachments G, H, I).

   d. The proposed release of the following Cabinet Decision and Wellbeing Impact Summaries as required under Section 23 of the *Freedom of Information Act 2016*:

      i. Cabinet agreed to the release of the draft Healthy Waterways Plan for Lake Tuggeranong for public consultation. The draft Plan describes current knowledge about what's causing blue-green algal blooms in Lake Tuggeranong, and, using modelling of catchment hydrology and mitigation costs, presents management options for addressing them.

      ii. Lake Tuggeranong's frequent blue-green algal blooms have negative visual and smell impacts, present health risks, and prevent people from recreating in and around the lake. Using current scientific understanding of what's causing Lake Tuggeranong's algal blooms, the draft Plan presents a ten-year vision to improve water quality in the catchment to reduce the frequency and severity of blooms. This will have positive wellbeing benefits for the Tuggeranong community through reducing health risks, providing access to blue-green space, and enhancing cultural and biodiversity values.

   e. The Minister for Climate Change, Environment, Energy and Water has brought forward a proposal relating to the implementation of the draft Plan for consideration in the 2025-26 budget (*Healthy Waterways – Improving Lake Tuggeranong – election commitment).*

SUPPORTING ARGUMENT

BACKGROUND

1) For at least the past decade Lake Tuggeranong has experienced poor water quality and regular blue-green algae blooms in summer, reducing the amenity and recreational values provided by the lake. This has been a consistent, high-profile issue for the Tuggeranong community and a complex problem to address.

2) The ACT Healthy Waterways program (Healthy Waterways) was established in 2014 to address water quality problems in Canberra —including in Lake Tuggeranong—through planning and on-ground actions. There have been two stages to the program:

   a. Stage 1 (2014-2021), a $94 million joint initiative of the Australian and ACT Governments

   b. Stage 2 (2021-June 2025) 'Expanding Healthy Waterways', to fulfil the Parliamentary and Governing Agreement for the 10th Legislative Assembly commitment to *Expand Healthy Waterways: $30 million over 4 years*. This commitment is to investigate water quality and plan and deliver pollution mitigation works for Lakes Tuggeranong, Burley Griffin and Ginninderra, Yerrabi Pond and the Nass/Gudgenby rural catchment. The outputs will be finalised through 2027.

3) Across the two stages approximately $44 million has been invested to better understand Lake Tuggeranong water quality issues and how to solve them, as well as on-ground works to begin to improve water quality in Lake Tuggeranong. These include:

   a. Building nine water quality assets

   b. Education programs

   c. Research and monitoring

   d. Catchment hydrological and water quality modelling and data analyses.

ISSUES AND OPTIONS

Plan scope - a water quality plan focusing on blue-green algae

4) The draft Plan presents, for the first time, a comprehensive suite of management options to reduce the nutrients coming off the catchment contributing to the formation of algal blooms, drawing on lessons learned from the past ten years of investment.

5) The draft Plan focuses on one aspect of water quality - nutrient pollution, and specifically the nutrient phosphorus, because of its key role driving algal blooms which most heavily impact the amenity of the Lake.

6) A ten-year timeframe is proposed to implement the Plan, with interim goals set for 2030. This timeframe is needed to implement management interventions and to evaluate their effectiveness.

Public Consultation Plan

7) The public consultation process described in this submission is an important way to confirm community support (or otherwise) for the proposed mitigation options. Feedback from this process will inform the final Plan.

8) The Communications and engagement strategy (Attachment D) has been developed to provide community with the opportunity to have their say and allows for an eight-week consultation period.

9) An 'At a glance snapshot' document (Attachment E) will form part of the communications materials, giving community a snapshot of what the consultation is about and how they can participate. The snapshot is designed to compliment the data rich and technically detailed draft Plan (Attachment F).

10) Communication consultants will be engaged to help facilitate engagement with the community, and with First Nations.

The options presented to reduce phosphorus to prevent algal blooms

11) Modelling suggests that the level of phosphorus reduction required to reduce the incidence of algal blooms in Lake Tuggeranong is 700 kg phosphorus/year (phosphorus reduction target). This target was derived using an in-lake model (Attachment G).

12) Modelling indicates that achieving the phosphorus reduction target would shift the lake away from a state of being primed for an algal bloom most summers to a state where algal blooms form in just three out of every four years on average.

13) Detailed analyses were undertaken of the cost and benefit (kg phosphorus removed/year) of ten management options for reducing phosphorus pollution, including:

   a. Increasing street sweeping to remove leaf litter from roads
   b. Using behaviour change strategies to encourage high-fertiliser-using households to use less fertiliser
   c. Implementing extra measures to prevent grass clippings from open space mowing operations ending up in waterways
   d. Subsidising the installation of household rainwater tanks
   e. Building stormwater recycling on sportsfields
   f. Retrofitting outlets into road kerbs (castellated kerbs) to divert stormwater to open green space
   g. Building bioretention swales on sportsfields (using vegetation to filter surface flow of nutrients)
   h. Building more large water quality assets low in the catchment (e.g. raingardens – a type of constructed wetland)
   i. Improving maintenance of existing water quality assets, built via the Healthy Waterways program, to optimise their phosphorus removal performance
   j. Building more floating wetlands.

14) The costs and phosphorus reduction benefits of each option are summarised in the draft Plan and detailed further in a supporting technical report (Attachment I).

15) Key conclusions are:

   a. The most effective way to reduce phosphorus is through increased street sweeping.

b. There is no 'silver bullet' for solving the problem. Multiple management options will need to be implemented to reach the phosphorus reduction target and so reduce the incidence of algal blooms.

c. Building additional large wetlands low in the catchment—the focus of Healthy Waterways investment to date—is necessary but not the answer on its own.

16) Two packages of mitigation options were developed to demonstrate how combinations of options might reach the target, and the cost of doing this: a 'cost-effective' package and a 'broad benefits' package. These were developed for indicative purposes only, with the intention that they would be informed by feedback from the community on the different options.

Alignment with other Territory planning priorities

17) The draft Plan aligns with community feedback heard during the development of the Tuggeranong District Strategy, in which the Tuggeranong community expressed that they value the lake for a range of recreational activities throughout the year, including walking, cycling, swimming, fishing and windsurfing (ACT Government, 2023).

18) Building and maintaining large water quality assets like wetlands and raingardens can also help achieve Territory Planning objectives to improve Biodiversity Sensitive Urban Design, enhance the Blue-Green network, and promote urban cooling.

a. Large water quality assets have an urban cooling effect, contributing to the implementation of Canberra's Living Infrastructure Plan: Cooling the City.

i. A recent study on ACT living infrastructure found two sites (Crace stormwater basin, and Bonner wetland) were 2-2.5^{0}C cooler than the overall average of sites measured (CSIRO. 2024. *Measuring the Cooling benefits of Living Infrastructure– report for EPSDD*).

b. Constructed wetlands and raingardens help to restore aquatic habitat to degraded urban channels, supporting the implementation of the ACT Nature Conservation Strategy and Connecting Nature Connecting People initiative.

FINANCIAL IMPACT

19) There are no financial impacts from this paper, there will be financial impacts arising from implementing actions under the Healthy Waterways Plan which will be subject to future budget processes. Cost modelling indicates that fully implementing the plan to achieve target phosphorus reductions would cost between $105-$144 million over ten years (Attachment I).

20) The Minister for Climate Change, Energy, Environment and Water has brought forward a business case for consideration in the 2025-26 budget for one year of investment to undertake trials into in-lake treatment in Isabella Ponds and plan for capital works.

WELLBEING IMPACT SUMMARY

21) Lake Tuggeranong's frequent blue-green algal blooms have negative visual and smell impacts, present health risks, and prevent people from recreating in and around the lake. Using current scientific understanding of what's causing Lake Tuggeranong's algal blooms, the draft Plan presents a ten-year vision to improve water quality in the catchment to reduce the frequency and severity of blooms. This

will have positive wellbeing benefits for the Tuggeranong community through reducing health risks, providing access to blue-green space, and enhancing cultural and biodiversity values.

CLOSING THE GAP - PRIORITY REFORMS

22) Not in scope for Closing the Gap – Priority Reforms.

CONSULTATION

External stakeholders

23) The draft Plan has been reviewed by two external experts, Prof Fiona Dyer (University of Canberra) and Prof Tim Fletcher (University of Melbourne).

24) The Healthy Waterways team have delivered presentations on the research findings and proposed direction of the draft Plan to the Tuggeranong Community Council, ACT and Region Catchment Management Coordination Group, and Upper Murrumbidgee Catchment Network.

25) Initial First Nations input on the draft Plan was through an Aboriginal Water Assessment, facilitated by the Office of Water's Ngunnawal Water Policy Officer. This will be augmented through a facilitated process with consultant Paul Knight, as part of an Office of Water project to strengthen engagement with First Nations on water issues. Paul will facilitate conversations with Ngunnawal Traditional Custodians and other Aboriginal and Torres Strait Islander people with connections to the lands and waters of the ACT and Region.

ACT Government Agencies

26) The Healthy Waterways team worked closely with TCCS on asset designs, street sweeping, sports field fertiliser management and grass clipping management on road verges in preparing the draft Plan.

27) The ACT Chief Health Officer provided advice on current understanding of the links between cyanobacteria (from blue-green algae) and motor neurone disease.

MEDIA AND COMMUNICATIONS

28) The Communications and Engagement Strategy is at Attachment D. A draft 'At a Glance' snapshot is at Attachment E.

IMPLEMENTATION

29) The final Plan will be presented to Cabinet in early February 2026, with more refined options based on community feedback from the draft. Further implementation will depend on ERC's consideration of future business cases.

Table 2: **Implementation milestones and timeframes to publishing of final Plan**

Milestones	**Date complete**
1. Public consultation on draft Plan (including with First Nations)	24 September 2025
2. Listening/consultation report published	24 October 2025
3. Final Plan brought to Cabinet	Early February 2026
4. Plan published	March 2026
Final completion date:	March 2026

HUMAN RIGHTS IMPACT

30) The right to a healthy environment is enshrined in the *Human Rights Act 2004*, with the right applying to all relevant policies and legislation. The Healthy Waterways Program aims to improve water quality for the Territory, contributing to healthy environments.

ATTACHMENTS

A	Table of comments
B	Open Access Assessment: Cabinet Decision and Wellbeing Impact Assessment summary
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G	Technical report #1 – Dey et al (2024) Lake Tuggeranong Catchment Model Calibration Report
H	Technical report #2 – Kahn and Dey (2024) Report supplement – Lake Tuggeranong In-Lake model
I	Technical report #3– Booksmythe et al (2024) Lake Tuggeranong Catchment Management Options Assessment Report

ACT Government

TABLE OF COMMENTS

Attachment A

EXPOSURE DRAFT COMMENTS – 25/222

Exposure circulation undertaken: Choose an item.

Dates circulated: Provide dates circulated

Directorate	Comment	Response
CMTEDD	Choose an item. [Provide comments.]	[Drafting directorate to provide response]
JACS	Choose an item. [Provide comments.]	[Drafting directorate to provide response]
HD	Choose an item. [Provide comments.]	[Drafting directorate to provide response]
CHS	Choose an item. [Provide comments.]	[Drafting directorate to provide response]
EDU	Choose an item. [Provide comments.]	[Drafting directorate to provide response]
TCCS	Choose an item. [Provide comments.]	[Drafting directorate to provide response]
CSD	Choose an item. [Provide comments.]	[Drafting directorate to provide response]
EPSDD	Choose an item. [Provide comments.]	[Drafting directorate to provide response]
MPC	Choose an item. [Provide comments.]	[Drafting directorate to provide response]
Statutory Office Holder	Choose an item. [Provide comments.]	[Drafting directorate to provide response]

FINAL COMMENTS – 25/222

Final circulation undertaken: Choose an item.

Dates circulated: Provide dates circulated

Directorate	Comment	Response
CMTEDD	Choose an item. [Provide comments.]	[Drafting directorate to provide response]
JACS	Choose an item. [Provide comments.]	[Drafting directorate to provide response]
HD	Choose an item. [Provide comments.]	[Drafting directorate to provide response]
CHS	Choose an item. [Provide comments.]	[Drafting directorate to provide response]
EDU	Choose an item. [Provide comments.]	[Drafting directorate to provide response]
TCCS	Choose an item. [Provide comments.]	[Drafting directorate to provide response]
CSD	Choose an item. [Provide comments.]	[Drafting directorate to provide response]
EPSDD	Choose an item. [Provide comments.]	[Drafting directorate to provide response]
MPC	Choose an item. [Provide comments.]	[Drafting directorate to provide response]
Statutory Office Holder	Choose an item. [Provide comments.]	[Drafting directorate to provide response]

ACT Government

OPEN ACCESS ASSESSMENT

CABINET DECISION AND WELLBEING IMPACT ASSESSMENT SUMMARY

Attachment B

The Chief Minister must proactively release the information described in section 23 of the *Freedom of Information Act 2016* (the FOI Act) unless the information is contrary to the public interest in accordance with sections 16 and 17, and schedules 1 and 2 of the FOI Act. Please refer to the **Cabinet SharePoint Site** for further guidance on what is within the scope of Open Access requirements.

If you believe that release of this information is within the scope of Open Access requirements and would be contrary to the public interest, please complete Part B.

Cabinet Number and title: 25/222 - Cabinet - [ERC 08-07-25] Draft Healthy Waterways Plan for Lake Tuggeranong - Public Consultation

Please select one of the following:

Proposed Release of Cabinet Decision Summaries - Please Complete Part A Only

PART A: Proposed Release or Delayed Release

Proposed Summary of the decision for public release

Cabinet agreed to the release of the draft Healthy Waterways Plan for Lake Tuggeranong for public consultation. The draft Plan describes current knowledge about what's causing blue-green algal blooms in Lake Tuggeranong, and, using modelling of catchment hydrology and mitigation costs, presents management options for addressing them.

Proposed summary of the Wellbeing Impact Assessment for public release

Lake Tuggeranong's frequent blue-green algal blooms have negative visual and smell impacts, present health risks, and prevent people from recreating in and around the lake. Using current scientific understanding of what's causing Lake Tuggeranong's algal blooms, the draft Plan presents a ten-year vision to improve water quality in the catchment to reduce the frequency and severity of blooms. This will have positive wellbeing benefits for the Tuggeranong community through reducing health risks, providing access to blue-green space, and enhancing cultural and biodiversity values.

If a Wellbeing Impact Assessment is not required, please select from the following:

Choose an item.

Other releases – how will the community be informed of the decision of Cabinet?

Expected Milestone for Release	Consultation through YourSay
Expected milestone completion date	14 August 2025

Wellbeing Impact Assessment (WIA)

Resources and support

The Wellbeing Toolkit provides a range of resources to support you to complete a WIA, including the WIA Drafting Guide and details of the Wellbeing Domains. The Drafting Guide includes definitions, prompting questions, examples and other advice related to each section of the WIA.

Support is available from Wellbeing Champions in each directorate. The Wellbeing Team can review and provide advice on draft WIAs where capacity allows – contact the team at WellbeingFeedback@act.gov.au.

Healthy Waterways Plan for Lake Tuggeranong

EPSDD

Purpose of proposal

This proposal seeks Cabinet approval to release the 'Options for Restoring Lake Tuggeranong (draft Healthy Waterways Plan for Lake Tuggeranong) for public comment. The Plan's purpose is to address the problem of blue-green algal blooms in Lake Tuggeranong to improve amenity for Tuggeranong residents and the lake's ecological health.
The Plan summarises current knowledge and scientific understanding about why blooms occur in Lake Tuggeranong and describes alternative ways to reduce nutrients in the catchment, a key contributor to algal blooms.

Wellbeing domains and impact description

Access and connectivity	Economy	Education and life-long learning	Environment and climate	Governance and institutions	Health
Housing and home	Identity and belonging	Living standards	Safety	Social connection	Time

Primary domain	Impact description
Environment and climate	By reducing the frequency and intensity of algal blooms, this proposal will improve the lake's ecological health as severe blue-green algal blooms can impact fish populations and other aquatic biota. There will also be improved urban ecosystem function locally throughout the catchment where non-polluting practices are adopted, and water quality assets are built.
Other domains	
Health	There are health risks to humans and pets associated with contact and/or ingestion of water from lakes affected by toxic blue-green algal blooms. This is why the Government closes lakes when algal populations rise above a threshold level. There are also potential health risks (neurological disorders) associated with aerosolised exposure to the cyanotoxins present in blue-green algae. This proposal aims to reduce the frequency of algal blooms, reducing the potential health risks. This proposal will also significantly improve Lake Tuggeranong's recreational and amenity value and the associated wellbeing of residents and visitors by reducing the frequency of algal blooms and providing access to blue-green spaces.
Social connection	Improved blue-green network (by improving the health of the lake and its catchment's waterways, including building new wetlands) will create more opportunities for increased social connection as people walk, run, cycle, and picnic near the waterways.
Economy	Businesses operating on and near the lake will benefit from reduced algal blooms - a recent literature review found there was a drop in property values of 2-22% for residences nearby waterways that experienced toxic algal blooms (NC Economics 2021).
Governance and institutions	The proposal will improve trust in Government because the Tuggeranong community will see the Government acting on an issue of longstanding concern.

Evidence base and data

Provide evidence that your proposal will have the wellbeing impacts described above. Note that it is not enough to only provide evidence that the issue exists.

Evidence	Source	Type of evidence

• Ecological impacts of blue-green algal blooms	• Potter et al (1983) Blue-green algae and fish population changes in a eutrophic estuary. *Marine Pollution Bulletin* V14 I6: 228-233.	National data or research
• Ecological impacts of blue-green algal blooms	• Sharma et al (2011) Freshwater cyanobacterial (blue-green algae) blooms: causes, consequences, and control. Impact Monitoring and Management	International data or research
• Reduced urban heat and risks of heat stress where water quality assets are built	• Tapsuwan, S, Ingleton, G & Capon, T (2024). Measuring the cooling benefits of living infrastructure in urban Canberra: a report of findings. Canberra.	ACT government data or research
• The importance of blue-green spaces for wellbeing	• Dushkova et al (2021). Human Dimensions of Urban Blue and Green Infrastructure during a pandemic. Case study of Moscow (Russia) and Perth (Australia). *Sustainability* 13: 414-4172	National data or research
• The importance of blue-green spaces for wellbeing	• UK Environment Agency (2020) The social benefits of blue space: a systematic review	International data or research
• Residents want an improved blue-green network and improved water quality in Lake Tuggeranong	• Tuggeranong District Strategy Planning System Review and Reform Project (Listening Report)	ACT government data or research
• Residents want an improved blue-green network and improved water quality in Lake Tuggeranong	• Tuggeranong Community Council 2024 survey of residents	ACT government data or research
• Residents want an improved blue-green network and improved water quality in Lake Tuggeranong	• Schirmer and Mylek (2016) Water Quality and the community: understanding the views, values and actions of residents of the ACT and surrounding region.	ACT government data or research
• Residents are willing to pay up to $280/pp/year to *greatly improve* the amenity of Lake Tuggeranong	• Natural Capital Economics 2023. Economic values of ACT Urban Lakes.	ACT government data or research
• Potential human health risks associated with exposure to blue-green algae	• Cox et al 2003 Biomagnification of cyanobacterial neurotoxins and neurodegenerative disease among the Chamorro people of Guam.	International data or research
• Potential human health risks associated with aerosolised exposure to blue-green algae	• Plaas, H & Paerl, H (2021). Toxic cyanobacteria: a growing threat to water and air quality. Environmental Science and Technology 55:44–64.	International data or research
• Economic impacts (property values reduced by 2-22% for residences nearby waterways that experience toxic algal blooms)	• Natural Capital Economics 2021 Economic impacts of blue-green algae for urban lakes: a literature review.	ACT government data or research

What don't we know?

- We don't have specific data on the links between Tuggeranong's natural spaces—green corridors between suburbs, ponds and lakes—and Tuggeranong residents' wellbeing.
- The causal links between toxins in blue-green algae and neurological disease have not been definitively established, and the scientific community does not agree on the level of risk posed through aerosolised exposure.

Measuring wellbeing outcomes

How will the Government know this proposal has achieved the anticipated wellbeing impacts?

Your thinking on this does not need to be finalised – this is an opportunity to set out ideas about what may need to be measured in order to understand whether this proposal has had the anticipated impact.

What is the measurable outcome?	How will you measure it?
• Decreasing phosphorus concentrations in stormwater	• Water quality monitoring (sampling)
• Decreasing lake closures due to blue-green algal blooms	• EPA monitoring data on lake closures

- Reduced frequency, intensity and or duration of blue-green algal blooms
- Improved ecological outcomes
- Contribution to urban cooling
- Residents' and visitors' wellbeing due to access to 'blue' spaces in the Tuggeranong catchment.
- Water quality monitoring
- CHIP reports
- WSUD assets to be included in ongoing studies as part of Living Infrastructure Plan
- Survey of residents, potentially through Omnibus survey.

Evaluation

- The impacts of this proposal will be evaluated as part of evaluating the implementation of the (draft) Healthy Waterways Plan for Lake Tuggeranong.

Who is impacted?

The population of Tuggeranong was approximately 87, 680 in 2021.People who use the lake for recreation (walking, running, picnicking, cycling, swimming, boating, fishing), as well as businesses and clubs nearby to the lake, will be most impacted.

Table 1.1 – Lake Tuggeranong lake user characteristics, from survey of 316 people who said they visit the lake once or more a year. Source: NC Economics, 2023.

Gender	
Male	48.7%
Female	50.6%
Non-binary/use other term	0.6%
Area of residence in Canberra	
Tuggeranong	35.7%
Other parts of Canberra	64.3%
Age	
18-34	34.1%
35-54	27.4%
55-74	33.1%
75 and over	5.4%
Aboriginal and Torres Strait Islander	2.5%

Will the proposal have a different or disproportionate impact (positive or negative) on any groups?

- The proposal will not have a disproportionate impact on any specific groups, using Tuggeranong District population data and the results of the lake user survey data shown in Table 1 above.

Gendered impacts

- To understand whether there are gendered impacts of this proposal, we would need data on to what extent cisgender, transgender, gender diverse and non-binary people use lake Tuggeranong. This data does not currently exist and would need to be collected through a survey of lake users.

Impacts on Aboriginal and Torres Strait Islander people

- The proposal will not explicitly support commitments under the National Agreement on Closing the Gap or the ACT Aboriginal and Torres Strait Islander Agreement 2019-2028. It is not predicted to have a disproportionate impact on Aboriginal and Torres Strait Islander people.
- The Healthy Waterways program has attempted to gain Ngunnawal perspectives in planning for the Tuggeranong catchment through undertaking a Healthy Waterways-funded Aboriginal Waterway Assessment, facilitated by the EPSDD Ngunnawal Water Policy Officer. This is undertaken by the Ngunnawal community on country, and as part of the assessment, Ngunnawal community members went on country in the Tuggeranong catchment to assess it for culturally significant values. The outcomes of the Aboriginal Waterway Assessment have not yet been shared with the Healthy Waterways team.
- Broader consultation with other Traditional Custodians and groups on cultural values and aspirations for the Tuggeranong catchment is planned to occur through an Office of Water First Nations engagement procurement in Q1 2025.

Impacts on future generations

- The proposal will positively impact future generations by securing their ability to enjoy a healthy Lake Tuggeranong and blue-green network.

Will the proposal have an impact on or be impacted by climate change?

Emissions reduction

- The proposed activities are unlikely to have a significant positive or negative impact on carbon emissions.

Adaptation and risk management

- Susceptibility to algal blooms will be impacted by projected changes to rainfall, storm intensity, and temperature because these influence nutrient dynamics in the catchment and lake. These effects have not yet been quantified in the Tuggeranong context, but it is expected that the net impact will be to increase the lake's susceptibility to algal blooms.
- The proposal will help support a more climate resilient waterbody, by reducing its susceptibility to algal blooms.
- The proposal helps support an adaptation response by contributing to urban cooling and providing people with access to blue spaces as temperatures increase.

Cross-portfolio collaboration and partnerships

- The Healthy Waterways Team has been collaborating with Transport Canberra and City Services (City Services) on how increasing street sweeping can help to address the problem of algal blooms, and with ACT No Waste on how we can support the community to more effectively pick up leaf litter from their properties (a source of nutrients causing algal blooms), and exploring options for recycling green waste collected from street sweeping.

Open Access Wellbeing Impact Summary (Cabinet Submission WIAs only)

Lake Tuggeranong's frequent blue-green algal blooms have negative visual and smell impacts, present health risks, and prevent people from recreating in and around the lake. Using current scientific understanding of what's causing Lake Tuggeranong's algal blooms, the draft Plan presents a ten-year vision to improve water quality in the catchment to reduce the frequency and severity of blooms. This will have positive wellbeing benefits for the Tuggeranong community through reducing health risks, providing access to blue-green space, and enhancing cultural and biodiversity values.

Attachment F

Options for Restoring Lake Tuggeranong

August 2025

ACT Government

ACT Healthy Waterways

Acknowledgement of Country

Yuma
Dhawura nguna ngurumbangu gunanggu Ngunnawal. Nginggada dindi dhawura Ngunnawalbun yindjumaralidjinyin.
Mura bidji mulanggaridjindjula.
Naraganawaliyiri yarabindjula.

Hello,
This country is Ngunnawal (ancestral/spiritual) homeland. We all always respect elders, male and female, as well as Ngunnawal country itself.
They always keep the pathways of their ancestors alive.
They walk together as one.

We acknowledge the Ngunnawal people as traditional custodians of the ACT and recognise any other people or families with connection to the lands of the ACT and region. We acknowledge and respect their continuing culture and the contribution they make to the life of this city and this region.

Privacy

Any personal information provided during your submission will be used solely for the purpose of this community engagement process. Submissions may be partially or fully published on an ACT Government website or incorporated into a subsequent consultation report. As the ACT operates under a pro-release policy, citizens and others have the right to access information obtained through this engagement process under the Freedom of Information Act 2016. While the names of organisations may be disclosed, individuals' identities will be de-identified unless explicit prior consent has been obtained.

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Options for Restoring Lake Tuggeranong

Executive summary

There is a rich history of Aboriginal use of the Tuggeranong valley and its waterways, with evidence of the Ngunnawal people occupying the valley for more than 20,000 years. The name 'Tuggeranong' comes from a Ngunnawal word for 'cold place' or 'cold plains'.

The valley has changed dramatically in the past 200 years. Sheep and cattle stations were established in the early 1800s. Since suburban development started in the 1970s, around 50% of the water catchment has been urbanised. Lake Tuggeranong was built in 1987 as a focal point for the growing town centre and to protect the downstream Murrumbidgee River from the water quality effects of development. Around the same time, a stormwater system was built to manage flood risk by converting natural creek lines such as Tuggeranong Creek into concrete channels.

Lake Tuggeranong has experienced elevated nutrient levels for more than ten years, which has led to frequent blue-green algal blooms. The algal blooms smell unpleasant, are unsightly and require the government to close the lake to activities such as swimming and water sports due to health risks. They also may pose health risks to residents of suburbs surrounding the lake who are exposed to aerosolised lake water on windy days.

These nutrient levels and algal blooms can be reduced to a manageable level using current knowledge.

Several key conclusions can be drawn from the analyses in this report:

- There is sufficient knowledge to have confidence that better water management can lead to a substantial reduction in the frequency of blue-green algal blooms in Lake Tuggeranong.
- A suite of pollution mitigation options to prevent nutrients entering the lake will be needed for success.
- There will be a limit to what can be done to prevent algal blooms; the best that can be achieved is to prevent algal blooms in three out of four years on average.
- Water managers may need to develop options to treat algal blooms when they do arise.

This report presents the best ways to apply our current knowledge in terms of impact and cost-effectiveness. This report builds on previous Healthy Waterways work in the Lake Tuggeranong catchment that saw the construction of nine important wetlands and funded research and community engagement to reduce the sources of nutrient pollutants.

Following consideration of community feedback on the report, the Government will present its preferred options for achieving a healthier Lake Tuggeranong as a *Healthy Waterways Plan for Lake Tuggeranong* (the Plan).

The vision

This report and the Plan that will follow, address an ACT Government commitment for the 11th Assembly to *Develop and deliver a 10-year plan for a healthier Lake Tuggeranong*.

The 10-year vision is:
By 2035, Lake Tuggeranong is more consistently free of blue-green algal blooms and, when they do occur, they are short-lived so the Tuggeranong community can enjoy the lake most of the year.

The underpinning research and analyses

Research and modelling funded through the ACT Healthy Waterways program over the past decade has greatly improved understanding of blue-green algal blooms in Lake Tuggeranong. It is now well established that the inflow of phosphorus and other nutrients from the catchment is the main factor driving the blooms. They effectively feed the blooms.

There is currently far more phosphorus entering the lake from its catchment than is released to the water column from lake-bottom sediments. Phosphorus is generated from many diffuse sources across the urban catchment such as leaves, grass clippings, fertiliser products (including composts and manures), soil and sewage. Roughly half of it is in a dissolved form that is readily taken up by algae.

The stormwater flowing off the catchment carries an average annual generation of 1,656 kg phosphorus/year. The seven constructed wetlands built in Stage 1 of Healthy Waterways have reduced this by about 214 kg a year (to 1,442 kg). However, under current flow and levels of phosphorus supply, Lake Tuggeranong will remain in a eutrophic state—which means it is primed for algal growth.

Research shows that blue-green algal blooms can be significantly reduced if the supply of phosphorus to the lake is curbed or 'mitigated' by about 50%, or around 700 kg a year. Once this happens, any further algal blooms can be prevented through in-lake actions.

If the average annual amount of phosphorus entering the lake can be reduced by another 700 kg, the water quality models predict a eutrophic state can be avoided for an average of three out of four years. The 700 kg target is based on annual averages. In very wet years the reductions in phosphorus will need to be higher, while in dry years they can be lower. Some blue-green algae will be present in all years, but if the 700 kg target can be achieved, the likelihood of problem blooms would be lower than at present and the lake should usually be available for contact-based activities.

Options for removing phosphorus

It is possible to remove phosphorus from the system, or to treat algae directly, at three stages during the 'journey of the stormwater':

1. At the sources of pollution, by preventing pollution from occurring in the first place.
2. Within the stormwater system, by slowing the flow and filtering pollution from the stormwater.
3. In the lake, by using agents that compete with algae for nutrients, or by using algicides.

Potential options are presented for reducing or mitigating phosphorus levels (pollution mitigation options) or directly treating algal blooms. A subset of ten options are examined in detail. These were chosen for

discussion because their costs and effectiveness could be well characterised based on local trials or the scientific literature.

The analyses clearly show that the most effective options for reducing phosphorus pollution are an increased frequency of street sweeping and building extra water quality assets, such as wetlands, which cleanse stormwater of pollutants. Street sweeping is by far the most cost-effective mitigation measure, decreasing phosphorous by 200–400 kg per year, depending on the frequency of sweeps. Constructing more water quality assets would decrease phosphorous by 100–200 kg per year, depending on the scale of the wetlands and other water quality assets already in the system.

However, the analyses highlight that no single option is a 'silver bullet' that has the potential to reach the phosphorus mitigation target on its own. Multiple options will be needed. Notably, options to prevent stormwater from getting polluted in the first place will be needed to substantially reduce the frequency of blue-green algal blooms.

Management scenarios

After outlining the options, this report investigates solutions by defining two management scenarios that are comprised of multiple pollution mitigation options:

1. A 'cost-effective' scenario that represents the most cost-effective set of options to reach the 700 kg target.
2. A 'broad benefits' scenario that recognises that some options that rank lower for cost-effectiveness, such as constructed wetlands, should nevertheless still be included in the solution because they provide additional values to the community beyond water quality improvement, such as wellbeing.

The management scenarios reflect reality; water managers implement pollution mitigation options concurrently (at the same time). However, the water quality models estimate that concurrent implementation would result in a lower amount of phosphorus being removed than when the options are implemented in isolation from one another. For example, the combination of street sweeping, additional wetlands and eight other options (the 'broad benefits' scenario) was modelled as decreasing phosphorus by just under 600 kg per year compared with 746 kg per year when the options were considered in isolation from one another. This makes sense. For example, campaigns to get residents to remove leaves from roadside gutters will reduce the amount of leaves collected by increased street sweeping, but the sweeping will still be needed.

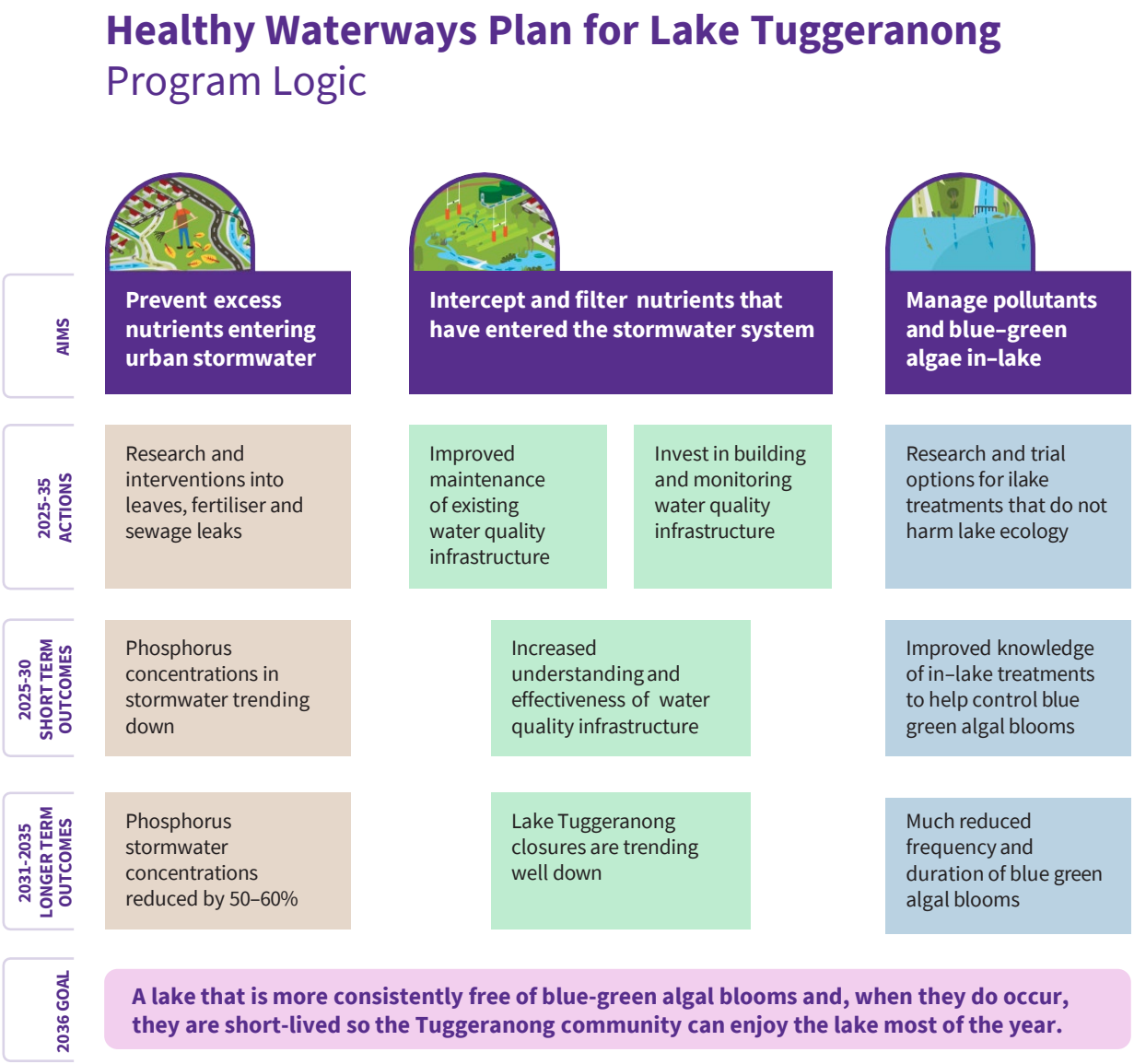
Despite the result of just under 600 kg per year being slightly lower than the 700 kg per year target, there are reasons to suggest the ACT Government could successfully curb algal blooms in the lake if it implements a program to reduce phosphorous pollution.

- First, reducing phosphorus pollution by just 500–600 kg/year would represent a substantial improvement and would significantly lower the frequency of blue-green algal blooms in Lake Tuggeranong.
- Second, the options to mitigate pollution have only been represented in models in a simple way and their refinement, both during implementation planning and in models, should both decrease their cost and increase their effectiveness.
- Last, there are several promising options that have yet to be tested that may help meet the phosphorus mitigation target of 700 kg/year, such as in-lake phosphorus adsorption materials.

The main cautionary note is about how quickly algae in Lake Tuggeranong will respond to reduced supplies of phosphorus from the catchment. If the phosphorus already in the lake sediments is able to sustain the blooms, it may take longer than the goal of a decade to fix the problem. However, there are options that the government can explore through research and trials for directly dealing with both phosphorus in lake sediments and algal blooms. This increases the likelihood of good progress over the next decade.

The costs

The analyses suggest the cost of mitigating phosphorus pollution in stormwater by 500–600 kg/year (or by the target 700 kg per year with refinement of the mitigation options) is $105 million over 30 years, or $146 million over 30 years for the broad benefits management scenario. However, refinement of the pollution mitigation options should not only increase the effectiveness of the management solutions but may reduce their costs.



Future research and monitoring

An active research and monitoring program has played a central role in the work to date. Ongoing research and monitoring will be critical to refining pollution mitigation options to maximise their effectiveness and minimise their costs. New evidence and knowledge can be incorporated into future versions of the Plan, and its implementation plans.

The highest research priorities are trials of promising options and investigations to better understand the fate of fertilisers applied to residents' blocks and to determine whether sewage (either through cross-connections or by other mechanisms) is a significant source of phosphorus in stormwater. It will be critical to continue to monitor the effectiveness of wetlands and other water quality assets, as well as other interventions.

Additional research will continue to refine knowledge and understanding of how to reduce phosphorus in the catchment. However, there is enough evidence already to identify priorities for restoration. Substantial improvements should occur in the lake within several years of the commencement of a material pollution mitigation program.

Next steps

Version 1 of the Healthy Waterways Plan for Lake Tuggeranong will be created based on this report and incorporating further inputs from First Nations people and feedback from the community and experts on the proposed approach. An implementation plan will then be developed to set out how the vision will be achieved over the next 10 years, including how it will be monitored and evaluated.

Aerial view of Lake Tuggeranong. Source: MetroMap

Part 1 Context

The ACT Healthy Waterways Program

Addressing water quality in our urban lakes, and specifically the issue of blue-green algae, is a major challenge. The ACT Healthy Waterways Program (Healthy Waterways) was created to address the issue of declining water quality in ACT's rivers and urban lakes.

Stage 1 Healthy Waterways (2014–21) was a joint Australian Government and ACT Government investment, while the ACT Government is fully funding Stage 2 (2021–25).

Over the last decade, Healthy Waterways has delivered a comprehensive suite of activities to help improve water quality and improve our understanding of the problem. It has built water quality assets (such as wetlands and raingardens); invested in research, monitoring and data analyses; built water modelling capability; and initiated community partnership programs to uplift catchment management practices.

Through this work, we have greatly improved our understanding about how ACT's urban catchments operate, the different sources of nutrient pollution that enter waterbodies and lead to algal blooms, the in-lake processes that promote algal blooms, and how the community wishes to participate in caring for waterways.

Of the urban lakes, Lake Tuggeranong has suffered the most chronically from water quality issues in recent years and has been the primary focus of investigative efforts to date. This report will underpin a *Healthy Waterways Plan for Lake Tuggeranong* (the Plan; Figure 1), which is the first of four Healthy Waterways plans for urban waterways.

Objective and scope of the report

The objectives of this report are to:

1. determine whether it is feasible to achieve a substantial reduction in the incidence of algal blooms in Lake Tuggeranong
2. evaluate various options for mitigating stormwater pollution that drives algal blooms.

The Government will finalise the report as a *Healthy Waterways Plan for Lake Tuggeranong* once the community has provided feedback on the options (Figure 1). Subsequently, funding will be investgated for the Plan to be implemented. Funded restoration activities will be monitored and evaluated, and further research and stakeholder engagement will be conducted. The Government will periodically update the Plan as new knowledge comes to hand to ensure the plan achieves maximum value for the community at least cost.

This report and the Plan prioritise focussing on algal blooms over other water quality issues because the ACT Government believes they are the highest priority for the Tuggeranong community (for example, TCC, 2024, Draft). Reducing the incidence of blue-green algal blooms in Lake Tuggeranong should improve its amenity and recreational values for residents and reduce health risks.

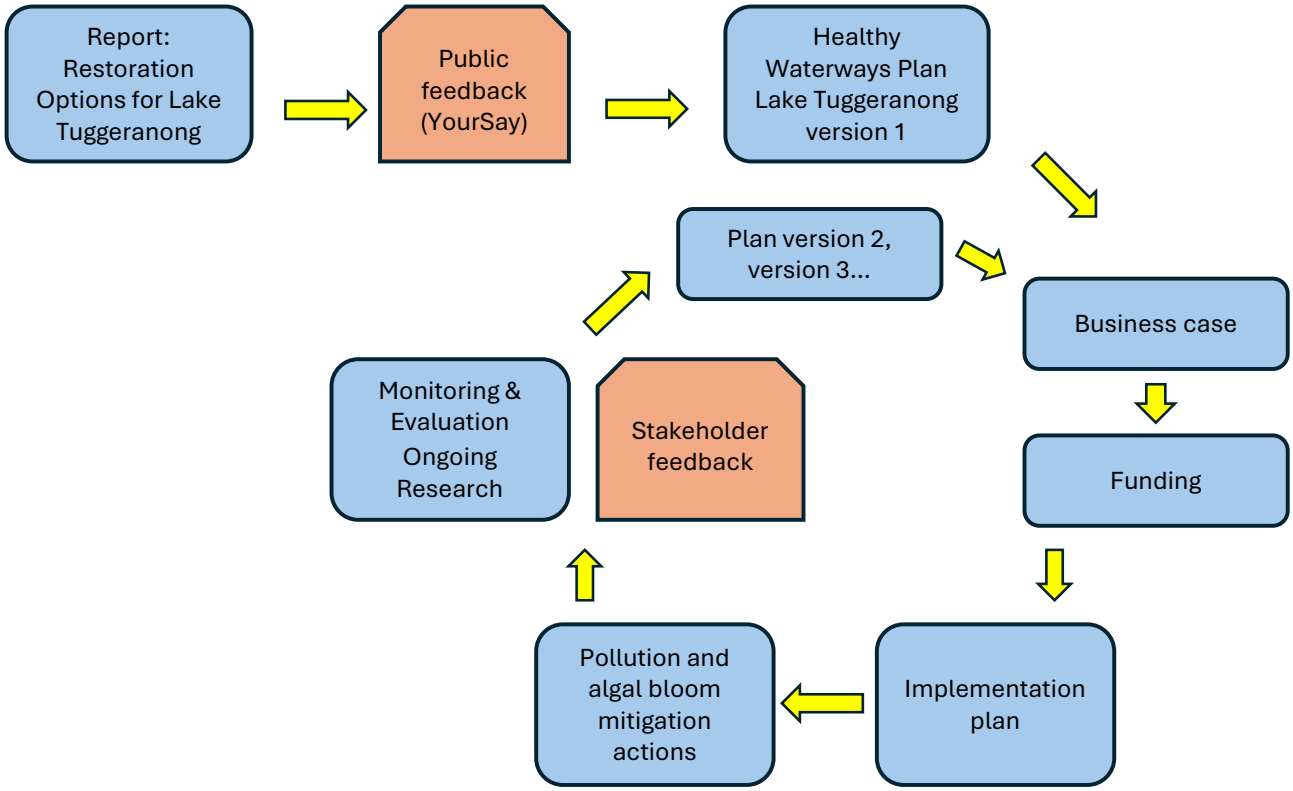


Figure 1. Role of Restoration Options for Lake Tuggeranong *in the adaptive management cycle for mitigating algal blooms in the lake.*

Vision

This report and the subsequent Plan address an ACT Government commitment for the 11th Assembly to *Develop and deliver a 10-year plan for a healthier Lake Tuggeranong*.

The 10-year vision is:
By 2035, Lake Tuggeranong is more consistently free of blue-green algal blooms and, when they do occur, they are short-lived so the Tuggeranong community can enjoy the lake for most of the year.

We need a 10-year time frame because new infrastructure assets will take time to build and become fully functional, and to allow enough time to assess the effectiveness of interventions while considering the background influence of year-to-year climate variability. Nevertheless, fulsome implementation of the Plan should lead to substantial improvements in water quality within several years.

Lake values

Lake Tuggeranong provides multiple social, economic and environmental values for the ACT and region community. However, the lake does not provide all these values consistently. The 2022 State of the Lakes and Waterways highlights that there are tensions between the competing values of urban lakes and waterways—for example the amenity of Lake Tuggeranong versus its role as a pollution trap—and widely differing expectations of urban water management (OCSE, 2022).

Mitigating downstream pollution

Canberra's lakes reduce downstream pollution by acting as sediment and pollution filters. NCEconomics (2023) estimated the market value of this function, known as 'avoided abatement cost', which describes how much it would cost to provide the equivalent pollution abatement if the lakes were not serving that function. They estimated value of Canberra's urban lakes as pollution filters using a hypothetical comparison of water quality outcomes 'with' and 'without' the lake, where water quality upstream of the lake was used as a proxy for water quality 'without' the lake (NCEconomics, 2023). Total nitrogen was used as the water quality indicator. This was used because pollution abatement assets can reduce multiple pollutants at the same time, so only the highest-cost pollutant for each lake was used, to avoid the risk of double counting. The abatement costs were based on the cost of creating equivalent abatement capacity by building water quality assets. The cost of water quality assets was derived from construction costs in the ACT in the six years from 2017 to 2023. The study estimated the net present value associated with Lake Tuggeranong's pollution abatement value is $133–144 million (over 30 years). As discussed in Part 7, water quality assets are not the most cost-effective option for mitigating phosphorus pollution, so this is likely an overestimate of Lake Tuggeranong's pollution abatement value.

However, Lake Tuggeranong is not always effective as a pollution filter. The 2023 State of the Environment Report concludes, 'Lake Tuggeranong does not appear to be consistently mitigating the effects of urbanisation for the downstream waters with periods of higher phosphorus and nitrogen concentrations within and downstream of the lake compared to upstream of the lake'.

Providing opportunities for recreation and amenity

Canberra's urban lakes and their catchments provide important social values for Canberra residents. Access to blue spaces also contributes to improving people's physical, mental and spiritual wellbeing (UK Environment Agency, 2020; Dushkova et al., 2021; Lal and Akhikari, 2024). It follows that when algal blooms require the government to close the lake for long periods, there may be negative consequences for people's health and wellbeing.

The high value that Canberra residents place in their waterways is reflected in several surveys and community engagements undertaken from 2016 to 2023:

- A 2016 survey of more than 7000 people on Canberra's urban lake use found that the activity most often rated as 'highly important' was walking with other people, followed by picnics/barbeques, cycling and using playground areas (Schirmer & Mylek, 2016).
- In community engagements as part of developing the Tuggeranong District Strategy, the Tuggeranong community said they value the lake for a range of recreational activities throughout the year, including walking, cycling, swimming, fishing and windsurfing (ACT Government, 2023b).
- In the findings of a 2018 ACT 'Better Suburbs' community survey, the citizen forum's first recommendation (out of 14) was to increase funding for lakes, ponds, wetlands, stormwater and water quality. This was ranked as more important for community members than issues such as street trees, roads, footpaths and public libraries (ACT Government, 2018).
- A report commissioned by the ACT Government in 2023 explored residents' willingness to pay for environmental amenity and recreational use of Canberra's lakes (NCEconomics, 2023). The report found that the total annual non-market economic value of the lakes based on pollution control and amenity was approximately $159 million a year for Lake Tuggeranong, with the economic value

from benefits to the community significantly outweighing the benefits attributable to water quality management (pollution abatement) provided by the lakes (Figure 2). (The much lower value of Lake Tuggeranong for pollution abatement in Figure 2 compared with its net present value is because Figure 2 reports annualised data whereas net present value is assessed for a 30-year period.)

- A 2023 survey of ACT residents indicated they were prepared to pay up to $70/per person/quarter (or $280/per person/year) to greatly improve the environmental (visual and smell) amenity of Lake Tuggeranong (NCEconomics, 2023). Across all lakes, the survey found that most lake users are infrequent, casual users who draw more value from lake amenity and lakeside facilities than from primary and secondary contact activities like swimming and boating. This finding is also consistent with findings from the earlier survey of Schirmer & Mylek (2016).

Environmental values

There is limited information on the ecological values of the lake. The Waterwatch Catchment Health Indicator Program (CHIP) 2023 report notes the lake has poor riparian condition with little native vegetation, but Eastern Long-necked Turtles, water dragons and occasionally Rakali (Australian native water rats) are present in the wetlands at the southern end of the lake (Upper Murrumbidgee Waterwatch, 2023).

The 2023 State of the Lakes Report found that the aquatic health of the lake supported ecological values to a 'fair' degree, noting limited information to determine a trend. This conclusion was based on the CHIP assessments and because water quality and ecosystem health of the lake are sufficient for the survival of stocked native fish (OCSE, 2022). Murray Cod and Golden Perch are stocked, primarily to support recreational fishing, it also to improve biodiversity and help balance the fish composition by adding native predators to the system. There are a lot of carp in the lake; surveys in 2015 and 2018 showed carp comprised around 90% of all biomass caught. This decreased to 60% in 2024 due to increased stocking of native fish (ACT Government, unpublished data, 2025).

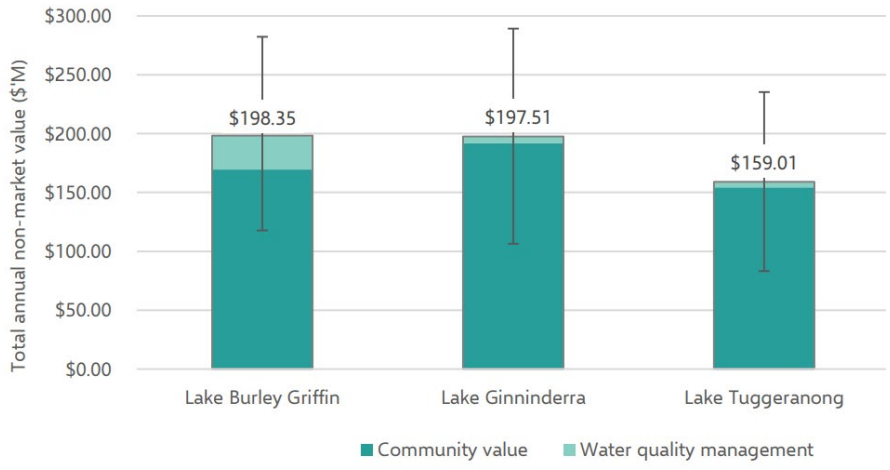


Figure 2. Total annual non-market value from ACT urban lakes. The community value is based on surveyed residents' willingness to pay for good water quality within the lakes through increases in rates. The water quality management value is based on the avoided cost of building water quality assets that provide the same level of treatment as the lake. Source: NCEconomics (2023).

Cultural values

In 2023 the Ngunnawal community conducted an Aboriginal Waterway Assessment (AWA) in the Tuggeranong catchment to assess the health of Country and the waterways from a cultural perspective. Their findings, summarised by Bradley Bell (pers. comm., February 2025), stressed the importance of:

- recognising Ngunnawal people as a part of the solution to restoring the health of Lake Tuggeranong
- reintroducing and respecting cultural practice in catchment management such as cultural burning and cultivation of pointer and keeping trees
- establishing Ngunnawal rangers
- continuing to conduct AWAs
- introducing more native plants to the creek and surrounding riparian and dry landscapes, including natives of cultural significance such as reeds for weaving
- restoring key features such as naturalising concrete drains
- creating a fully connected cultural way from the headwaters of Tuggeranong Creek to its confluence with the Murrumbidgee River; concerns were raised about pollution, including blue-green algae, entering the Tuggeranong Creek reach below Lake Tuggeranong
- considering river health and Country health as intertwined
- exploring opportunities for an entitlement to water for cultural purposes.

Lake Tuggeranong looking north towards Mount Taylor (photo: Jennifer Smits)

Legislative and policy context for managing water quality in Lake Tuggeranong

Lake Tuggeranong's management is prescribed by the *Planning Act 2023 (ACT),* which prioritises management objectives for all public land (including waterways) in the following order:

- Prevent and control floods by providing a reservoir to receive flows.
- Prevent and control pollution of waterways.
- Provide for public use for recreation.
- Provide habitat for fauna and flora (Schedule 3 [Part 3.2]).

Since there is little urban infrastructure downstream of Lake Tuggeranong to protect from floods, the primary management objective for Lake Tuggeranong under the Planning Act is to prevent and control pollution.

The Plan aligns with and supports the implementation of other ACT legislative and policy commitments on water quality, specifically the following:

- The ACT Water Strategy 2024–2044 Striking the Balance sets a 20-year vision for ACT water management as: *'A community working together, managing water wisely to support a vibrant, sustainable and thriving region'.*
  Outcome 1 of the Strategy—Healthy Catchments and Waterbodies—aims to achieve 'Well managed, functioning catchments that provide sufficient clean water for the environment and human consumption, support healthy waterbodies, and contribute to liveability of the ACT community'.
- Focus on improved water quality standards to support identified environmental values and permitted uses for Lake Tuggeranong. Environmental values and permitted uses are defined through the Water Use and Catchment General Code (the Code), a subordinate instrument of the *Water Resources Act 2007* (ACT). Under the Code, Lake Tuggeranong and its catchment is defined as drainage and open space with the following environmental values and permitted uses of:
  - discharge of stormwater
  - irrigation water supply
  - waterscape view
  - aquatic habitat (lowland streams, urban lakes and ponds, urban wetland)
  - water-based recreation (boating).
- Water quality standards are set through the Environment Protection Regulation 2005 (ACT), a subordinate instrument under the *Environment Protection Act 1997* (ACT), and support the policies, management objectives and values of the Code.
- The ACT and Region Catchment Strategy 2016–2046 establishes a 30-year vision to guide priority actions for a healthy Upper Murrumbidgee River region (upstream of Burrinjuck Dam to Tantangara Dam in NSW). Developed in partnership with the Australian Government, ACT Government, NSW Government, local councils, Icon Water and the community, it is currently undergoing a 5-yearly review.
- The 2002 Legislative Assembly committed to manage downstream water quality through an agreed motion that the water leaving the ACT via the Murrumbidgee River should be of no less quality than the water flowing into the ACT (ACT Legislative Assembly motion 5 June 2002 9.1[b]).
- The Canberra Urban Lakes and Ponds Land Management Plan's vision is to: *enrich local communities through the aesthetic, recreational, sporting, tourism, cultural and ecological values of*

lakes and ponds, and to provide opportunities for people to be involved in their use, care and management. Under this plan, 'recreation' and 'visual landscape' are listed as Lake Tuggeranong's highest values (Figure 3, ACT Government, 2022b).

- The ACT's Water Resource Plan, developed under the Murray–Darling Basin Plan, contains a Water Quality Management Plan that sets locally relevant water quality targets.

None of these legislative and policy commitments consider whether and how to reduce the problem of blue-green algal blooms in Lake Tuggeranong, but they do underpin this report, which fills that gap.

Lake Tuggeranong and its catchment

Three major tributaries deliver inflows to Lake Tuggeranong—Kambah and Village creeks in the north (draining a fully urban area) and Tuggeranong Creek in the south (draining urban and rural areas)—as do several minor drains (Figure 4). Tuggeranong Creek runs through a series of settling ponds to improve water quality—Isabella Pond then Lake Tuggeranong wetlands—before discharging into Lake Tuggeranong (Figure 4). Key lake statistics are shown in Table 1 and Figure 5.

Geographical setting and early history

Before it was developed, the Tuggeranong Creek catchment featured hills and valleys with a large, shallow gravel aquifer with 1.5 times the current lake's volume. Tuggeranong Creek would have had a hydrology consistent with a 'chain-of-ponds' system (Lawrence, 2012). Chain-of-ponds systems usually occur in shallow, alluvial valleys where a river doesn't carry flow under baseflow conditions; instead of a continuous channel the river forms a series of irregularly spaced ponds (Mould and Fryirs, 2016). The other tributaries may originally also have been damp valleys, chains of ponds or small creeks.

There is evidence to suggest Ngunnawal people have occupied the Tuggeranong Valley for more than 20,000 years. The name 'Tuggeranong' comes from a Ngunnawal word for 'cold place' or 'cold plains'. Tuggeranong Creek would have provided an important source of water. Important cultural sites in the valley include scarred trees found at Lanyon (canoe tree) and the Wanniassa–Kambah area (ACT Heritage Council, 2024). Axe-grinding grooves have been found in a sandstone outcrop in what is now the suburb of Theodore (Flood, 1996). Tuggeranong Creek remains a culturally and spiritually important part of country for Ngunnawal people today.

Europeans began grazing the valley with sheep and cattle in the late 1820s and homesteads were established close to watercourses, including Tuggeranong Creek. Lanyon Station was established in 1835 and the Tuggeranong and Lanyon Homesteads, which remain today, are reminders of this period.

Values

Value	Ecological	Fish	Visual landscape	Aboriginal	Historic	Recreation	Sporting	Tourism	Commercial	Flood management
Icon										
Status	Moderate	Moderate	High	Moderate	Moderate	High	Moderate	Low	Low	Moderate

Figure 3. Canberra Urban Lakes and Ponds Land Management Plan values for Lake Tuggeranong (ACT Government, 2022b).

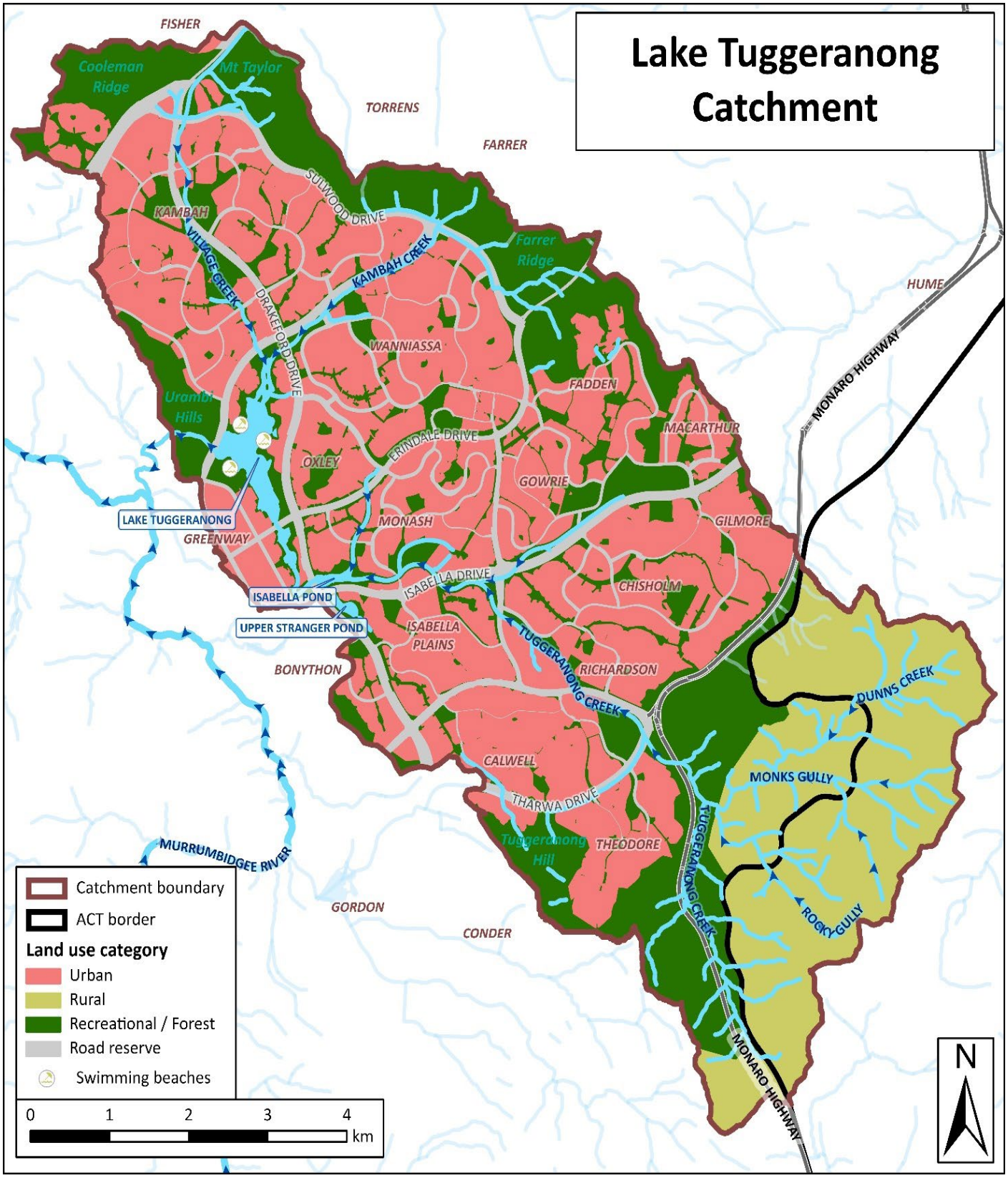


Figure 4. Lake Tuggeranong catchment showing its tributaries. The lake discharges into a short section of Tuggeranong Creek via an outflow channel and weir at the west corner of the lake. This creek then flows into the Murrumbidgee River.

Table 1. Lake characteristics and Tuggeranong climate. Source: (GHD, 2024) and www.bom.gov.au

Lake characteristic	
Size	**57 hectares**
Volume	**1790 megalitres (at normal operation)**
Average depth	**2.9 metres**
Maximum depth	**12.2 metres**
Average residence time of water	**58 days**
Average annual inflows	**9000 megalitres**
Minimum inflows (dry year)	**3000 megalitres**
Maximum inflows (wet year)	**18000 megalitres**
Tuggeranong climate	
Summer mean maximum temperature	**28.1 ^{0}Celcius**
Summer mean minimum temperature	**13.6 ^{0}Celcius**
Winter mean maximum temperature	**14.4 ^{0}Celcius**
Winter mean minimum temperature	**0.7 ^{0}Celcius**

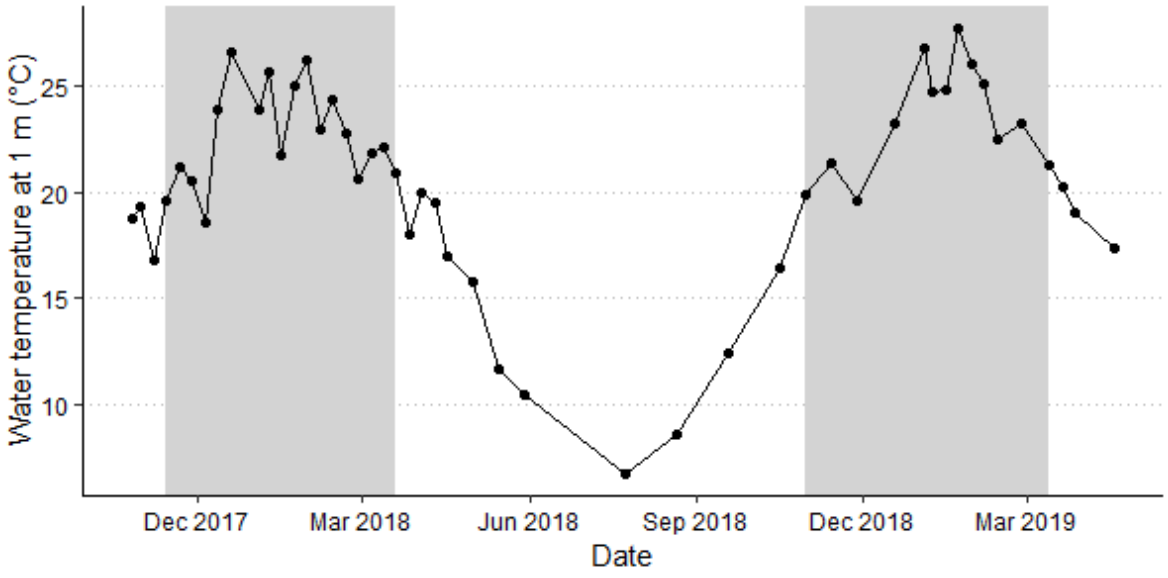


Figure 5. Surface water temperature in Lake Tuggeranong: Mean water temperature at a depth of 1 metre in the central basin of the lake. The grey rectangles that overlay the plot indicate the period from the first detected stratification to the final breakdown of stratification in the lake for the year. (Source: Figure 4-2 in Ubrihien et al., 2019, p.77).

An urbanised catchment—a new lake to filter sediment and concrete drains to channel flows

Tuggeranong was earmarked to be the third town centre of Canberra and was rapidly developed into suburbs throughout the 1970s and 1980s. Much of the shallow aquifer was drained using agricultural drains, stormwater pipes and concreting of the channel bed inset into the aquifer (Lawrence, 2012). To manage the flood impacts of urban runoff, most of the catchment's tributaries have been modified to become a constructed stormwater system of concreted open channels and underground pipes. Lake Tuggeranong was built in 1987 by damming the Tuggeranong Creek at Athllon Drive. While some rural land still exists within the Tuggeranong catchment, it now has a built-up area of more than 50% (Table 2).

Urbanisation changes flow regimes by increasing the impervious surface area (Walsh et al., 2012). Dey et al. (2024) estimated that runoff is four times higher in the Lake Tuggeranong catchment now than when it was a natural catchment. This is because roads, buildings and concrete are water-resistant materials that prevent water from being absorbed into the landscape. This leads to high surface water runoff that makes its way to the stormwater system (Ladson et al., 2006), carrying pollutants with it.

Table 2. Land use in the Tuggeranong catchment

Built-up area		Green space area	
Urban	**41.2%**	**Rural land**	**28.3%**
Roads/transport	**8.9%**	**Urban open space**	**10.2%**
Commercial land use	**1.8%**	**Natural bushland**	**9.5%**
Approx total	**52%**	**Approx total**	**48%**

Part 2 Water quality problems in Lake Tuggeranong

Lake Tuggeranong currently experiences frequent blue-green algal blooms and periods of elevated bacteria levels. Other water quality issues in the lake or its tributaries include high turbidity and industrial pollution events; for example, from paint (Upper Murrumbidgee Waterwatch, 2022).

This report and the subsequent Healthy Waterways Plan focus primarily on addressing algal blooms over other water quality issues. This is because of the higher potential health risk associated with blue-green algal blooms, the fact they contribute to a large proportion of lake closures, and the significant visual and odour impact on the community during severe blooms, such as reported in TCC (in draft).

Blue-green algae

Blue-green algae (Cyanobacteria) are a group of bacteria present in virtually all aquatic environments worldwide. Blue-green algae are not plants but are photosynthetic bacteria, reproducing rapidly when given sunlight and warm, nutrient-rich conditions (Joehnk et al., 2008). They are buoyant, forming surface scums known as a blue-green algal bloom. When this happens, they block the light that would otherwise be available for favourable plant growth, discolour the water and may release a range of toxins. Such blooms are a growing problem in Lake Tuggeranong, especially in summer. Algal blooms reduce visual amenity, release foul odours, pose a health hazard to residents and visitors and require the ACT Government to close the lake to recreational use.

Blue-green algae and human health

Some types of blue-green algae produce toxins (cyanotoxins) that can be harmful for humans, domestic animals and livestock that drink or make contact with the water, and for fish and other organisms living in the water.

There is increasing research and community interest in Australia and overseas into potential associations between cyanobacteria and neuro-degenerative diseases in humans (as noted, for example, by NSW Health, 2023). For example, studies have found an increased incidence of motor neurone disease in people living near waterbodies with blue-green algal blooms (Cox et al., 2003; Caller et al., 2009; Andrew et al., 2017; ABC Online, 2023; Torbick et al., 2018), although most of these studies could not confirm whether direct exposure to cyanobacteria had occurred.

The link between exposure to blue-green algae through primary or secondary contact and neuro-degenerative diseases has not been proven, except where foods have been grown in the presence of blue-green algae (Cox et al. 2003). Clusters of residents with motor neurone disease might be caused by a myriad of factors unrelated to blue-green algae blooms. However, researchers have yet to fully evaluate all plausible cause–effect mechanisms related to blue-green algae blooms and there is an argument for adopting the precautionary principle to mitigate potential risks to human health (Dunlop et al., 2021; Cox, 2021). This is particularly important while investigating airborne exposure pathways such as chronic exposure to aerosolised cyanotoxins downwind of affected waterbodies (Sutherland et al., 2021; Schaefer et al., 2020; Plaas & Paerl, 2021).

Lake Tuggeranong experienced a significant blue-green algae bloom over the summer of 2019/20 (photo: Alica Tschierschke)

Blue-green algae monitoring and lake closures

The Environment Protection Authority (EPA) monitors five sites in Lake Tuggeranong during the recreational season, which runs from October to April. The lake is closed to recreational use if either blue-green algae or faecal bacteria concentrations exceed the levels specified in the ACT Guidelines for Recreational Water Quality. Data analysed from 2015 to 2024 shows frequent closures throughout the recreational season with at least one swimming beach closed for more than 50% of the time for seven of those nine years (Figure 6).

In the 2022–23 season, EPA monitoring showed that all three swimming beaches were closed for almost the entire recreational season. In addition, blue-green algal blooms kept the lake closed to primary contact recreation from mid-January 2023 through to the beginning of June 2023, well beyond the recreational season.

Information about how water quality in Lake Tuggeranong is monitored, and current alerts and closures, is published on the ACT City Services website www.cityservices.act.gov.au.

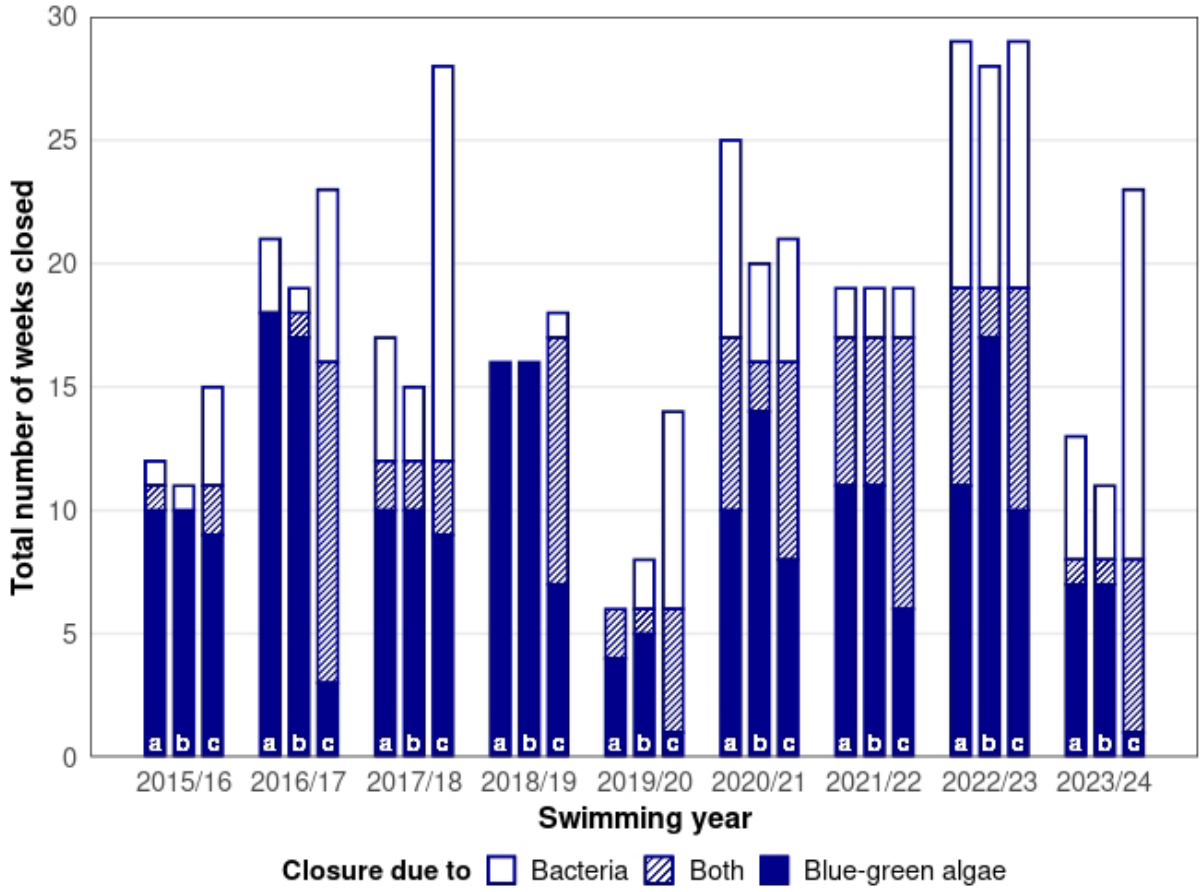


Figure 6. Number of weeks of the swimming season (30 weeks from Oct–April) that Lake Tuggeranong was closed to swimming at one or more beaches due to blue-green algae or bacteria between 2015 and 2024. Column a: Ngadyung Beach, Column b: Nguru Beach, Column c: Tuggeranong Town Beach

Faecal indicator bacteria

As Figure 6 shows, lake closures can also be due to the presence of faecal indicator bacteria, with Tuggeranong Town Beach showing a higher incidence of closures due to this cause.

ACT Health routinely tests ACT lakes for faecal contamination using the faecal indicator bacteria enterococci. These are a group of bacteria found in the intestines of humans and animals; their presence in water may indicate domestic sewage leaks or contamination from diffuse sources of human and animal waste. Water managers use enterococci as the standard faecal indicator bacteria to test water quality in recreational waters in Australia because they are well understood, easy to detect and their presence reliably predicts health risks associated with exposure to waterborne bacterial pathogens.

Monitoring work using Microbial Source Tracking is currently underway to understand the extent the faecal matter is coming from human or animal sources. Findings from this work will inform future iterations of the Plan. In the meantime, many of the interventions proposed to reduce algal blooms will also remove bacteria and other pollutants, such as excess carbon, nitrogen and total dissolved solids, that are potentially causing issues in the catchment.

Part 3: The cause of algal blooms

Drivers of algal blooms

The prevalence of blue-green algae is linked to the trophic state of a water body. Trophic state is a description of the biological productivity of a water body and depends on factors such as the concentration of nutrients used by plants (and blue-green algae) such as phosphorus and nitrogen (South Dakota State University Extension, 2022).

Water bodies in an oligotrophic state have very low nutrient concentrations and tend to have very clear water with little plant or algal growth and high oxygen concentrations that depress the release of algal nutrients stored in lake-bottom sediments. Hence, oligotrophic lakes are not prone to algal blooms. Water bodies in a mesotrophic state have a moderate amount of nutrients, moderately clear water, some algal blooms in late summer and oxygen depletion at bottom of lake as biomass decomposes. Most of the time, the water quality is within an acceptable limit to provide recreation, amenity and ecological benefits. Finally, water bodies in a eutrophic state are nutrient rich, with highly productive plant growth and high turbidity. They are seasonally deficient in oxygen, which may lead to fish kills. Eutrophic lakes may experience regular algal blooms.

When a waterway is in a eutrophic state, nutrient concentrations are so high that blue-green algae blooms are likely to occur whenever the conditions are stable (low flow), the water is warm enough and there is enough light penetrating through the water column (Paerl, 1988). These have been the conditions in Lake Tuggeranong for more than a decade, with blooms occurring every summer.

Nutrient overload in Lake Tuggeranong

It is widely accepted that phosphorus is the main nutrient that drives algal blooms in freshwater systems; without it, algal growth is severely limited (Carvalho et al., 2013). While nitrogen is also essential for algal growth, its absence in lake water does not limit algal growth in the same way as phosphorus because blue-green algae can source nitrogen from the atmosphere (a process called nitrogen fixing) as well as from the water. Therefore, to reduce the incidence and severity of algal blooms, we need to reduce the availability of phosphorus in the system. However, most management options to reduce phosphorus in stormwater will also reduce nitrogen.

In 2019, Healthy Waterways funded research into the conditions leading to algal blooms in Lake Tuggeranong (Ubrihien et al., 2019). This research found high concentrations of both dissolved phosphorus and nitrogen in the lake and determined that a large proportion of these nutrients were being delivered to the lake through the stormwater system. The research, conducted during a significant algal bloom, also demonstrated the importance of controlling phosphorus for limiting the severity of algal growth in Lake Tuggeranong.

Supply of phosphorus: catchment versus lake sediments

To reduce the phosphorus available to blue-green algae in the lake, and therefore the risk of severe algal blooms, we need to know where the phosphorus is coming from; whether it's mainly coming from the Tuggeranong catchment and reaching the lake via stormwater inflows, or if it is mainly coming from

phosphorus already trapped within the lake bottom sediments (Lawrence et al. 2000; e.g. Nikolai and Dzialowski, 2014).

Phosphorus is transported to the lake in stormwater, either in a dissolved or particulate form. Particulate forms are small pieces of plant matter containing phopshorus or phosphorus bound to sediments. Sediment-bound phosphorus is often a result of erosion in the catchment, or is blown into drains as dust and dirt. In its dissolved forms, phosphorus, especially phosphate, is more readily available for use by blue-green algae (bioavailable; Lawrence et al. 2000), making it more immediately problematic in causing algal blooms.

Much of the particulate phosphorus that is washed by storms into Lake Tuggeranong settles on the bottom of the lake and creates a nutrient-rich sediment layer. This creates an internal supply of phosphorus in the lake that can be released in a dissolved form later to become bioavailable through in-lake processes (Box 1).

Research by the University of Canberra (Ubrihien et al., 2019) found that the concentration of phosphorus observed in the surface water of Lake Tuggeranong was more than three times that required to support an algal bloom, with further significant amounts detected in sediments at the bottom of the lake. The internal supply of phosphorus—released from lake-bottom sediments—was enough to drive an algal bloom. However, the research found that the external supply of phosphorus to the lake from its catchment was five times the internal supply of phosphorus from lake sediments.

These findings suggest that internal supply of phosphorus is not driving most algal blooms in Lake Tuggeranong. Therefore, to mitigate blooms, water managers need to address catchment sources of phosphorus pollution before dealing with sources within Lake Tuggeranong.

Catchment sources of phosphorus

There are many potential sources of nutrients and other pollutants from urban catchments (as shown, for example, by Muller et al. 2020). Recent research and water quality monitoring in the Tuggeranong catchment has found that:

- phosphorus is mainly coming from urban, not rural, areas (Ubrihien et al., 2020; Upper Murrumbidgee Waterwatch, 2023)
- phosphorus is coming from many small sources across the whole catchment (diffuse sources), rather than from one or two large, concentrated locations (point-source) (Ubrihien et al. 2019)
- around 50% of the catchment-based phosphorus is in dissolved, bioavailable forms (Ubrihien et al., 2019), meaning it is available for uptake by blue-green algae
- leaves, grass clippings, fertiliser products (including composts and manures), soil and sewage are all likely contributing to catchment-based phosphorus (Ubrihien et al., 2019; Concepts of Change, 2023).

Soil

Soil can contain phosphorus both in its crystalline structure and adsorbed to soil particles. Sediments can release the adsorbed portion of phosphorus to water, after which algae can take it up. Because this is a slow process, most of the adsorbed phosphorus is not immediately bioavailable. However, sediments may release phosphorus over time once they are deposited in a lake.

Phosphorus adsorbed to clays suspended in the water column can take hours to weeks or longer to be released into water and available for uptake by algae.

Development sites

Tuggeranong District's population is predicted to be stable between 2022 and 2060, but there is still a potential future housing demand of 1100 dwellings by 2050 in the district forecast (ACT Government, 2022c, 2023b). While there are no greenfield suburbs planned, there are plans to redevelop existing areas through infill, and smaller-scale construction projects like knock-down rebuilds or major home renovations will also occur.

Development sites might contribute phosphorus to the stormwater system as phosphorus bound to the sediments in drainage or from roads that construction vehicles track mud onto. The University of Canberra examined the overall effect of urban development sites on the stormwater system in Lake Tuggeranong catchments in 2024 (Ubrihien et al., 2024b). They found that during storms, stormwater concentrations of total suspended solids were significantly higher downstream of development sites compared to upstream. However, levels of total and dissolved phosphorus did not vary significantly between stormwater sampled above and below development sites. The sediments from development sites are likely to be subsurface soils and thus low in phosphorus.

Leaf litter and grass

Phosphorus from plant materials can make up a substantial portion of the total phosphorus inputs in an urban catchment (Duan et al., 2014; Janke et al. 2017; Selbig, 2016; Muller et al. 2020). Plant materials have different amounts of phosphorus depending on the plant species and part of the plant (blossoms, fruits or leaves; Hill, et al., 2022).

Leaf litter (leaves, sticks, nuts, flowers) and grass clippings release nutrients as they decompose or are wet. This can happen quickly; research in the Tuggeranong catchment by the University of Canberra suggests that leaves will leach out most of their phosphorus within two days of either continuous or periodic inundation (Ubrihien et al., 2024a). In an urban environment with lots of impervious surfaces, leached, dissolved phosphorus cannot soak into the soil where soil particles could adsorb it or vegetation take it up. Instead, it enters the stormwater system where concrete channels and pipes convey it rapidly to lakes and waterways.

While much of Canberra is known for its deciduous street trees, nearly 80% of street trees in the Tuggeranong catchment are eucalypts (ACT Government, 2022a). From December 2022 to November 2023 the University of Canberra investigated the potential contribution of street trees' leaves to nutrients in the Tuggeranong catchment (Ubrihien et al. 2024a). They measured the deposition rate of leaves for the four most common eucalypt species onto impervious surfaces to determine their potential nutrient leaching rates, and then extrapolated this across the catchment by using estimates of tree canopy hanging over impervious surfaces. They found:

- the amount of leaf fall from these species was greatest in summer
- the phosphorus leached from leaves differed greatly between eucalypt species, with *Eucalyptus sideroxylon* leaching the most phosphorus
- the annual supply to Lake Tuggeranong of dissolved nitrogen, phosphorus and organic carbon contributed by leaves across the catchment as 25, 43 and 6,748 kg per year, respectively. They note these are probably underestimates because they only capture litter that falls directly from the overhanging canopy, not any that is blown or washed onto roads.

Box 1. Why did dry weather in 2019–2020 limit algal blooms?

The Tuggeranong catchment experienced a dry period from September 2019 to January 2020, with only 6 mm of rain falling in the catchment. In Lake Tuggeranong, no blooms occurred and there were no lake closures due to blue-green algae during that time.

Dry conditions impact the lake's susceptibility to algal blooms by impacting in-lake processes. During the warmer months, Lake Tuggeranong experiences thermal stratification. This is where a marked, stable zone of cooler water forms at depth in the lake where daylight does not penetrate and a warmer, light-filled, less-dense layer of water sits on top. In this top layer the light allows for photosynthesis to occur and bacteria, algae and other micro-organisms consume the available nutrients, most of which are washed in from the catchment. During dry periods, these top-layer nutrients are not replenished as they are consumed, which prevents blue-green algae from blooming.

Catchment phosphorus can also end up in the cool lower layer, with much of it bound to sediment on the lake floor where it's not bioavailable. Carbon also gets washed into the lake from the catchment as organic matter such as leaves. As bottom-dwelling bacteria feed on the carbon, they use up oxygen in the water; if the lake is stratified for a long time, this process creates an oxygen-depleted (anoxic) environment. Under anoxic conditions, phosphorus can be released from the sediment to become bioavailable. The released, bioavailable phosphorus can be brought to the top layer by diffusion or by mixing of bottom and surface waters as stratification later weakens or breaks down with winds, cool weather or rainfall.

In autumn in Lake Tuggeranong, the top layer of water cools and eventually sinks, forcing the bottom water, with its bioavailable phosphorus, to the surface. This is known as turnover and can cause a late season blue-green algal bloom. These are often of a shorter duration and less severe than summer blooms.

Blue-green algae can also access nutrients in bottom waters by modifying their buoyancy to move up and down through the water column.

University of Canberra researchers monitored phosphorus concentrations in the lake over the 2019/20 dry period and hypothesised that blooms didn't occur during this time because low baseflows meant there was a limited supply of nutrients in the top layer of the lake (Ubrihien et al., 2020). Their data also suggested that lack of carbon inputs may have led to reduced bacteria in the bottom layer, meaning less oxygen was consumed and the phosphorus remained bound to the sediments rather than becoming bioavailable.

One implication of this is that removing sources of phosphorus *and* carbon in the catchment may have a greater combined impact on reducing the incidence of algal blooms. The influence of dry vs wet weather conditions is also a key part of understanding year-to-year variability in the number, duration and intensity of blue-green algal blooms in Lake Tuggeranong.

The phosphorus content of *E. sideroxylon* leaves as measured here is comparable to the average phosphorus content of leaves from a variety of deciduous trees measured in northern hemisphere studies (Duan et al. 2014; Hill et al. 2022). The average phosphorus content of leaves from all the eucalypt species studied in the Tuggeranong catchment was generally slightly lower than the average for deciduous leaves.

In the same study the University of Canberra also measured grass clippings deposition (Ubrihien et al. 2024a). It found:

- nutrient deposition from grass clippings varies between seasons (with higher releases in summer) and between different mowing events
- an average 'mowing event' releases 33–76 mg of phosphorus for each square metre of impervious surface next to a mown area. The average varied depending on the season and whether clippings were continuously or intermittently soaked during the experiments.

Booksmythe et al. (2024) extrapolated these estimates to all the road surface within two metres of mown open space in the Lake Tuggeranong catchment, multiplied by the around 11 mowing events per year undertaken by ACT City Services, and found that this equates to clippings contributing between 85–200 kg of phosphorus per year to the lake.

Together, according to these estimates, leaves and grass contribute around 130–240 kg phosphorus per year on average to Lake Tuggeranong.

Urban open space mowing

ACT City Services manage the mowing of all urban open spaces in accordance with Canberra's Lakes and Ponds Land Management Plan and the complementary Urban Open Space Land Management Plan. Together, these plans require that:

- mowing programs aim to improve the ACT's water quality outcomes
- verge managers remove cut vegetation from guttering
- mowing cannot occur within five metres of waterbodies
- verge managers seek the Conservator of Flora and Fauna's advice on mowing areas next to certain waterbodies including Lake Tuggeranong District Park (south) and Isabella Ponds grassland.
- However, some cut vegetation will still end up blowing into gutters. The government is exploring ways to minimise this impact.

Fertiliser

Some residents and businesses use fertilisers to enrich soils with nutrients important for plant growth and health, including phosphorus, nitrogen and potassium. They fertilise residential lawns and gardens as well as public and private green spaces like sports fields, golf courses and gardens. Fertilisers can be a major source of phosphorus pollution of stormwater (Muller at al. 2020).

Fertiliser products come in different forms (manure, compost, chemical/synthetic) and have different release rates. The type of fertiliser used, how much is applied and when it is applied determine how well the plants can take it up, and whether it will stay in (or on) the soil or be transported out of the lawn, turf or garden bed and into waterways.

Nutrients can end up being 'exported' from residences to waterways either in dissolved or particulate form if too much fertiliser is applied (more than can be taken up by soils and plants), it is applied just before rain, or it is applied to soils that don't absorb water well.

Household fertiliser use

A Healthy Waterways funded survey in 2023 heard from 400 Canberra residents about the type and quantity of fertiliser they use (Concepts of Change, 2023). The findings of this survey were that:

- households use an average 84 kg of garden nutrient boosters (fertilisers, manures, compost) annually, which equates to 0.59 kg of phosphorus per household
- 6% of households use a paid gardening service and these accounted for 0.11 kg of annual phosphorus use by households, making a total of 0.70 kg phosphorus applied per household
- around half of Canberra residents use no fertiliser at all, with most of the fertiliser applied by the top 20% of users
- by volume, compost and manure are the most used fertiliser.

There are 21,000 low to medium density residential, detached and semi-detached dwellings with gardens in Tuggeranong (Booksmythe et al. 2024). Survey data on the amount of fertiliser applied by Canberra householders to their blocks combined with data from a literature review on the proportion of phosphorus that leaks into stormwater from different fertilisers (Booksmythe et al. 2024) yields a wide-ranging estimate of around 90–1,200 kg of phosphorus per year entering stormwater from fertilisers applied by householders, with an intermediate estimate of around 550 kg per year. The wide range is because of significant uncertainty in the export rates for phosphorus in fertilisers applied by residents or their gardeners.

Sports field fertiliser use

The Tuggeranong catchment includes approximately 70 hectares of managed sports grounds. Most of these are public grounds managed by ACT City Services Sport and Recreation, with about 7 hectares being privately managed.

The University of Canberra's research in the Tuggeranong catchment found that water samples taken near sports fields had slightly elevated phosphorus concentrations (total and dissolved) (Ubrihien et al., 2020). While they still represent a relatively small component of overall catchment phosphorus, they warrant further investigation.

More work is needed to understand the nutrient transport pathways around sports fields**.** Soil moisture testing and on-ground observations of public sports fields don't indicate high volumes of surface water runoff, so it's possible the elevated concentrations detected represent historical fertiliser use (going back decades) that is leaching out through the system at a subsurface level.

In general, both public and private sports field managers practice careful application of fertiliser as it represents a significant input cost. In 2022 several private sports field managers were surveyed about their fertiliser application practices (Edmonson, 2022). The survey found that private managers had a detailed knowledge of turf nutrient requirements and, as fertiliser is a major expense, were managing fertiliser application as efficiently and effectively as possible.

ACT City Services Sport and Recreation manage public sports fields in Tuggeranong using practices to improve irrigation efficiency and water retention, prevent surface water runoff and manage the chemical composition of the soil profile to improve nutrient uptake. These help prevent nutrients being exported from sports fields in runoff.

Installing additional bioretention swales between a sports field and the stormwater channel would help intercept and filter any nutrients exported from the sports fields.

Leaky sewerage pipes

Leaking sewers can be a major contributor to water quality issues in urban areas, causing increased nutrients, suspended solids and microbial pollutants to enter waterways. Sewers can become defective and leak from structural problems (broken joints, cracks, fractures and holes), operational problems (root intrusion, sediment accumulation and grease build up) and hydraulic capacity failures (Nguyen & Venohr, 2021). As holes are drilled in urban catchments for a variety of purposes, pipes can be damaged and leak into the stormwater system.

Healthy Waterways has commissioned a study to help characterise how large a problem sewage leaks might be, noting that they might affect not only nutrient concentrations but levels of faecal pollution, which can also result in lake closures. Results will be delivered in 2025 and will be incorporated into later versions of the Plan.

Part 4: Identifying solutions to the algal bloom problem

This report presents a series of analyses to identify and evaluate potential solutions to the problem of algal blooms in Lake Tuggeranong. The analyses were designed to achieve the following:

1. Model the effects of phosphorus inputs from the catchment on in-lake algal responses to help establish a target for reducing phosphorus pollution in Lake Tuggeranong (Part 5).
2. Identify options to either reduce levels of phosphorus in waterways or directly lower algal concentrations within the lake (Part 6).
3. Formulate potential water management scenarios made up of various pollution mitigation options that together reduce the level of phosphorus entering Lake Tuggeranong to the target level (Part 7):
    a. Estimate the costs, effectiveness and cost-effectiveness of a subset of the most feasible pollution mitigation options to help achieve the phosphorus mitigation target.
    b. Define two water quality management scenarios or combinations of workable pollution mitigation options that together reach the phosphorus mitigation target (and thus a substantial reduction in the incidence of blue-green algal blooms in Lake Tuggeranong):
        i. The most cost-effective option to achieve the phosphorus mitigation target.
        ii. A broader benefits option that not only achieves the target but provides stronger benefits than the cost-effective option in relation to supporting health outcomes, amenity and biodiversity, promoting climate resilience by reducing urban heat and recycling stormwater to irrigate sports fields.
    c. Re-configure the catchment water quality model to reflect the two management scenarios to understand the effect of implementing the pollution mitigation options together.
    d. Consider aspects of the feasibility and likelihood of being able to reach the required phosphorus mitigation target.

Based on the analyses, Part 8 plots a path forward.

Form of phosphorus

The models and other analyses presented below predict total phosphorus or its effects. There are not enough data to inform what proportion of the particulate fraction of phosphorus in Tuggeranong stormwater is bioavailable, so total phosphorus is used to predict algal responses—and total phosphorus data used in model calibrations—rather than dissolved or bioavailable phosphorus. So, even though algae actually take up dissolved phosphate, in these analyses, 'phosphorus' refers to total phosphorus.

Part 5: The target – how much phosphorus to mitigate?

Water quality modelling approach

Dey et al. (2024) developed two coupled water quality models to help estimate how much the supply of phosphorus from the catchment to the lake needs to drop to substantially decrease the incidence of algal blooms in the lake.

The first model is a catchment model that predicts how much water and phosphorus will reach Lake Tuggeranong and how this changes with daily variations in rainfall. The researchers initially used pollution generation rates from different types of land use, derived from the scientific literature, which they then calibrated with observations of water quality and flow in storm events that came from research by the University of Canberra (Ubrihien at al. 2019, 2020).

The second model is a simple in-lake model that predicts how phosphorus concentrations in the lake will change in response to varying runoff and inflow of phosphorus, and then the amount of algae that will grow in response to this. Kahn and Dey (2024) predicted the algal response indirectly using chlorophyll *a* concentration. Chlorophyll *a* is a pigment in many plants and algae that helps them absorb light and is used to assess the amount of algae (ANZECC and ARMCANZ, 2000). They then assigned predicted concentrations of chlorophyll *a* concentration to trophic states: Oligotrophic <5 µg/L, Mesotrophic <15 µg/L, and Eutrophic >15 µg/L.

Inputs of phosphorus from the catchment

The water quality modelling has shown that that the stormwater flowing off the catchment carries very high levels of phosphorus, with an average annual supply to the lake of 1,656 kg phosphorus/yr (Dey et al., 2024; Table 3). This is greater than the annual estimate of 500 kg estimated by Ubrihien, et al. (2019), which was based on data collected in a dry period, with reduced inflows from the catchment.

Table 3. Modelled annual total phosphorus (TP) supply to Lake Tuggeranong (kg/yr) generated for each combination of functional land use and surface type imperviousness: road, hardstand, roof and pervious (from Appendix 5 in Dey et al., 2024).

FUNCTIONAL LAND USE	Road TP (kg/yr)	Hardstand TP (kg/yr)	Roof TP (kg/yr)	Pervious TP (kg/yr)	Total TP (kg/yr)
Suburban	**322**	**169**	**314**	**140**	**945**
Commercial	**17**	**45**	**30**	**16**	**108**
Open space	**243**	**76**	**5**	**88**	**412**
Rural	**0**	**0**	**1**	**132**	**133**
Sports field	**0**	**0**	**0**	**58**	**58**
Total annual supply (kg/yr)	**582**	**290**	**350**	**434**	**1,656**

Based on research data (Ubrihien et al., 2019, 2020), about 50% of this input is in a dissolved form, with most of it ready for uptake by algae. Dey et al. (2024) predict that the seven constructed wetlands built in Stage 1 of Healthy Waterways have reduced the amount of phosphorus entering the lake annually by 214 kg, from 1,656 kg to 1,442 kg.

Current and target supply of phosphorus to the lake

Current supply

Kahn and Dey (2024) used an in-lake algal response model to determine the phosphorus mitigation target (Figure 7). Under current flow and levels of phosphorus supply (Figure 7, 'No P reduction'), their modelling clearly indicates that Lake Tuggeranong will remain in a eutrophic state, with chlorophyll *a* concentrations over 15 μg/L, even in years with relatively little rainfall when smaller amounts of nutrient are transported to the lake. This fits with observations of consistently high levels of phosphorus and frequent blue-green algal blooms in the lake in recent years. It also supports the findings of a 1982 hydrological study of the catchment, which predicted that based on nutrient levels at the time, the lake would exist in a eutrophic state for most of the time (Beer et al., 1982).

A suitable and realistic chlorophyll *a* concentration target range to aim for in Lake Tuggeranong, correlating to a mesotrophic state, is in the range of 5–15μg/L. This target range is based on the following considerations:

- The model predicts that in a predevelopment scenario (when the area was entirely native bushland), Lake Tuggeranong would typically have been in a mesotrophic state, with a chlorophyll *a* concentration in the range of 0–18 μg/L (Figure 7: 'Predevelopment') (Dey et al., 2024).
- The ANZECC guidelines specify a range of 5–15 μg/L for mesotrophic conditions (see Table 8.2.1 in ANZECC and ARMCANZ, 2000).
- In the nearby Googong Reservoir, a water supply with a reduced level of disturbance, chlorophyll *a* concentrations are typically in the range of 0–28 μg/L, with annual averages consistently in the range of 4–10 μg/L.
- The Australian Environment Council recommends that chlorophyll *a* concentrations in recreational waterbodies be kept below 20 μg/L for recreational lakes and 5 μg/L for water supply reservoirs (AEC, 1987). In the ACT, the Environment Protection Regulation sets a more stringent target of less than 10 μg/L for contact-based activities (noting that direct observations of algal counts rather than chlorophyll *a* concentrations are used to determine when to close lakes in the ACT).

Target supply to mitigate algal blooms

Kahn and Dey (2024) predict that a mesotrophic state can be achieved in Lake Tuggeranong for most the time if the average annual phosphorus supply to the lake is reduced by 700 kg, having already accounted for the effect of the seven constructed wetlands built in Stage 1 of Healthy Waterways (Figure 7). They did not adopt a higher target because the further reduction in phosphorus would not significantly reduce algal blooms but would cost a lot more to achieve.

A target of 700 kg represents approximately 50–60% of the total supply of phosphorus to the lake from the catchment.

Note that these targets are indicative only, developed for the purpose of supporting the modelling exercise and communicating the benefits of different management scenarios. While the 700 kg target is based on annual averages, the required reductions will be higher in very wet years and lower in dry years.

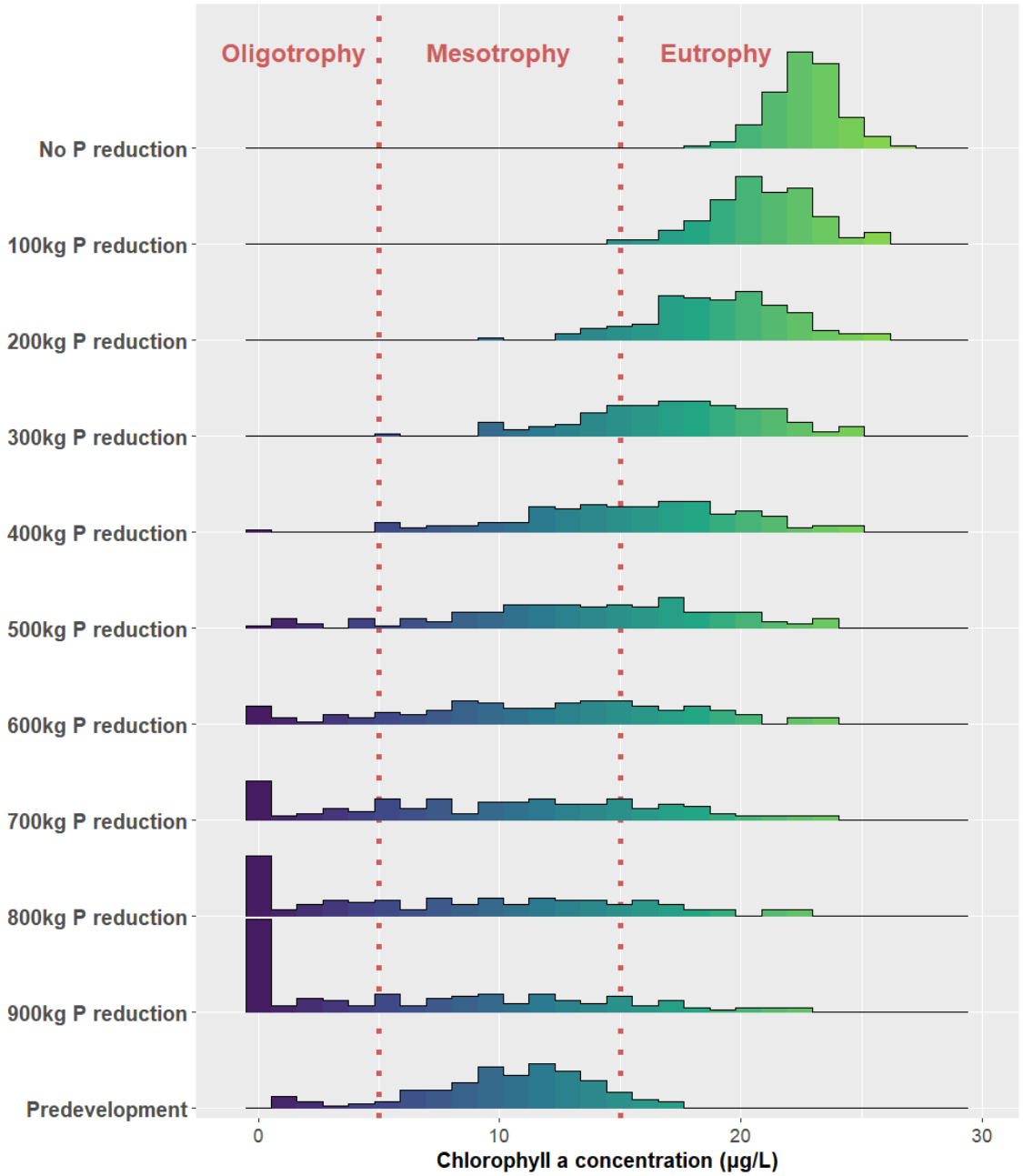


Figure 7. Modelled distribution of predicted chlorophyll a concentrations (an indicator of trophic state) in Lake Tuggeranong under varying supply of phosphorus (P). The top row 'No P reduction' shows the lake in its current, eutrophic state. The bottom, 'Predevelopment' row shows the predicted chlorophyll a concentrations if there were no urban development upstream of the lake, indicating that it would have been in a mesotrophic state in most years, but still occasionally have reached a eutrophic state, supporting algal blooms.

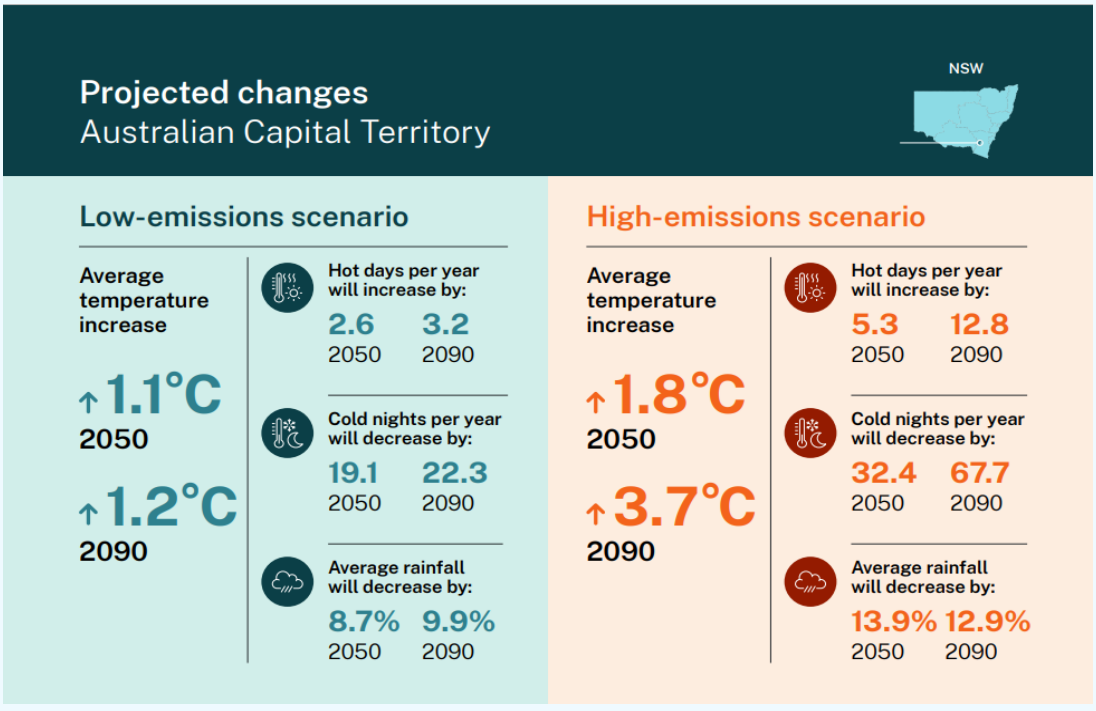
Box 2. How will climate change affect nutrient dynamics and algal blooms?

In the future, the ACT will experience hotter average temperatures, more hot days per year and decreased average rainfall, particularly in spring (NSW Department of Climate Change, the Environment and Water, 2024). Across Australia, including the ACT, extreme rainfall events (storms) will become more intense. The Australian Rainfall and Runoff Guidelines project the biggest increases for very short storms. For example, under scenario SSP3-7.0, storms of under one hour will increase in intensity by 18% by 2030, and by 29% by 2050 (Wasko et al., 2024). More intense localised storms may increase the frequency of 1% Annual Exceedance Probability (AEP) (in layman's terms, 1 in 100 year storms) flooding events in the ACT. The ACT Government's ACTMapi website shows the extent of riverine flooding that would be expected during a 1% AEP flood event.

These changes to temperature, rainfall averages and storm intensity will likely impact nutrient dynamics in the Tuggeranong catchment, for example:

- higher storm intensity will impact streamflow and the way that nutrients are mobilised in, and transported through, the catchment
- hotter temperatures will affect when eucalypt species drop their leaves, how much they drop and the phosphorus content of the leaves
- higher water temperatures will affect in-lake processes like thermal stratification and turnover.

These effects are anticipated but have not yet been studied or quantified in the Lake Tuggeranong context. However, a response framework developed for Victoria's waterbodies argues that climate change will exacerbate blue-green algal blooms through factors including increased temperatures, stronger stratification, increased nutrient levels due to extreme wet/dry periods, longer residence times of water in water bodies and storm events (HydroNumerics, 2020).



Climate change projections for the ACT (NARCliM 2024)

How will the lake behave if the target phosphorus reduction is achieved?

With a 700 kg annual reduction in phosphorus, modelling by Kahn and Dey (2024) suggests the lake will be in a mesotrophic state—or better, in an oligotrophic state—in approximately 75% of years (Figure 7). Under these conditions, some blue-green algae would be present, but the likelihood of problem blooms would be lower than now, and the lake should mainly be in a condition suitable for contact-based activities. Closures may still occur due to elevated levels of faecal indicator bacteria.

The modelling also reveals there will likely always be considerable variation in the concentration of phosphorus in Lake Tuggeranong over time, driven by variation in climatic conditions. Specifically, in very wet years the significant amount of phosphorus coming off the catchment will likely overwhelm any attempts to reduce nutrient levels in the lake, leading to eutrophic conditions.

For example, with a target 700 kg annual reduction in phosphorus, the modelling predicts that in about 25% of years (the wettest years) the lake will still be in a eutrophic state, with sufficient nutrients to promote algal blooms. However, wet years also tend to be relatively cooler, which would reduce the likelihood of severe blooms. Some algae would also flush from the lake in wet years.

Conversely, in relatively dry years, any phosphorus removed from the system represents a relatively larger proportion of the total supply reaching the lake. So, for a target 700 kg annual reduction in phosphorus, modelling by Kahn and Dey (2024) suggests about 25% of years (the driest years) will experience oligotrophic conditions in the lake, with very low concentrations of nutrients, relatively clear water and very little risk of algal blooms occurring.

Reconciling some estimates based on research and modelling

There are two notable instances where the predictions from catchment water quality modelling and results from catchment research are not fully aligned.

The first relates to the contribution that fertiliser applied on residential gardens makes to phosphorus levels in stormwater. The Lake Tuggeranong catchment water quality model predicts that only around 140 kg/year of phosphorus is generated from pervious suburban land use (Table 3). This is the land use category representing residential yards and gardens, which would include fertiliser use by residents or their gardeners and other sources of phosphorus from residential blocks. The model is based on published literature of phosphorus draining from household blocks and was calibrated to the observed data on phosphorus concentrations in runoff and waterways around the catchment.

In Part 4, the amount of phosphorus entering stormwater from residences, based on surveys of residents, is conservatively estimated at around 90–1,200 kg of phosphorus per year, with an intermediate estimate of around 550 kg per year. The model prediction of around 140 kg/year leakage is within, but at the very lower end, of the estimate of around 90–1,200 kg of phosphorus per year based on the surveys of residents. Since 140 kg/year is well below the middle estimate of 550 kg/year, the difference between the prediction based on modelling and the estimate based on research warrants further investigation.

The second instance where the catchment water quality model and research yield different results relates to the contribution of phosphorus due to leaves and grass. The effect of nutrients leaching from leaf and grass litter—and soils and other road detritus—on roads was assessed through the catchment model as 582 kg/year (Table 3). This is greater than the research estimate of around 130–240 kg/year based on leaf-fall patterns plus biomass

of grass on road verges in Part 3 (Ubrihien et al., 2024a). However, there are reasons to believe that the estimates for leaf-fall biomass are underestimated (see Part 3). To date there have been no independent estimates for how much soil and non-leaf debris is on the roads and how much extra phosphorus this contains.

Further research is required to ensure fertilisers applied to household blocks are not making a larger contribution than suggested by the modelling, and to clarify the contribution of leaves and grass. However, both sources of phosphorus pollution are likely to be significant and are preventable so consideration needs to be given to reducing both sources of pollution.

Part 6: Options to mitigate phosphorus pollution

Previous research and programs in the ACT and elsewhere have identified and trialled a range of potential phosphorus mitigation options. For this report, options were shortlisted based on the availability of data to support cost-effectiveness analyses. In some instances, cost-effectiveness data were based on local trials of options. The Healthy Waterways team has yet to evaluate some other very promising options because of a lack of relevant data on which to base cost-effectiveness. These options will be evaluated as data on their cost-effectiveness becomes available through ongoing research and trials.

Conceptually, there are three stages in the 'journey of the stormwater' where phosphorus might be removed from the system or algae may be directly treated through various options (Table 4 and Figure 8). This section describes these options.

Table 4. Pollution mitigation options to remove phosphorus in the 'journey of the stormwater'.

	Where to remove phosphorus/treat algae	Mechanism
1	**At the source/s**	Reduce the amount of phosphorus before it enters the stormwater system (phosphorus pollution prevention).
1.1	Enhanced street sweeping	Increase the frequency that streets are swept.
1.2	Pollution prevention partnerships	Promote waterways-friendly gardening practices by working with community and business.
1.3	Water sensitive urban design (WSUD)	Adopt suburb designs—or retrofit elements to existing suburbs—that minimise the impacts of urban development on the natural water cycle and better integrate suburbs into the natural landscape.
2	**In the stormwater system**	Use water sensitive urban design infrastructure to divert runoff in storms, allowing it to slow down, be filtered naturally by wetlands and/or to seep slowly back into the landscape.
2.1	Infrastructure that reduces stormwater peaks	Retain stormwater in green belts, detain it in tanks and/or recycle it.
2.2	Infrastructure that improves stormwater quality	Create various types of constructed wetlands.
2.3	Maximised effectiveness of water quality infrastructure	Sequentially place constructed wetlands and other water quality/quantity assets along drainage lines and waterways to reach end-of-system targets and maintain the infrastructure in good condition.
3	**In the lake**	Use anti-algal agents that either compete with algae or treat the algae once it grows to bloom proportions.
3.1	Reduction of nutrient levels and/or competition with blue-green algae	Deploy materials or processes that remove nutrients from surface waters, where algae live, or promote natural competitors to algae.
3.2	Direct treatment of algae	Apply algicides or physical mechanisms to destroy or remove algae.

Reduce the amount of phosphorus entering stormwater at the source

There are several ways to prevent waters from becoming polluted in the first place, rather than allowing them to become polluted and then treating the pollution or its effects within the stormwater system.

Street sweeping

The ACT Government's street sweeping program removes leaves and debris from kerbs and gutters along Canberra's urban roads. Every street in Canberra receives at least two full sweeps each year, with additional local sweeps between April and September during the heavy period of leaf-fall (See: https://www.cityservices.act.gov.au/roads-and-paths/road-infrastructure-and-maintenance/street-sweeping).

One option is to increase the frequency of sweeps. As described in Part 4, leaf litter and grass clippings release nutrients quickly as they decompose or are wet. They lose most of their phosphorus within two days of either continuous or periodic inundation (Ubrihien et al., 2024a). The intent of increasing the frequency of street sweeping is therefore to remove leaf and grass litter from gutters before the phosphorus and other nutrients have had a chance to leach out of the litter.

Pollution prevention partnerships

Canberra's residents affect waterway health in the way they manage leaves, grass and fertilisers on their blocks. Through Healthy Waterways, the ACT Government has been building expertise in supporting households to prevent stormwater pollution since 2016. It is working with the community to improve awareness and to support households to adopt practices that promote waterway health, like collecting leaves from the road verge.

Since the evidence began to point strongly to leaf litter in gutters and on paved surfaces as one of the top pollutants, programs have been developed and tested that target leaves directly.

From 2020–23, the government partnered with Griffith University and community stakeholders to test numerous interventions under the project title 'The Leaf Collective'. Three iterations of the program were run—two during autumn and one during summer. In all three campaigns householders reported an increase in the volume of leaf litter they collected from areas draining to stormwater. On average, they collected 20% more than the control groups collected. Attitudes towards the value of leaf litter also changed, with more people adding leaves to compost or using them to create leaf mould, and fewer people disposing of them inappropriately in their general waste bins.

From 2023–25, the government has delivered a smaller program. It features the most popular elements of the earlier pilots, such as the leaf-bag giveaway and leaf cages in schools, and is gradually building in more offerings. Community stakeholders and individual community members consistently give positive feedback about these initiatives.

While our understanding of the impacts of fertiliser use on phosphorus pollution in stormwater is less advanced, the ACT Government piloted a 'Love the Lakes' program in May 2024 that aimed to reduce garden fertiliser use in households that use high amounts. Concepts of Change (2023) interviewed 600 households across Tuggeranong and coached householders (via telephone or in-person) about ways they could reduce fertiliser use. When the householders were contacted again in late 2024, they reported an average 36% decrease in fertiliser use during spring.

Through the **Healthy Waterways Plan for Lake Tuggeranong**, we can at look to how to remove phosphorus at three distinct stages in the 'journey of the stormwater'.

Reduce the amount of phosphorus entering the stormwater system:

1. Support the community to help stop leaves and grass from accumulating along our verges and street drains.
2. Work with government, businesses and the community to minimise the amount of fertiliser entering urban stormwater.
3. Work with government and universities to better understand and manage the link between street tree leaves and grass clippings and the amount of nutrients in the stormwater.

Slow the flow and filter – reconnect water back into the landscape and filter nutrients out of the stormwater:

4. Intercept and treat nutrient–laden stormwater running off sports fields. Also reuse stormwater from elsewhere to water the sports fields. This will reduce the amount of runoff and amount of nutrients flowing into Lake Tuggeranong.
5. Provide opportunities for stormwater to be absorbed and treated in the landscape while improving habitat connectivity, through green infrastructure like swales, raingardens and wetlands.

Manage the in-lake environment

6. Investigate the drivers, habitat enhancements and possible in–lake treatments to reduce the incidence of blue green algal blooms.

ACT Government

Figure 8. Conceptual model showing where phosphorus can be removed from its source to the lake.

Garden service providers were also contacted. They reported applying an average 1.78 kg of phosphorus per garden per year, which accounts for about 15% of the total amount of phosphorus applied across Canberra. Working with garden service providers offers another potential avenue to reduce fertiliser use.

Water Sensitive Urban Design

For many decades, town planning adopted engineering solutions aimed at flood mitigation that turned many ACT waterways into straight pipes and concrete drains. These engineered systems are very efficient at conducting stormwater, and the nutrients it carries, rapidly and directly out of urban landscapes to the natural waterways without opportunities for treatment by catchment soils and vegetation. Studies into urban runoff in storms suggest it has fewer adverse impacts on water quality in natural waterways if there is less direct flow from impervious surfaces, such as roads, to natural waterways (Ladson et al 2006, Walsh et al. 2022).

Water Sensitive Urban Design (WSUD) planning, landscaping and infrastructure promote infiltration of urban stormwater into the soil, increase water retention, reduce flow rates and filter out nutrients from stormwater in the catchment. Using WSUD helps reduce runoff and improve water quality before stormwater enters natural waterways such as Lake Tuggeranong (for example, see Ubrihien et al. 2020).

WSUD infrastructure has been a key feature of Healthy Waterways over its 10 years to date. The program has built 27 water quality assets, predominantly ponds, wetlands, rain gardens and channel restorations across urban Canberra since 2014.

In developing these assets, Healthy Waterways worked across government to ensure the asset designs were either approved against Municipal Infrastructure Standards (MIS) or Municipal Infrastructure Technical Standards (MITS) or are new and effective designs. The new designs allow for an expansion of the MIS and MITS standards, which means there are now more options in the infrastructure toolkit that water managers can use to improve stormwater quality.

Infrastructure that reconnects storm runoff with its catchment

WSUD infrastructure may target either reducing the amount of runoff in storms or improving stormwater quality or both. Features can be added to an urban area to retain water in the landscape or route small streams of stormwater back into green space, such as castellated kerbs and landscape contours (Table 5). This allows stormwater to soak back into natural catchment areas where it is mostly retained (for example, it evaporates or is taken up by plants) or is cleansed by surface vegetation and soils. At one end of the spectrum these features are capital works; for example, Healthy Waterways built some small runoff infrastructure assets such as castellated kerbs to reduce the volume of water in the stormwater system. At the other end of the spectrum, landcare groups can improve stormwater retention simply by roughening drainage lines (Alluvium, 2023). In the case of stormwater recycling, water is diverted from pipes, drains or WSUD infrastructure and usually treated before being used, sometimes to irrigate green space like sports fields and golf courses, and sometimes for other purposes, such as in construction.

Table 5. Types of runoff infrastructure built in the ACT.

Type of infrastructure	How it works
Castellated kerbs	Roadside drains have gaps in them where some of the stormwater is diverted into adjacent green space where the stormwater can be absorbed into the soil.
Landscape roughening	Small mounds are dug into slopes to temporarily capture runoff and allow it to sink into the soil (Alluvium, 2023).
Rainwater tanks	Hold water in the landscape using above or below ground storage tanks for rainwater usually sourced from roofs.
Detention tanks	Built underground to temporarily store stormwater sourced from drains and often used to irrigate sports fields.
Stormwater recycling	Stormwater is diverted to tanks before being cleaned and used instead of potable water; for example, to irrigate sports fields. It may be cleaned by a combination of constructed wetlands, groundwater aquifers, and/or a filtering unit in a shipping container.

Slow the flow and filter the stormwater

Infrastructure that reduces stormwater peaks

Tanks can be used to temporarily store stormwater before the water is either used (for example, to water resident's gardens) or released back into the stormwater system. The delayed release of stormwater reduces peak flows and allows downstream wetlands and ponds more time to process and treat a greater volume of the stormwater.

Infrastructure that improves stormwater quality

WSUD infrastructure is built with a primary function of treating pollutants and improving water quality. This infrastructure includes a variety of constructed wetlands, where plants and soil media filter nutrients and fine sediment particles from the stormwater. Different types of constructed wetlands are shown in Table 6. Constructed wetlands can also have several added benefits such as providing riparian (waters-edge) and aquatic habitat for wildlife within urban areas, reducing urban heat, enhancing Traditional Owner values and contributing to urban amenity. The wetlands, ponds and raingardens built in the Healthy Waterways program are examples of WSUD infrastructure that target improving stormwater quality by removing pollutants.

In the Tuggeranong catchment, research by the University of Canberra has shown that most nutrients are mobilised and transported during big storm events where flow volumes are high (Ubrihien et al., 2020). In this situation, wetlands are only able to treat a small proportion of the nutrient-laden flows, with the remainder bypassing the wetlands. Part 7 further considers the implications of this.

Maximising the effectiveness of WSUD infrastructure

Treatment trains

The effectiveness of water quality assets can be maximised through careful design and sequential placement of different types of assets. A series of assets working in sequence to reduce and improve stormwater quality is known as a treatment train.

Box 3. Urban catchments create more runoff in storms

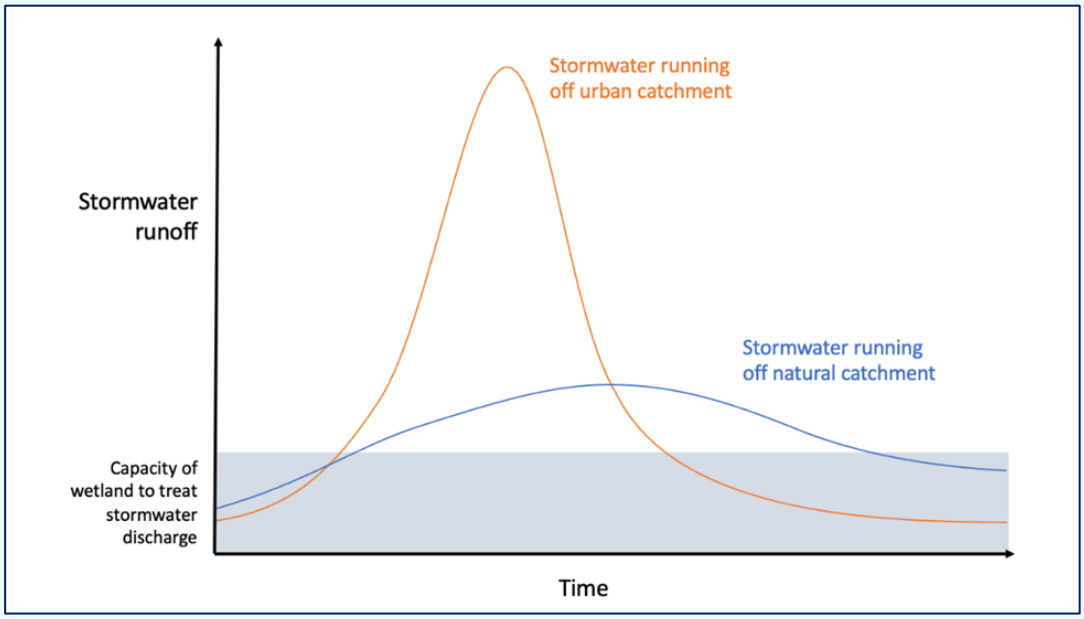
Phosphorus pollution in Lake Tuggeranong is, in large part, a result of urbanisation. Water that flows over the land surface is known as runoff, which in urban areas quickly enters the engineered stormwater system.

In a natural catchment, rain falls on trees and vegetation, which take energy out of the water and allow it to be absorbed into the soil and bedrock. When the ground is saturated, water will eventually start to run off, but at lower volumes and speeds than in an urbanised catchment. When the runoff ceases, water will be slowly released from the landscape, allowing waterways to flow at a gentler rate over a longer period.

The highly urbanised nature of the Lake Tuggeranong catchment means that much of the catchment is covered by buildings, roads, concrete paving and other surfaces that water can't soak into, known as impermeable surfaces (Codner et al., 1988). Rain therefore runs off impermeable surfaces. This runoff washes lots of phosphorus from these impermeable surfaces into the stormwater system, which is also highly impermeable, and on to Lake Tuggeranong. Models estimate that the volume of runoff from the Lake Tuggeranong catchment is three times higher than that of a natural catchment (Dey et al., 2024). Consequently, urban stormwater systems are very 'flashy' waterways, with water levels rising quickly after rainfall, and falling back to baseflow levels almost as quickly (see the hydrograph in the figure below).

Large amounts of runoff in an urban system make it difficult to treat the high levels of phosphorous in stormwater. A wetland only has the capacity to treat a limited amount of stormwater per hour, so the smaller the volume and longer the duration of flow from a storm event, the greater the proportion of stormwater that will be treated.

By reconnecting more runoff and stormwater back into the landscape, we can start to return the catchment to a more natural flow state. This would provide more opportunities for water to be absorbed into the landscape, and for wetlands and their plants to better capture phosphorus from the remaining stormwater and prevent it from reaching Lake Tuggeranong.



Stormwater flow in an urban vs natural catchment and the capacity of a wetland to treat the stormwater. The grey area indicates the volume of water that a wetland can treat over a given period and shows the 'flashy' nature of stormwater coming off an urban catchment.

For example, placing runoff infrastructure such as castellated kerbs higher up in the catchment can divert water back onto grassy areas, which reduces the volume of phosphorus-laden stormwater running down the drains. Detention tanks, like rainwater tanks connected to roofs of houses, can capture stormwater peaks and either release some of the stormwater slowly after the storm has passed (for example, by using a specially designed 'leaky tank') or be used for watering gardens. Around playing fields, smaller swales and raingardens filter out coarse sediments and some nutrients from the stormwater before it flows downstream to bigger wetlands and ponds.

Using a treatment train in this way is particularly effective during big storm events by allowing bigger wetlands downstream to more effectively treat more of a storm event's runoff (and for longer) because flow volumes have been reduced upstream and the first pass through smaller filtering infrastructure that has already filtered some nutrients and sediments, reducing the pressure on the bigger downstream wetland.

Maintenance

When sediments do build up in a constructed wetland and the water plants absorb all the nutrients they can, the wetland needs to be maintained to retain its ability to clean the stormwater. This is an often-overlooked part of managing them for optimal effectiveness. Maintenance can include removing built-up sediments, which reduce the wetland's capacity to hold and filter stormwater, and harvesting water plants regularly to remove the nutrients they contain from the system and prevent them from decaying back into the water.

Raingardens are renowned within the stormwater industry as particularly sensitive to poor maintenance. They can become completely dysfunctional if their inlets become blocked and their surface sediments clogged and overgrown with trees or weeds that disrupt their ability to function properly. Operational and maintenance requirements are a key design feature of WSUD infrastructure. The choice of assets and the level of maintenance funding need to be considered before committing to such projects.

Table 6. Types of constructed wetlands built in the ACT.

Type of infrastructure	How it works
Ponds	Stormwater is routed to one or more settling ponds fringed with emergent aquatic plants. The overflow is returned to the stormwater channel.
Traditional wetlands	Stormwater is diverted from channels and routed through a sequence of pools and shallower beds of emergent aquatic plants before being returned to the stormwater drain.
Raingardens	Stormwater floods the soil surface, which has dense growth of emergent aquatic plants, then percolates downwards through the soil and is collected in pipes and returned to the stormwater drain.
Bioretention swales	These smaller, vegetated drains operate in the same way as raingardens and are often targeted at point sources of pollution such as sports fields.
Subsurface wetlands	Stormwater is routed horizontally through gravel beds overlain by soils and emergent aquatic plants. Plant roots extend into the gravel beds. The overflow is returned to the stormwater drain. The aquatic plants remove dissolved nutrients, as in a hydroponic garden.
Channel re-naturalisations	Concrete stormwater open drains or channels are replaced with various combinations of pools, riffles, runs and beds of aquatic plants. In the process, the channels may be reconnected with surrounding floodplain sediments and aquifers.

Box 4. Examples of Water Sensitive Urban Design (WSUD) in Tuggeranong

WSUD infrastructure has been a key feature of Healthy Waterways. Twenty water quality assets, predominantly ponds, wetlands, rain gardens and channel restorations, were built in Healthy Waterways Stage 1. Seven of eight assets have been built in Stage 2, with the final asset slated to be built in 2025.

1. Bioretention swale at Kambah District Playing Fields

2. Pond at Kett St near the Kambah shops

3. Drain naturalisation at Tuggeranong Creek in Calwell – before

4. Drain naturalisation at Tuggeranong Creek in Calwell – after (but before plantings have grown)

Treat the polluted water in-lake

Alongside pollution reduction programs and infrastructure, in-lake treatments are a complementary management tool to further reduce nutrient levels in the system and curb blue-green algal blooms. Blue-green algal blooms are an issue across Australia and globally, affecting drinking water catchments, recreational water bodies and the agricultural industry. Governments, industry and the research community have invested heavily in trying to find solutions and a range of in-lake treatments have been developed (see Table 7).

Broadly, these in-lake treatments try to address blue-green algal bloom by either:

- reducing nutrient levels in a waterbody (adsorptive materials, lake water treated by a lakeside bioretention, biological competitors, water treatment plant) or
- treating the algae directly with chemicals such as algicides or through physical actions or with water treatment plant.

Trials of in-lake treatments—past and future

In 2019–2020 the ACT Government engaged the University of Canberra to conduct in-lake mesocosm experiments using Phoslock™ (adsorptive material), Diatomix™ (modifies the nutrient composition of the water to favour species that promote the growth of diatoms at the expense of blue-green algae) and peroxide (an algicide). The experiments found these methods to be ineffective at reducing established blue-green algal blooms in Lake Tuggeranong. However, the timing of their application, after a bloom was established, may have limited the effectiveness of at least the Phoslock and peroxide treatments. The experiment report suggests that Phoslock offers a promising way to limit internal phosphorus loading, provided catchment sources can be controlled first. It recommends further trials that apply treatments before the onset of a bloom (Ubrihien et al., 2019).

Two floating wetlands have been deployed; one in Lake Tuggeranong and the other outside the Tuggeranong catchment at Yerrabi Pond. The floating wetlands directly compete with algae for light and nutrients. They have yet to be evaluated for their performance.

A range of existing and emerging technologies and methods to treat phosphorus in the lake have been identified, including filtration, sedimentation, floatation, biological and chemical removal (GHD, 2024). This work pointed to potential opportunities to use a combination of bioretention basins and phosphorus adsorptive (chemically binding) material. For example, Poseidon Pellets™ are a patented product made of magnesium carbonate beads, which adsorb phosphorus and ammonia from water. They could be used in a variety of ways; a water-permeable bag containing the beads can be placed in stormwater or suspended in the surface waters of the lake or in a bioretention basin. Once the pellets become saturated with phosphorus they need to be replaced.

Other in-lake treatments may also be trialled in the future through the Healthy Waterways research program, but the immediate priority will be to reduce catchment sources of phosphorus.

Table 7. Different types of in-lake treatments. All have potential adverse environmental impacts and most are likely to have low effectiveness until pollution from the Lake Tuggeranong catchment is reduced. Only a small number of these treatments have been trialled in Canberra, where the focus has been on reducing pollution in the catchment.

Treatment type	How it works
	By reducing nutrient levels and/or competing with blue-green algae
Adsorptive materials	Materials deployed to the lake bind phosphorus strongly, removing dissolved forms from water so the phosphorus is not available for uptake by blue-green algae.
Bubblers	Bubblers increase levels of dissolved oxygen in the water column, which encourages the formation of iron and manganese precipitates that bind dissolved phosphorus. The precipitates then sink and are stored in the lake sediments.
Bioretention	Water from the lake is circulated through raingardens at the edges of the lake, which partially filter the phosphorus by binding it to soil media and incorporating it into plant biomass.
Biological competitors	Competitors promote the growth of water plants or beneficial algae or bacteria that compete with blue-green algae, suppressing their growth.
	By treating algae directly, either in-lake or with water treatment plant
Algicides	Chemical agents aim to selectively kill algae.
Physical	Physical methods either physically break up blue-green algal cells or force them to the surface of the lake where they can be removed by skimming.

Conclusion for in-lake treatments

Unfortunately, there is no treatment that is effective in all contexts or that does not adversely affect the aquatic environment. Since in-lake treatments are unlikely to ever be effective enough to curb nutrient levels that fuel algal blooms, and the excessive use of algicides would present a heightened risk of impacts to non-target organisms, they do not represent a sustainable, stand-alone solution. However, water managers may need to use them both as an interim measure over the next decade, while we work to mitigate the sources of catchment loads, and then as a periodic solution when algal blooms arise despite best efforts to prevent them.

Selection of options for consideration

Booksmythe et al. (2024) analysed a subset of options for mitigating phosphorus pollution for their potential to contribute to solving the algal bloom problem in Lake Tuggeranong (Table 8). They only analysed options if their costs and effectiveness could be well characterised based on local trials or scientific literature. Of the nine selected options to remove phosphorus, five prevent phosphorus entering the stormwater system and four treat it once it's in the system.

They did not select any options for directly treating algae in-lake, and selected only one in-lake treatment for reducing nutrient levels and/or competing with blue-green algae (floating wetlands). This is because the initial focus is to mitigate the phosphorus pollution that is driving algal blooms. Other in-lake options will be considered in future once their costs and benefits (and risks) are better understood and phosphorus pollution to Lake Tuggeranong has been reduced.

Table 8. Options considered in this report to reduce phosphorus pollution of stormwater (Booksmythe et al., 2024).

Option	Description
Street sweeping	Increase the amount of street sweeping in the catchment to remove more organic material from the roads, preventing it from leaching phosphorus into the stormwater drains. The implementation level reflects sweeping frequency ranging from 12 to 48 sweeps per year.
Fertiliser management	Identify and target the relatively small number of households that use excessive amounts of fertiliser to help them use either low-phosphorus fertiliser or no fertiliser at all. The implementation level reflects the reach of the program.
Open space mowing	Reduce the amount of grass clippings from municipal mowing that end up on the road, preventing them from leaching phosphorus into the stormwater drains. The implementation level reflects different management approaches, from having designated street sweeping trucks follow immediately after mowing events to towing electric blowers behind mowers to divert clippings away from the road.
Rainwater tanks	Capture stormwater from roofs for reuse on residential blocks. This may aid in removing some phosphorus in the system as well helping to reduce urban runoff. The implementation level reflects the number of houses that would have a tank installed.
Stormwater recycling	Divert and filter stormwater to storage tanks at sports fields for use in irrigating the fields. The implementation level reflects the number of sports field sites at which water managers would install this infrastructure.
Castellated kerbs	Retrofit outlets into road kerbs to divert some of the stormwater to open green space and allow it to filter into the ground. The implementation level reflects the number of outlets installed (water managers are limited by availability of suitable places in the Tuggeranong catchment; that is, areas adjacent to green space).
New water quality infrastructure—sports fields	Build swales around sports fields to potentially capture any phosphorus leaching out from fertiliser. Sports field managers are attempting to use fertiliser optimally and the leaching is more a legacy issue. The investment level reflects the number of sports field sites at which water managers would install this infrastructure.
New water quality infrastructure	Construct more wetlands at suitable locations in the catchment to treat phosphorus in the stormwater. The implementation level reflects the number of wetlands constructed, ranging from the two most effective builds to the ten most effective builds
Maintenance of existing water quality infrastructure	Ensure maintenance (such as dredging out built-up sediment and harvesting plants) of existing WSUD infrastructure in the Lake Tuggeranong catchment to maximise its performance and capture the largest amount of nutrients possible. The implementation level reflects the number of assets maintained.
Floating wetlands	Install more floating wetlands on Lake Tuggeranong to draw phosphorus out of the lake water. The implementation level reflects the number and size of wetlands installed.

Part 7: Identifying solutions to the problem

Booksmythe et al. (2024) derived potential solutions to the problem of phosphorus pollution that drives algal blooms in Lake Tuggeranong by comparing the cost-effectiveness of mitigation options in two ways: first separately and secondly together using the catchment water quality model. The former provides an indication of the most promising pollution mitigation options. The latter is important because it mirrors what will happen in the real world; that is, water managers will implement options together, not in isolation from each other, and implementing one option may affect the cost-effectiveness of other options.

Estimated cost-effectiveness of options

Method for determining cost-effectiveness of options

Booksmythe et al. (2024) defined four investment levels for each pollution mitigation option (Table 8). For example, for the option 'increased street sweeping', the investment levels were 12, 24, 36 and 48 sweeps a year.

They then derived data for costs and effectiveness (in terms of phosphorus reduction) of the investment levels from the scientific literature and the results of local trials. They estimated the benefits (kg phosphorus removed), costs (Net Present Value or 'NPV' over a 30-year period) and cost-effectiveness ($/kg phosphorus removed) of all investment levels. Cost-effectiveness represents the cost/effectiveness ratio of each investment level and was calculated as marginal annual benefit (kg phosphorus removed/year) / marginal annual cost (NPV to implement over 30 years divided by 30).

The researchers used a 30-year timeframe to calculate total costs because it allows for the comparison of options with very different cost schedules. For example, some options have large upfront costs but low ongoing costs (for example, castellated kerbs) and some options have lower upfront costs, but higher ongoing costs (for example, street sweeping).

Results

Table 9 and Figure 9 present the annual load of phosphorus removed (effectiveness), the 30-year cost and the cost-effectiveness of each option's four levels of investment to mitigate phosphorus pollution. Note that the 30-year cost in Table 9 is the total cost of this option/investment level and any previous investment levels of the option.

It is clear from these data that street sweeping and adding extra water quality assets are the most effective options for reaching the 700 kg target, with the rest of the options bunched below these two in their effectiveness. Street sweeping is the standout option for cost-effectiveness; only the management of grass clippings comes close to the cost-effectiveness of street sweeping. The different pattern of the curve for grass clippings management in Figure 9 is due to the nature of the investment levels, which are effectively a matrix of two levels of assumed cost-effectiveness (low and high) by two separate types of removal, blowers and street sweeping (Booksmythe et al., 2024).

Table 9. Summary of phosphorus (P) removal performance, total cost and cost-effectiveness for four levels of investment for each of ten pollution mitigation options assessed independently (Booksmythe et al., 2024).

P mitigation option and level	Unit	P removed (kg/year)	30-year cost ($)[1]	Cost-effectiveness ($/kg P)
Install additional WSUD 1	Build 2 new WSUD assets	106.21	$22,507,500	$7,064
Install additional WSUD 2	Build 5 new WSUD assets	169.67	$48,369,492	$9,502
Install additional WSUD 3	Build 8 new WSUD assets	226.22	$73,862,467	$10,884
Install additional WSUD 4	Build 10 new WSUD assets	240.46	$84,519,403	$11,716
Maintenance of existing WSUD 1	Enhanced maintenance of 2 assets	35.84	$10,177,128	$9,465
Maintenance of existing WSUD 2	Enhanced maintenance of 3 assets	61.78	$19,086,579	$10,298
Maintenance of existing WSUD 3	Enhanced maintenance of 4 assets	79.93	$26,352,433	$10,990
Maintenance of existing WSUD 4	Enhanced maintenance of 5 assets	88.02	$30,352,433	$11,495
Increase street sweeping 1	12 street sweeps per year	203.70	$7,030,414	$1,150
Increase street sweeping 2	24 street sweeps per year	320.10	$14,060,827	$1,464
Increase street sweeping 3	36 street sweeps per year	372.50	$21,091,242	$1,887
Increase street sweeping 4	48 street sweeps per year	395.80	$28,121,656	$2,369
Manage grass clippings 1	Blow clippings into verge, low P removal estimate	16.40	$2,018,874	$4,103
Manage grass clippings 2	Blow clippings into verge, high P removal estimate	26.10	$2,018,874	$2,578
Manage grass clippings 3	Sweep clippings in verge, low P removal estimate	32.70	$1,521,462	$1,551
Manage grass clippings 4	Sweep clippings in verge, high P removal estimate	52.30	$1,565,956	$998
Sports field fertilizer management 1	Protect 25% of sports fields with bioretention swales	14.93	$4,204,451	$9,387
Sports field fertilizer management 2	Protect 50% of sports fields with bioretention swales	29.85	$11,817,327	$13,196
Sports field fertilizer management 3	Protect 75% of sports fields with bioretention swales	44.78	$19,430,204	$14,463
Sports field fertilizer management 4	Protect 100% of sports fields with bioretention swales	59.70	$31,445,222	$17,557
Household fertilizer management 1	Low P target (assume cost is $10,000/kg P/year)	20.00	$6,000,000	$10,000
Household fertilizer management 2	Medium P target (assume cost is $10,000/kg P/year)	32.67	$9,800,000	$10,000
Household fertilizer management 3	High target (assume cost is $10,000/kg P/year)	45.33	$13,600,000	$10,000
Household fertilizer management 4	Very high target (assume cost is $10,000/kg P/year)	58.00	$17,400,000	$10,000
Install castellated kerbs 1	Install 1 kerb outlet for every 4 sumps (or 453 outlets)	15.56	$4,532,500	$9,708
Install castellated kerbs 2	Install 1 kerb outlets for every 3 sumps (or 604 outlets)	20.75	$5,990,823	$9,624
Install castellated kerbs 3	Install 1 kerb outlets for every 2 sumps (or 906 outlets)	31.13	$8,539,901	$9,146
Install castellated kerbs 4	Install a kerb outlet for every sumps (or 1813 outlets)	62.25	$14,349,291	$7,684
Install floating wetlands 1	Deploy 1000 m^2 of wetland	3.00	$1,226,000	$13,622
Install floating wetlands 2	Deploy 2000 m^2 of wetland	6.00	$2,452,000	$13,622
Install floating wetlands 3	Deploy 3000 m^2 of wetland	9.00	$3,678,000	$13,622
Install floating wetlands 4	Deploy 1000 m^2 of wetland	12.00	$4,904,000	$13,622

P mitigation option and level	Unit	P removed (kg/year)	30-year cost ($)[1]	Cost-effectiveness ($/kg P)
Stormwater recycling for irrigation 1	Build best 2	8.81	$2,673,863	$10,115
Stormwater recycling for irrigation 2	Build best 4	15.12	$4,588,909	$10,115
Stormwater recycling for irrigation 3	Build best 6	19.19	$7,339,284	$12,748
Stormwater recycling for irrigation 4	Build best 8	21.78	$10,816,870	$16,558
Household rainwater tanks 1	2,500 new households to install water tanks	15.00	$12,500,000	$27,778
Household rainwater tanks 2	2,500 new households to install water tanks	30.00	$25,000,000	$27,778
Household rainwater tanks 3	2,500 new households to install water tanks	45.00	$37,500,000	$27,778
Household rainwater tanks 4	2,500 new households to install water tanks	60.00	$50,000,000	$27,778

[1]Total lifecycle cost is the estimated cost of implementing and operating a mitigation option over 30 years, with annual operation and maintenance costs discounted by 7% per annum after the first year.

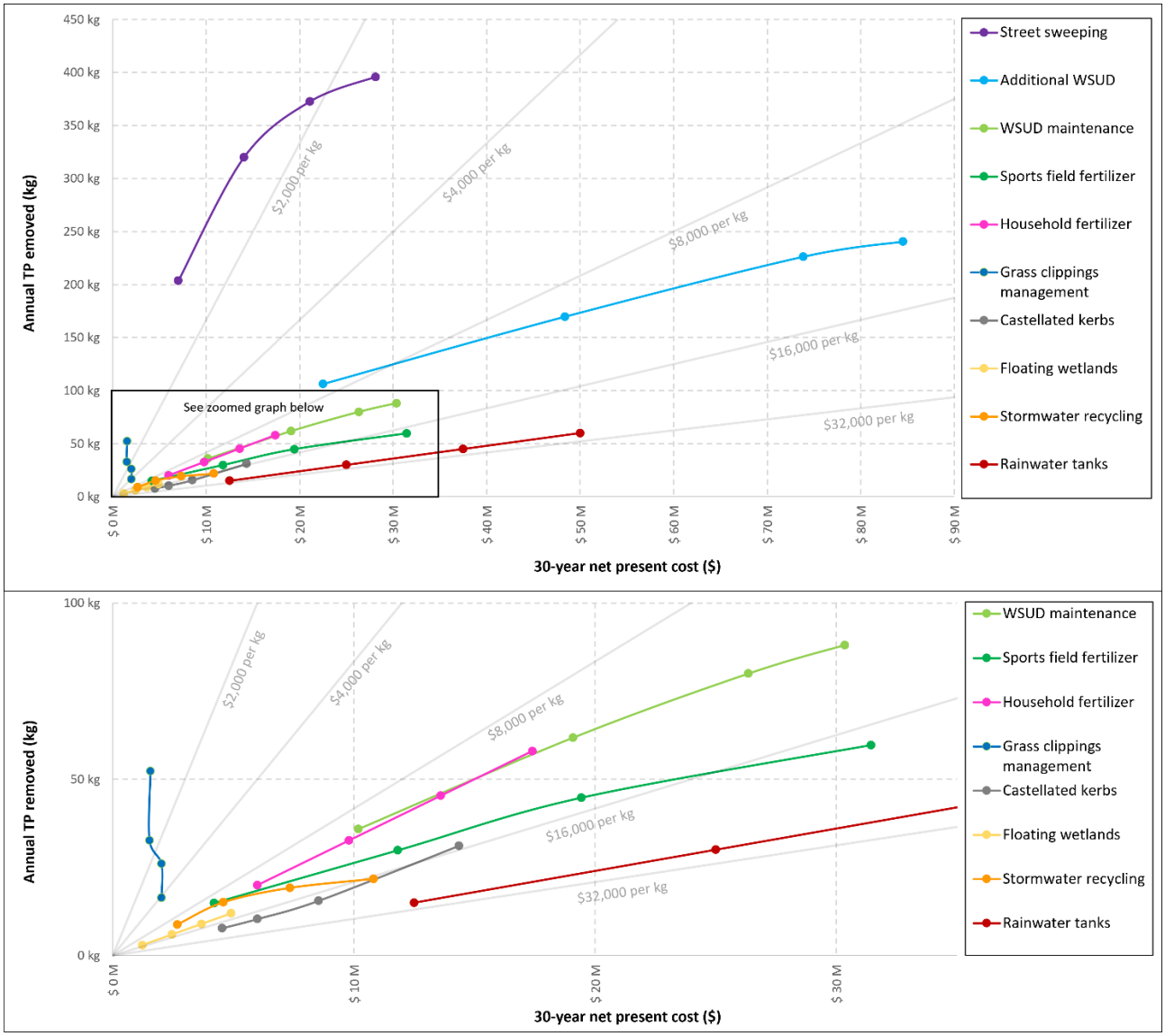


Figure 9. Annual total phosphorus load removed and 30-year lifecycle cost of each incremental investment level for the 10 assessed options for mitigating phosphorus pollution (Booksmythe et al., 2024). Coloured lines connect the four estimates for each option. Grey lines are a guide indicating the cost-effectiveness (cost per kg phosphorus removed) of the estimates. The top panel shows all estimates; the bottom panel shows a zoomed in view of the estimates within the inset box.

An important conclusion of this work is that options to prevent waters from becoming polluted in the first place—street sweeping and ensuring grass clippings from road verges do not enter drains—are more cost-effective than all other options, most notably, the construction of water quality assets. Thus, the most cost-effective way to improve water quality is to prevent waters from becoming polluted rather than relying on water treatment to achieve clean water.

Management scenarios to solve the problem

Booksmythe et al. (2024) define two water quality modelling scenarios: 'cost-effective' and 'broad benefits'. These scenarios are packages of various levels of investment in pollution mitigation options that would theoretically reach the target phosphorus reduction needed to achieve a mesotrophic lake in three out of four years (Dey et al., 2024). These are not the only management scenarios they could imagine but represent two common ways of approaching water management. If water managers can successfully

implement either of these scenarios, we can expect the lake to be more consistently free of blue-green algal blooms and thus open for the Tuggeranong community to use and appreciate for most of the year. In three out of four years, on average, we would expect no blue-green algal blooms. In the one out of four years where blooms arise, we will develop ways to clear the blooms.

Cost-effective scenario

The cost-effective water management scenario ranked the investment levels of each pollution mitigation option/investment level by its cost-effectiveness and selected the most cost-effective option/investment levels until the total annual phosphorus load removed met the 700 kg target. An increment of an option that represented a higher level of investment was excluded if the increments of lower investment were not also included in the list; that is, managers cannot double a $100,000 investment if they have not already invested $100,000. This resulted in the selection of nine pollution mitigation options (Table 10).

Broad benefits scenario

The 'broad benefits' management scenario started by taking the most cost-effective options and investment levels, as above, but recognised that some lower ranking options should still be included because they provide additional benefits to the community beyond water quality. For example, constructed wetlands can provide:

- Ngunnawal cultural benefits as identified in the Aboriginal Water Assessment (see Part 1); for example:
    - ensuring the locations of living infrastructure—drain re-naturalisations and other constructed wetlands—promote the creation of a cultural and ecological corridor that connects the Lake Tuggeranong catchment, its waterways and areas downstream of the dam at least to the Murrumbidgee River
    - considering the re-naturalisation of concrete drains as options for water quality assets
    - including reeds for weaving among the native seedlings added as water quality plantings
- foundations for residents' wellbeing including opportunities to improve physical and mental health (Lal and Adhikari, 2024)
- greater climate resilience by reducing urban heat (NC Economics, 2019, Tapsuwan et al 2024)
- enhanced amenity of suburbs
- support for urban biodiversity
- a source for recycled stormwater to irrigate sports fields, which relieves pressure on ACT's potable water supply (for example, as implemented at Kambah playing fields).

Under the broad benefits scenario, Booksmythe et al. (2024) considered the level of confidence in their estimates of cost-effectiveness for each pollution mitigation option. They developed confidence criteria for each option based on whether the information and data are robust, from a local source and from a single source or confirmed by multiple sources. Then, to create the broad benefits scenario, they adjusted the cost-effective scenario by increasing levels of investment in options with broader benefits and reducing investment in options with less certainty about their costs or effectiveness.

Compared with the cost-effective scenario, the broad benefits scenario:

- includes a wider variety of pollution mitigation options
- has slightly less street sweeping

- invests less in fertiliser management (because of lower confidence in the estimates of its contribution to phosphorus removal)
- has more investment in WSUD infrastructure because of its broader benefits to the community; for example, a benefit–cost ratio conservatively estimated as 1.66 (NCEconomics, 2019) is conservative because the analysis could not evaluate all benefits including Ngunnawal cultural benefits.

Table 10. Pollution mitigation options for reducing phosphorus in stormwater and levels of investment in these options modelled in the cost-effective and broad benefits scenarios.

	Level of investment	
Mitigation option	***Cost-effective scenario***	***Broad benefits scenario***
Increase street sweeping	48 sweeps uniformly over the year	36 sweeps, seasonally optimised
Improve open space mowing practices	Dedicated street sweeper to sweep after mowers go through	Dedicated street sweeper to sweep after mowers go through
Castellated kerbs	Not included in this scenario	Castellated kerbs retrofitted to replace every 4th sump along roads adjacent to open space (total 453 kerbs)
Improve fertiliser management in households through behaviour change program	Very high investment in program—$17.4 million (NPV, 30 years)	Lower investment in program—$6 million (NPV, 30 years)
Improve maintenance of water quality assets built in Stage 1 of Healthy Waterways	Improve maintenance of four most cost-effective water quality assets	Improve maintenance of five most cost-effective water quality assets
Build and maintain new large constructed wetlands or raingardens, e.g. drawn from the reserve list of assets proposed but not built under Healthy Waterways	Add the two most cost-effective assets	Add the five most cost-effective assets
Build and maintain water quality assets (bioretention swales) on sportsgrounds to capture fertiliser runoff	Add 1,000m^2 of bioretention swales at the biggest four sportsgrounds	Add 5,000 m^2 of bioretention swales at the biggest seven sportsgrounds
Install stormwater recycling tanks at sports fields for irrigation	Tanks installed at four sports fields (Greenway, Calwell, Kambah, Wanniassa)	Tanks installed at six sports fields (Greenway, Calwell, 2 x Kambah, Wanniassa, Gowrie)
Build new floating wetlands	Not included in this scenario	Build new 4000 m^2 of floating wetland in Lake Tuggeranong that is harvested once annually

Analysis of management scenarios

The overall performance of the two scenarios in mitigating phosphorus pollution is analysed in two ways:

1. Summing the costs (net present value, $ over 30 years) and effectiveness (kg phosphorus mitigated) of the pollution mitigation options/investment levels as if they were implemented in isolation, independently of one another. This provides an indication of which are the most promising pollution mitigation options.
2. Summing the costs and effectiveness of the options/investment levels as if they were implemented together at the same time. This is important because, in the real-world, water managers would implement options concurrently, not in isolation from each other, and the implementation of one option may affect the cost-effectiveness of another. Dey et al. (2024) used the catchment water quality model to estimate the combined effects of the options/investment levels on phosphorus supply to or availability in Lake Tuggeranong.

Performance of two scenarios to solve the problem

Options considered independently

The effects of the two scenarios, where the pollution mitigation options/investment level are considered independently of one another, are illustrated in Table 9 and Figures 9 and 10.

The cost-effective scenario is dominated by various investments in pollution prevention options that help prevent stormwater from getting polluted in the first place, such as street sweeping and fertiliser management (Table 9 and Figure 10). Options such as rainwater tanks, floating wetlands and castellated kerbs were less cost-effective (based on available data) than alternatives, so were not included in this scenario.

Only two constructed wetlands were included in the cost-effective scenario because wetlands are only moderately cost-effective in reducing phosphorus (Table 9). In older suburbs like Tuggeranong, there is limited space and it is expensive to retrofit large infrastructure. For example, during Stage 1 of Healthy Waterways, seven different types of constructed wetlands were built in the Lake Tuggeranong catchment at a cost of $30 million. The Lake Tuggeranong catchment water quality model estimates these assets remove 214 kg of phosphorus/year (Dey et al., 2024), approximately 13% of the catchment phosphorus load. While not insignificant, it highlights that wetlands alone will not remove enough phosphorus to reach the target. Even if enough space could be identified to build them, it appears that building more wetlands in the catchment could not reduce total phosphorous by more than 200 kg/year (Figure 9). The cost to attempt to use water quality assets alone to reach the phosphorus mitigation target would be prohibitive and, in medium to large storms, a significant amount of stormwater bypasses them and flows directly to Lake Tuggeranong untreated.

The cost of the cost-effective scenario for mitigating phosphorus pollution in stormwater by 700 kg per year is estimated at around $105 million over 30 years (Table 11).

A broad benefits scenario would remove 64 kg or 9% more phosphorus (Figure 10 and Table 11), while costing $141 million, which is $36 million or 34% more than the cost-effective scenario (Table 11). In both scenarios, street sweeping, water quality assets and WSUD maintenance account for the greatest phosphorus mitigation. In the broad benefits scenario, fertiliser management by households contributes

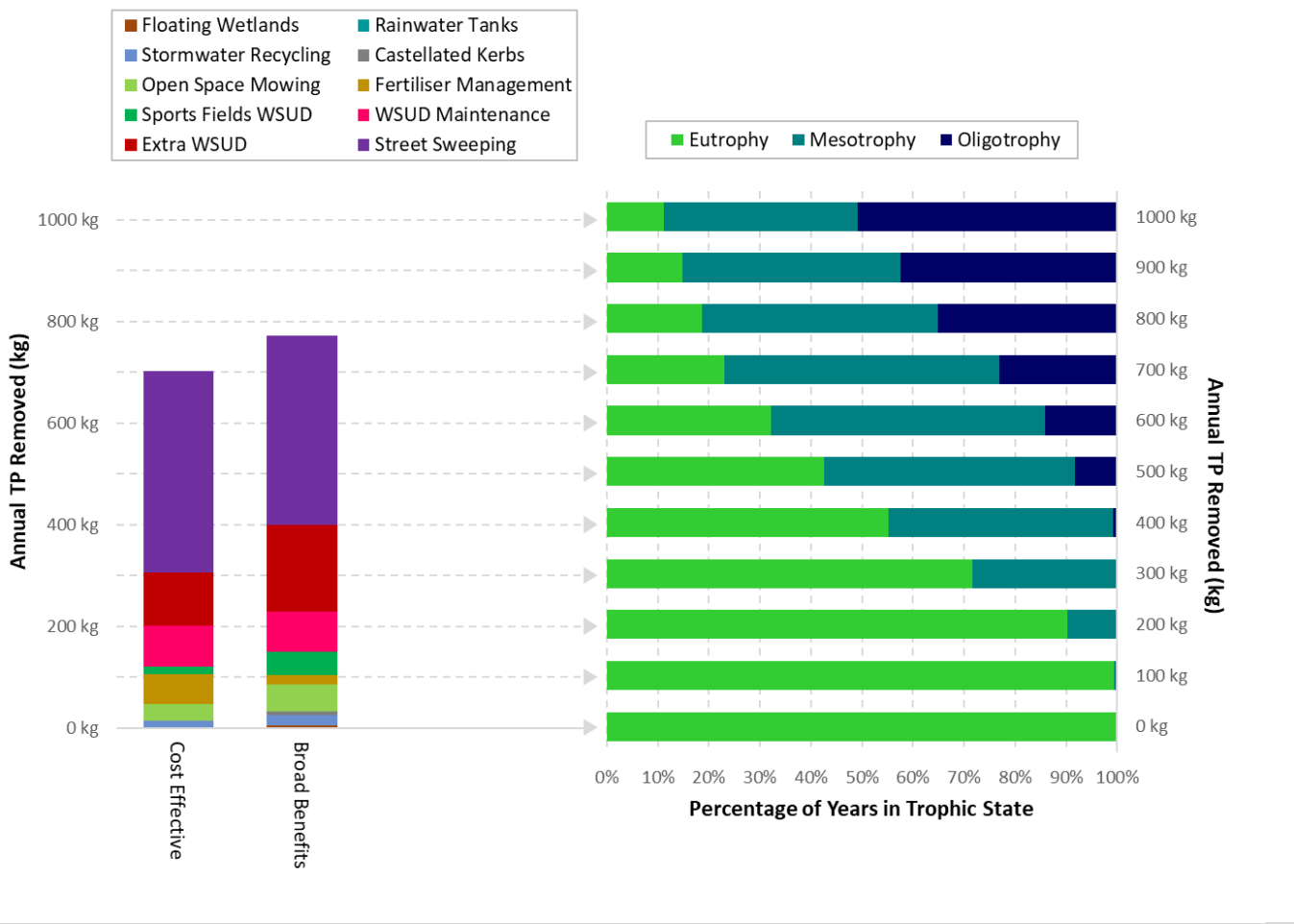


Figure 10. Two scenarios offering of a range of possible phosphorus-reducing options and increments of intensity of implementation, packaged up to reach the 700 kg target for phosphorus mitigation. This will enable Lake Tuggeranong to mostly exist in a mesotrophic state. The effects of the option increments have been analysed independently of one another.

Table 11. Comparison of the cost of two different management scenarios for mitigating phosphorus pollution. NPV is net present value.

Management scenario	Number of pollution mitigation options included	Cost (NPV – $ million over 30 years)	Benefit (kg phosphorus removed / year)	Cost-effectiveness $ / year / kg phosphorus removed
Cost-effective	**7**	**105**	**703**	**4,967**
Broad benefits	**9**	**141**	**767**	**6,241**

less than at sports fields, and open-space mowing and stormwater recycling contribute more to phosphorus mitigation. Five large water quality assets such as raingardens were included in the broad benefits scenario due to the other benefits they provide in addition to phosphorous removal, as described above.

Options implemented concurrently

In practice, water managers will implement various pollution mitigation options in either of the two scenarios concurrently, and this will affect their combined performance. Dey et al. (2024) used the catchment water quality model to model the two management scenarios to predict any impact to overall phosphorus reduction due to this interactive effect.

Their modelling indicates that when all pollution mitigation options are implemented together, the interactive effect reduces the total phosphorus removed by 14% under the cost-effective approach and by 12% under the broad benefits approach (Table 12, Figure 11). This decrease arises in part because the models assume that the cleaner the stormwater becomes, the less the water quality assets will filter out whatever pollutants remain. Monitoring of asset performance over time at different levels of stormwater flow will help to confirm or clarify this assumption. The decrease is also because some pollution mitigation options partially offset the effects of others. For example, having a dedicated street sweeper follow mowers of road verges would diminish some of the effect of sweeping suburbs 36–48 times a year. However, the uncertainties inherent in all estimates based on research and modelling (see Booksmythe et al. 2024 for details) probably mean that this reduction in supply is indistinguishable from the target of 700 kg (or from a lower level of performance of 400 kg).

Implications

Several key findings emerge from these results:

- There are no silver bullets; no pollution mitigation option has the potential to reach the 700 kg/year phosphorus mitigation target on its own. Managers will need to implement multiple options to reduce phosphorus pollution to a substantial extent and thus restrict the incidence of algal blooms.
- Street sweeping is the most cost-effective option in both scenarios and removes the largest amount of phosphorus (as also indicated in figures 9 and 10).
- Large water quality assets placed low down in catchments are necessary to treat unavoidable pollution but are not sufficient on their own to achieve the target reduction in phosphorus pollution of stormwater. Managers will need to implement options that prevent stormwater from getting polluted in the first place to substantially reduce the incidence of blue-green algal blooms in Lake Tuggeranong.

Table 12, Effects of implementing phosphorus pollution mitigation options together as determined by water quality modelling compared with the sum of benefits when multiple options are considered independently. Source: (Dey et al., 2024). Figures are for average kg phosphorus per year entering Lake Tuggeranong, or percentage decrease in the amount of phosphorus entering Lake Tuggeranong per year.

Average kg phosphorus/year entering Lake Tuggeranong						
Scenario	**Before Stage 1 assets were built**	**Current (with Stage 1 assets)**	**Current + added pollution mitigation options considered independently**	**% decrease from before Stage 1 assets were built**	**Current + added pollution mitigation options considered together (water modelling)**	**% decrease from before Stage 1 assets were built**
Cost-effective	**1656**	**1442**	**739**	**55%**	**979**	**41%**
Broad benefits	**1656**	**1442**	**662**	**60%**	**859**	**48%**

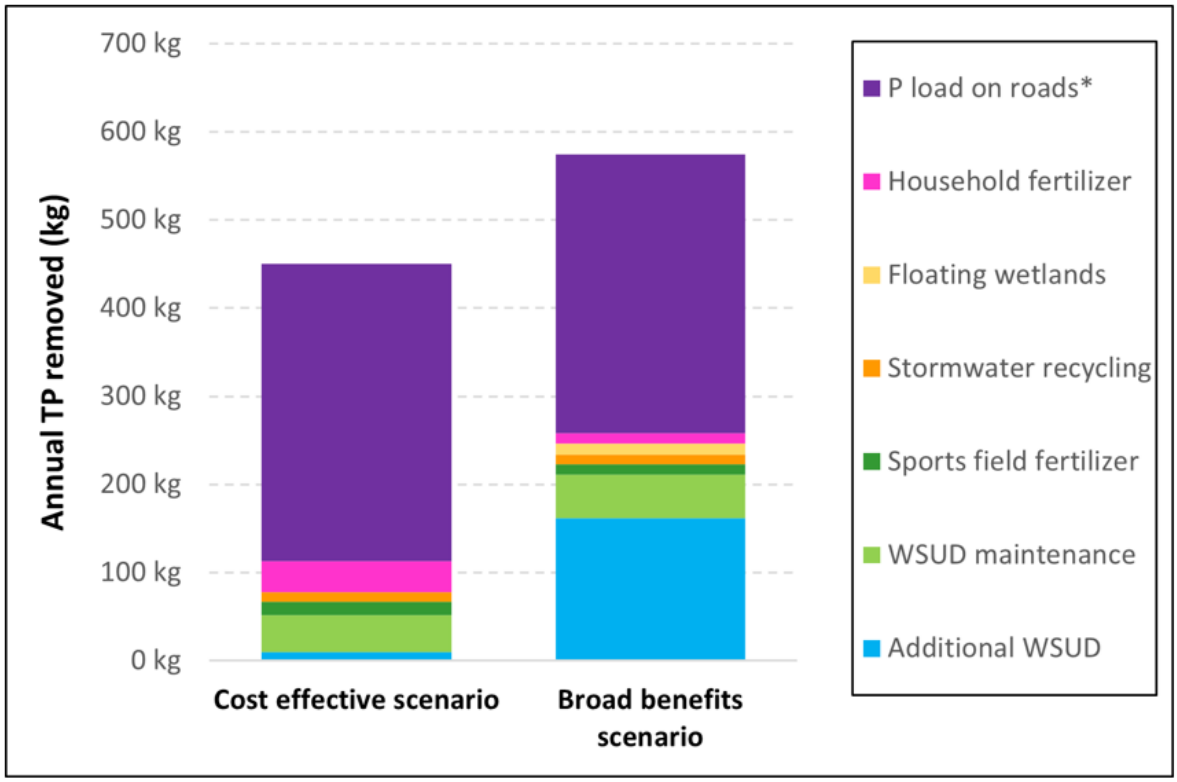


Figure 11. Modelled average annual reduction in the load of total phosphorus (TP) generated in the Lake Tuggeranong catchment under the cost effective and broad benefits management scenarios. Colours indicate the reduction in phosphorus due to different mitigation options in each scenario.
** 'P load on roads' includes the reductions in TP load due to street sweeping, grass clippings management and installation of castellated kerbs.*

Box 5. Street sweeping pilot

Based on the research findings that leaves contribute to stormwater pollution (see Part 3), a pilot street sweeping program was conducted over the summer of 2023/24 to better understand how much the leaves and other organic matter from streets contribute to the amount of nutrients in urban stormwater, and to begin to understand the efficacy of increasing the frequency of street sweeping as an option to mitigate pollution.

Over three months, two sub-catchments in the Lake Tuggeranong catchment were swept every fortnight and two sub-catchments were left unswept. Stormwater samples were collected during storm events to see if the fortnightly-swept catchments showed a reduction in nutrient concentrations. Samples of the material swept off the roads by the trucks were also taken to a lab for analysis.

The results indicate that leaves and other organic material on the roads are contributing significant amounts of phosphorus to stormwater in the catchment. Analysis of the material collected by street sweeping trucks (which included leaves, soil, grass clippings, gravel and road material) estimated that 39.2 kg of phosphorus was removed from the roads in the swept sub-catchments during the experiment. Scaled up to the Tuggeranong catchment, this pilot suggests that a fortnightly program of street sweeping could intercept around 300 kg a year of phosphorus, which is more than 40% of the target of 700 kg/year.

Analysis of the stormwater samples showed a modest decrease in phosphorus concentrations in stormwater from the swept sub-catchments over time, compared to the unswept sub-catchments. As there are many other factors that can influence nutrient concentrations in stormwater, the project was repeated in the summer of 2024/25 to strengthen our understanding of how much leaves contribute to phosphorus in the stormwater. Analysis of this second trial is underway.

The street sweeper used in the pilot program.

Can we reach the phosphorus reduction target?

The analyses suggest that the ACT Government can succeed in curbing algal blooms in the lake if it implements a program to reduce phosphorous pollution.

Firstly, a reduction of 500–600 kg/year in phosphorus pollution in the two scenarios presented would substantially reduce the frequency of blue-green algal blooms in Lake Tuggeranong (Figure 7).

Secondly, the management options to mitigate pollution are currently conceived, and thus modelled, in a simple way. Refinement of the options, both during implementation planning and in models, should both decrease their cost and increase their effectiveness. For example, street sweeping in winter, when cold temperatures limit algal growth, may have little impact on lake closures. Eliminating winter street sweeping will reduce costs. Conversely, targeting sweeping efforts in summer, and adding a complementary community program for collecting leaves, may intercept a greater amount of pollution from leaves and grass on verges, reducing the nutrient pollution from these sources beyond that predicted by Dey et al. (2024) for the most intense investment level of this option in the model. There are many nuances to the design of community partnerships and the design and siting of water quality assets that could increase their effectiveness above the average value used in the modelling.

Thirdly, several promising pollution mitigation options have yet to be explored that may help to meet the phosphorus mitigation target. Apart from floating wetlands, in-lake treatments have not been included in the modelled options, and these could contribute to further phosphorus reduction. For example, new products are emerging that draw and capture phosphorus out of stormwater, both in the catchment and in the lake itself. One potential intervention that has shown promising results in trials overseas is Poseidon Pellets™. These pellets consist of porous granules that adsorb dissolved phosphorus from water. They promise a high rate of phosphorous adsorption at a relatively low cost but remain untested locally.

The uncertainty about the extent that fertilisers applied to residents' gardens contribute to stormwater pollution (Part 5) does not preclude taking action now. If it turns out from further research that the fraction of phosphorus attributed to fertiliser use is more than is currently estimated, and the fraction due to leaves and grass is less, there would be a shift in emphasis from options that target leaves to ones that target fertilisers. The same is true if sewer leaks turn out to be an important source of phosphorus; the leaks would need to be fixed but it would still be necessary to deal with leaves, grass and fertilisers.

The main cautionary note is about how quickly algae in Lake Tuggeranong will respond to reduced supplies of phosphorus from the catchment. Algal blooms may persist if the phosphorus in the sediments is able to sustain the blooms. This may mean it takes longer than the goal of a decade to fix the algal bloom problem. The long-term research focus should include investigations into in-lake treatments that reduce the supply of phosphorus from the sediments or compete with algae for phosphorus, such as Poseidon Pellets™.

Key conclusions can be drawn from the analyses in this report:

- There is sufficient knowledge to have confidence that a suite of actions can lead to a substantial reduction in the frequency of blue-green algal blooms in Lake Tuggeranong. Inflows of phosphorus pollution can be reduced by up to 700 kg/year within ten years, but whether this would significantly reduce algal blooms in the same time frame may depend on the development of in-lake treatments to deal with phosphorus stored in lake sediments.

- Algal blooms probably cannot be prevented from forming altogether. The analyses carried out for this report suggest the best that can be achieved is for algal blooms to be prevented in three out of four years on average.
- This means that the ACT Government may need to consider developing ways to treat algal blooms as they arise in the years where pollution levels may permit their formation. These may range from the promotion of algal competitors to the use of algicides (see Part 6).

Part 8: The path forward

The research findings and modelling work presented in this report provide confidence that the ACT Government can make real progress in addressing the problem of algal blooms in Lake Tuggeranong. The target level of phosphorus reduction is realistically achievable and this would reduce the impacts of blue-green algal blooms. Figure 12 shows a high-level plan for how this could be achieved, from which funding for implementation can be investigated and an implementation developed.

Research agenda

Ongoing research and monitoring is critical to refining options to mitigate pollution, to maximise their effectiveness and minimise their costs. The ACT is one of only a small number of jurisdictions in the world actively monitoring constructed wetlands. This is important for testing how well wetland assets perform against design model expectations (including as stormwater entering them becomes cleaner over time) and for informing how the assets are operated and maintained.

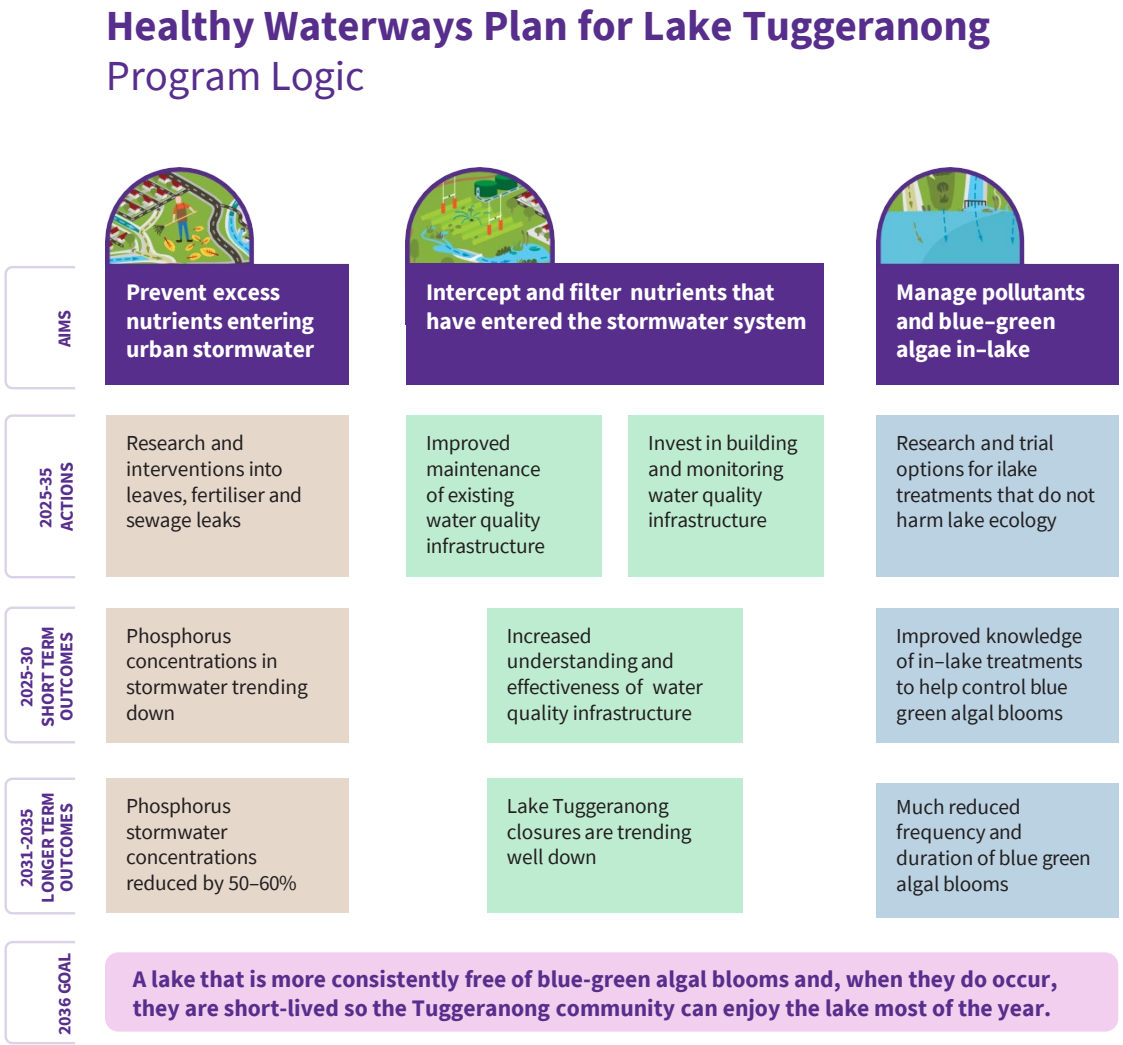


Figure 12. Draft program logic to guide more detailed implementation plan.

The highest priorities for research are to:

- trial promising pollution mitigation options
- investigate, to better understand, the fate of fertilisers applied to residents' blocks
- determine whether sewer cross-connections are a significant source of phosphorus in stormwater.

Table 14 describes the Healthy Waterways research program up to the summer of 2025/26.

Priorities for restoration

Additional research will continue to refine knowledge and understanding of how to reduce phosphorus in the Lake Tuggeranong catchment, but there is enough evidence already to investigate funding for several priority actions.

Expand street sweeping program to be more often and seasonally optimised

Research by the University of Canberra (Ubrihien et al., 2019) plus the street sweeping pilot by the University of Canberra, Healthy Waterways and City Services demonstrated that leaves contribute a significant amount of phosphorus to catchment loads in the Tuggeranong catchment. Modelling by Booksmythe et al. (2024) indicates that an expanded street sweeping program would remove a significant amount of phosphorus from the catchment. If, for example, streets were to be swept 36 times a year, this would remove up to 316 kg/year or 53% of the target phosphorus reduction amount of 700 kg/year and cost up to around $1.4 million annually (Table 10, noting that the cost of investment level 3 has been annualised).

The Healthy Waterways team and ACT City Services ran a street sweeping pilot again in the summer of 2024/2025 to strengthen findings and inform how best to optimise a future street sweeping program to capture seasonal leaf fall.

New community pollution prevention programs

A successful community pollution prevention program that encourages communities to collect leaves and reduce fertiliser use will complement increased street sweeping by reducing the volume of leaves that make it onto roads. This will reduce the green waste going to landfill and disposal costs since, at present, all waste from streetsweeper trucks is deemed contaminated waste and goes to landfill.

The Leaf Collective and Love the Lakes pilot programs received positive feedback from the community and provide valuable insights into how to engage the community to change their practices around fertiliser use and leaves. In late 2024 a new program that builds upon the successes of the pilots was rolled out as the Waterways Friendly Gardening program.

Build new WSUD infrastructure

WSUD infrastructure cannot solve the problem of blue-green algal blooms on its own and is relatively costly to build and maintain (Table 10). However, there is value in building some additional water quality assets in the Tuggeranong catchment because there will always be some unavoidable pollution of stormwater, which these assets will help to intercept before the pollution reaches the lake. Constructed wetlands also provide other benefits to the community including habitat for native plants and animals, urban cooling (Tapsuwan et al., 2024), public amenity (NCEconomics, 2023) and cultural value.

Table 14. Healthy Waterways forward research agenda to 2026 for Lake Tuggeranong.

Area of research	Description	Estimated start date
Investigate potential leaks from sewerage—caffeine tracking study	Use caffeine in stormwater samples from across the catchment as an indicator of sewerage ingress.	Underway
Performance of constructed wetlands	Monitor the performance of four Stage 1 assets: two wetlands and two raingardens.	Underway
Street material content analysis	As part of the street sweeping project, run a study to understand what proportion of road matter phosphorus comes from non-leaf matter sources (e.g. from car tyres).	Summer 2024/ 2025
Maintenance of channel naturalisations	Develop methods to remove sediments accumulated in plant beds without destroying the plants.	Mid 2025
Investigate potential leaks from sewerage—Microbial Source Tracking	Test and compare the location, quantity and type of faecal matter (animal or human) found in different catchments after rain events, including Lake Tuggeranong.	Mid 2025
Investigate contribution of leaves on roofs to nutrient loads in stormwater	Examine how much leaves that fall on roofs are contributing to stormwater pollution given roofs are the biggest impervious area in the ACT.	Mid 2025
Circular economy—enhancing cost effectiveness of bioretention	Investigate income-generating potential from harvesting of vegetation from stormwater treatment ponds, floating wetlands etc., including when it's combined with swept material being used for biochar feedstock.	Mid 2025
Trial of Poseidon Pellets™	Run small-scale laboratory and field trials to test viability of Poseidon Pellets in the Lake Tuggeranong context.	Spring/Summer 2025/2026
Phosphorus content in leaves and soil	Investigate whether urban street trees of Tuggeranong shed unusually high levels of phosphorus in their leaves and where they access phosphorus from (soil or other sources such as the sewerage network).	Spring/Summer 2025/2026
Fertiliser leaching rates	Investigate runoff from residential blocks or gardens to estimate export rates of nutrients from fertiliser.	Spring/Summer 2025/2026
Maintenance of constructed wetlands	Develop approaches to harvesting macrophytes to increase the export of nutrients from wetlands and stimulate further uptake of nutrients.	Spring/Summer 2025/2026

As with all existing suburbs, space constraints and underground services limit the locations where new water quality assets can be built. However, Healthy Waterways feasibility studies have identified several potential locations that could be investigated further.

Improve maintenance of existing water quality assets

The ongoing performance of all water quality assets relies on good operation and maintenance practices. Modelling by Booksmythe et al. (2024) indicates that improving the maintenance of existing Stage 1 and 2 water quality assets would deliver substantial phosphorus reduction benefits (Table 10). The Healthy Waterways and ACT City Services teams are exploring several ideas for facilitating the operation and maintenance of water quality assets to improve their performance.

Next steps to finalise the Plan

Version 1 of the Healthy Waterways Plan for Lake Tuggeranong will incorporate further inputs from First Nations people and feedback from the community and experts on the proposed approach. An implementation plan will then be developed to set out how the vision will be achieved over the next 10 years, including how it will be monitored and evaluated.

Glossary

Term	As defined in the Plan
Adsorption, adsorbed	The adhesion of a substance (e.g. charged phosphorus ions) to a surface (such as charged clay particles in soil or Poseidon Pellets™).
Bacterial pathogen	Bacteria that can lead to illness.
Baseflow	Streamflow continues between rain events.
Bioavailable	(for plant nutrient–algae relationship) Plant nutrients that are in a form that can be absorbed and used by algae to support growth and metabolism.
Bioretention	Infrastructure (for example, swales or raingardens) comprised of soil, plants and microbes to treat and filter stormwater. Stormwater is spread through the surface of the infrastructure, percolates vertically and is collected in outlet pipes at the base of the asset, leaving behind filtered pollutants.
Bioretention basin	Landscaped depression to manage and treat runoff. See 'Bioretention'
Bioretention swale	Type of bioretention system using linear, vegetated drains in a landscape to capture and filter runoff.
Blue-green algae	A group of photosynthesising, algae-like bacteria that live in freshwater, estuarine and marine environments. Also known as cyanobacteria.
Calibrate, calibration (models)	Adjusting water quality models so they provide a good description of the water quality in Tuggeranong's waterways. This is achieved by comparing model predictions with actual measurements of water quality in the stormwater system and making adjustments to the model to minimise its differences with the observed data.
Catchment	Area of land where precipitation collects and drains to a common outlet (for example, a river or waterbody). May also be known as a drainage basin.
Chlorophyll *a*	A pigment in many plants and algae that helps them absorb light energy and convert it to chemical energy in a process called photosynthesis. Chlorophyll *a* is often used as a proxy to assess algae biomass as it is easier to measure than biomass.
Constructed wetlands	Both a general term for water quality assets comprised of soil, plants and microbes to treat and filter urban runoff, and a reference to a specific type of asset where stormwater that is diverted to the wetland flows laterally to an outlet at its downstream end (as compared to 'bioretention'; see definition above).
Cyanobacteria	See blue-green algae.
Diffuse source	A non-point source, where pollutants are generated from many sources across the catchment.
Deposition rate	(for leaves) The volume of leaves that fall from trees for a given area/time.
Enterococci	Bacteria commonly found in the intestines of humans and animals, used to indicate faecal pollution in waterbodies.
Eutrophic	Water bodies in a eutrophic state are nutrient rich, with highly productive plant growth and high turbidity. They are seasonally deficient in oxygen, which may lead to fish kills. Eutrophic lakes may experience regular algal blooms.
Export rate	% of nutrient (in this case phosphorus) in applied fertilisers lost to runoff.
Hydrograph	A way to display the flow of water over time.
Impervious surface	Water-resistant surface that is a partial or total barrier to water, such as concrete, roofs, roads.
Management scenarios	Packages of phosphorus pollution mitigation options that together are intended to achieve a desirable water quality outcome.
Mesocosm	Enclosure set up in the lake to study aquatic responses under controlled conditions.
Mesotrophic	Water bodies in a mesotrophic state have a moderate amount of nutrients, moderately clear water, some algal blooms in late summer and oxygen depletion at

Term	As defined in the Plan
	bottom of lake as biomass decomposes. If they do experience algal blooms, it is typically in late summer.
Microbial Source Tracking	Method to identify the sources of faecal contamination in water bodies; that is, whether it comes from humans or animals (domestic pets, wildlife, livestock).
Net Present Value (NPV)	The difference between the present value of cash inflows and outflows over time.
Nitrogen	Key nutrient essential for the growth of aquatic plants and algae. Excess nitrogen can lead to nutrient pollution which can cause algal blooms.
Nutrient load	Refers to the amount of nutrients entering a waterbody in a given time period; for example, kg phosphorus entering Lake Tuggeranong per year.
Oligotrophic	Water bodies in an oligotrophic state have very low nutrient concentrations and tend to have very clear water with little plant or algal growth. High oxygen concentrations depress the release of algal nutrients stored in lake-bottom sediments. Hence, oligotrophic lakes are not prone to algal blooms.
Phosphorus	Key nutrient essential for the growth of aquatic plants and algae. Excess phosphorus can lead to nutrient pollution which can cause algal blooms. Can be either particulate (sediment-bound) or present in dissolved forms. Total phosphorus (TP) is the sum of all forms of phosphorus present in a sample. In this report, phosphorus refers to total phosphorus unless otherwise stated and these terms are used interchangeably.
Phytoplankton	Photosynthesising microscopic organisms that live suspended in water. Blue-green algae/cyanobacteria are a type of phytoplankton.
Point-source	Where pollutants are generated from specific sources in the catchment such as nutrients from a sewage treatment plant outlet.
Pollutant, Pollution (of water)	A substance (like phosphorus) that is present at levels that can cause harm to life. Phosphorus is not directly harmful but is a pollutant at high concentrations or supply because it promotes the growth of harmful algae.
Pollution mitigation options	Individual approaches to reducing the level of phosphorus in stormwater such as increasing the frequency of street sweeping or building water quality assets.
Raingarden	A water quality asset using bioretention technology in a shallow, landscaped depression to capture and filter urban runoff.
Runoff	Water that flows over the surface of the ground when it cannot sink into the ground.
Runoff infrastructure	Infrastructure or landscaping that holds, redirects and/or slows runoff to allow it to sink into the landscape.
Sediments	In this context, sediments are bits of soil and organic matter eroded from the catchment into stormwater and lake water. Sediments may become deposited in the bottom of lakes.
Stormwater	Water generated through rain that has made its way into the stormwater system.
Stormwater runoff	Rain that isn't absorbed into the ground and flows over the landscape.
Stormwater system	Concrete channels and pipes designed to direct stormwater away from built up areas to reduce flood risk.
Stratification	Formation of distinct thermal layers in the water column, which affect the distribution of oxygen and nutrients within the lake.
Suspended solids	Small particles that remain suspended in water, affecting water quality and aquatic life by reducing light penetration and temperature.
Total dissolved solids	The inorganic and organic substances dissolved in water. They are used as an indicator of water quality.
Treatment train	Water quality infrastructure working in sequence to remove pollutants and manage water flow to a target level.

Term	As defined in the Plan
Trophic state	Describes the biological productivity of a water body and depends on factors such as the concentration of nutrients like phosphorus and nitrogen (see oligotrophic, mesotrophic, eutrophic).
Turnover	Seasonal process where water layers mix resulting in the redistribution of oxygen and nutrients throughout the lake.
Water Sensitive Urban Design (WSUD)	WSUD seeks to minimise impacts of urban development on the natural water cycle by integrating developments with a site's natural features and promoting the integration of stormwater, water supply and sewage management.
Water quality assets	Infrastructure solutions that aim to filter water of pollutants, such as constructed wetlands, raingardens and ponds. Water quality assets are also commonly referred to as 'WSUD infrastructure'.

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Attachment G

ACT Government

Lake Tuggeranong Catchment Model

Technical Report: Configuration and Calibration of the Water Quantity and Quality Model

Water Information Services, ACT Office of Water

December 2024

Environment, Planning and Sustainable Development Directorate

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ACT Government Disclaimer

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Executive Summary

Lake Tuggeranong is a small (57 ha) urban lake in southern Canberra. Lake Tuggeranong was constructed in the late 1980s on Tuggeranong Creek, a 66 km^2 catchment that is predominantly (62%) urbanised. In recent decades, Lake Tuggeranong has been plagued by poor water quality. Since 2017, there has been a concerted effort to improve water quality in the lake through the construction of Water Sensitive Urban Design (WSUD) infrastructure throughout the catchment, and a major research program to understand the causes of poor water quality, and sources of pollutants entering the lake. This work has been undertaken as part of the ACT Healthy Waterways program.

In 2022, the ACT Government commited to developing Healthy Waterways Plans for priority catchments in the ACT. The Lake Tuggeranong catchment Healthy Waterways Plan aims to provide a suite of potential management options to Government to further improve water quality in Lake Tuggeranong. To acheive this, modelling and analyses have been undertaken to examine a broad range of management scenarios and identify cost-effective options to improve water quality in Lake Tuggeranong. To support these analyses, a catchment model was developed in the eWater model platform Source to support the testing of water quality management scenarios, and rank these scenarios based on cost-effectiveness.

This report presents an overview of the development, calibration and outputs of the Lake Tuggeranong catchment model. The underlying rainfall-runoff model chosen for this task was a Sacremento daily timestep model, implemented in Source. Fine-scale delineation of subcatchments, land use and imperviousness, flow regulation infrastructure and WSUD infrastructure were included in the model, to provide a complete, current assessment of the Lake Tuggeranong catchment. A total of 75 subcatchments were delineated to key infrastructure within the catchment, existing monitoring locations, and other features of interest. LIDAR data captured in 2020 was used to quantify surface imperviousness within subcatchments, facilitating an explicit representation of imperviousness in the model.

A comprehensive compilation of water quality data and streamflow data collected in the catchment from 2014 to the present was used to calibrate the Source model. The initial flow calibration is rated as suitable for estimating long-term catchment mean annual flow and long-term mean annual pollutant loads. The water quality model is parameterised against observed end-of-catchment median event concentrations of total phosphorus, total nitrogen, and total suspended solids, in the absence of load-based water quality data. The model estimates pollutant loads generated in the catchment based on land use and imperviousness data.

The parameterised model was used to simulate daily flows and pollutant loads generated in the Lake Tuggeranong catchment between 1889 and 2023, the period for which observed rainfall and climate data was available. Under current catchment land use and management conditions, the modelled average annual inflow to Lake Tuggeranong is 8.8 GL/year. The modelled mean annual loads of pollutants entering Lake Tuggeranong are 1,442 kg/year total phosphorus, 11,894 kg/year total nitrogen, and 397,064 kg/year total suspended solids.

The results provide a robust foundation for future catchment management plans and strategies.

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1. Introduction

Lake Tuggeranong is a small (57 ha) urban lake in southern Canberra. The lake was constructed in the late 1980s on Tuggeranong Creek, a 66 km^2 catchment that is predominantly (62%) urbanised. In recent decades, Lake Tuggeranong has been plagued by poor water quality, with high loads of nutrients (phosphorus and nitrogen) and sediments entering the lake. Since 2017, there has been a concerted effort to improve water quality in the lake through the construction of Water Sensitive Urban Design (WSUD) infrastructure such as wetlands, swales and raingardens throughout the catchment, and a major research program to understand the causes of poor water quality, and sources of pollutants. This work has been undertaken as part of the ACT Healthy Waterways program.

In 2022, the ACT Government commited to developing Healthy Waterways Plans for priority catchments in the ACT. The Lake Tuggeranong catchment Healthy Waterways Plan aims to provide a suite of potential management options to Government to further improve water quality in Lake Tuggeranong. To acheive this, modelling and analyses have been undertaken to examine a broad range of management scenarios and identify cost-effective options to improve water quality in Lake Tuggeranong. To support these analyses, a catchment model was developed in the eWater model platform Source (Argent, et al., 2005) to support the testing of water quality management scenarios, and rank these scenarios based on cost-effectiveness.

This report documents the development of a new, daily timestep water quantity and quality model for the Lake Tuggeranong catchment. The purpose of the model is to simulate long-term mean annual flows and associated pollutant loads entering Lake Tuggeranong, to inform and support catchment improvement studies and associated management strategies.

The model builds upon and extends previous models describing the Lake Tuggeranong catchment by:

- Including long-term, gap-filled climate data to extend the time period over which simulated results are available (1889-2023);
- Incorporating and combining up-to-date spatial data on land use and land surface imperviousness in the catchment;
- Undertaking hydrological model calibration;
- Adopting a model structure delineated to
    - water quality monitoring points to facilitate water quality model parameterisation;
    - existing and potential water quality improvement infrastructure (i.e., WSUD infrastructure) to facilitate estimation of pollutant load reduction from this infrastructure.

1.1 Overview of previous modelling and monitoring studies in the catchment

The model presented in this report builds on several published and unpublished modelling and monitoring studies undertaken in the Lake Tuggeranong catchment to describe flows and water quality in Lake Tuggeranong. These studies are reviewed briefly below, highlighting how the data has been used to inform the current study.

1.1.1 Modelling studies

Lake Tuggeranong catchment MUSIC 6 model, GHD (2015)

To inform the early stages of the Basin Priority Project, GHD developed a model of the Lake Tuggeranong catchment using the software MUSIC (Model for Urban Stormwater Improvement Conceptualisation) to aid in identifying sources of pollutant loads entering Lake Tuggeranong (GHD, 2015). The Lake Tuggeranong catchment was delineated based on contour information and the ACT stormwater network. Existing WSUD infrastructure in the catchment at the time comprised only gross pollutant traps (GPTs) with or without sedimentation basins, as well as Lake Tuggeranong, Isabella Pond, and Upper Stranger Pond. These assets were each represented as GPT, sedimentation basin, or wetland nodes in the MUSIC model. Land use classification in the model was based on ACT Government land zoning data aggregated to six broad categories, and imperviousness was based on values for each land use category from the published literature. Likewise, water quality parameters (event mean concentration, EMC, and dry weather concentration, DWC, of pollutants) were taken from the literature, rather than derived from existing data in the Lake Tuggeranong catchment.

The MUSIC model simulated flows and pollutant loads in the catchment under rainfall and evaporation conditions for the 10-year period from 1968-1977. It predicted an annual flow volume of 20,600 ML in the Lake Tuggeranong catchment, with an annual average of 2.7 tonnes TP, 31.5 tonnes N, and 2230 tonnes TSS generated given the existing WSUD infrastructure in the catchment at the time.

Lake Tuggeranong catchment MUSIC X model, eWater Ltd (2022)

eWater developed another MUSIC model of the Lake Tuggeranong catchment to assess the potential pollutant load reductions associated with WSUD assets that were constructed up to June 2019 as part of the ACT Healthy Waterways project (eWater Ltd, 2022). The Lake Tuggeranong catchment was delineated to 11 subcatchments, 7 of which drained through WSUD assets. The model operated on a 6-minute time step for the period 2010-2015. Published or MUSIC default values for hydrology and water quality parameters were applied to the model, which adopted a land use -based stochastic EMC/DWC approach to water quality modelling.

Land use was derived from 0.5m LIDAR coverage mapping impervious surfaces in the catchment and was divided into 6 classes (roof, road, hardstand, pervious, bushland, and rural). WSUD assets were incorporated in the model by importing and combining the 7 existing MUSIC models representing the detailed design configurations of each asset. Design configurations are expected to differ slightly from works-as-executed configurations.

The MUSIC model predicted an annual flow volume of 14,284 ML, with an annual average of 4.8 tonnes P, 39.8 tonnes N, and 2320 tonnes TSS generated in the Lake Tuggeranong catchment. However, the model was uncalibrated and over the period 2010-2015 overestimated flows by 57.2%, compared to observed data from the gauge immediately downstream of Lake Tuggeranong (Tuggeranong Creek upstream of Sewer Crossing, gauge 410779). The model is therefore also likely to overestimate pollutant loads in the catchment. However, the percentage removal of pollutants associated with each WSUD asset may be used as a starting point in the current modelling study to represent the treatment performance of existing assets.

Upper Murrumbidgee catchment Source models, Alluvium (2017) and eWater Ltd (2019)

Alluvium (Alluvium, 2017) developed an Upper Murrumbidgee catchment model in Source with the best available data and methods as a part of a project to meet requirements for the Murray-Darlin Basin Plan and the ACT Water Resource Plan. Alluvium's model delineated the Upper Murrumbidgee catchment into 440 subcatchments, using a 20 m digital elevation model (DEM), water management and hydrological boundaries, and stream gauging locations. Current ACT and NSW land use classifications, consistent with the Australian Land Use Mapping (ALUM) codes, were combined into 20 functional units for use in the model. The model used climate data from 1980-2016 and a combination of SIMHYD and GR4J rainfall-runoff models, assigned to urban and agricultural subcatchments, respectively. Observed discharge and water quality data from storages (dams and lakes) and sewage treatment plants (STPs) were used to parameterise the model. The model calibration was moderate for most of the gauges, with missing data at both hydrology and water quality monitoring gauges constituting a major limitation of the model. Moreover, due to the large number of subcatchments, model performance was very slow.

Alluvium's Source catchment model did not estimate flows and pollutant loads entering Lake Tuggeranong, instead providing estimates for the outlet of the Lake Tuggeranong catchment, including the effect of the lake itself on these parameters. The model predicted an annual flow volume of 5,868 ML for the outflow from the Lake Tuggeranong catchment, with an annual average load of 0.29 tonnes P, 5.63 tonnes N and 128.9 tonnes TSS.

In 2019, eWater identified a number of potential improvements to Alluvium's Upper Murrumbidgee catchment model and rebuilt the model (eWater Ltd, 2019). Their updated catchment model defined fewer subcatchments outside the ACT, delineating a total of 163 subcatchments, to improve model performance. eWater's model retained the climate data, land use and functional unit classifications used in Alluvium's model, but used the LASCAM rainfall-runoff model across all subcatchments to enable assessment of the hydrological impacts of land use change. The updated catchment model also incorporated Canberra's water supply, with storages configured to operate, albeit without implementation of operating rules.

Water quality parameters (EMC and DWC) in this model used values taken from the literature, rather than being fitted to observed data. While flow parameters were calibrated to observed data from 32 gauges across the Upper Murrumbidgee catchment, the model did not calibrate end-of-catchment values for the Lake Tuggeranong catchment to the downstream gauge Tuggeranong Creek at Sewer Crossing (410779). Therefore this model configuration cannot provide reliable estimates of the total flow and loads generated from the Lake Tuggeranong catchment.

1.1.2 Monitoring studies

University of Canberra Lake Tuggeranong research project, Stage 3 report (2020)

The University of Canberra's Lake Tuggeranong research project has demonstrated the importance of external sources of nutrients to water quality in Lake Tuggeranong. Stage 3 of the Lake Tuggeranong research project analysed the nutrient contribution from different subcatchments, in order to understand the relative influence of different land uses on nutrient inputs to the lake (Ubrihien, et al., 2020). Water sampling during rainfall events was undertaken in the Kambah Creek and Village Creek subcatchments over two years (2018 – 2020), with more than 2000 grab samples collected and analysed. The monthly total

phosphorus (TP), total nitrogen (TN) and total suspended solids (TSS) loads to Lake Tuggeranong were calculated for each subcatchment.

It was found that event discharge and loads of TP, TN, and TSS were much greater than those from baseflow. Event samples from urban areas of the subcatchments had high concentrations of nutrients with an unexpectedly high proportion in dissolved form. This study was constrained by extremely dry weather conditions over the spring and summer of 2019-20, which limited opportunities to collect event samples in a season of key interest. The movement of water and associated nutrients measured during these extreme conditions are unlikely to be representative of wetter years. Additionally, the lack of streamflow gauging at water quality sampling sites made it difficult to accurately estimate the nutrient loads entering the lake. Flow-weighted mean concentrations of nutrients from event samples were essential to calculate the load.

Despite these limitations, Stage 3 of the Lake Tuggeranong research project provides a significant water quality dataset including manual grab-sampling as well as data from 6 autosamplers at fixed locations on inflows to Lake Tuggeranong. The median measured concentrations of TP, TN and TSS from this work have been used in the parameterisation of our water quality model.

ACT Government water quality data

Several water quality monitoring programs supported or contracted by the ACT Government have measured pollutant (nutrient and sediment) concentrations at sampling sites across ACT waterways, including in the Lake Tuggeranong catchment. These have been collated into a single dataset and used in the parameterisation of our water quality model.

Waterwatch

This dataset includes water quality samples collected from eight different sampling sites in the Lake Tuggeranong catchment from 2017 to the present. The water quality parameters recorded include concentrations of TP and nitrates. Waterwatch data are publicly accessible at https://biocollect.ala.org.au/actwaterwatch. Following review and a focus on event flow water quality samples for model configuration, Waterwatch data were not used in the parameterisation of our water quality model.

Land Use Monitoring program (LUM)

Water quality data was collected from a single site in the Lake Tuggeranong catchment over 2018 and 2019. The water quality parameters recorded include concentrations of TP, TN and TSS.

Basin Plan Phase 1 (BPP1)

Under this program grab-samples were collected from 20 sampling sites in the Lake Tuggeranong catchment and analysed for water quality parameters including concentrations of TP, TN, and TSS.

ACT Lakes and Rivers water quality monitoring program

The ACT Lakes and Rivers water quality monitoring program has maintained two grab-sampling locations on Lake Tuggeranong. While these data were not used explicitly in the Source model calibration, they are

relevant to the in-lake modelling described in the supplement to this report, *Predicting phosphorus concentration and trophic state of Lake Tuggeranong* (Kahn & Dey, 2024).

1.2 Key gaps addressed by this study

The brief review above highlights the considerable amount of new water quality data that is now available for the Lake Tuggeranong catchment, including some event-based concentration data. The new data can be used to refine model water quality parameters that were previously based on values derived from the published literature. The modelling studies described above are limited in their utility as catchment models in the current planning context, as they either did not have the tools or resources available to calibrate model hydrology or were calibrated over a spatial resolution too coarse to investigate detailed catchment management strategies. Additionally, these previous studies simulated results over relatively short timeframes (6 – 36 years).

This study therefore aims to address these gaps by:

1. Preparing a high spatial resolution catchment model that uses a long-term historical climate observations dataset to simulate results over the 133-year period 1889-2023.
2. Calibrating the catchment model to ensure that end-of-catchment observed flows match modelled flows over the long term, so that the model accurately represents long-term water yield.
3. Using available event-based and baseflow water quality data to parameterise land use -based water quality models and derive new estimates of mean annual pollutant loads to Lake Tuggeranong.

Section 2 of this report collates and summarises the input data used to build and parameterise the model including terrain models, land use, water quality assets, hydrological and water quality data. Section 3 describes the model construction and parameterisation procedures and associated results and limitations. Section 4 presents the results of long-term flow and load estimates for the catchment under the current conditions including spatial results and estimated loads to Lake Tuggeranong. Section 5 presents the predevelopment and current scenario analysis of the catchment. Section 6 provides the conclusions and recommendations for next steps to improve model performance through additional data collection or by upgrading the model techniques.

2. Model input data

The Source modelling framework allows the simulation of catchment hydrology and pollutant generation in response to rainfall and climatic processes, catchment characteristics, land use and imperviousness, and waterway management. This requires the input of data describing each of these elements, enabling the catchment to be represented as a connected patchwork of areas for which the conversion of rainfall to runoff, the generation of pollutants, and the flow of surface waters between areas, can be calculated. Dividing the catchment into subcatchments for which flow and water quality data are available allows finer-scale calibration of the model to observed data in the catchment.

This section describes the input data sets used for model creation and parameterisation including:

- Subcatchment delineation;
- Land use classification and imperviousness;
- Water quality data;
- Climate data;
- Lake configuration;
- Streamflow and storage level data;
- WSUD asset configuration.

2.1 Subcatchment delineation

The Lake Tuggeranong catchment is approximately 6,600 hectares and is mostly (62%) urbanised. The southeastern part of the catchment is rural and extends across the ACT border into NSW. Catchment development began in the 1980s (Beer, Young, Humphries, & Burgess, 1982) and continued into the early 1990s. The Lake Tuggeranong catchment is the smallest Water Management Area in the ACT, and also encompasses a small component of the Upper Murrumbidgee water management area due to diversion of the upper Stranger Pond catchment to Lake Tuggeranong at Isabella Pond.

Because the subcatchments delineated to WSUD assets for the eWater (2022) study contained some discrepancies with the ACT Government stormwater network map, a new subcatchment map was created using a pit-filled, 1 m DEM based on high-resolution LIDAR data (ACT Government, 2016) and the ACT Government stormwater network map. Subcatchments within the Lake Tuggeranong catchment were delineated to:

- known water quality monitoring locations;
- known streamflow monitoring locations;
- existing WSUD assets;
- ponds and storages.

This resulted in 75 subcatchments, shown in Figure 1. When identifying water quality monitoring sites for catchment delineation, University of Canberra water quality monitoring sites based on the stormwater network were prioritised.

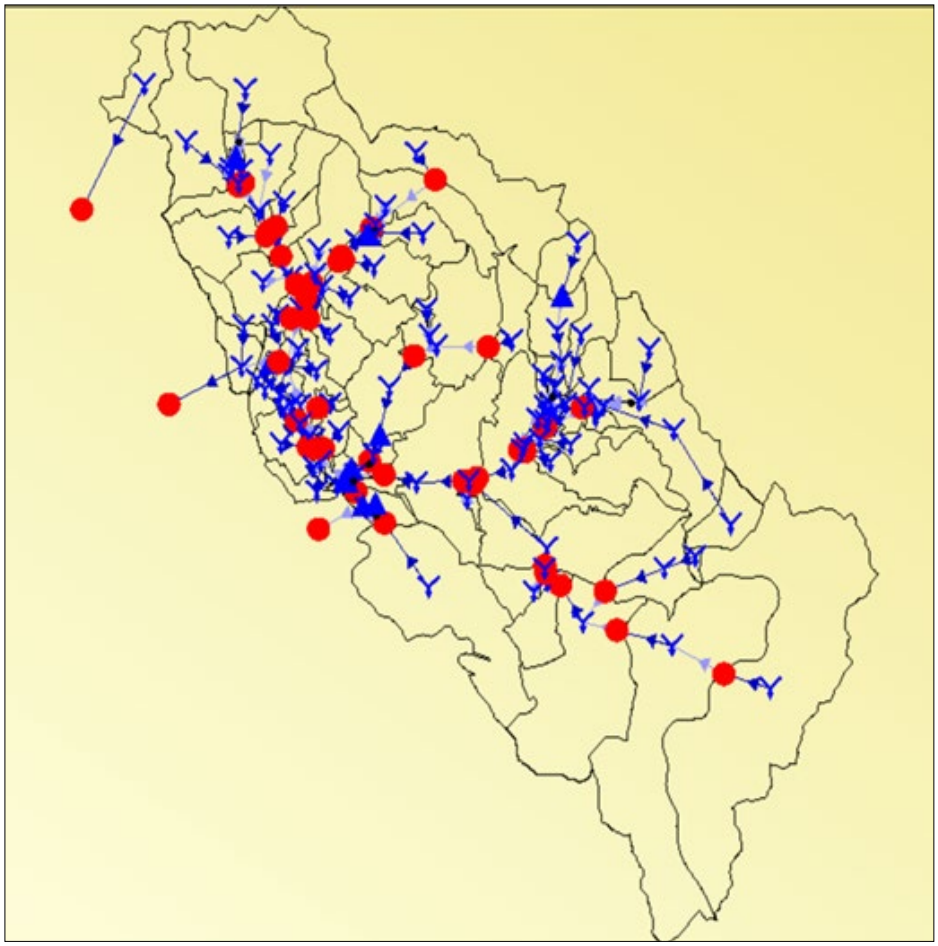

Figure 1. Screenshot of the Source model-generated Lake Tuggeranong subcatchment map, showing nodes defined by flow and water quality monitoring locations (large red points) and WSUD infrastructure (large blue triangles). Blue 'Y' symbols represent flow and pollutant generation within subcatchments and small blue arrows indicate the direction of flow.

2.2 Land use classification and imperviousness

Land use classification for the Lake Tuggeranong catchment model aims to represent a wide range of land uses that could be subject to different structural and non-structural catchment management actions, such as suburban street sweeping, construction of additional WSUD assets, or education around private household fertilizer use. To this end, broad land use classifications adopted for previous modelling studies (eWater Ltd, 2022) were disaggregated to a more granular set of classifications based on ACT Government land zoning. These were combined with data on land surface imperviousness to derive land use for the Lake Tuggeranong catchment model as follows:

1. Aerometrix (2020) LIDAR data at 0.5m pixel resolution was trimmed to the Lake Tuggeranong catchment, mapping 5 land surface imperviousness classes:
    - Impermeable ground level (i.e., roads and hardstand)
    - Impermeable above ground level (i.e., roofs)
    - Permeable ground level (i.e., pervious, unpaved ground)
    - Permeable above ground level (i.e., tree canopy)

- Water

2. The LIDAR data was converted to shapefile and intersected with the 2023 ACT Government land zoning GIS layer trimmed to the Lake Tuggeranong catchment, consisting of 17 land use zones consistent with ALUM codes:
   - Business zone
   - Community Facilities
   - Core zone
   - Leisure and accommodation
   - Local centre
   - Services
   - Services zone
   - Medium density residential
   - Suburban
   - Suburban core
   - Transport
   - Urban open space
   - Restricted access recreation zone
   - Hills ridges and buffer areas
   - Designated
   - River corridor
   - Rural

   The entire NSW portion of the catchment was classed as 'Rural' land use.
3. This cross-classified land use layer was intersected with the ACT Government road edges GIS layer, to identify road area within each land use zone. Areas classified as impermeable ground level that fell outside of the roads boundary were deemed hardstand, and areas classified as permeable above ground level that fell within the roads boundary (i.e. where trees overhung road) were reclassified as road (impermeable ground level). This approach yields a more precise classification of road area than the approach of eWater (eWater Ltd, 2022), where road centrelines buffered by 5m were used to estimate the area of impermeable road surface within the transport classification of the land zoning map, which includes the entire road corridor consisting of largely permeable open space.
4. Finally, visual inspection of aerial imagery was used to identify and manually delineate irrigated sports fields based on their "greenness" relative to nearby open spaces, and assign them a specific land use classification.
5. The land use and imperviousness layer was converted to a 0.5m grid, which was intersected with the Lake Tuggeranong subcatchment map to obtain the area of each land use - imperviousness combination within each subcatchment.
6. The detailed land use types were grouped into six major functional units for incorporation into the Source catchment model: suburban, commercial, open space, rural, bushland and sports field, each containing imperviousness classifications of road, hardstand, roof, permeable ground level, permeable above ground level, and water. The final land use and imperviousness classification schedule, and the area associated with each land use functional unit in the model domain is provided in Appendix C.

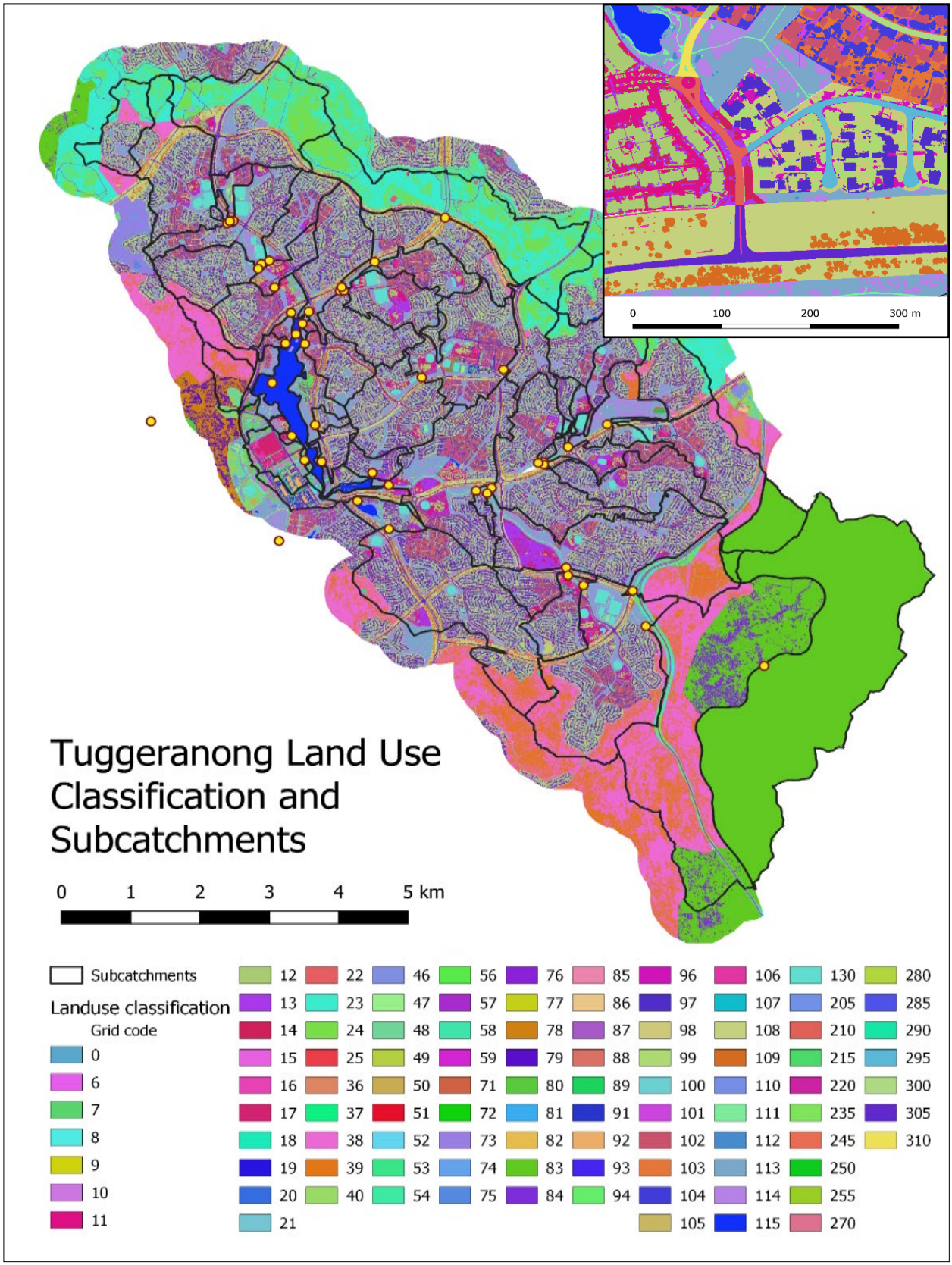

Figure 2. Land use map of the Lake Tuggeranong catchment with colours representing the unique code for each land use - imperviousness combination. Yellow dots indicate water quality or streamflow monitoring locations. **Inset:** close-up detail of a section of the map showing roads, rooftops and open space.

2.3 Water quality data

Water quality data from within the Lake Tuggeranong catchment was collected by a range of programs between 2014 and 2021 (Table 1). Some of the programs entailed event-based monitoring of specific land uses whilst others were focussed on grab sampling from many sites throughout the catchment to try and understand spatial variation of water quality and how it may relate to land use.

Table 1. The number of water quality samples collected across five monitoring programs and analysed for 3 pollutants used in model calibration. TP, total phosphorus; TN, total nitrogen; TSS, total suspended solids.

Monitoring program	Years active	Number of sites	TP	TN	TSS
Basin Plan Phase 1 (event sampling)	2014-2015	19	93	93	93
ACT Government Land Use Monitoring program (event sampling)	2018-2019	1	93	93	93
Lake Tuggeranong Research Project (event sampling)	2017-2018	7	1385	1376	1071
University of Canberra (grab sampling)	2018-2020	29	315	315	316
Upper Murrumbidgee Waterwatch (grab sampling)	2014-2021	8	585		
Total			2471	1877	1573

Table 1 shows there is a large amount of historical water quality data potentially available for use. However, no study in the catchment has converted the measured pollutant concentrations to loads, which requires simultaneously monitoring of flows in order to calculate flow-weighted mean concentrations.

Catchment models typically adopt a land use based EMC/DWC approach to estimate mean annual pollutant load, with model calibration achieved by matching observed loads to modelled loads. As no observed load data is currently available, we adopted the following model parameterisation approach:

1. All pollutant concentration data from the available water quality studies was compiled into a single data frame. For days where multiple samples were collected from a site, the mean of these samples was calculated as an approximation of the mean concentration occurring on that day.
2. Modelled daily flows and modelled pollutant concentrations were compiled into a single data frame and the event flow threshold, defined as the flow threshold that is exceeded in the top 10% of all modelled flow days, was identified.
3. For each day that observed pollutant concentration data was available, we retrieved the modelled flow and associated modelled concentration for the pollutant and monitoring site in question. We split this date-matched data between event and baseflow conditions and calculated the medians of the observed and modelled data for each site.

The median observed pollutant concentration value was compared to the median modelled pollutant concentration value for sites at the six major lake inlet points and a scaling factor estimated to scale the EMC values for that pollutant. The scaling factor was applied across all land uses for that pollutant.

Parameterisation steps 1-3 above were then re-run to test the model fit. This model parameterisation approach preserves the typical difference between land use-based EMC/DWC combinations whilst date-matching median observed lake inflow concentrations to the median modelled concentrations.

Figure 3 provides example plots and data for the monitoring point at the Village Creek inlet to Lake Tuggeranong. Modelled median event-based concentrations of TP exceed observed concentrations, however across all observed data (event and baseflow), median modelled concentrations match observations (n = 275). The time series of modelled concentrations can never attain the variability of observations due to the fixed nature of the EMC/DWC modelling method.

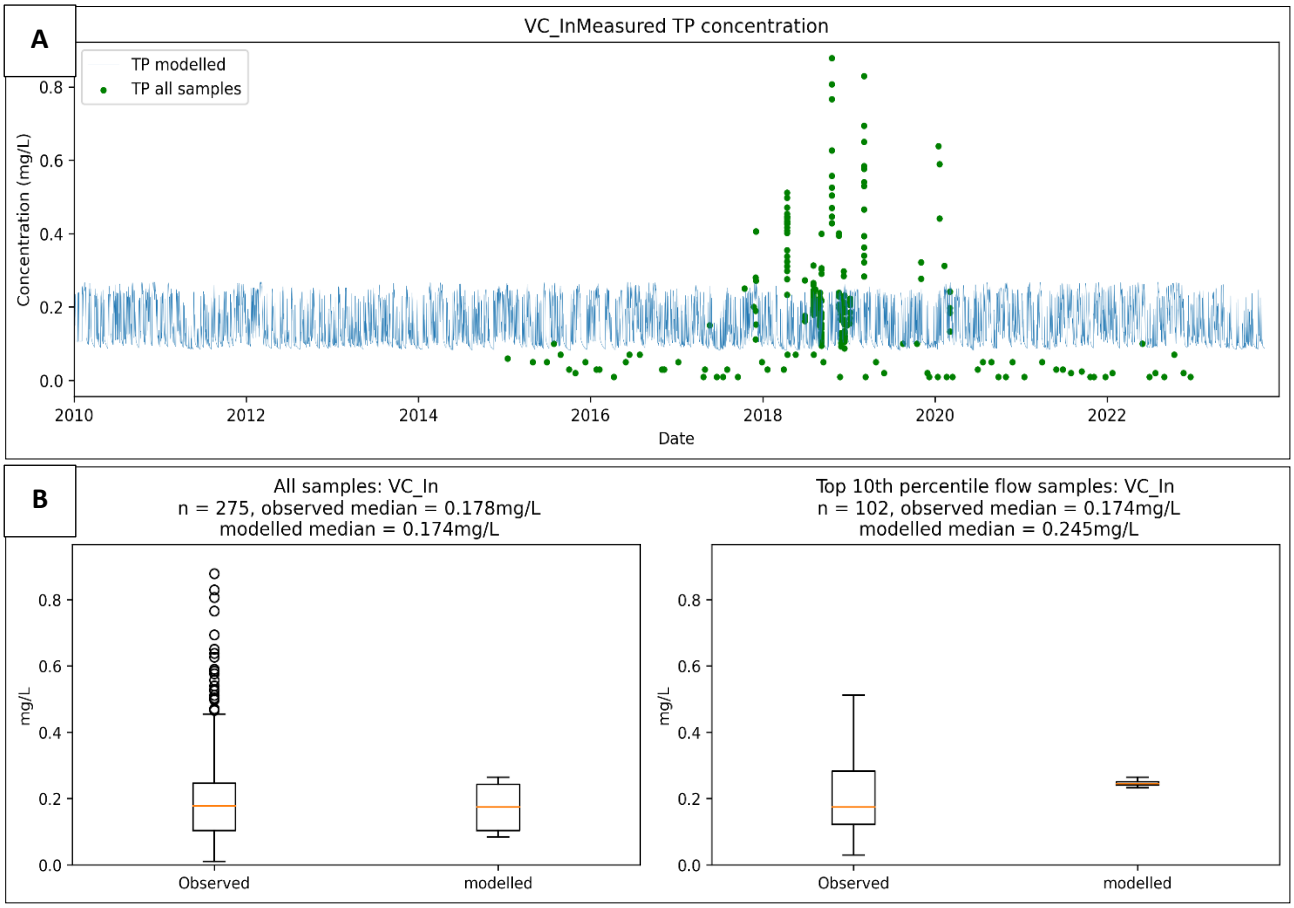

Figure 3. Example of the comparison of observed vs. modelled pollutant concentration data for a single water quality monitoring point. A) Time series of modelled total phosphorus (TP) concentrations (blue line) and date-matched observed median TP concentrations (green points) for the monitoring point at the Village Creek inlet to Lake Tuggeranong. B) Boxplots showing the distributions of modelled and observed median TP concentrations for all samples (left panel) and samples from the top 10th percentile of flow events (right panel) for the monitoring point at the Village Creek inlet to Lake Tuggeranong.

2.4 Climate data

Several climatological stations located within the Lake Tuggeranong catchment could provide data for sub-daily rainfall-runoff modelling. However, to meet the aims of the current model a long-term daily rainfall record without gaps is required. We therefore used patched daily data from the Tuggeranong (Isabella Plains) climatological station (Bureau of Meteorology station number 070339). This station is located within

the Lake Tuggeranong catchment (Figure 4) and has been open since May 1996 - present with 99% completeness of the data record. For this post-1996 period we were able to provide complete observed climate data to the model. To cover the entire period 1889-2023, we used patched data for the pre-1996 period from the SILO (Scientific Information for Land Owners) patch point dataset for this station (https://www.longpaddock.qld.gov.au/silo/).

The following climate variable time series associated with this site were used for catchment modelling:

- Rainfall (mm/d) for rainfall-runoff modelling and water body water balance modelling;
- Morton's wet-environment areal evapotranspiration over land (mm/d) for rainfall-runoff modelling (MWet);
- Morton's shallow lake evaporation (mm/d) for water body water balance modelling (MLake);
- Maximum and minimum temperature for experimental stormwater and lake temperature modelling (Tmax and Tmin) ;
- Evapotranspiration (mm/d) of short crop for irrigation modelling.

2.5 Lake Tuggeranong storage configuration

Lake Tuggeranong is modelled as a completely mixed storage, taking inflows from the whole catchment and releasing flows according to the stage (water level) -discharge relationship of its outflow point at Lake Tuggeranong weir. The lake is also subject to daily rainfall and daily evaporation (MLake), modelled using the SILO daily time-series for the Tuggeranong (Isabella Plains) climatological station (station ID 070339). As Lake Tuggeranong does not have any water supply requirements, no water use is modelled for this storage.

To configure the Lake Tuggeranong storage node, a rating curve was derived from the bathymetry data and imported into the model. This was calculated from the observed water level measured at the Lake Tuggeranong weir (gauge 410784), using the level-volume-area (LVA) relationship for Lake Tuggeranong obtained from bathymetry data collected in 2015 by Steger and Associates Registered Land Surveyors under the Basin Priority Project (data provided in Appendix A).

The lake outlet was configured as an ungated spillway, using the stage-discharge rating table for the Lake Tuggeranong weir (gauge 410784) supplied by ALS Hydrographics via their HYDSTRA database. The stage-discharge data is provided in Appendix B.

2.6 Streamflow and storage level data

2.6.1 Gauge 410779: Tuggeranong Creek upstream of Sewer Crossing

The key streamflow data available for this catchment comes from the gauge at Tuggeranong Creek upstream of Sewer Crossing (gauge 410779; Figure 4) which is located a short distance below the Lake Tuggeranong outflow. Recorded streamflow data is available from 1986 and the gauge remains current. Gauge records show that the maximum recorded flow rate is approximately 200 cumecs, while the maximum rated flow is 108 cumecs or approximately 50% of the maximum recorded flow. Flows greater than 100 cumecs have occurred approximately 6 times since 1990. 216 gaugings (validating measurements) have been undertaken at the site since 1986, with the highest flows being gauged within the first few years of site establishment. Since 2000, the maximum gauged flow has been approximately 6.5 cumecs.

Consequently, higher recorded flows have higher associated uncertainty. However, the gauging record shows a stable relationship with little scatter, with gaugings covering the majority of observed flows at the site, indicating a reliable stage-discharge curve. The site is therefore rated as suitable for model calibration.

2.6.2 Additional short-term streamflow monitoring sites

Additional streamflow records collected by the ACT government for various short-term studies are included in the model:

- 410650 Upper Stranger Pond (1990-1990) Inflow to the pond at GPT
- 410651 Upper Stranger Pond (2017-2018) Outflow from Upper Stranger Pond
- ES1701 Tuggeranong Channel @ Clive Steele (2017-2018)
- ES1702 Monash Channel @ Charleston (2017-2018)

As validation gaugings are generally unavailable for these short-term monitoring sites, they are used for indicative comparison purposes rather than model calibration.

2.7 Water Sensitive Urban Design assets

Geographic location and pollutant reduction performance data were available for eight existing WSUD assets in the Lake Tuggeranong catchment, built under Stage 1 of the ACT Healthy Waterways program. eWater (eWater Ltd, 2022) modelled the flow and water quality performance of these assets using MUSIC (Table 2). Each of these eight WSUD assets is represented in the current Lake Tuggeranong catchment model as a splitter node that diverts flow to the asset, and a storage node that applies a water quality decay function, representing the percentage reduction in pollutant loads (TP, TN, and TSS) achieved by the asset. Splitter nodes are configured with a maximum flow rate that is diverted into the asset, and any flow above this bypasses the asset, based on the MUSIC modelled high-flow bypass threshold. Storage nodes are configured based on asset design information from their respective preliminary sketch plan (PSP) or design acceptance reports, and their pollutant load decay rate was initially set to match the MUSIC modelled percent reduction rate with a default half-life of 1 day. Field observations indicated that some assets are not currently performing to their full capacity, and the pollutant load decay rates were adjusted to reflect the reduced performance of these assets (Table 2).

Table 2. Adjusted efficiencies (% reduction) of water quality parameters for eight Healthy Waterways Stage 1 WSUD assets, matching the current observed working condition of assets. These values were implemented in the Lake Tuggeranong catchment model. Values in parentheses are the predicted efficiencies from MUSIC models in the technical reports for each asset *(eWater Ltd, 2022)*.

Asset	% Flow bypassed	% TP reduction	% TN reduction	% TSS reduction
TG008	41	27 (54)	25 (51)	41 (82)
TG010	28	54 (78)	51 (74)	66 (95)
TG011N	75	39 (66)	31 (53)	45 (75)
TG011S	75	39 (66)	31 (53)	45 (75)
TG012	29	20 (20)	9 (9)	24 (24)
TG017	52	60 (60)	47 (47)	65 (65)
TG029	49	10 (51)	9 (47)	14 (74)
TG030	66	28 (28)	15 (15)	32 (32)

3. Model build and parameterisation

3.1 Hydrology

3.1.1 Lake Tuggeranong catchment model build

A single catchment model representing the Lake Tuggeranong catchment was developed in Source version 5.3 (https://ewater.org.au/ewater-solutions/tools/source/). The model operated on a daily timestep using long-term, gap-filled climate observations from 01/01/1889 to 30/10/2023. Using a 1 m pit-filled DEM and the ACT Government stormwater network, the catchment was delineated into subcatchments based on flow gauging and water quality monitoring sites as well as WSUD asset locations. A node link network of the catchment model was established. Land use classifications and land surface imperviousness data were combined to define functional units implemented in the model.

The gauge downstream of Lake Tuggeranong (Tuggeranong Creek upstream of Sewer Crossing, gauge 410779) was identified as the node for flow calibration. For hydrologic parameterisation for this gauge, daily timestep streamflow data from 06/02/1986 to 30/10/2023 was input to the catchment model. The internal calibration tool using the objective functions square root daily, exceedance, and bias, was implemented to achieve a suitable fit between modelled and measured data. The daily Nash-Sutcliffe efficiency (NSE) coefficient (Nash & Sutcliffe, 1970) was used as the model performance criterion.

3.1.2 Model calibration

SIMHYD and Sacramento rainfall-runoff models were tested for their suitability for model calibration. The initial flow calibration was conducted for the Lake Tuggeranong catchment before delineation into subcatchments, for the period 01/01/1996 to 30/10/2023, with a warm-up period of 10 years (1986-1995). The permanent impervious fraction of the catchment (pctim) for roads, roofs and hardstand was set to 90% impervious in the Sacramento model as these land uses generate more runoff than permeable surfaces. The objective functions used in the calibration were square root daily, exceedance, and bias. Shuffled Complex Evolution (SCE) followed by Rosenbrock were chosen for optimisation, with 5 iterations and a population number of 500. The Sacramento rainfall-runoff model performed better than the SIMHYD model, providing a better fit with the recorded flow data (Table 3).

Table 3. Model performance statistics for the Sacramento and SIMHYD rainfall-runoff models.

Rainfall-runoff model	Daily Nash-Sutcliffe coefficient	% Volume bias
Sacramento	0.803	-0.85
SIMHYD	0.744	0.001

The initial calibration results confirmed the selection of the Sacramento rainfall-runoff model for the Lake Tuggeranong catchment. The calibrated hydrologic parameters for this model are provided in Table 4.

Table 4. Calibrated hydrologic parameters for the Lake Tuggeranong catchment model using a Sacramento rainfall-runoff model.

Parameter	Suburban	Open space	Commercial	Rural	Bushland	Sports field
Soil moisture store (Lztwm) (mm)	75	75	75	75	75	75
Soil moisture store (Lzfsm) (mm)	15	15	15	15	15	15
Soil moisture store (Lzfpm) (mm)	267.5	267.5	267.5	267.5	267.5	267.5
Rate of lateral outflows (Lzsk)	0.03	0.03	0.03	0.03	0.03	0.03
Rate of lateral outflows (Lzpk)	0.003	0.003	0.003	0.003	0.003	0.003
Rserv	0.346	0.346	0.346	0.346	0.346	0.346
Losses (Side)	0	0	0	0	0	0
Time delay in runoff (UH1)	0.88	0.88	0.88	0.88	0.88	0.88
Time delay in runoff (UH2)	0	0	0	0	0	0
Time delay in runoff (UH3)	0	0	0	0	0	0
Time delay in runoff (UH4)	0.0109	0.0109	0.0109	0.0109	0.0109	0.0109
Time delay in runoff (UH5)	0.03	0.03	0.03	0.03	0.03	0.03
Soil moisture store (Uztwm) (mm)	75.44	75.44	75.44	75.44	75.44	75.44
Soil moisture store (Uzfwm) (mm)	75	75	75	75	75	75
Rate of lateral outflows (Uzk)	0.5	0.5	0.5	0.5	0.5	0.5
Water percolation (Zperc)	153.46	153.46	153.46	153.46	153.46	153.46
Water percolation (Rexp)	3.02	3.02	3.02	3.02	3.02	3.02

Parameter	Suburban	Open space	Commercial	Rural	Bushland	Sports field
Impervious runoff (Pctim)	0.5	0.5	0.5	0.5	0.5	0.5
Losses (Sarva)	0	0	0	0	0	0
Losses (Ssout) (mm)	0	0	0	0	0	0
Impervious runoff (Adimp)	0.30	0.30	0.30	0.30	0.30	0.30
Water percolation (Pfree)	0.19	0.19	0.19	0.19	0.19	0.19

Table 4 continued. See caption previous page.

3.1.3 Model verification

To verify the modelled flow generation of the Lake Tuggeranong catchment, a comparison was made with the Jerrabomberra catchment, which has similar geographic features and location.

A model of the Jerrabomberra catchment was set up in Source using the climate variables daily rainfall and Morton's wet-environment areal evapotranspiration over land (MWet). The rainfall data was obtained from SILO, using station ID 70066 for the NSW portion of the catchment, and station 70249 for the ACT portion. The MWet data was obtained from SILO station ID 70072. The gauged flow data used for calibrating this catchment came from Jerrabomberra at Hindmarsh (gauge 410790), obtained from ALS Pty Ltd. The model was calibrated using a Sacramento rainfall-runoff model, and the objective functions square root daily, exceedance, and bias. SCE followed by Rosenbrock were chosen for optimisation, with 5 iterations and a population number of 500. The calibration was a moderate fit with a daily Nash-Sutcliffe coefficient of 0.59 and volume bias of 0%.

The runoff coefficients of both the Lake Tuggeranong and Jerrabomberra catchments were calculated to compare their performance under predevelopment conditions, represented by 100% bushland land use. The runoff coefficient of the Lake Tuggeranong catchment was approximately 7%, and that of the Jerrabomberra catchment was approximately 8.5%. The two catchments performed similarly under pre-development conditions, verifying the flow generation of the Lake Tuggeranong catchment model.

3.1.4 Model uncertainty estimation

At this stage, model uncertainty estimation has not been undertaken.

3.1.5 Flow routing calibration

Due to the small catchment size and largely urban land use, flow routing was not undertaken in any reach in the Lake Tuggeranong catchment model.

3.1.6 Lake water balance

The lake water balance accounted for all inflows, outflows, rainfall, and evaporation from the lake.

3.2 Water quality

Source catchment models are best suited to estimating long-term mean annual catchment pollutant loads rather than daily concentrations. Ideally, empirical measurements of EMC and DWC from different land uses would be used to parameterise the model. However, as described in section 2.3, water quality data from the Lake Tuggeranong catchment has not been collected concurrently with quantitative flow data, precluding the calculation of EMC. As a result of these data limitations, and noting that long-term inflows and pollutant load into the lake are a key predictive output of the model, a simple approach was adopted to adjust land use -based model water quality parameters using available monitoring data:

1. For each water quality monitoring site, daily median event flow concentrations for each pollutant were calculated for all available dates, as described in section 2.3.
2. A baseline simulation run of the model was performed using EMC and DWC values adapted from the literature (Fletcher, Duncan, Poelsma, & Lloyd, 2004), (Witt, Mainwright, & Weber, 2015), (Melbourne Water, 2024), (Blacktown City Council, 2020), and the modelled daily flows and predicted pollutant concentrations for all monitoring sites were extracted.
3. Baseline modelled pollutant concentrations were date-matched with observed median flows and concentrations to allow for later flow stratification (if appropriate) and to account for sample population representativeness (dry periods or wet periods).
4. Median observed and modelled pollutant concentrations for six major lake inflow sites were then calculated, and used to estimate scaling factors to adjust the literature-derived EMC values for majority land uses (roads, roofs, hardstand, and pervious areas of suburban, commercial, and open space land use categories). Where data allowed, inflow-specific scaling factors were applied.
5. The model was re-run using the scaled EMC values (Appendix D), and modelled median concentrations were once again compared against observed median concentrations.
6. When median modelled and observed values were in agreement, the model parameters were checked against literature values to ensure that the model estimate remained in the anticipated range.

4. Results

4.1 Flow calibration

A hydrograph time series for flows in the Lake Tuggeranong catchment over the model calibration period, 1996-2023, is presented in Figure 4. The hydrograph demonstrates good agreement between the timing and magnitude of modelled and observed flows, which are highly correlated with a daily Nash-Sutcliffe coefficient of 0.88 indicating a very good fit (Moriasi, et al., 2007). There is acceptable peak flow matching with an overall low bias, suggesting the model is reliable in simulating high flow events (Table 5). This strong performance across flow magnitudes confirms the robustness of the model calibration and its suitability for simulating the hydrology of the Lake Tuggeranong catchment.

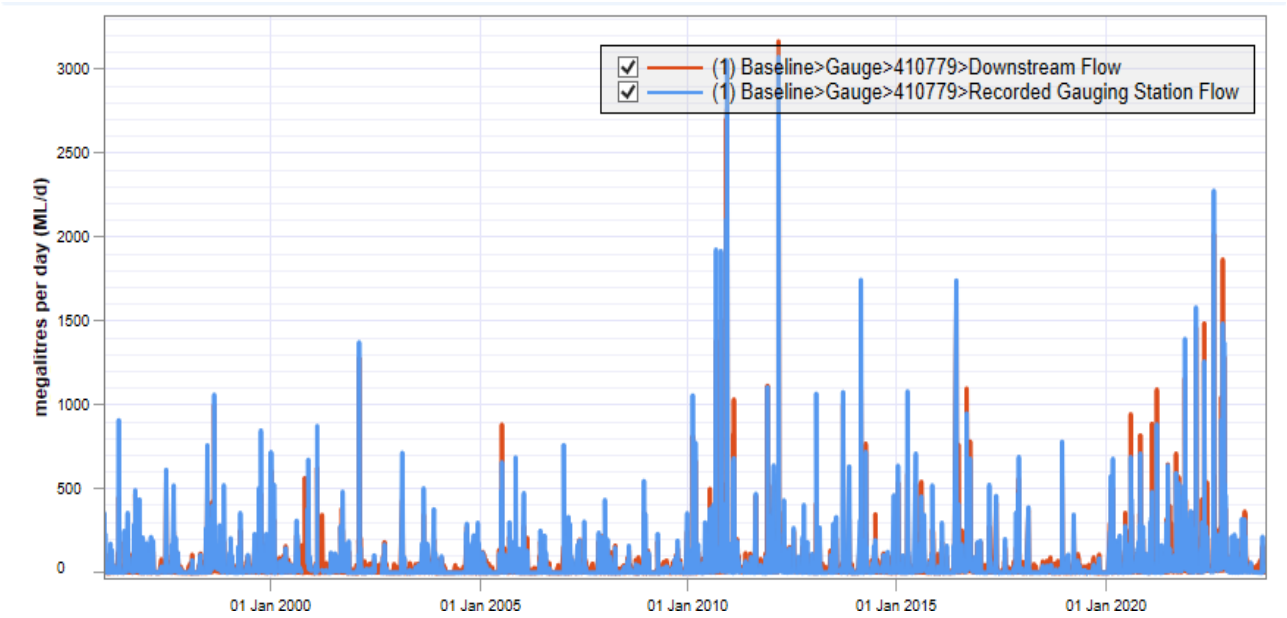

Figure 4. Modelled (red) and observed (blue) flows (daily discharge, ML/d) for Tuggeranong Creek upstream of Sewer Crossing (gauge 410779).

Table 5. Flow calibration model performance statistics for Tuggeranong Creek upstream of Sewer Crossing (gauge 410779).

Performance criterion	
Daily Nash-Sutcliffe Efficiency coefficient	0.88
Monthly Nash-Sutcliffe Efficiency coefficient	0.92
% Volume bias	-0.25

Figure 5 depicts the cumulative flow curve over the calibration period, demonstrating good agreement between modelled and observed flow over the entire period. This agreement indicates that the model accurately captures the total volume of water passing through the catchment, validating its performance in representing the overall hydrological processes.

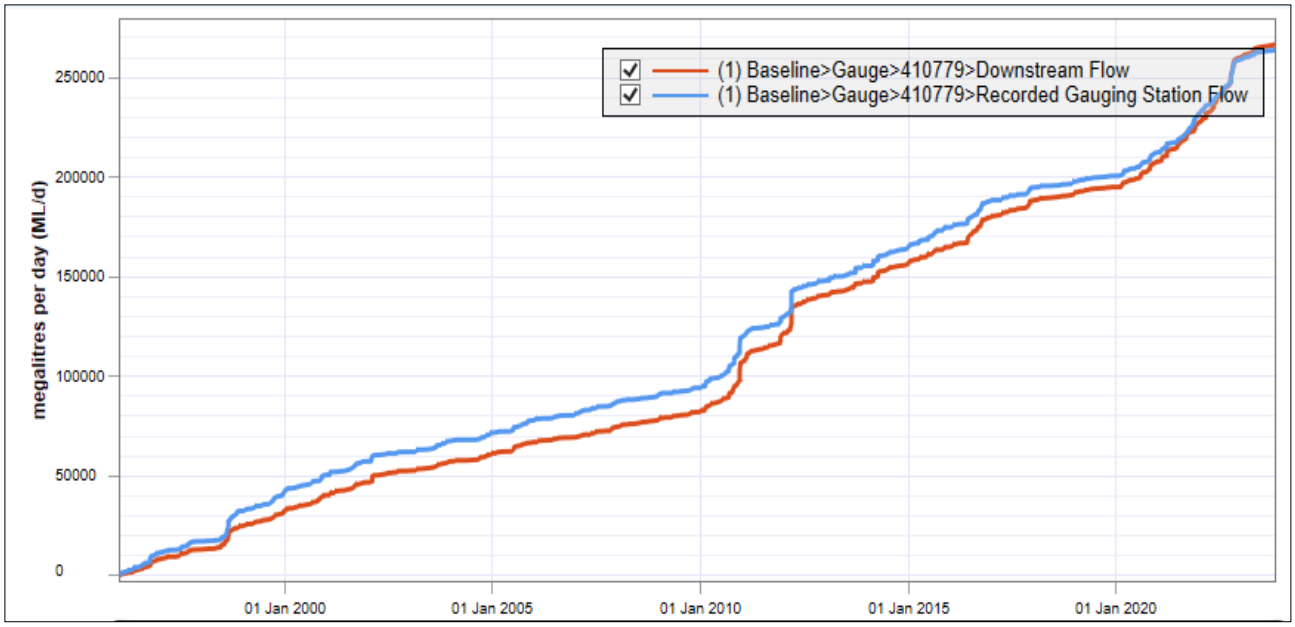

Figure 5. Modelled (red) and observed (blue) cumulative flow for Tuggeranong Creek upstream of Sewer Crossing (gauge 410779), 1996-2023.

Figure 6 illustrates the flow duration curve for flows in the calibration period, showing generally good agreement between modelled and observed flow across most flow conditions. However, discrepancies are noted particularly at low flows. This suggests that while the model performs well overall, there may be areas where the representation of low-flow conditions could be further refined or calibrated.

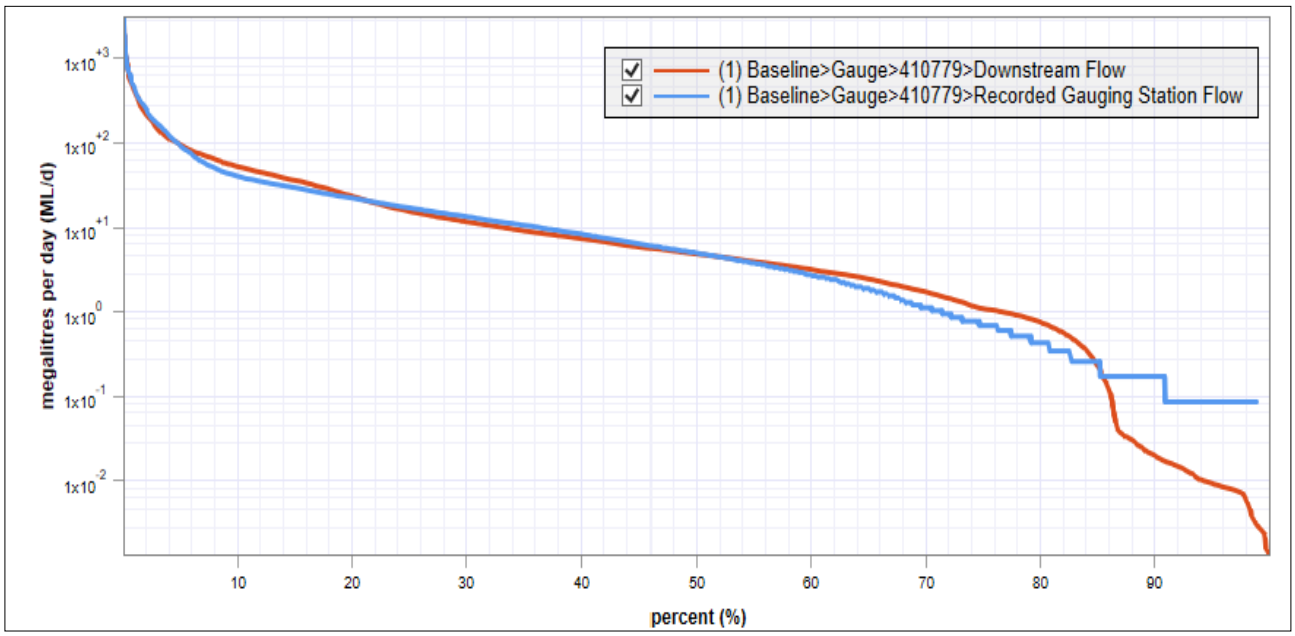

Figure 6. Modelled (red) and observed (blue) flow exceedance curve for Tuggeranong Creek upstream of Sewer Crossing (gauge 410779), 1996-2023.

Figure 7 presents the residual mass curves for observed and modelled flows over the calibration period. The difference between the curves indicates the cumulative difference between observed and modelled flows over time. Ideally, this difference should hover around zero, indicating minimal bias or systematic error in the model.

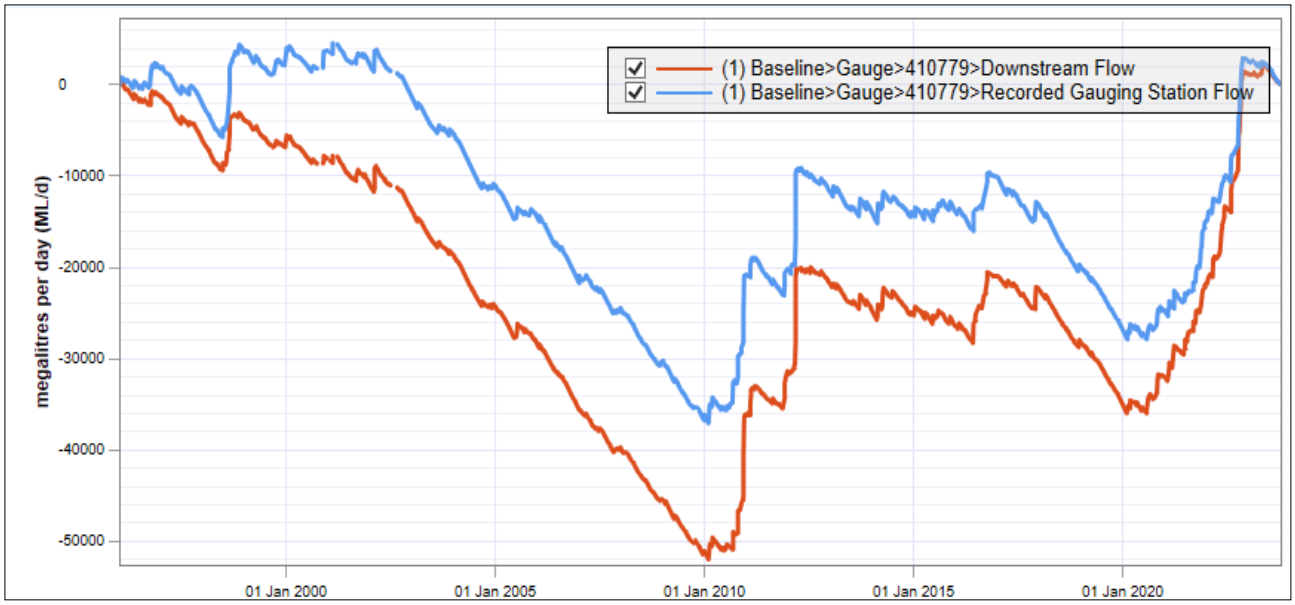

Figure 7. Modelled (red) and observed (blue) residual mass for Tuggeranong Creek upstream of Sewer Crossing (gauge 410779), 1996-2023.

The above plots collectively provide a comprehensive evaluation of the model's performance in simulating hydrological processes in the Lake Tuggeranong catchment, capturing overall flow patterns.

4.2 Water quality calibration

Figure 8 illustrates the comparisons between the median observed and modelled concentrations of TP, TN, and TSS for 34 sites across the Lake Tuggeranong catchment where water quality monitoring was undertaken. These comparisons provide a visual representation of the model's performance in simulating water quality across the catchment. At well-sampled sites, there is generally good agreement between the observed and modelled concentrations. Discrepancies at other sites are primarily due to insufficient sample numbers (Figure 9). Higher median TP concentrations are noted for sites in the Village Creek, Kambah Creek, and Wanniassa subcatchments (site codes beginning with VC, KC, WS respectively) compared to other areas within the Lake Tuggeranong catchment.

As there were multiple sampling locations across the catchment the mean of site medians can provide a robust central tendency measure. The mean of the median modelled concentration for TP is 0.17 mg/L, for TN is 1.33 mg/L, and for TSS is 49.7 mg/L.

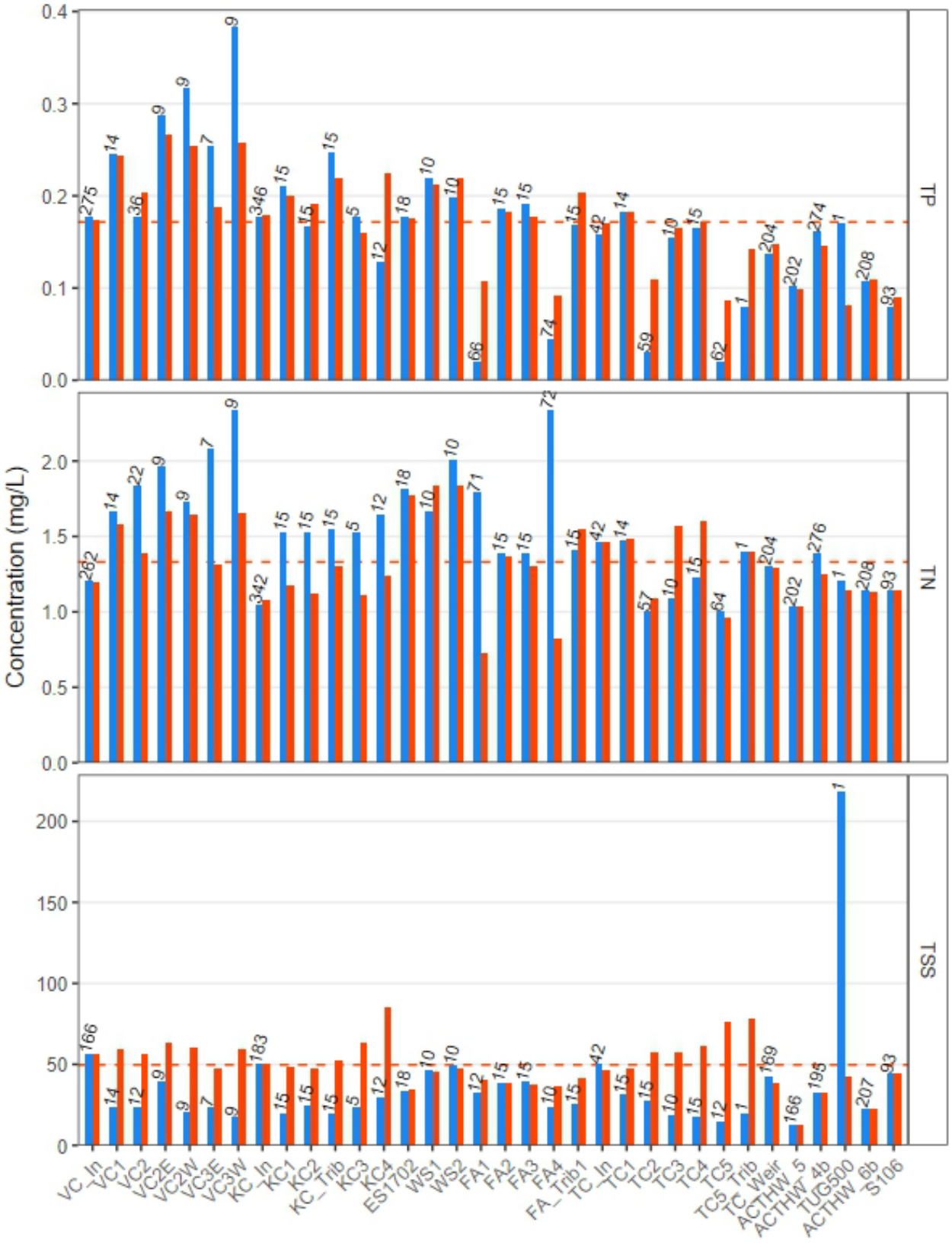

Figure 8. Observed (blue) and modelled (red) median concentrations of total phosphorus (TP; top panel), total nitrogen (TN; middle panel), and total suspended solids (TSS; bottom panel) for each water quality monitoring site in the Lake Tuggeranong catchment. Blue bars are labelled with the number of samples per site analysed for each parameter. The red dashed lines indicate the means of the median modelled concentrations of each pollutant (see text).

Figure 9 illustrates the deviations of modelled from observed site median concentrations for the three water quality parameters, as a function of the number of samples at the monitoring site. A value of zero indicates no bias in the model estimates for that site (i.e. no consistent over- or under-estimation of concentrations, compared to observed values). For all three parameters, deviations decline sharply with increasing sample size. The median deviation for TP is close to zero with a narrow interquartile range, indicating low overall bias. TN deviations are more spread out, with a slight overall positive bias indicated by the median just above zero. TSS deviations have a narrow interquartile range, with a median deviation below zero indicating an overall negative bias, and a notable positive outlier. As for TP and TN, the vast majority of substantial deviations for TSS occur for sites with very low sample sizes.

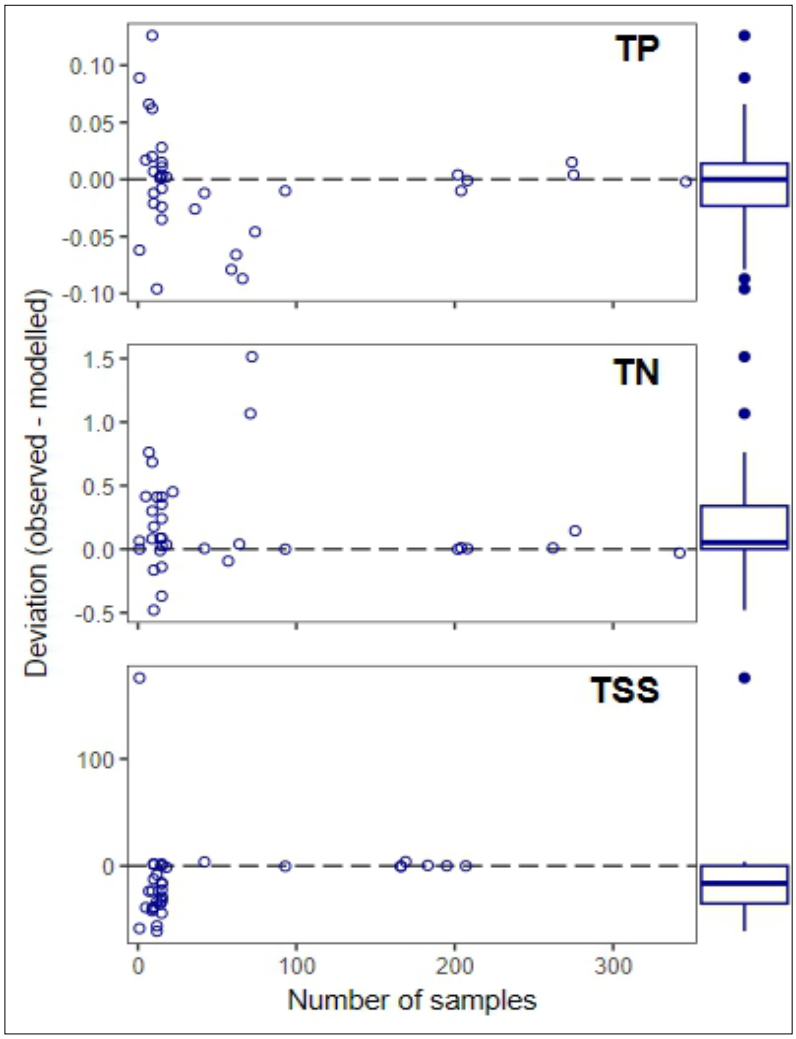

Figure 9. Scatter plots showing the deviation of modelled from observed median concentrations of total phosphorus (TP), total nitrogen (TN), and total suspended solids (TSS) as a function of sample size at 34 water quality monitoring sites in the Lake Tuggeranong catchment. The dashed grey line at zero indicates no bias in the model estimates for a given site. Box-and-whisker plots illustrate the spread of deviations.

4.3 Catchment modelling results

The calibrated catchment model was simulated over the climate period January 1889 – October 2023, and summaries of the total flow and pollutant loads were calculated for each complete year (1889-2022). Under current catchment land use and management conditions, the modelled mean annual inflow to Lake

Tuggeranong was 8.8 GL/year. The modelled mean annual loads of pollutants entering Lake Tuggeranong were 1,442 kg/year total phosphorus, 11,894 kg/year total nitrogen, and 397,064 kg/year total suspended solids.

Figure 10 presents a series of heat maps illustrating the modelled mean annual loads of TP, TN and TSS generated in different subcatchments of the Lake Tuggeranong catchment, with darker shading indicating a higher load. The pollutant load generated depends on the land uses within each subcatchment. The highest mean subcatchment TSS loads fall between 160 – 180 kg/ha/yr. The highest TN loads are between 3.5 – 4 kg/ha/yr, and the highest TP loads are between 0.6 – 0.7 kg/ha/yr. For all three pollutants, higher load generation occurs in more urbanised catchments. This broad visual representation can help in identifying the areas requiring critical attention to improve water quality in the catchment.

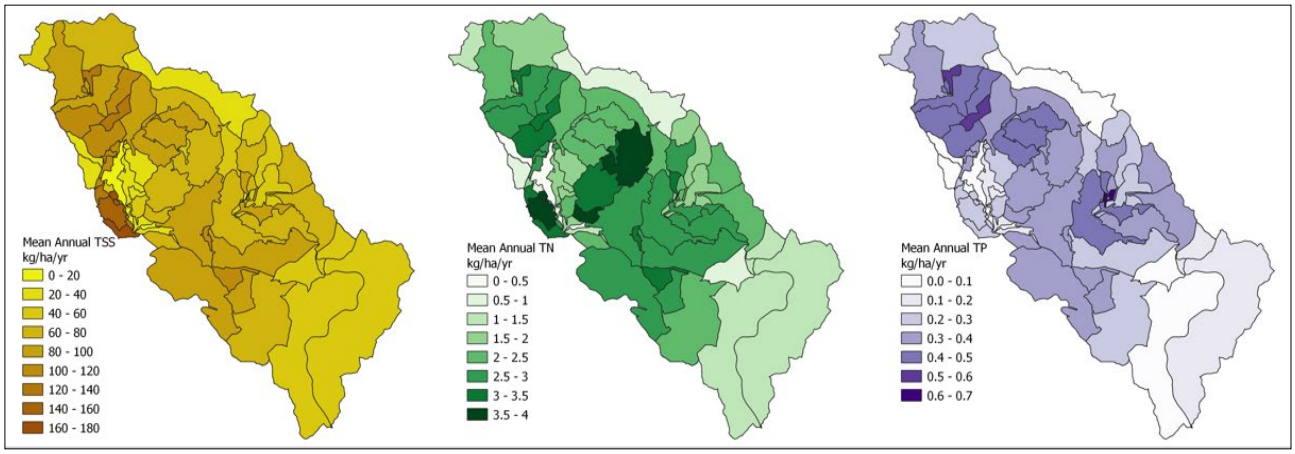

Figure 10. Heat maps of the Lake Tuggeranong catchment for mean annual loads of total suspended solids (TSS, left), total nitrogen (TN, centre) and total phosphorus (TP, right) generated in each subcatchment. Darker shading indicates higher mean annual concentrations.

Figures 11-13 show time-series of modelled daily inflows, pollutant concentrations, and pollutant loads entering Lake Tuggeranong in 2016, a year with a good spread of wet and dry periods. High flow events, likely driven by rainfall, lead to increased runoff, which carries higher concentrations and loads of phosphorus, nitrogen, and suspended solids into the lake. In 2016, the model estimates that the largest flow event saw over 1600 ML enter Lake Tuggeranong in a single day, representing 10% of the total annual inflow that year. This event carried loads of approximately 300 kg TP, 2,500 kg N, and 75,000 kg TSS to the lake, representing 12-13% of the total annual load of each pollutant entering Lake Tuggeranong in 2016. This pattern highlights the impact of storm events on water quality and the importance of managing runoff from the catchment to the lake.

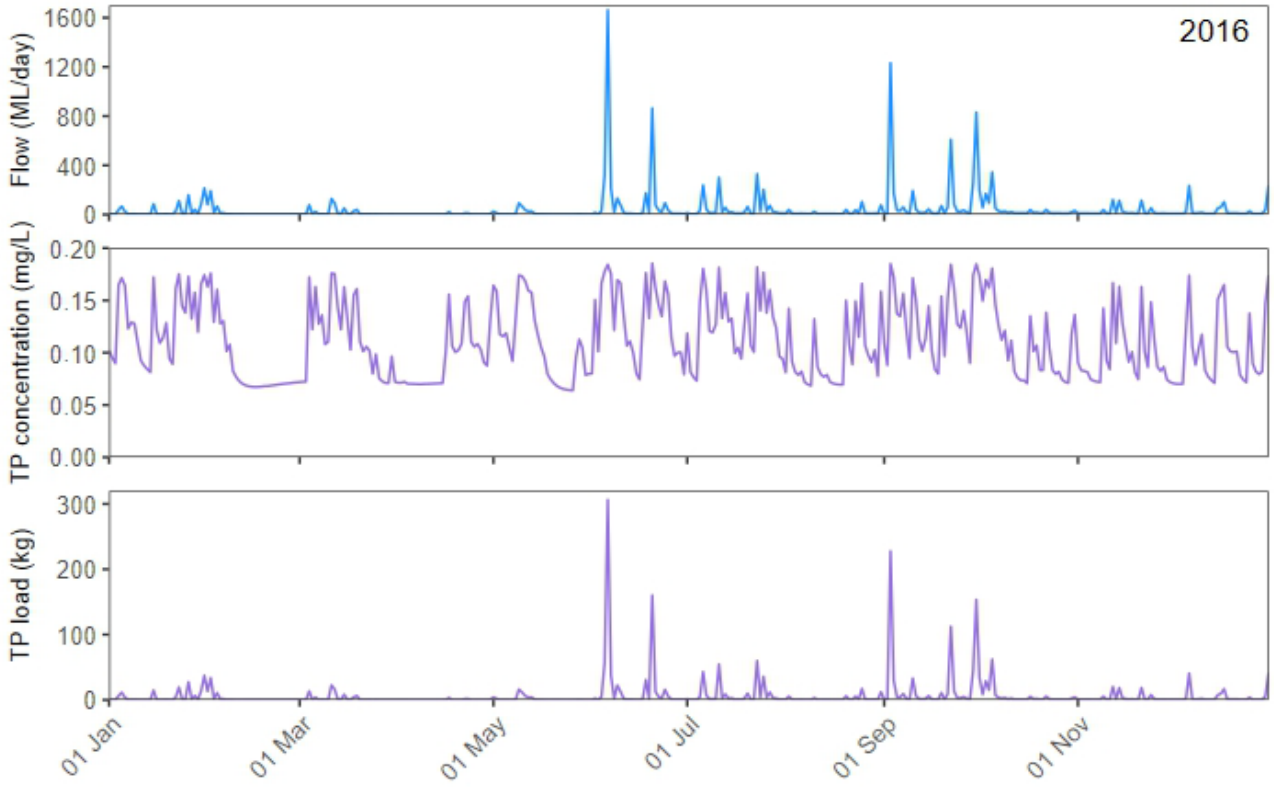

Figure 11. Modelled daily flow and total phosphorus (TP) concentration and load entering Lake Tuggeranong, 2016.

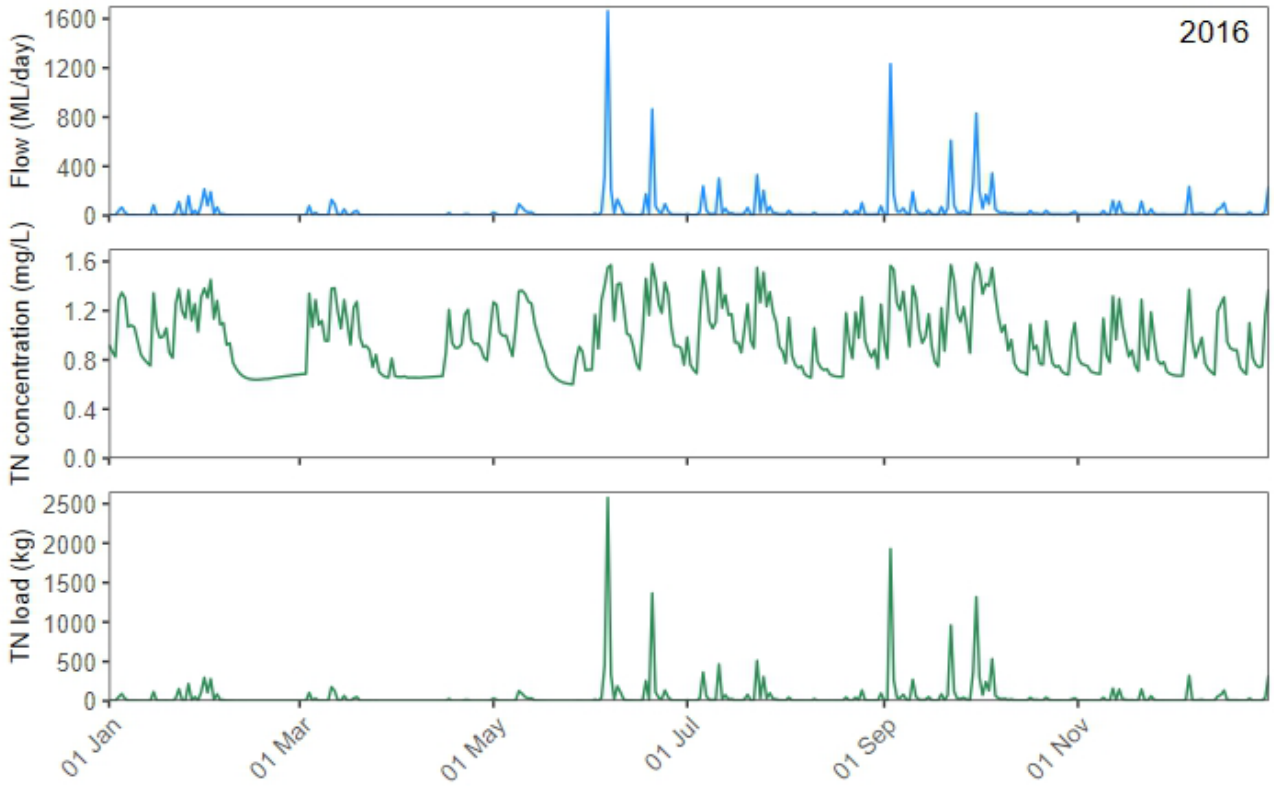

Figure 12. Modelled daily flow and total nitrogen (TN) concentration and load entering Lake Tuggeranong, 2016.

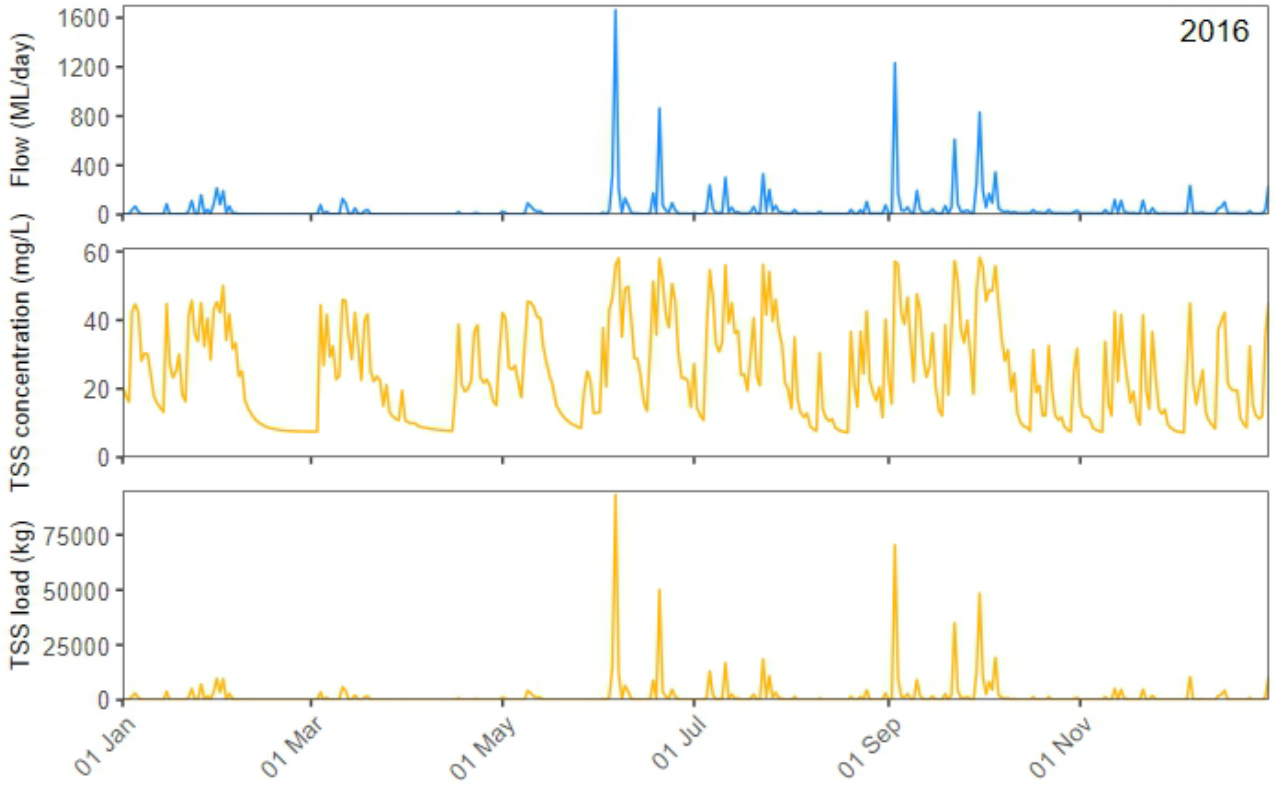

Figure 13. Modelled daily flow and total suspended solids (TSS) concentration and load entering Lake Tuggeranong, 2016.

Figure 14 shows the relationships between daily inflows, concentrations, and loads in 2016 for TP; TN and TSS showed the same patterns in the shape of these relationships.

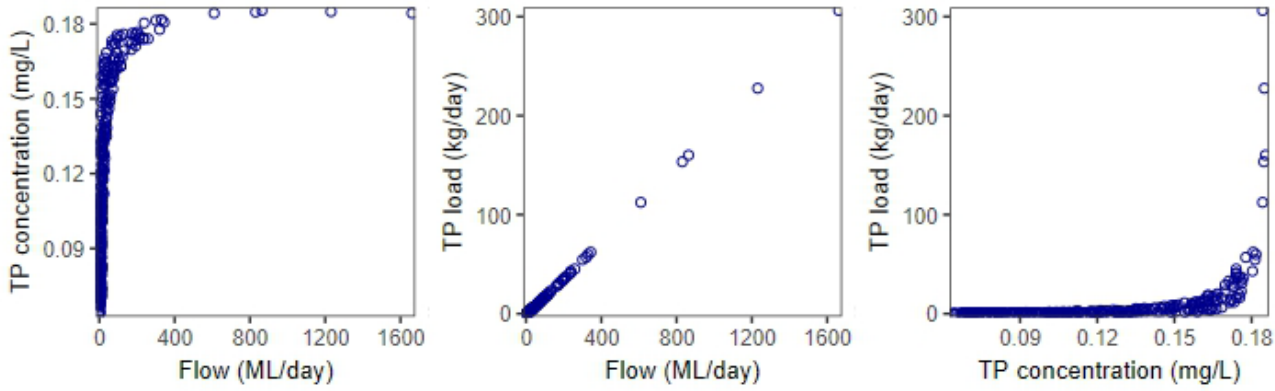

Figure 14. Relationships between the daily inflows and concentrations and loads of total phosphorus (TP) entering Lake Tuggeranong in 2016. The same relationships were seen for total nitrogen and total suspended solids.

4.4 Scenario analysis

4.4.1 Current and predevelopment scenarios

To understand the impact of changes to land use and urban development on the hydrology and water quality of the Lake Tuggeranong catchment, two contrasting land use scenarios were simulated using the

calibrated catchment model. The first, 'current' scenario was the model of current land use and infrastructure conditions described in Section 4.3. Under the current scenario the modelled mean annual inflow to Lake Tuggeranong was approximately 8.8 GL, and the modelled mean annual pollutant loads were 1,442 kg TP, 11,894 kg TN, and 397,064 kg TSS. Figure 15 presents the long-term modelled annual inflow and pollutant loads entering Lake Tuggeranong under the current scenario, for the period 1889-2022.

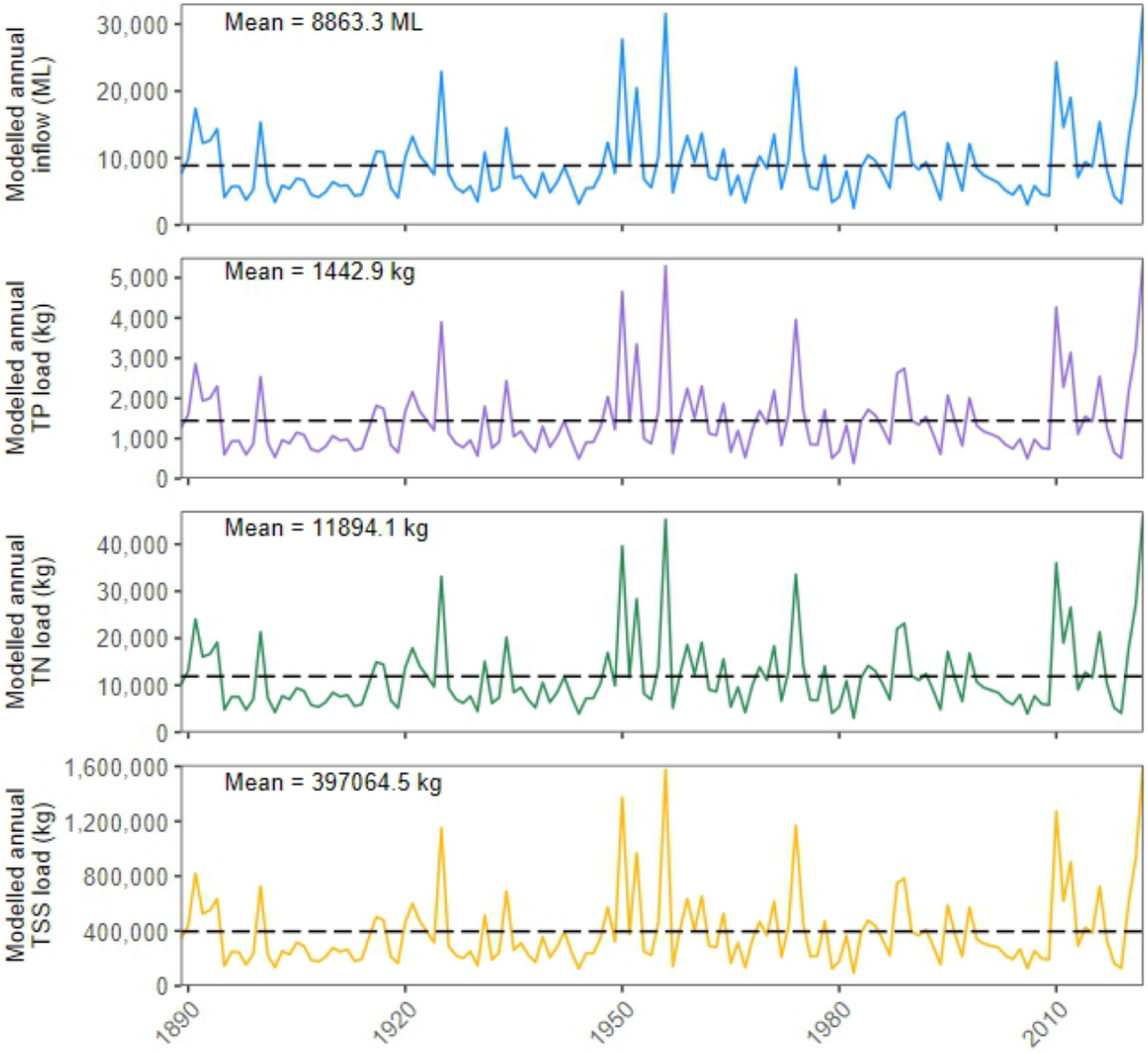

Figure 15. Long-term modelled annual inflows and annual loads of total phosphorus (TP), total nitrogen (TN), and total suspended solids (TSS) entering Lake Tuggeranong under current catchment conditions, for the period 1889 – 2022.

We compared this current scenario to a 'predevelopment' scenario, where all infrastructure (apart from Lake Tuggeranong itself) and developed land uses were removed from the model. Land use for all subcatchments was configured to be entirely bushland, to allow estimation of the runoff and pollutant generation under natural conditions. The results of the predevelopment scenario for the Lake Tuggeranong catchment were validated using the adjacent Jerrabomberra catchment, which has similar geographic conditions, for comparison (see Section 3.1.2). Figure 16 presents the long-term modelled annual inflow and pollutant loads entering Lake Tuggeranong under the predevelopment scenario, for the period 1889-

2022. The mean long-term annual inflow to the lake under predevelopment conditions was approximately 3,268 ML, and the modelled mean annual pollutant loads were 325 kg TP, 2470 kg TN, and 99,673 kg TSS.

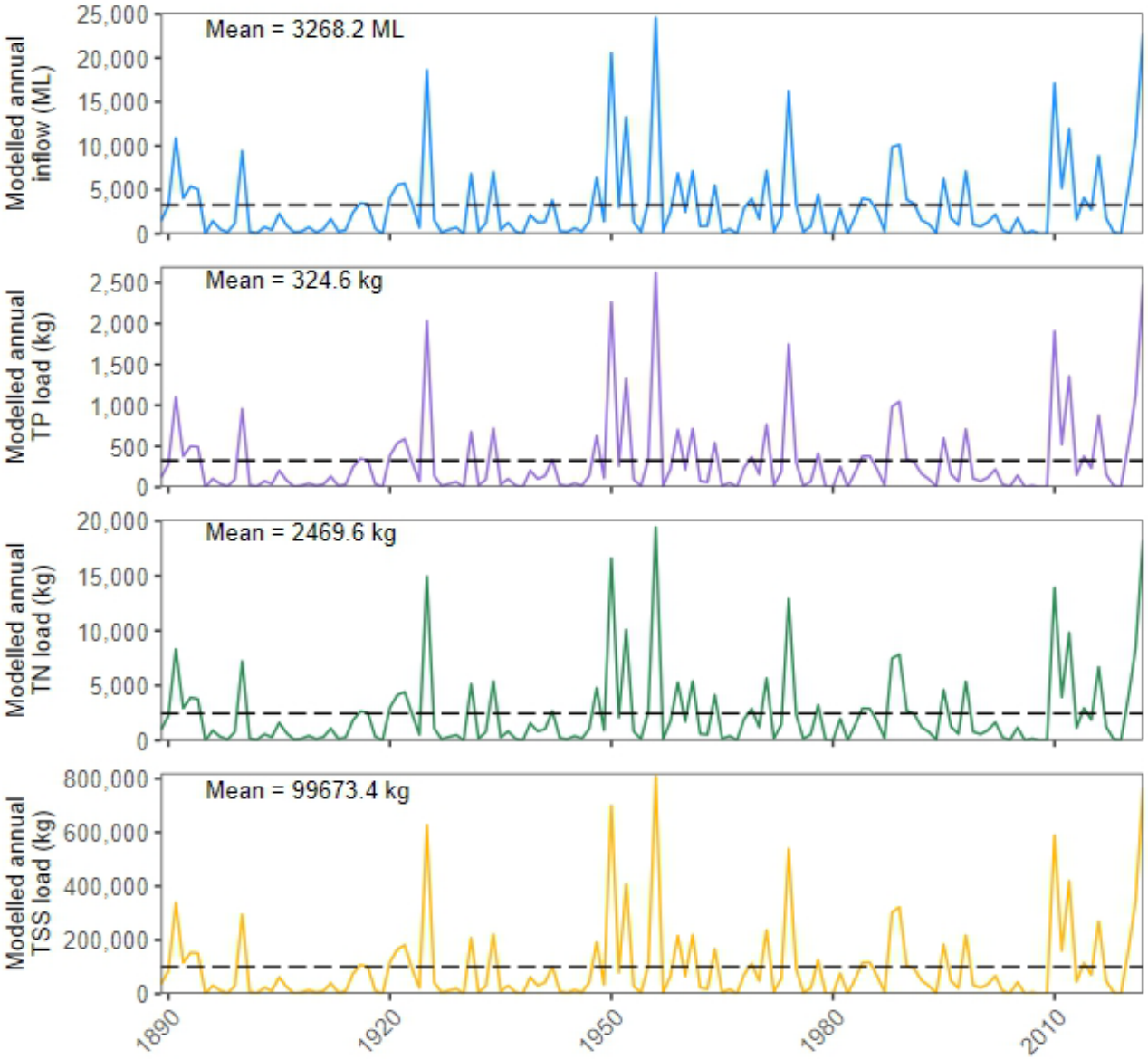

Figure 16. Long-term modelled annual inflows and annual loads of total phosphorus (TP), total nitrogen (TN), and total suspended solids (TSS) entering Lake Tuggeranong under predevelopment catchment conditions, for the period 1889 – 2022.

Table 6 and Figure 17 present comparisons of summary statistics for modelled annual inflows and pollutant loads generated under the current and predevelopment scenarios, for the period 1889-2022. On average, annual inflows to Lake Tuggeranong under predevelopment conditions were 25.5% of annual inflows under current conditions. The reduction in annual inflows, as well as reduced pollution generation modelled from the undeveloped catchment, meant that annual pollutant loads entering Lake Tuggeranong under predevelopment conditions were on average approximately 15% of annual pollutant loads under current conditions.

Table 6. Summary statistics describing modelled annual inflow volumes and loads of total phosphorus (TP), total nitrogen (TN), and total suspended solids (TSS) entering Lake Tuggeranong under the 'current' and 'predevelopment' model scenarios, for the period 1889-2022.

Parameter	Modelled scenario	Minimum	25th percentile	Median	Mean	75th percentile	Maximum
Annual inflow (GL)	Current scenario	2.50	5.39	7.39	8.86	10.37	32.3
Annual inflow (GL)	Predevelopment scenario	0	0.31	1.44	3.27	4.01	24.56
Annual TP load (kg)	Current scenario	377	857	1,176	1,442	1,705	5,412
Annual TP load (kg)	Predevelopment scenario	0	25	133	324	376	2,622
Annual TN load (kg)	Current scenario	3,019	6,893	9,508	11,894	14,100	46,236
Annual TN load (kg)	Predevelopment scenario	0	195	1,041	2,469	2,920	19,420
Annual TSS load (kg)	Current scenario	93,394	221,932	313,352	397,064	471,056	1,607,545
Annual TSS load (kg)	Predevelopment scenario	0	7,558	40,575	99,673	115,094	808,385

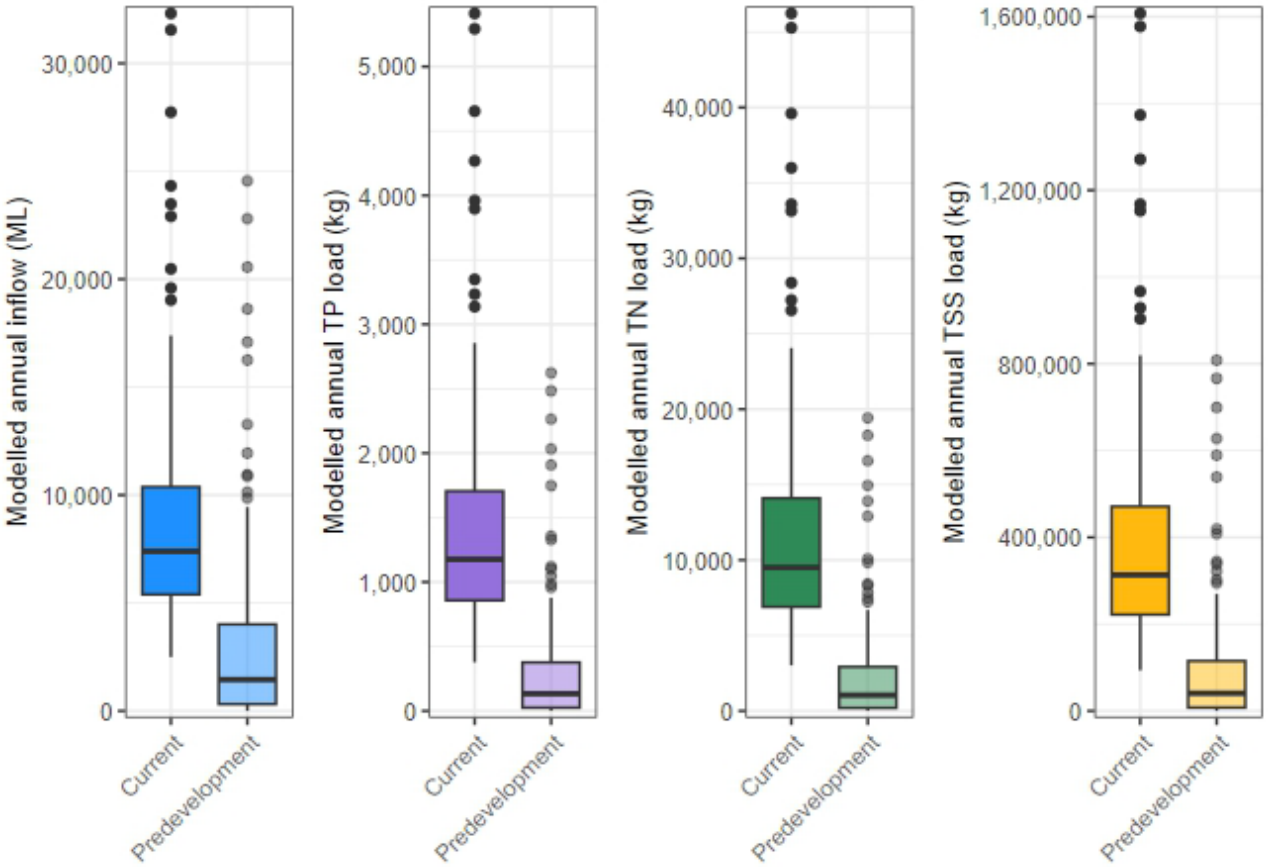

Figure 17. Box-and-whisker plots illustrating the distribution of modelled annual inflows and loads of total phosphorus (TP), total nitrogen (TN), and total suspended solids (TSS) entering Lake Tuggeranong under current and predevelopment catchment conditions, over the period 1889-2022.

Comparing the current and predevelopment scenarios is important for understanding catchment hydrology and pollutant generation before and after development, as well as the impacts of changes in hydrology and pollutant generation on trophic conditions in Lake Tuggeranong. The results from both modelled scenarios were used to parameterise a model of in-lake processes, which estimates the concentrations of phosphorous and chlorophyll a in the lake (Kahn & Dey, 2024). These concentrations were used to predict the distribution of trophic conditions in Lake Tuggeranong under the current and predevelopment scenarios. These analyses help to understand how conditions in the lake are predicted to respond under different inflow and pollutant conditions, and inform management decisions aimed at reducing the occurrence of blue-green algal blooms.

4.4.2 Catchment management option scenarios

The effects of specific management actions aimed at reducing pollutant inputs into the waterways and stormwater network of the Lake Tuggeranong catchment, or filtering or diverting water before it reaches the lake, were investigated in two additional scenarios implemented in the calibrated Source catchment model. Each scenario ('cost-effective' and 'broad benefits') consisted of a combination of different management actions, each with four possible levels of implementation, detailed in the companion to this report, *Lake Tuggeranong Catchment Management Options Assessment* (Booksmythe, Dey, Kahn, Stewart, & Starrs, 2024). The management options included in the two scenarios are detailed in Table 7.

Table 7. Details of the management options included in two scenarios…

Management option	Cost-effective scenario	Broad benefits scenario
Install additional WSUD infrastructure	Investment level 1: install 2 raingardens	Investment level 2: install 5 raingardens
Maintenance of existing WSUD infrastructure	Investment level 3: maintain 4 existing WSUD assets to their designed performance	Investment level 4: maintain 5 existing WSUD assets to their designed performance
Increase frequency of street sweeping	Investment level 4: 48 sweeps per year	Investment level 3: 36 sweeps per year
Manage grass clippings from municipal mowing	Investment level 3: designated street sweeping truck to follow mowers	Investment level 3: designated street sweeping truck to follow mowers
Sports field fertilizer management	Investment level 1: install bioretention swales to intercept 25% of total sports field P	Investment level 3: install bioretention swales to intercept 75% of total sports field P
Household fertilizer management	Investment level 4: very high implementation of community partnership programs aimed at reducing household fertilizer P inputs	Investment level 1: low implementation of community partnership programs aimed at reducing household fertilizer P inputs
Install castellated kerbs	n/a	Investment level 1: install castellated kerb outlets at a rate of 1 per 4 stormwater sumps adjacent to urban open space
Install floating wetlands	n/a	Investment level 4: install 4000 m^2 of floating wetlands
Stormwater recycling for sports field irrigation	Investment level 2: install stormwater recycling infrastructure at 4 sports field sites	Investment level 3: install stormwater recycling infrastructure at 6 sports field sites

Different management actions are implemented in different ways in the catchment model. Some options are explicitly represented by the addition or modification of specified links and nodes in the model:

- **Additional WSUD infrastructure** Proposed raingardens were represented in the catchment model by new storage nodes placed at the locations indicated in the original plans for the raingardens. As for existing assets, each proposed asset was modelled as a splitter node that diverts flow to the asset, and a storage node that applies a water quality decay function, representing the percentage reduction in pollutant loads (TP, TN, and TSS) achieved by the asset. Splitter nodes are configured with a maximum flow rate that is diverted into the asset, and any flow above this bypasses the asset, based on the MUSIC modelled high-flow bypass threshold. The proposed raingarden storage nodes were configured

using the size indicated in the original plans, and the performance details of similar existing WSUD assets.

- **Maintenance of existing WSUD infrastructure** The catchment model includes storage nodes representing each WSUD asset in the Lake Tuggeranong catchment, with the performance of each asset configured to reflect its current phosphorus removal efficiency (Table 2). To represent maintenance of these assets to their designed performance, the performance details were reconfigured to the phosphorus removal rates given in the detailed design reports for each asset.
- **Sports field fertilizer management** For each scenario, we modelled sufficient bioretention swales to intercept the required amount of sports field generated phosphorus (i.e., 25% or 75% of all sports field generated phosphorus, Table 7). We modelled one bioretention swale per subcatchment, starting with the subcatchment containing the largest sports field area, and divided the total swale area across the number of swales included in each scenario, proportionally to the area of sports field in each subcatchment.
    - Each bioretention swale was represented by a storage node configured based on the detailed design of a similar, existing WSUD asset.The percentage removal of TP, TN, and TSS were calculated for each bioretention swale using a MUSIC model consisting of a source, GPT, bioretention, and receiving node.
        - The source node was configured to have the size of the subcatchment's sports field area, and land use set at 100% pervious; remaining parameters used default values.
        - The GPT node was configured with high flow bypass.
        - The bioretention node was configured with size proportional to the subcatchment's sports field area, filter area set to 90% of total swale area, and an extended detention depth of 0.3 m based on recommended MIS08 guidelines; remaining parameters used default values.
        - The MUSIC model for each bioretention swale was run on a 6-minute timestep.
    - As the scale of the catchment model does not delineate sports fields from their subcatchments, a controlled splitter node was added to divert water to the storage node. Because sports fields typically generate higher TP concentrations than the catchment average, but splitters do not allow the adjustment of concentration in the diverted water, we instead increased the load of TP treated by bioretention swales by diverting more water to each sports field storage node. We divided the sports field TP concentration by the subcatchment TP concentration and multiplied this ratio by the proportion of sports field area in the subcatchment, to find the proportion of runoff volume to divert to the storage node.
- **Stormwater recycling infrastructure for sports field irrigation** Each sports field with stormwater recycling infrastructure was represented by a storage node and an irrigator node. A maximum of 1 ML water was diverted to the storage node via a controlled splitter during event flows. The irrigator node was configured as a perennial pasture crop using the crop coefficient from the NSW Environmental Guidelines on the used of effluent by irrigation (NSW Department of Environment and Conservation, 2004), with soil moisture capacity set at 20% and default soil configuration. The subcatchment's sports field area was used to set the size of the irrigated area, determining the water demand for irrigation. Daily rainfall and evapotranspiration (short crop) were obtained from SILO (https://www.longpaddock.qld.gov.au/silo/), covering the climatic period represented in the model (1899 – 2023). During dry periods the irrigation demand specified by the irrigator node was met by the water in the storage node, while in wet periods the demand is first met by rainfall. Excess water was

returned to the stormwater system downstream of the sports field via a link, maintaining water and mass balance.

- **Floating wetlands** To represent floating wetlands in the catchment model, a storage routing link was added just upstream of the Lake Tuggeranong storage node. This was configured using a decay model to reduce the phosphorus concentration in the water passing through the routing link, without affecting water volume. The percentage removal of phosphorus was calculated based on the estimated annual load of TP removed per square metre of floating wetland.

The remaining options cannot be explicitly modelled, and their effects were incorporated in the model by calculating the percentage phosphorus removal attained by each option, compared to the current load of phosphorus available to be intercepted by that option, and adjusting phosphorus concentrations within the catchment model based on these percentage reductions:

- **Household fertilizer management** The percentage reduction in phosphorus concentration due to management of household fertilizer use was applied to all area classified as suburban pervious, and calculated based on the difference in total phosphorus load generated from suburban pervious land across the catchment with and without household fertilizer management.
- **Increase street sweeping frequency | Manage grass clippings from municipal mowing | Install castellated kerbs** The percentage reduction in phosphorus concentration due to these options was applied to all area classified as road. As street sweeping, grass clipping management, and castellated kerbs all act to reduce the load of phosphorus generated from roads, the combined effects of these management options were modelled using a build-up wash-off model (Booksmythe, Dey, Kahn, Stewart, & Starrs, 2024) to predict the total percentage reduction in the phosphorus load from roads for the selected combination of these options in each scenario.

Table 8 presents summary statistics for modelled annual inflows and pollutant loads generated under the cost-effective and broad benefits catchment management scenarios, for the period 1889-2022. The management actions included in these scenarios are not predicted to have a large impact on runoff generation or inflows into Lake Tuggeranong; on average, annual inflows to Lake Tuggeranong under the catchment management scenarios were 97-98% of annual inflows under current conditions. However, the annual TP loads entering Lake Tuggeranong were substantially reduced under the catchment management scenarios. Under the cost-effective scenario annual TP loads were on average approximately 67% of annual TP loads under current conditions, and under the broad benefits scenario annual TP loads were on average approximately 56% of annual TP loads under current conditions.

Table 8. Summary statistics describing modelled annual inflow volumes and loads of total phosphorus (TP) entering Lake Tuggeranong under the 'cost-effective and 'broad benefits' catchment management model scenarios, for the period 1889-2022. Compare to the 'current' scenario, Table 6.

Parameter	Modelled scenario	Minimum	25th percentile	Median	Mean	75th percentile	Maximum
Annual inflow (GL)	Cost-effective scenario	2.36	5.29	7.31	8.76	10.27	32.30
Annual inflow (GL)	Broad benefits scenario	2.31	5.22	7.22	8.64	10.15	31.93
Annual TP load (kg)	Cost-effective scenario	236	551	771	992	1,179	4,076
Annual TP load (kg)	Broad benefits scenario	173	441	639	868	1,041	3,877

5. Summary and future model refinements

5.1 Summary

This report has described the data and methods used to parameterise, configure and calibrate the Lake Tuggeranong catchment model. The model was used to explore four scenarios of different catchment land use and management actions, providing long-term mean annual inflows and pollutant loads to Lake Tuggeranong under each scenario.

The catchment model improves on previous modelling work for the Lake Tuggeranong catchment:

- The model simulates flows and pollutant loads across the Lake Tuggeranong catchment on a daily timestep over 133 years of climate data from 1889-2023.
- The model incorporates updated land use and imperviousness layers to simulate runoff and pollutant generation across six functional land use classes.
- The model is delineated to water quality monitoring locations to facilitate parameterisation with concentrations of three pollutants – total phosphorus (TP), total nitrogen (TN), and total suspended solids (TSS).
- The model is delineated to existing stormwater treatment infrastructure to facilitate estimates of pollutant load reduction after treatment.
- The model hydrology is calibrated to a gauge immediately downstream of Lake Tuggeranong, with a very good fit between observed and modelled flow.
- The model incorporates recently constructed WSUD infrastructure in the Lake Tuggeranong catchment.
- The model incorporates a storage node representing Lake Tuggeranong, simulating flow and pollutant loads entering and leaving the storage.

Key results of the model include:

- Under current catchment land use and management, the model estimates a mean annual inflow to Lake Tuggeranong of approximately 8.8 GL for the period 1889-2022. Under predevelopment conditions, annual flows are on average 75% lower, with an estimated mean annual flow of approximately 3.3 GL.
- Under current catchment land use and management, the model estimates mean annual pollutant loads entering Lake Tuggeranong of 1,442 kg TP, 11,894 kg TN, and 397,064 kg TSS. Under predevelopment conditions, annual pollutant loads to the lake are on average 85% lower.
- By implementing combinations of catchment management options chosen by the ACT Healthy Waterways program, the model estimates that average annual TP loads to Lake Tuggeranong would be reduced to 868-992 kg, a 33-44% decrease compared to current catchment conditions.
- Land use is the major determinant of simulated subcatchment pollutant loads.

5.2 Future model refinements

The reliability and information provided by the Lake Tuggeranong catchment model could be enhanced by improvements to the data used for subcatchment delineation and calibration, and by undertaking assessments of model uncertainty:

- The calibration of water quality (pollutant) estimates in the model was based on observed median concentrations during event flows, which were the only available water quality data. However, observed pollutant loads provide a more robust framework for calibration in Source. Collecting data on pollutant loads requires simultaneous measures of concentration and flow volume and represents a significant change to the water quality and quantity monitoring currently undertaken in the ACT.
- Incorporating observed flow data from additional gauging stations within the Lake Tuggeranong catchment would enhance model reliability by broadening the data available for hydrological calibration.
- Undertaking an uncertainty estimation for the flows and pollutant loads estimated by the catchment model would provide a quantitative assessment of model reliability. Understanding model uncertainty is important when comparing across modelled scenarios, to ensure that differences are explained by modelled management options rather than measurement/estimation error.
- Understanding uncertainty in the model would also allow identification of areas where more hydrological and/or water quality data could improve the reliability of model estimates.

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Appendices

Appendix A: Level-volume-area data for Lake Tuggeranong

To configure the Lake Tuggeranong storage node in the catchment model requires information on the relationship between the water level and volume of the lake. Figure A1 shows the stage-volume rating curve used in configuring the Lake Tuggeranong storage node in the model. The level-volume-area (LVA) relationship for Lake Tuggeranong was derived from bathymetry data collected by Steger and Associates Registered Land Surveyors in 2015, presented in Table A1.

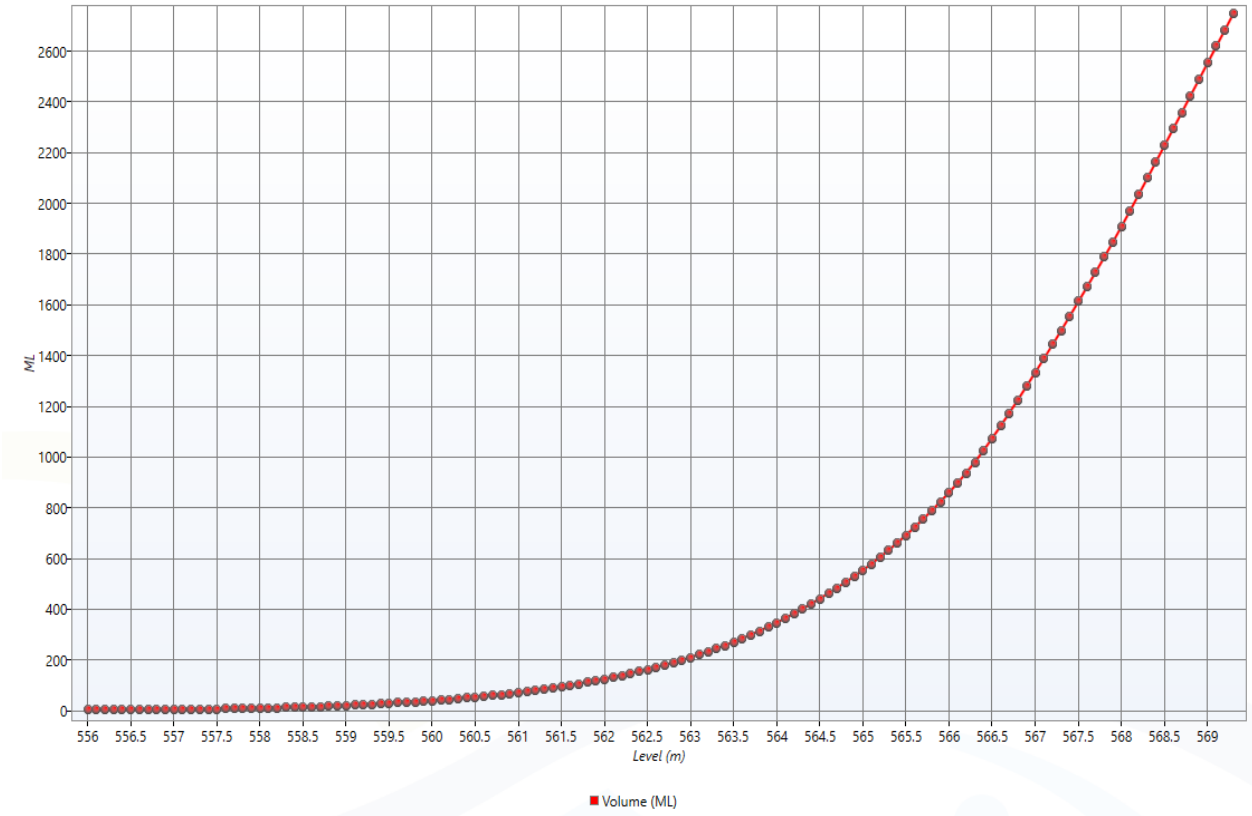

Figure A1. Water level - volume ratings curve for Lake Tuggeranong (gauge 410784) derived from bathymetry data (see Table A1). Source: Steger and Associates Registered Land Surveyors, 2015.

Table A1. Lake Tuggeranong water level, volume, and surface area data. Source: Steger and Associates Registered Land Surveyors, 2015.

Level (m)	Volume (ML)	Surface area (km^2)	Level (m)	Volume (ML)	Surface area (km^2)	Level (m)	Volume (ML)	Surface area (km^2)
556.0	0	0	558.4	10.1361	0.009721	560.8	60.19836	0.035167
556.1	0.014874	0.000119	558.5	11.18874	0.010526	560.9	63.92854	0.037302
556.2	0.036423	0.000215	558.6	12.31101	0.011223	561.0	67.9121	0.039836
556.3	0.072831	0.000364	558.7	13.49978	0.011888	561.1	72.14851	0.042364
556.4	0.122048	0.000492	558.8	14.76326	0.012635	561.2	76.63992	0.044914
556.5	0.222146	0.001001	558.9	16.10082	0.013376	561.3	81.38454	0.047446
556.6	0.374086	0.001519	559.0	17.52169	0.014209	561.4	86.36409	0.049795
556.7	0.570277	0.001962	559.1	19.02266	0.01501	561.5	91.56732	0.052032
556.8	0.808589	0.002383	559.2	20.60679	0.015841	561.6	97.00797	0.054406
556.9	1.104417	0.002958	559.3	22.27321	0.016664	561.7	102.6982	0.056902
557.0	1.442882	0.003385	559.4	24.02014	0.017469	561.8	108.6627	0.059645
557.1	1.824143	0.003813	559.5	25.84861	0.018285	561.9	114.8979	0.062353
557.2	2.241786	0.004176	559.6	27.79639	0.019478	562.0	121.405	0.065071
557.3	2.690724	0.004489	559.7	29.85126	0.020549	562.1	128.2425	0.068375
557.4	3.16953	0.004788	559.8	32.00766	0.021564	562.2	135.4093	0.071668
557.5	3.677818	0.005083	559.9	34.26355	0.022559	562.3	142.8931	0.074838
557.6	4.218615	0.005408	560.0	36.62414	0.023606	562.4	150.7054	0.078123
557.7	4.79095	0.005723	560.1	39.09346	0.024693	562.5	158.8814	0.08176
557.8	5.397505	0.006066	560.2	41.67477	0.025813	562.6	167.4558	0.085744
557.9	6.045165	0.006477	560.3	44.38028	0.027055	562.7	176.4338	0.08978
558.0	6.744306	0.006991	560.4	47.21816	0.028379	562.8	185.8594	0.094256
558.1	7.488318	0.00744	560.5	50.20973	0.029916	562.9	195.7887	0.099293
558.2	8.290076	0.008018	560.6	53.35829	0.031486	563.0	206.241	0.104523
558.3	9.164035	0.00874	560.7	56.6817	0.033234	563.1	217.2403	0.109993

Level (m)	Volume (ML)	Surface area (km^2)
563.2	228.7825	0.115422
563.3	240.9099	0.121274
563.4	253.6379	0.12728
563.5	266.9702	0.133322
563.6	280.9174	0.139472
563.7	295.4839	0.145666
563.8	310.6996	0.152156
563.9	326.6404	0.159409
564.0	343.3933	0.167529
564.1	360.9095	0.175162
564.2	379.1175	0.18208
564.3	398.0267	0.189093
564.4	417.6585	0.196317
564.5	437.9539	0.202954
564.6	458.8675	0.209136
564.7	480.4328	0.215652
564.8	502.7146	0.222818
564.9	525.8767	0.231621
565.0	549.963	0.240863
565.1	575.1935	0.252304
565.2	601.5961	0.264027
565.3	629.1803	0.275842
565.4	657.9845	0.288043
565.5	687.9878	0.300033
565.6	719.1112	0.311234
565.7	751.5013	0.323901
565.8	785.1463	0.336449
565.9	820.0771	0.349308
566.0	856.4557	0.363786
566.1	894.2724	0.378167
566.2	934.0697	0.397974
566.3	976.8441	0.427744
566.4	1022.38	0.455357
566.5	1070.137	0.477574
566.6	1119.482	0.493452
566.7	1170.426	0.509434
566.8	1222.593	0.521672
566.9	1275.738	0.531451
567.0	1329.908	0.541698
567.1	1384.869	0.549609
567.2	1440.435	0.555666
567.3	1496.534	0.56099
567.4	1553.159	0.566248
567.5	1610.312	0.571526
567.6	1668.006	0.576945
567.7	1726.277	0.582703
567.8	1785.19	0.589135
567.9	1844.844	0.596536
568.0	1906.38	0.615362
568.1	1968.905	0.625256
568.2	2032.357	0.634518
568.3	2096.546	0.641889
568.4	2161.172	0.646257
568.5	2226.008	0.648362
568.5	2226.008	0.648362
568.6	2290.955	0.649472
568.7	2355.947	0.649921
568.8	2420.965	0.650178
568.9	2485.993	0.650283
569.0	2551.028	0.650344
569.1	2616.068	0.650402
569.2	2681.113	0.650454
569.3	2746.163	0.650495

Appendix B: Level – discharge data for Lake Tuggeranong outflow

The Lake Tuggeranong outflow was configured as an ungated spillway in the Source model, using the level-discharge relationship from Lake Tuggeranong weir (gauge 410784), presented in Table B1.

Table B1. Lake Tuggeranong weir rating table. *Source: ALS Pty Ltd.*

Level (m)	Discharge (ML/d)	Level (m)	Discharge (ML/d)	Level (m)	Discharge (ML/d)	Level (m)	Discharge (ML/d)
0	0	568.14	740.448	568.43	3957.12	568.72	9072
567.86	0	568.15	809.568	568.44	4121.28	568.73	9244.8
567.87	1.08	568.16	881.28	568.45	4285.44	568.74	9417.6
567.88	6.10848	568.17	959.04	568.46	4458.24	568.75	9676.8
567.89	16.848	568.18	1036.8	568.47	4631.04	568.76	9849.6
567.90	34.56	568.19	1123.2	568.48	4812.48	568.77	10022.4
567.91	41.2992	568.20	1209.6	568.49	4993.92	568.78	10281.6
567.92	48.816	568.21	1296	568.50	5184	568.79	10454.4
567.93	57.1104	568.22	1382.4	568.51	5339.52	568.80	10713.6
567.94	66.096	568.23	1468.8	568.52	5503.68	568.81	10886.4
567.95	76.032	568.24	1563.84	568.53	5667.84	568.82	11059.2
567.96	86.4	568.25	1667.52	568.54	5840.64	568.83	11318.4
567.97	98.496	568.26	1771.2	568.55	6013.44	568.84	11491.2
567.98	110.592	568.27	1874.88	568.56	6186.24	568.85	11664
567.99	124.416	568.28	1978.56	568.57	6359.04	568.86	11923.2
568.00	138.24	568.29	2090.88	568.58	6540.48	568.87	12096
568.01	162.432	568.30	2211.84	568.59	6721.92	568.88	12355.2
568.02	189.216	568.31	2324.16	568.60	6912	568.89	12528
568.03	219.456	568.32	2436.48	568.61	7076.16	568.90	12700.8
568.04	251.424	568.33	2557.44	568.62	7240.32	568.91	12960
568.05	285.984	568.34	2678.4	568.63	7404.48	568.92	13132.8
568.06	323.136	568.35	2808	568.64	7577.28	568.93	13392
568.07	362.88	568.36	2937.6	568.65	7750.08	568.94	13564.8
568.08	406.08	568.37	3067.2	568.66	7922.88	568.95	13824
568.09	451.872	568.38	3205.44	568.67	8095.68	568.96	13996.8
568.10	501.12	568.39	3343.68	568.68	8277.12	568.97	14256
568.11	555.552	568.40	3490.56	568.69	8458.56	568.98	14428.8
568.12	613.44	568.41	3646.08	568.70	8640	568.99	14601.6
568.13	675.648	568.42	3801.6	568.71	8812.8		

Appendix C: Land use and imperviousness classification

Table C1 lists the detailed land use classifications included in each of the six functional land use units defined for the Lake Tuggeranong catchment. Table C2 provides a breakdown of the major and minor subcatchments delineated in the Source catchment model, and Figure C1 shows a map of the major subcatchments. Table C3 provides the subcatchment area breakdown in hectares and area ratio based on land use functional units used in the catchment model.

Table C1. Detailed land use classifications based on ACT Government land zoning grouped into 6 functional units for use in the catchment model.

ACT land zoning	Functional unit
Business zone	commercial
Community Facilities	commercial
Core zone	commercial
Leisure and accommodation	commercial
Local centre	commercial
Services	commercial
Services zone	commercial
Medium density residential	suburban
Suburban	suburban
Suburban core	suburban
Transport	open space
Urban open space	open space
Restricted access recreation zone	open space
Hills ridges and buffer areas	bushland
Designated	bushland
River corridor	bushland
Rural	rural
Sports field (estimated)	sports field

Table C2. Major subcatchments of the Lake Tuggeranong catchment and their component minor subcatchments delineated in the Source catchment model.

Major subcatchment	Minor subcatchments
Village Creek (VC)	VC0, VC1, VC2, VC3, VC4, VC6, VC7, VC8, VC9, VC10, VC11
Kambah Creek (KC)	KC0, KC1, KC2, KC3, KC4, KC5, KC6, KC7
Tuggeranong Creek (TC)	TC0, TC1, TC2, TC3, TC4, TC5, TC6, TC7, TC6_NSW, TC8_NSW
Lake Tuggeranong (Lake T)	
East Lake (EL)	EL1, EL2
West Lake (WL)	WL0, WL1, WL2, WL3, WL4, WL5, WL6, WL7, WL8, WL9, WL10, WL11
Downstream of Lake Tuggeranong (DSL)	DSL1, DSL2
Drakeford Drive South (DDS)	DDS1, DDS2
(DLC)	DLC_N, DLC_S
Stranger Pond (SP)	SP1, SP2
Wanniassa (WS)	WS0, WS1, WS2, WS3, WS4
Fadden stormwater (FA)	FA0, FA1, FA2, FA3, FA5, FA6, FA7, FA8, FA9, FA10, FA11, FA12, FA13, FA14, FA15, FA16, FA17, FA9_NSW

Fig. C1. Map of Lake Tuggeranong catchment showing major subcatchment boundaries. VC, Village Creek; KC, Kambah Creek; WS, Wanniassa; FA, Fadden stormwater; TC, Tuggeranong Creek; DSL, Downstream of Lake Tuggeranong; Lake T, Lake Tuggeranong; DLC, XXX; WL, West Lake; EL, East Lake; DDS, Drakeford Drive South; SP, Stranger Pond.

Table C3. Area of land use functional units within Lake Tuggeranong subcatchments (see Table C2), in hectares (ha) and as a percentage of subcatchment area (%).

Functional unit	VC0 (ha)	VC0 (%)	VC1 (ha)	VC1 (%)	VC2 (ha)	VC2 (%)	VC3 (ha)	VC3 (%)	VC4 (ha)	VC4 (%)	VC6 (ha)	VC6 (%)
Commercial road	1.16654	1.28342	0.55272	1.45670	0.06191	0.06184	0.00053	0.00081	0.00000	0.00000	0.52402	2.40107
Commercial hardstand	2.96745	3.26478	3.54531	9.34381	0.09628	0.09617	0.75895	1.17555	0.72954	0.59131	1.30516	5.98024
Commercial roof	3.62099	3.98381	3.96793	10.45763	0.40466	0.40420	0.96058	1.48785	0.96820	0.78476	1.85026	8.47786
Commercial pervious	3.42116	3.76396	2.91630	7.68602	0.33240	0.33202	2.63463	4.08081	1.87153	1.51694	1.60472	7.35280
Commercial water	0	0	0	0	0	0	0	0	0	0	0	0
Suburban road	3.73592	4.11026	1.45375	3.83141	5.77357	5.76696	3.69303	5.72018	6.43127	5.21276	0.40714	1.86552
Suburban hardstand	5.17332	5.69168	1.37583	3.62604	5.56696	5.56059	2.89318	4.48128	5.92845	4.80520	0.73999	3.39064
Suburban roof	17.15034	18.86877	4.56512	12.03155	22.63823	22.61229	11.73104	18.17036	22.69013	18.39110	2.30035	10.54015
Suburban pervious	29.87385	32.86716	7.64501	20.14873	38.47253	38.42845	20.42040	31.62942	36.44461	29.53956	2.69231	12.33615
Suburban water	0	0	0	0	0.01395	0.01393	2.50E-05	3.87E-05	0.00095	0.00077	0	0
Open space road	4.47567	4.92413	2.24256	5.91036	4.15447	4.14971	2.77265	4.29460	4.04727	3.28044	1.83831	8.42312
Open space hardstand	1.61398	1.77570	0.76704	2.02155	2.45150	2.44869	1.30548	2.02207	3.76469	3.05140	0.72845	3.33773
Open space roof	0.20061	0.22071	0.07460	0.19661	0.48495	0.48439	0.25650	0.39730	0.80075	0.64903	0.14520	0.66532
Open space pervious	14.24994	15.67776	8.83674	23.28958	12.97204	12.95718	16.26664	25.19562	29.51479	23.92272	7.48905	34.31473
Open space water	0.03960	0.04357	0	0	0	0	0	0	0	0	0.19962	0.91466
Bushland road	0	0	0	0	0	0	0	0	0	0	0	0
Bushland hardstand	0.04743	0.05218	0	0	0.24205	0.24177	0	0	0	0	0	0
Bushland roof	0.00363	0.00399	0	0	0.00097	0.00097	0	0	0	0	0	0
Bushland pervious	3.15228	3.46813	0	0	6.44823	6.44084	0	0	0	0	0	0
Bushland water	0	0	0	0	0	0	0	0	0	0	0	0
Rural road	0	0	0	0	0	0	0	0	0	0	0	0
Rural hardstand	0	0	0	0	0	0	0	0	0	0	0	0
Rural roof	0	0	0	0	0	0	0	0	0	0	0	0
Rural pervious	0	0	0	0	0	0	0	0	0	0	0	0
Rural water	0	0	0	0	0	0	0	0	0	0	0	0
Sports field	0	0	0	0	0	0	0.86778	1.34411	10.18341	8.25399	0	0
Total subcatchment area	90.89270	100	37.94290	100	100.11470	100	64.56140	100	123.37560	100	21.82460	100

Table C3 cont. Area of land use functional units within Lake Tuggeranong subcatchments (see Table C2), in hectares (ha) and as a percentage of subcatchment area (%).

Functional unit	VC7 (ha)	VC7 (%)	VC8 (ha)	VC8 (%)	VC9 (ha)	VC9 (%)	VC10 (ha)	VC10 (%)	VC11 (ha)	VC11 (%)	Lake T (ha)	Lake T (%)
Commercial road	0	0	0	0	0.01835	0.00688	0	0	0	0	0	0
Commercial hardstand	0	0	0	0	1.02446	0.38388	1.19452	0.64653	0	0	0	0
Commercial roof	0	0	0	0	0.62828	0.23543	1.79132	0.96955	0	0	0	0
Commercial pervious	0	0	0	0	2.96747	1.11196	4.26940	2.31081	0	0	0	0
Commercial water	0	0	0	0	0	0	0	0	0	0	0	0
Suburban road	0.31054	9.59627	0.00158	0.03398	5.07906	1.90321	10.61841	5.74720	2.75089	3.36567	0	0
Suburban hardstand	0.24232	7.48839	0.00455	0.09815	3.93032	1.47275	6.24872	3.38211	1.53092	1.87306	0	0
Suburban roof	0.71997	22.24891	0.00000	0.00000	17.65425	6.61534	29.89265	16.17935	8.30131	10.15654	0	0
Suburban pervious	1.00224	30.97160	0.09433	2.03477	29.37379	11.00684	51.34650	27.79122	16.30805	19.95268	0	0
Suburban water	0	0	0	0	0	0	0	0	2.50E-05	3.06E-05	0	0
Open space road	0.01912	0.59088	0.73261	15.80361	9.13640	3.42356	3.42844	1.85564	0.08557	0.10470	0.16068	0.22103
Open space hardstand	0.07169	2.21524	0.14298	3.08425	4.31557	1.61712	2.79452	1.51253	0.16162	0.19775	0.31379	0.43165
Open space roof	0.01592	0.49202	0.02103	0.45355	0.45775	0.17152	0.31814	0.17220	0.01235	0.01511	0.30226	0.41579
Open space pervious	0.85420	26.39669	3.63864	78.49169	44.29813	16.59923	34.55149	18.70095	5.38125	6.58389	2.76054	3.79745
Open space water	0	0	0	0	0.17846	0.06687	0	0	0	0	69.15733	95.13407
Bushland road	0	0	0	0	3.77569	1.41481	0.43221	0.23393	1.15907	1.41811	0	0
Bushland hardstand	0	0	0	0	1.75254	0.65671	0.10256	0.05551	0.23837	0.29165	0	0
Bushland roof	0	0	0	0	0.24923	0.09339	0.00665	0.00360	0.11275	0.13795	0	0
Bushland pervious	0	0	0	0	142.00602	53.21198	30.50463	16.51058	45.69143	55.90287	0	0
Bushland water	0	0	0	0	0.02273	0.00852	0	0	0	0	0	0
Rural road	0	0	0	0	0	0	0	0	0	0	0	0
Rural hardstand	0	0	0	0	0	0	0	0	0	0	0	0
Rural roof	0	0	0	0	0	0	0	0	0	0	0	0
Rural pervious	0	0	0	0	0	0	0	0	0	0	0	0
Rural water	0	0	0	0	0	0	0	0	0	0	0	0
Sports field	0	0	0	0	0	0	7.25782	3.92829	0	0	0	0
Total subcatchment area	3.23600	100	4.63570	100	266.86850	100	184.75800	100	81.73360	100	72.69460	100

Table C3 cont. Area of land use functional units within Lake Tuggeranong subcatchments (see Table C2), in hectares (ha) and as a percentage of subcatchment area (%).

Functional unit	KC0 (ha)	KC0 (%)	KC1 (ha)	KC1 (%)	KC2 (ha)	KC2 (%)	KC3 (ha)	KC3 (%)	KC4 (ha)	KC4 (%)	KC5 (ha)	KC5 (%)
Commercial road	0	0	0	0	0	0	0	0	0	0	0.22272	0.32619
Commercial hardstand	0.23590	0.18352	0.10135	0.12613	0.11103	0.12613	0.00800	0.12613	0.00045	0.02089	1.68770	2.47178
Commercial roof	0.46683	0.36317	0.10200	0.12693	0.11174	0.12693	0.00805	0.12693	0.00003	0.00116	1.91152	2.79958
Commercial pervious	0.80327	0.62490	0.02740	0.03410	0.03002	0.03410	0.00216	0.03410	0.01793	0.83192	2.24089	3.28197
Commercial water	0	0	0	0	0	0	0	0	0	0	0	0
Suburban road	7.27826	5.66213	6.20275	7.71915	6.79539	7.71915	0.48981	7.71915	0.00000	0.00000	4.54340	6.65420
Suburban hardstand	7.37201	5.73507	5.85418	7.28537	6.41351	7.28537	0.46229	7.28537	0.02456	1.13940	4.10095	6.00621
Suburban roof	28.02338	21.80082	19.67904	24.49003	21.55926	24.49003	1.55399	24.49003	0.15034	6.97445	14.86127	21.76563
Suburban pervious	45.12123	35.10210	33.59659	41.81005	36.80656	41.81005	2.65302	41.81005	0.19061	8.84250	26.44537	38.73156
Suburban water	0	0	0	0	0	0	0	0	5.00E-05	0.00232	2.50E-05	3.66E-05
Open space road	6.75730	5.25685	2.59264	3.22647	2.84036	3.22647	0.20473	3.22647	0.00375	0.17404	2.08079	3.04750
Open space hardstand	2.98208	2.31991	1.45161	1.80649	1.59030	1.80649	0.11463	1.80649	0.41023	19.03093	1.24580	1.82459
Open space roof	0.23348	0.18164	0.19942	0.24818	0.21848	0.24818	0.01575	0.24818	0.06228	2.88910	0.11700	0.17135
Open space pervious	29.18828	22.70705	10.54832	13.12710	11.55616	13.12710	0.83297	13.12710	1.29149	59.91344	8.08024	11.83421
Open space water	0.01618	0.01258	0	0	0	0	0	0	0	0	0	0
Bushland road	0	0	0	0	0	0	0	0	0	0	0	0
Bushland hardstand	0	0	0	0	0	0	0	0	0	0	0	0
Bushland roof	0	0	0	0	0	0	0	0	0	0	0	0
Bushland pervious	0	0	0	0	0	0	0	0	0	0	0	0
Bushland water	0	0	0	0	0	0	0	0	0	0	0	0
Rural road	0	0	0	0	0	0	0	0	0	0	0	0
Rural hardstand	0	0	0	0	0	0	0	0	0	0	0	0
Rural roof	0	0	0	0	0	0	0	0	0	0	0	0
Rural pervious	0	0	0	0	0	0	0	0	0	0	0	0
Rural water	0	0	0	0	0	0	0	0	0	0	0	0
Sports field	0	0	0	0	0	0	0	0	0.00388	0.17984	0.74094	1.08517
Total subcatchment area	128.54280	100	80.35530	100	88.03280	100	6.34540	100	2.15560	100	68.27860	100

Table C3 cont. Area of land use functional units within Lake Tuggeranong subcatchments (see Table C2), in hectares (ha) and as a percentage of subcatchment area (%).

Functional unit	KC6 (ha)	KC6 (%)	KC7 (ha)	KC7 (%)	SP1 (ha)	SP1 (%)	SP2 (ha)	SP2 (%)	EL1 (ha)	EL1 (%)	EL2 (ha)	EL2 (%)
Commercial road	0	0	0	0	0.34455	0.09473	0.25623	0.65596	0	0	0.1566	0.8058
Commercial hardstand	0.06448	0.04990	0	0	2.55082	0.70133	0.34418	0.88112	0	0	0.7782	4.0044
Commercial roof	0.08659	0.06701	0	0	2.85592	0.78521	1.33480	3.41714	0	0	1.1017	5.6688
Commercial pervious	0.00426	0.00329	0	0	8.95477	2.46205	1.59170	4.07482	0	0	1.6979	8.7366
Commercial water	0	0	0	0	0	0	0	0	0	0	0	0
Suburban road	6.73670	5.21343	0	0	16.71164	4.59474	0.75529	1.93357	1.96217	3.10053	0	0
Suburban hardstand	6.08694	4.71059	0	0	21.71844	5.97132	2.18503	5.59379	5.25066	8.29684	0	0
Suburban roof	23.68161	18.32684	0	0	73.29687	20.15242	5.26468	13.47782	7.70244	12.17103	0.00198	0.01016
Suburban pervious	41.86302	32.39716	0	0	102.74356	28.24856	5.68414	14.55165	10.69712	16.90309	0.03886	0.19994
Suburban water	0	0	0	0	0.00210	0.00058	0	0	0	0	0	0
Open space road	5.30084	4.10224	2.16018	0.69905	12.17165	3.34650	1.47995	3.78873	1.76602	2.79058	1.38581	7.13058
Open space hardstand	2.65729	2.05644	2.24234	0.72564	5.34020	1.46825	1.23752	3.16811	2.27993	3.60263	0.97812	5.03284
Open space roof	0.16133	0.12485	0.10101	0.03269	0.58110	0.15977	0.09868	0.25262	0.39105	0.61793	0.08547	0.43977
Open space pervious	38.37112	29.69483	13.61355	4.40542	58.24083	16.01287	12.63747	32.35250	32.93501	52.04237	12.78198	65.76885
Open space water	0	0	0	0	0	0	4.32094	11.06181	0.30060	0.47500	0.06847	0.35228
Bushland road	0	0	6.17691	1.99888	0.86652	0.23824	0	0	0	0	0	0
Bushland hardstand	0.00225	0.00174	2.42975	0.78628	0.74172	0.20393	0	0	0	0	0	0
Bushland roof	0.00093	0.00072	1.47904	0.47863	0.70985	0.19517	0	0	0	0	0	0
Bushland pervious	4.20082	3.25095	280.72872	90.84543	52.08091	14.31925	0	0	0	0	0	0
Bushland water	0	0	0.08650	0.02799	0	0	0	0	0	0	0	0
Rural road	0	0	0	0	0	0	0	0	0	0	0	0
Rural hardstand	0	0	0	0	0	0	0	0	0	0	0	0
Rural roof	0	0	0	0	0	0	0	0	0	0	0	0
Rural pervious	0	0	0	0	0	0	0	0	0	0	0	0
Rural water	0	0	0	0	0	0	0	0	0	0	0	0
Sports field	0	0	0	0	3.80112	1.04509	1.87120	4.79037	0	0	0.35953	1.84994
Total subcatchment area	129.21820	100	309.01800	100	363.71260	100	39.06180	100	63.28500	100	19.43470	100

Table C3 cont. Area of land use functional units within Lake Tuggeranong subcatchments (see Table C2), in hectares (ha) and as a percentage of subcatchment area (%).

Functional unit	WL0 (ha)	WL0 (%)	WL1 (ha)	WL1 (%)	WL2 (ha)	WL2 (%)	WL3 (ha)	WL3 (%)	WL4 (ha)	WL4 (%)	WL5 (ha)	WL5 (%)
Commercial road	4.3703	7.9703	0.8347	3.1681	1.0011	6.7299	0	0	0.62984	11.02963	0	0
Commercial hardstand	11.5970	21.1500	6.8472	25.9884	1.2159	8.1740	0.00085	0.01072	2.13908	37.45934	0	0
Commercial roof	25.6801	46.8340	5.6090	21.2888	4.2901	28.8403	0.00085	0.01072	1.99816	34.99153	0	0
Commercial pervious	4.4233	8.0669	3.4839	13.2230	2.1629	14.5404	0.00355	0.04478	0.60119	10.52793	0.13435	2.80000
Commercial water	0	0	0	0	0	0	0	0	0	0	0	0
Suburban road	0	0	0.01252	0.04754	0	0	0	0	0	0	0	0
Suburban hardstand	0	0	0.10727	0.40713	0	0	0	0	0	0	0	0
Suburban roof	0	0	0.09979	0.37877	0	0	0	0	0	0	0	0
Suburban pervious	0	0	0.23981	0.91019	0	0	0	0	0	0	0	0
Suburban water	0	0	0	0	0	0	0	0	0	0	0	0
Open space road	3.84955	7.02060	3.52733	13.38791	2.07414	13.94361	0.01007	0.12708	0.00397	0.06961	0.76260	15.89337
Open space hardstand	2.01038	3.66643	0.97456	3.69894	1.33538	8.97721	0.81178	10.24202	0.06327	1.10804	0.59875	12.47873
Open space roof	0.65246	1.18991	0.17189	0.65240	0.72916	4.90187	0.14906	1.88065	0.04205	0.73636	0.43773	9.12289
Open space pervious	2.24307	4.09078	4.41994	16.77583	2.06527	13.88395	6.94281	87.59543	0.22977	4.02371	2.82017	58.77550
Open space water	0.00605	0.01103	0.01925	0.07306	0	0	0.00702	0.08861	0.00307	0.05385	0.00874	0.18216
Bushland road	0	0	0	0	0	0	0	0	0	0	0	0
Bushland hardstand	0	0	0	0	0	0	0	0	0	0	0	0
Bushland roof	0	0	0	0	0	0	0	0	0	0	0	0
Bushland pervious	0	0	0	0	0.00130	0.00874	0	0	0	0	0.03586	0.74736
Bushland water	0	0	0	0	0	0	0	0	0	0	0	0
Rural road	0	0	0	0	0	0	0	0	0	0	0	0
Rural hardstand	0	0	0	0	0	0	0	0	0	0	0	0
Rural roof	0	0	0	0	0	0	0	0	0	0	0	0
Rural pervious	0	0	0	0	0	0	0	0	0	0	0	0
Rural water	0	0	0	0	0	0	0	0	0	0	0	0
Sports field	0	0	0	0	0	0	0	0	0	0	0	0
Total subcatchment area	54.83220	100	26.34710	100	14.87520	100	7.92600	100	5.71040	100	4.79820	100

Table C3 cont. Area of land use functional units within Lake Tuggeranong subcatchments (see Table C2), in hectares (ha) and as a percentage of subcatchment area (%).

Functional unit	WL6 (ha)	WL6 (%)	WL7 (ha)	WL7 (%)	WL8 (ha)	WL8 (%)	WL9 (ha)	WL9 (%)	WL10 (ha)	WL10 (%)	WL11 (ha)	WL11 (%)
Commercial road	0.22090	9.12689	0.48320	9.59071	0.10770	9.94735	0	0	0.00152	0.00688	0.00052	0.00688
Commercial hardstand	0.75873	31.34842	0.70091	13.91191	0.09505	8.77898	0.09312	8.05055	0.08472	0.38388	0.02891	0.38388
Commercial roof	1.34172	55.43604	1.17561	23.33390	0.22848	21.10234	0.28581	24.70893	0.05195	0.23543	0.01773	0.23543
Commercial pervious	0.07700	3.18144	0.66586	13.21619	0.21683	20.02632	0.09627	8.32271	0.24539	1.11196	0.08373	1.11196
Commercial water	0.00003	0.00103	0.01950	0.38706	0	0	0	0	0	0	0	0
Suburban road	0	0	0	0	0	0	0	0	0.42001	1.90321	0.14331	1.90321
Suburban hardstand	0	0	0	0	0	0	0	0	0.32501	1.47275	0.11090	1.47275
Suburban roof	0	0	0	0	0	0	0	0	1.45989	6.61534	0.49813	6.61534
Suburban pervious	0	0	0	0	0	0	0	0	2.42902	11.00684	0.82882	11.00684
Suburban water	0	0	0	0	0	0	0	0	0	0	0	0
Open space road	0	0	0.00018	0.00347	0.09565	8.83440	0	0	0.75552	3.42356	0.25779	3.42356
Open space hardstand	0.01015	0.41951	0.59345	11.77910	0.07803	7.20652	0.22165	19.16190	0.35687	1.61712	0.12177	1.61712
Open space roof	0.00730	0.30172	0.15618	3.09997	0.03780	3.49127	0.12877	11.13295	0.03785	0.17152	0.01292	0.17152
Open space pervious	0.00448	0.18496	1.22931	24.39981	0.19978	18.45156	0.30532	26.39594	3.66317	16.59923	1.24992	16.59923
Open space water	0	0	0.01400	0.27789	0.02340	2.16126	0.02576	2.22702	0.01476	0.06687	0.00504	0.06687
Bushland road	0	0	0	0	0	0	0	0	0.31222	1.41481	0.10654	1.41481
Bushland hardstand	0	0	0	0	0	0	0	0	0.14492	0.65671	0.04945	0.65671
Bushland roof	0	0	0	0	0	0	0	0	0.02061	0.09339	0.00703	0.09339
Bushland pervious	0	0	0	0	0	0	0	0	11.74298	53.21198	4.00686	53.21198
Bushland water	0	0	0	0	0	0	0	0	0.00188	0.00852	0.00064	0.00852
Rural road	0	0	0	0	0	0	0	0	0	0	0	0
Rural hardstand	0	0	0	0	0	0	0	0	0	0	0	0
Rural roof	0	0	0	0	0	0	0	0	0	0	0	0
Rural pervious	0	0	0	0	0	0	0	0	0	0	0	0
Rural water	0	0	0	0	0	0	0	0	0	0	0	0
Sports field	0	0	0	0	0	0	0	0	0	0	0	0
Total subcatchment area	2.42030	100	5.03820	100	1.08270	100	1.15670	100	22.06830	100	7.53000	100

Table C3 cont. Area of land use functional units within Lake Tuggeranong subcatchments (see Table C2), in hectares (ha) and as a percentage of subcatchment area (%).

Functional unit	DDS1 (ha)	DDS1 (%)	DDS2 (ha)	DDS2 (%)	DSL1 (ha)	DSL1 (%)	DSL2 (ha)	DSL2 (%)	DLC N (ha)	DLC N (%)	DLC S (ha)	DLC S (%)
Commercial road	0	0	0	0	0	0	0	0	0	0	0	0
Commercial hardstand	0	0	0	0	0.00817	0.01807	0	0	0	0	0.08175	0.12357
Commercial roof	0	0	0	0	0.00840	0.01857	0	0	0	0	0.14145	0.21382
Commercial pervious	0	0	0	0	6.11195	13.52072	0	0	0	0	0.03060	0.04626
Commercial water	0	0	0	0	0	0	0	0	0	0	0	0
Suburban road	0.89352	7.67025	1.04632	3.69542	0	0	0	0	0.25714	8.61201	3.97777	6.01283
Suburban hardstand	0.63470	5.44849	2.06447	7.29133	0	0	0	0	0.35156	11.77441	5.04227	7.62195
Suburban roof	1.85668	15.93838	4.99336	17.63565	0	0	0	0	1.31517	44.04747	15.13896	22.88422
Suburban pervious	3.18648	27.35385	5.69499	20.11369	0	0	0	0	0.74893	25.08312	22.82264	34.49895
Suburban water	0	0	0	0	0	0	0	0	0	0	0	0
Open space road	0.74070	6.35840	3.08179	10.88433	0	0	0	0	0	0	3.06436	4.63212
Open space hardstand	0.10360	0.88930	1.21974	4.30791	0.00737	0.01631	0.00040	0.00118	0.02711	0.90785	1.28473	1.94201
Open space roof	0.02935	0.25194	0.11342	0.40059	0.00070	0.00155	0	0	0.00355	0.11892	0.17930	0.27103
Open space pervious	4.20409	36.08938	10.09991	35.67110	0.25166	0.55672	0.09442	0.27857	0.28234	9.45621	14.39076	21.75323
Open space water	0	0	0	0	0	0	0	0	0	0	0	0
Bushland road	0	0	0	0	0	0	0	0	0	0	0	0
Bushland hardstand	0	0	0	0	0.65479	1.44850	0.28300	0.83498	0	0	0	0
Bushland roof	0	0	0	0	0.05969	0.13205	0.00107	0.00317	0	0	0	0
Bushland pervious	0	0	0	0	37.96401	83.98318	33.51431	98.88211	0	0	0	0
Bushland water	0	0	0	0	0.13757	0.30434	0	0	0	0	0	0
Rural road	0	0	0	0	0	0	0	0	0	0	0	0
Rural hardstand	0	0	0	0	0	0	0	0	0	0	0	0
Rural roof	0	0	0	0	0	0	0	0	0	0	0	0
Rural pervious	0	0	0	0	0	0	0	0	0	0	0	0
Rural water	0	0	0	0	0	0	0	0	0	0	0	0
Sports field	0	0	0	0	0	0	0	0	0	0	0	0
Total subcatchment area	11.64910	100	28.31400	100	45.20430	100	33.89320	100	2.98580	100	66.15460	100

Table C3 cont. Area of land use functional units within Lake Tuggeranong subcatchments (see Table C2), in hectares (ha) and as a percentage of subcatchment area (%).

Functional unit	TC0 (ha)	TC0 (%)	TC1 (ha)	TC1 (%)	TC2 (ha)	TC2 (%)	TC3 (ha)	TC3 (%)	TC4 (ha)	TC4 (%)	TC5 (ha)	TC5 (%)
Commercial road	0.58272	0.22654	0	0	0.32153	0.12952	0.06495	0.12948	0.06495	0.12948	0.33632	0.09282
Commercial hardstand	6.51431	2.53251	0	0	1.28484	0.51756	0.77034	1.53569	0.77034	1.53569	3.38792	0.93498
Commercial roof	7.38043	2.86922	0	0	1.32700	0.53454	0.64949	1.29477	0.64949	1.29477	3.90561	1.07785
Commercial pervious	17.78314	6.91338	0	0	32.92973	13.26479	2.22145	4.42849	2.22145	4.42849	9.11530	2.51558
Commercial water	0	0	0	0	0.05460	0.02199	0	0	0	0	0	0
Suburban road	10.77831	4.19018	0.73186	6.26525	12.30299	4.95590	2.64384	5.27054	2.64384	5.27054	12.01325	3.31534
Suburban hardstand	13.56212	5.27241	1.15220	9.86371	14.49177	5.83759	3.18411	6.34758	3.18411	6.34758	12.88176	3.55503
Suburban roof	49.75319	19.34207	3.12461	26.74904	46.70982	18.81570	11.68760	23.29944	11.68760	23.29944	47.17029	13.01776
Suburban pervious	55.40174	21.53800	3.50165	29.97680	72.67577	29.27533	14.37982	28.66642	14.37982	28.66642	77.11695	21.28225
Suburban water	7.51E-05	2.92E-05	0	0	2.51E-05	1.01E-05	0	0	0	0	0.00033	8.97E-05
Open space road	10.01014	3.89155	0	0	5.67404	2.28562	2.44259	4.86935	2.44259	4.86935	6.28860	1.73549
Open space hardstand	6.52754	2.53765	0.53100	4.54575	4.94635	1.99249	1.51306	3.01630	1.51306	3.01630	5.23212	1.44393
Open space roof	0.72237	0.28083	0.00733	0.06271	0.39423	0.15880	0.12290	0.24500	0.12290	0.24500	0.85361	0.23557
Open space pervious	46.04883	17.90196	2.63256	22.53675	49.70804	20.02344	10.34895	20.63080	10.34895	20.63080	50.24425	13.86609
Open space water	0.52547	0.20428	0	0	0	0	0	0	0	0	0	0
Bushland road	0	0	0	0	0	0	0	0	0	0	3.29003	0.90796
Bushland hardstand	0	0	0	0	0	0	0	0	0	0	0.86734	0.23936
Bushland roof	0	0	0	0	0	0	0	0	0	0	0.11853	0.03271
Bushland pervious	0	0	0	0	4	2	0	0	0	0	116.54473	32.16329
Bushland water	0	0	0	0	0	0	0	0	0	0	0	0
Rural road	0	0	0	0	0	0	0	0	0	0	0	0
Rural hardstand	0	0	0	0	0	0	0	0	0	0	0	0
Rural roof	0	0	0	0	0	0	0	0	0	0	0	0
Rural pervious	30.00000	11.66281	0	0	0	0	0	0	0	0	0	0
Rural water	0	0	0	0	0	0	0	0	0	0	0	0
Sports field	1.63753	0.63661	0	0	1.16687	0.47004	0.13350	0.26613	0.13350	0.26613	12.98638	3.58390
Total subcatchment area	257.22790	100	11.68120	100	248.24920	100	50.16260	100	50.16260	100	362.35330	100

Table C3 cont. Area of land use functional units within Lake Tuggeranong subcatchments (see Table C2), in hectares (ha) and as a percentage of subcatchment area (%).

Functional unit	TC6 (ha)	TC6 (%)	TC7 (ha)	TC7 (%)	TC6 NSW (ha)	TC6 NSW (%)	TC8 NSW (ha)	TC8 NSW (%)
Commercial road	0	0	0	0	0	0	0	0
Commercial hardstand	0	0	0	0	0	0	0	0
Commercial roof	0	0	0	0	0	0	0	0
Commercial pervious	0	0	0	0	0	0	0	0
Commercial water	0	0	0	0	0	0	0	0
Suburban road	0	0	0	0	0	0	0	0
Suburban hardstand	0.00375	0.00369	0	0	0	0	0	0
Suburban roof	0.00153	0.00150	0	0	0	0	0	0
Suburban pervious	0.00685	0.00674	0	0	0	0	0	0
Suburban water	0	0	0	0	0	0	0	0
Open space road	0.20877	0.20533	0.04334	0.00706	0	0	0	0
Open space hardstand	0.07513	0.07389	0.03677	0.00599	0	0	0	0
Open space roof	0.01225	0.01205	0.00597	0.00097	0	0	0	0
Open space pervious	4.06725	4.00025	0.25709	0.04191	0.00258	0.02625	2.64149	0.31220
Open space water	0	0	0	0	0	0	0	0
Bushland road	6.02788	5.92859	6.56298	1.06977	0	0	0	0
Bushland hardstand	0.71094	0.69923	1.62155	0.26431	0	0	0	0
Bushland roof	0.27050	0.26604	0.35840	0.05842	0	0	0	0
Bushland pervious	90.27019	88.78316	298.69189	48.68689	0.00055	0.00561	0.00130	0.00015
Bushland water	0.01985	0.01952	0.10036	0.01636	0	0	0	0
Rural road	0	0	0.24039	0.03918	0	0	0	0
Rural hardstand	0	0	0.53294	0.08687	0	0	5.00E-05	5.91E-06
Rural roof	0	0	0.64118	0.10451	0	0	7.50E-05	8.87E-06
Rural pervious	0	0	304.00698	49.55325	9.82337	99.96815	843.45908	99.68764
Rural water	0	0	0.39566	0.06449	0	0	0	0
Sports field	0	0	0	0	0	0	0	0
Total subcatchment area	101.67490	100	613.49550	100	9.82650	100	846.10200	100

Table C3 cont. Area of land use functional units within Lake Tuggeranong subcatchments (see Table C2), in hectares (ha) and as a percentage of subcatchment area (%).

Functional unit	WS0 (ha)	WS0 (%)	WS1 (ha)	WS1 (%)	WS2 (ha)	WS2 (%)	WS3 (ha)	WS3 (%)	WS4 (ha)	WS4 (%)
Commercial road	0	0	0	0	1.54112	0.82442	0	0	0	0
Commercial hardstand	0.22877	0.74891	1.55212	1.03660	6.70734	3.58810	0	0	0.01836	0.02462
Commercial roof	0.36464	1.19371	2.44706	1.63431	8.64741	4.62595	0	0	0.00633	0.00849
Commercial pervious	1.71141	5.60254	3.03841	2.02924	8.14436	4.35684	0	0	0.07058	0.09467
Commercial water	0	0	0	0	0	0	0	0	0	0
Suburban road	1.18540	3.88057	9.03820	6.03629	7.84594	4.19720	0.67185	6.88093	1.71359	2.29845
Suburban hardstand	2.50062	8.18613	9.28827	6.20331	8.99315	4.81090	0.51682	5.29313	2.21056	2.96504
Suburban roof	8.63839	28.27903	32.95523	22.00964	32.99276	17.64954	2.46192	25.21422	8.27366	11.09754
Suburban pervious	8.11016	26.54977	49.31735	32.93733	54.74475	29.28581	4.14976	42.50066	12.91723	17.32601
Suburban water	0	0	2.50E-05	1.67E-05	0.00105	0.00056	0	0	0.00045	0.00060
Open space road	1.26220	4.13198	4.93795	3.29788	9.44718	5.05379	0.16886	1.72939	5.19069	6.96232
Open space hardstand	0.97098	3.17863	3.53733	2.36246	5.75370	3.07795	0.07289	0.74654	1.88015	2.52187
Open space roof	0.11025	0.36091	0.46175	0.30838	1.12409	0.60134	0.00465	0.04762	0.24454	0.32801
Open space pervious	5.43135	17.78029	31.69643	21.16893	35.70274	19.09925	1.71724	17.58751	15.71887	21.08387
Open space water	0.03285	0.10754	0.00560	0.00374	0	0	0	0	0	0
Bushland road	0	0	0	0	0	0	0	0	0.51420	0.68970
Bushland hardstand	0	0	0	0	0.00187	0.00100	0	0	0.06840	0.09175
Bushland roof	0	0	0	0	0	0	0	0	0.02153	0.02888
Bushland pervious	0	0	0	0	0.32207	0.17229	0	0	25.70486	34.47818
Bushland water	0	0	0	0	0	0	0	0	0	0
Rural road	0	0	0	0	0	0	0	0	0	0
Rural hardstand	0	0	0	0	0	0	0	0	0	0
Rural roof	0	0	0	0	0	0	0	0	0	0
Rural pervious	0	0	0	0	0	0	0	0	0	0
Rural water	0	0	0	0	0	0	0	0	0	0
Sports field	0	0	1.45519	0.97187	4.96317	2.65506	0	0	0	0
Total subcatchment area	30.547	100	149.7309	100	186.9327	100	9.764	100	74.554	100

Table C3 cont. Area of land use functional units within Lake Tuggeranong subcatchments (see Table C2), in hectares (ha) and as a percentage of subcatchment area (%).

Functional unit	FA0 (ha)	FA0 (%)	FA1 (ha)	FA1 (%)	FA2 (ha)	FA2 (%)	FA3 (ha)	FA3 (%)	FA5 (ha)	FA5 (%)	FA6 (ha)	FA6 (%)
Commercial road	0.00155	0.00077	0.00178	0.00390	0	0	0	0	0	0	0	0
Commercial hardstand	0.68547	0.33986	1.27610	2.80488	0	0	0.56164	0.42239	0	0	0	0
Commercial roof	1.04842	0.51982	1.47323	3.23817	0	0	0.68604	0.51595	0	0	0	0
Commercial pervious	3.23227	1.60258	6.71763	14.76535	0	0	4.86537	3.65908	0	0	0	0
Commercial water	0	0	0	0	0	0	0	0	0	0	0	0
Suburban road	12.21125	6.05443	3.05012	6.70417	0.26349	3.19399	8.76270	6.59013	0	0	1.31484	1.83693
Suburban hardstand	12.72037	6.30686	2.42518	5.33055	0.25484	3.08907	9.77361	7.35040	0.00222	0.03223	1.43267	2.00154
Suburban roof	48.91619	24.25304	7.39270	16.24915	1.04438	12.65981	33.22342	24.98620	0.05123	0.74231	5.36633	7.49712
Suburban pervious	74.69462	37.03419	11.53219	25.34776	1.75898	21.32205	50.77288	38.18454	0.10458	1.51540	8.99825	12.57116
Suburban water	0.00150	0.00074	0	0	0	0	0.00090	0.00068	0	0	0	0
Open space road	8.37676	4.15327	2.07507	4.56101	0.00935	0.11339	2.20094	1.65525	0.33517	4.85688	1.70013	2.37520
Open space hardstand	4.42618	2.19454	1.77967	3.91171	0.03974	0.48167	1.71507	1.28985	0.20396	2.95548	2.54351	3.55345
Open space roof	0.47688	0.23644	0.10978	0.24129	0.00427	0.05176	0.20312	0.15276	0.04800	0.69560	1.01666	1.42034
Open space pervious	34.29041	17.00146	6.51373	14.31717	0.42130	5.10688	18.91811	14.22766	2.77117	40.15607	40.27044	56.26052
Open space water	0	0	0	0	0.04402	0.53359	0	0	0	0	5.00E-05	6.99E-05
Bushland road	0	0	0	0	0.15460	1.87402	0	0	0	0	0.00000	0.00000
Bushland hardstand	0	0	0	0	0.01489	0.18053	0	0	0	0	0.00713	0.00995
Bushland roof	0	0	0	0	0.01464	0.17746	0	0	0	0	0.01075	0.01502
Bushland pervious	0	0	0	0	4.22510	51.21578	0	0	0	0	8.91775	12.45869
Bushland water	0	0	0	0	0	0	0	0	0	0	0	0
Rural road	0	0	0	0	0	0	0	0	0	0	0	0
Rural hardstand	0	0	0	0	0	0	0	0	0	0	0	0
Rural roof	0	0	0	0	0	0	0	0	0	0	0	0
Rural pervious	0	0	0	0	0	0	0	0	0	0	0	0
Rural water	0	0	0	0	0	0	0	0	0	0	0	0
Sports field	0.60912	0.30201	1.14873	2.52490	0	0	1.28330	0.96513	3.38467	49.04604	0	0
Total subcatchment area	201.69100	100	45.49590	100	8.24960	100	132.96710	100	6.90100	100	71.57845	100

Table C3 cont. Area of land use functional units within Lake Tuggeranong subcatchments (see Table C2), in hectares (ha) and as a percentage of subcatchment area (%).

Functional unit	FA7 (ha)	FA7 (%)	FA8 (ha)	FA8 (%)	FA9 (ha)	FA9 (%)	FA10 (ha)	FA10 (%)	FA11 (ha)	FA11 (%)	FA12 (ha)	FA12 (%)
Commercial road	0	0	0	0	0.96626	0.58898	0	0	0.15920	0.21730	0	0
Commercial hardstand	0	0	0.09825	0.09336	2.87939	1.75511	0.01547	0.62058	0.81899	1.11787	0.84147	7.30903
Commercial roof	0	0	0.28170	0.26767	2.81759	1.71744	0.01910	0.76595	0.99322	1.35568	1.03335	8.97575
Commercial pervious	0	0	1.17809	1.11941	3.34845	2.04102	0.12335	4.94762	2.15616	2.94302	2.27579	19.76764
Commercial water	0	0	0	0	0	0	0	0	0	0	0	0
Suburban road	0.24393	1.83693	3.40824	3.23849	7.53109	4.59051	0	0	2.25456	3.07734	0.05280	0.45865
Suburban hardstand	0.26579	2.00154	4.42791	4.20736	8.06460	4.91570	0	0	2.19261	2.99278	0.08285	0.71968
Suburban roof	0.99555	7.49712	18.40574	17.48898	28.53998	17.39629	0	0	9.76619	13.33023	0.71281	6.19152
Suburban pervious	1.66934	12.57116	29.18282	27.72928	45.86605	27.95723	0	0	14.57372	19.89220	1.08328	9.40943
Suburban water	0	0	0	0	2.49E-05	1.52E-05	0	0	2.50E-05	3.41E-05	0	0
Open space road	0.31540	2.37520	4.65181	4.42011	3.14482	1.91690	0.41795	16.76375	1.63615	2.23324	0.58038	5.04121
Open space hardstand	0.47187	3.55345	2.44401	2.32228	1.98188	1.20804	0.17292	6.93569	1.13037	1.54288	0.57485	4.99321
Open space roof	0.18861	1.42034	0.20423	0.19406	0.18810	0.11466	0.00655	0.26267	0.17858	0.24375	0.09548	0.82934
Open space pervious	7.47089	56.26052	15.52775	14.75434	17.56257	10.70510	1.50429	60.33586	10.68431	14.58340	4.16896	36.21182
Open space water	9.28E-06	6.99E-05	0.01460	0.01387	0	0	0	0	0	0	0.01068	0.09273
Bushland road	0.00000	0.00000	0.14620	0.13892	2.44566	1.49073	0	0	0.18495	0.25245	0	0
Bushland hardstand	0.00132	0.00995	0.74621	0.70904	0.57236	0.34888	0	0	0.12498	0.17059	0	0
Bushland roof	0.00199	0.01502	0.21660	0.20581	0.06938	0.04229	0	0	0.00813	0.01109	0	0
Bushland pervious	1.65440	12.45869	24.30774	23.09701	34.67503	21.13585	0	0	25.02885	34.16279	0	0
Bushland water	0	0	0	0	0.01220	0.00744	0	0	0	0	0	0
Rural road	0	0	0	0	0	0	0	0	0	0	0	0
Rural hardstand	0	0	0	0	0	0	0	0	0	0	0	0
Rural roof	0	0	0	0	0	0	0	0	0	0	0	0
Rural pervious	0	0	0	0	0	0	0	0	0	0	0	0
Rural water	0	0	0	0	0	0	0	0	0	0	0	0
Sports field	0	0	0	0	3.39245	2.06784	0.23356	9.36789	1.37250	1.87337	0	0
Total subcatchment area	13.27909	100	105.24190	100	164.05787	100	2.49320	100	73.26347	100	11.51270	100

Table C3 cont. Area of land use functional units within Lake Tuggeranong subcatchments (see Table C2), in hectares (ha) and as a percentage of subcatchment area (%).

Functional unit	FA13 (ha)	FA13 (%)	FA14 (ha)	FA14 (%)	FA15 (ha)	FA15 (%)	FA16 (ha)	FA16 (%)	FA17 (ha)	FA17 (%)	FA9 NSW (ha)	FA9 NSW (%)
Commercial road	0	0	0	0	0	0	0	0	0	0	0	0
Commercial hardstand	0	0	0	0	0	0	0.00048	0.00069	0	0	0	0
Commercial roof	0	0	0	0	0	0	0.01188	0.01718	0	0	0	0
Commercial pervious	0.02585	1.29481	0	0	0	0	0.04275	0.06184	0	0	0	0
Commercial water	0	0	0	0	0	0	0	0	0	0	0	0
Suburban road	0	0	0	0	0.99534	6.47445	4.91072	7.10386	2.05614	3.19399	0	0
Suburban hardstand	0	0	0	0	0.98473	6.40548	4.14411	5.99488	1.98860	3.08907	0	0
Suburban roof	0	0	0	0	4.20349	27.34277	16.32055	23.60934	8.14979	12.65981	0	0
Suburban pervious	0	0	0	0	5.84599	38.02693	24.30567	35.16064	13.72613	21.32205	0	0
Suburban water	0	0	0	0	0	0	0	0	0	0	0	0
Open space road	0.02215	1.10948	0	0	0.84631	5.50505	1.22231	1.76820	0.07299	0.11339	0	0
Open space hardstand	0.01945	0.97424	0.01723	4.25808	0.46344	3.01456	1.04693	1.51450	0.31008	0.48167	0	0
Open space roof	0.02070	1.03685	0.00050	0.12360	0.07351	0.47819	0.07243	0.10477	0.03332	0.05176	0	0
Open space pervious	0.62372	31.24084	0.38697	95.61832	1.84850	12.02407	7.92437	11.46341	3.28757	5.10688	0.02229	0.03109
Open space water	0	0	0	0	0	0	0.00198	0.00286	0.34350	0.53359	0	0
Bushland road	0	0	0	0	0	0	0.04578	0.06622	1.20641	1.87402	0	0
Bushland hardstand	0	0	0	0	0	0	0.00348	0.00503	0.11622	0.18053	0	0
Bushland roof	0	0	0	0	0	0	0.00023	0.00033	0.11424	0.17746	2.50E-05	3.49E-05
Bushland pervious	0	0	0	0	0	0	9.02073	13.04941	32.97031	51.21578	0.00283	0.00394
Bushland water	0	0	0	0	0	0	0	0	0	0	0	0
Rural road	0	0	0	0	0	0	0	0	0	0	0	0
Rural hardstand	0	0	0	0	0	0	0	0	0	0	0	0
Rural roof	0	0	0	0	0	0	0	0	0	0	0	0
Rural pervious	0	0	0	0	0	0	0	0	0	0	71.66356	99.96493
Rural water	0	0	0	0	0	0	0	0	0	0	0	0
Sports field	1.28462	64.34376	0	0	0.11200	0.72851	0.05313	0.07685	0	0	0	0
Total subcatchment area	1.99650	100	0.40470	100	15.37330	100	69.12750	100	64.37530	100	71.68867	100

Appendix D: Literature-derived EMC and DWC values

Baseline values of the event mean concentrations (EMC) and dry weather concentrations (DWC) of total phosphorus (TP), total nitrogen (TN) and total suspended solids (TSS) generated by functional land use units were derived from the literature for initial parameterisation of the model. The EMC values were then scaled based on date-matched observations. Tables D1-D3 present the baseline EMC and DWC values for each functional unit.

Table D1: Baseline total phosphorus (TP) EMC and DWC values (mg/L) derived from the literature for each combination of functional land use and surface imperviousness.

Land surface imperviousness	Suburban	Commercial	Open space	Rural	Bushland	Sports field
Road	EMC: 0.501 DWC: 0.015	EMC: 0.501 DWC: 0.015	EMC: 0.501 DWC: 0.015	EMC: 0.251 DWC: 0.015	EMC: 0.251 DWC: 0.015	
Hardstand	EMC: 0.251 DWC: 0.015	EMC: 0.251 DWC: 0.015	EMC: 0.251 DWC: 0.015	EMC: 0.251 DWC: 0.015	EMC: 0.251 DWC: 0.015	
Roof	EMC: 0.128 DWC: 0.015	EMC: 0.128 DWC: 0.015	EMC: 0.128 DWC: 0.015	EMC: 0.251 DWC: 0.015	EMC: 0.251 DWC: 0.015	
Pervious	EMC: 0.251 DWC: 0.04	EMC: 0.251 DWC: 0.04	EMC: 0.251 DWC: 0.04	EMC: 0.218 DWC: 0.04	EMC: 0.079 DWC: 0.04	EMC: 0.251 DWC: 0.015
Water	EMC: 0 DWC: 0	EMC: 0 DWC: 0	EMC: 0 DWC: 0	EMC: 0 DWC: 0	EMC: 0 DWC: 0	

Table D2: Baseline total nitrogen (TN) EMC and DWC values (mg/L) derived from the literature for each combination of functional land use and surface imperviousness.

Land surface imperviousness	Suburban	Commercial	Open space	Rural	Bushland	Sports field
Road	EMC: 2.187 DWC: 1.0	EMC: 2.187 DWC: 1.0	EMC: 2.187 DWC: 1.0	EMC: 2.187 DWC: 1.0	EMC: 2.187 DWC: 1.0	
Hardstand	EMC: 2.187 DWC: 1.0	EMC: 2.187 DWC: 1.0	EMC: 2.187 DWC: 1.0	EMC: 2.187 DWC: 1.0	EMC: 2.187 DWC: 1.0	
Roof	EMC: 1.995 DWC: 1.0	EMC: 1.995 DWC: 1.0	EMC: 1.995 DWC: 1.0	EMC: 1.995 DWC: 1.0	EMC: 1.995 DWC: 1.0	
Pervious	EMC: 1.995 DWC: 0.4	EMC: 1.995 DWC: 0.4	EMC: 1.995 DWC: 0.4	EMC: 1.995 DWC: 0.4	EMC: 1.995 DWC: 0.4	EMC: 1.995 DWC: 1.0
Water	EMC: 0 DWC: 0	EMC: 0 DWC: 0	EMC: 0 DWC: 0	EMC: 0 DWC: 0	EMC: 0 DWC: 0	

Table D3: Baseline total suspended solids (TSS) EMC and DWC values (mg/L) derived from the literature for each combination of functional land use and surface imperviousness.

Land surface imperviousness	Suburban	Commercial	Open space	Rural	Bushland	Sports field
Road	EMC: 269.15 DWC: 15.849	EMC: 269.15 DWC: 15.849	EMC: 269.15 DWC: 15.849	EMC: 269.15 DWC: 15.849	EMC: 269.15 DWC: 15.849	
Hardstand	EMC: 269.15 DWC: 15.849	EMC: 269.15 DWC: 15.849	EMC: 269.15 DWC: 15.849	EMC: 269.15 DWC: 15.849	EMC: 269.15 DWC: 15.849	
Roof	EMC: 19.95 DWC: 15.849	EMC: 19.95 DWC: 15.849	EMC: 19.95 DWC: 15.849	EMC: 19.95 DWC: 15.849	EMC: 19.95 DWC: 15.849	
Pervious	EMC: 141.25 DWC: 15.849	EMC: 141.25 DWC: 15.849	EMC: 141.25 DWC: 15.849	EMC: 89.12 DWC: 15.849	EMC: 39.81 DWC: 15.849	EMC: 141.25 DWC: 15.849
Water	EMC: 0 DWC: 0	EMC: 0 DWC: 0	EMC: 0 DWC: 0	EMC: 0 DWC: 0	EMC: 0 DWC: 0	

Appendix E: Modelled annual load of total phosphorous

The table below provides total phosphorous generated for each combination of functional land use and surface imperviousness annually.

Table E1: Modelled annual total phosphorus (TP) load (kg/yr) generated for each combination of functional land use and surface imperviousness.

Land surface imperviousness	Road TP (kg/yr)	Hardstand TP (kg/yr)	Roof TP (kg/yr)	Pervious TP (kg/yr)	Water TP (kg/yr)
Suburban	322	169	314	140	0
Commercial	17	45	30	16	0
Open space	243	76	5	88	0
Rural	0	0	1	132	0
Sports field	0	0	0	58	0
Total annual load (kg/yr)	582	290	350	434	0

Attachment H

ACT Government

Predicting phosphorus concentration and trophic state of Lake Tuggeranong

Technical report supplement to the Lake Tuggeranong Catchment Model

Water Information Services, ACT Office of Water

December 2024

Environment, Planning and Sustainable Development Directorate

Version History

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1. Introduction

Vollenweider's (1975, 1976) mass-balance equations, overall, model how the total phosphorous (TP) concentration of a lake ($\mathrm{TP_{lake}}$) is related to the TP concentration of inflows ($\mathrm{TP_{in}}$) and the hydraulic residence/retention time (τ_w). This residence time can be thought of as the average time an incoming water molecule can expect to remain in the lake before leaving the lake through outflow and is calculated by simply dividing the volume of the lake by the outflow rate.

Vollenweider (1976 – Equation 2.13) described this relationship mathematically with the equation below (as re-stated in Brett & Benjamin 2008 – Equation 6):

$$\mathrm{TP_{lake}} = \frac{\mathrm{TP_{in}}}{1+\sigma\tau_w} \qquad (1)$$

Where σ is the first-order rate coefficient of TP loss within the lake due to sedimentation. As this rate is not easily quantified, several different approaches have been proposed to approximate it. Brett & Benjamin (2008) summarised and compared the relative performance of these different approaches using known values from 305 lakes from Europe and North America. They found that all approaches provided a useful fit with real-world values, but that the best-fitting approach was to assume that σ is a function of ${k\tau_w}^x$, where k and x are constants, fitted statistically. This approach was previously used by Larsen & Mercier (1976), who reported a value of x near -0.5.

With this approximation, equation 1 becomes:

$$\mathrm{TP_{lake}} = \frac{\mathrm{TP_{in}}}{1+(k{\tau_w}^x)\tau_w} \qquad (2)$$

Brett & Benjamin (2008) found that values of around k=1.12 and x=-0.53 yielded a correlation between predicted and observed TP_{lake} values with r^2>0.8 for the dataset investigated, yielding the following relationship:

$$\mathrm{TP_{lake}} = \frac{\mathrm{TP_{in}}}{1+\left(1.12\times\tau_w^{-0.53}\right)*\tau_w} \qquad (3)$$

If we then approximate k=1 and x=-0.5, equation 3 simplifies to:

$$\mathrm{TP_{lake}} = \frac{\mathrm{TP_{in}}}{1+\sqrt{\tau_w}} \qquad (4)$$

Vollenweider (1976) previously suggested this approximation of the general equation fits with empirical studies, and this relationship was used by Beer *et al.* 1982 in their early work on Lake Tuggeranong.

2. In-Lake Model

2.1 Parameterisation of the modified Vollenweider model

The adjusted Vollenweider model (equation 2) was parameterised using estimates of inflow TP concentrations and inflow and outflow volumes from the Lake Tuggeranong catchment model (Dey et al. 2024), and observed Lake Tuggeranong TP concentrations from the ALS Lakes and Rivers Water Quality Monitoring Program, but with the following caveats:

- The model assumes a steady state of inflows and influent concentrations, which is a limitation to real-world applications, so it is unclear how reliable we should expect its predictions over shorter time periods to be. That being said, past modelling of TP loads has suggested that 3 hydraulic residence times is sufficient for 95% convergence with steady-state predictions (Sonzogni *et al.* 1976), which is <1 year for most years in Lake Tuggeranong. For this reason, our modelling approach will work with annual time steps, with all model inputs and outputs to be interpreted as annual averages.
- In past applications of this model-fitting approach, data across many different lakes were used, with each lake representing a separated datapoint (e.g. Brett & Benjamin 2008, Larsen & Mercier 1976). Here, the datapoints are all from Lake Tuggeranong, just from different years, and are thus pseudo-replicated. However, to provide a Lake Tuggeranong -specific model that will not be applied elsewhere this approach is probably reasonable. It would be informative to repeat this modelling approach in other ACT lakes and compare fitted values later, to investigate the appropriateness of an overall ACT-wide model using data from all different lakes.
- In other applications of Vollenweider model the same value for water inflow and outflow are used (i.e. assumption of no other source of water loss). Since the catchment model have taken into account of the lake water balance.

To parametrise the modified Vollenweider model, we can use annual total TP loads and water inflows and outflows from the Tuggeranong Source Catchment Model. Specifically:

- l_{in}: the annual TP load flowing into Lake Tuggeranong (converted to mg),
- v_{in}: the annual inflow volume of water into Lake Tuggeranong (converted to L)
- v_{out}: the annual outflow volume of water from Lake Tuggeranong (converted to L)

We can then combine these parameters, along with the approximate total volume of Lake Tuggeranong (V= 1,780,000,000L), to calculate the TP concentration of inflows (TP_{in}, measured in mg/L) and the hydraulic residence time (τ_w, measured in years) as follows:

$$\text{TP}_{\text{in}} = \frac{l_{\text{in}}}{v_{\text{in}}} \quad (5)$$

$$\tau_w = \frac{V}{v_{\text{out}}} \quad (6)$$

The predicted annual average TP_{in} and τ_w values from 1990-2022 are summarised in Table 1 and shown in Figure 1.

Table 1. Summary of Lake Tuggeranong annual values of inflow total phosphorus concentration TP_{in} and hydraulic residence time τ_w from 1990-2022.

	$\mathbf{TP_{in}}$ **(mg/L)**	$\boldsymbol{\tau_w}$ **(y)**
Minimum	0.152	0.055
Median	0.163	0.251
Maximum	0.174	0.727

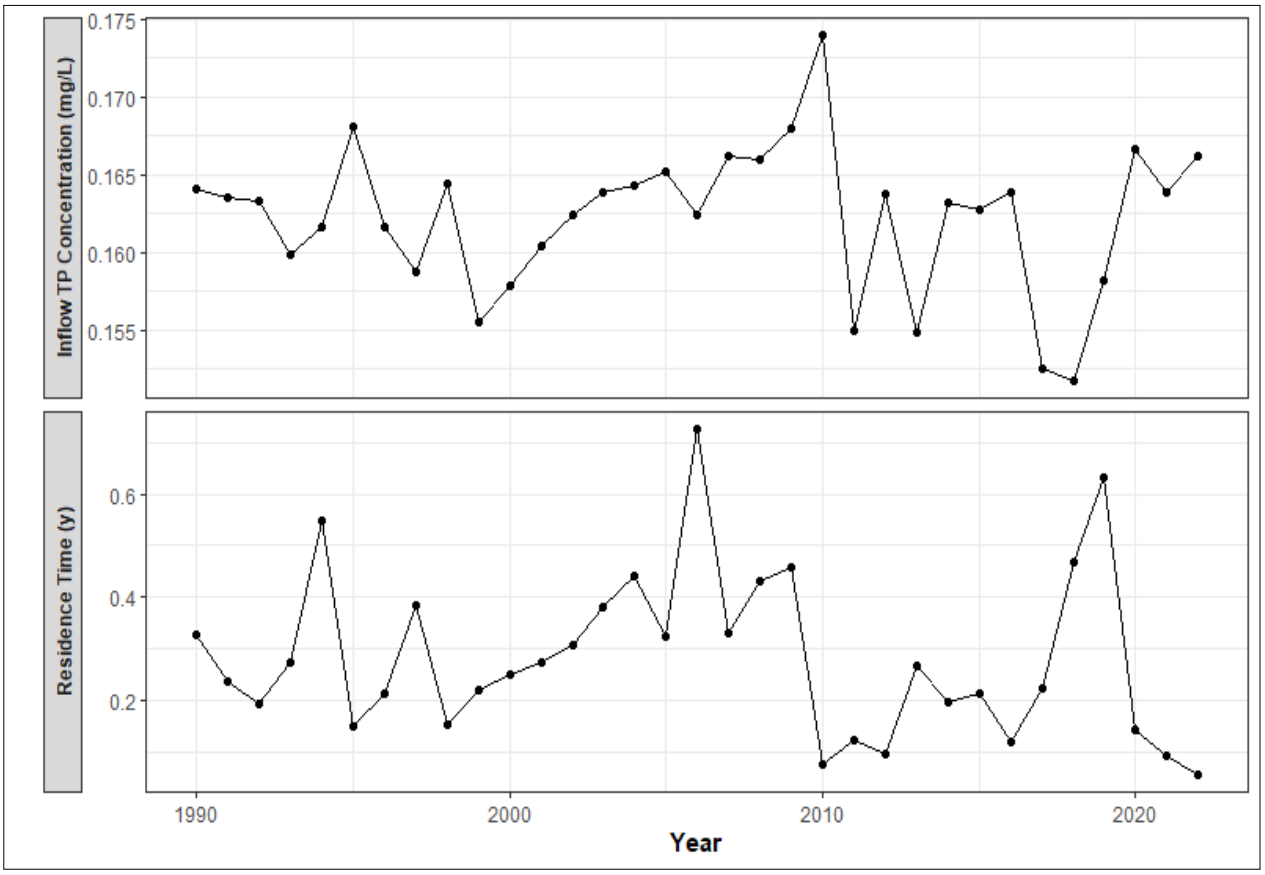

Figure 1. Annual changes in inflow concentrations of total phosphorus (TP_{in}, top panel) and residence time (τ_w, bottom panel) in Lake Tuggeranong, 1990-2022.

2.2 Estimation of total phosphorus and chlorophyll a concentration

Using the modified Vollenweider model (equation 2) $\mathrm{TP_{lake}}$ concentration can be predicted using $\mathrm{TP_{in}}$ and τ_w values. Before estimating the TP_{lake}, fitting of the constants k and x is required such that modelled $\mathrm{TP_{lake}}$ values provide as close-as-possible match to observed $\mathrm{TP_{lake}}$ values. Here, our source of observed $\mathrm{TP_{lake}}$ values come from the ALS Lakes and Rivers Water Quality Monitoring Program from 2005-2022. This period was chosen because it represents the longest run of annual sampling of LT TP concentrations with

relatively constant annual sampling effort (most years had 8 samples from each of two locations within Lake Tuggeranong: LTG248 and LTG249). Other sources of data (e.g. University of Canberra research) did not provide a similar temporal scope, meaning their inclusion would have led to large variability in the underlying sampling effort behind annual averages, which was undesirable here. Waterwatch data was also not used here due to questions about data reliability specifically related to TP measures relative to lab techniques (Harrison *et al.* 2013).

To fit optimal values of k and x to our modified Vollenweider model, an approach similar to Brett & Benjamin (2008) was adopted. Specifically, a function was created in R that would, for given values of k and x, predict lake TP concentrations ($\mathrm{TP}_{\mathrm{predicted}}$) and compare them to average annual observed lake TP concentrations $\mathrm{TP}_{\mathrm{observed}}$ values to calculate the weighted error sum of squares (WESS) as follows:

$$\mathrm{WESS} = \sum \mathrm{weight} \times \left(\mathrm{TP}_{\mathrm{observed}} - \mathrm{TP}_{\mathrm{predicted}}\right)^2 \qquad (7)$$

The number of samples that each annual average was based on as weights was used, such that years that had annual averages based on relatively few datapoints (e.g. 2020 due to lockdowns) contributed relatively less to the WESS. This WESS provides a measure of how closely matched predicted and observed TP values are, with low WESS values indicating a better fitting model.

This function was then used alongside a solver function in R to find a combination of k and x values that minimised the WESS and thus represented the best fit to the observed data. This solver yielded values of $k = 1.093$ and $x = -0.791$. These values are similar to those reported elsewhere (e.g. Brett & Benjamin 2008) and not particularly inconsistent with the unmodified Vollenweider model used by Beer *et al.* 1982 in their early work on LT. Sensitivity analysis of this optimisation was performed by re-calculating the

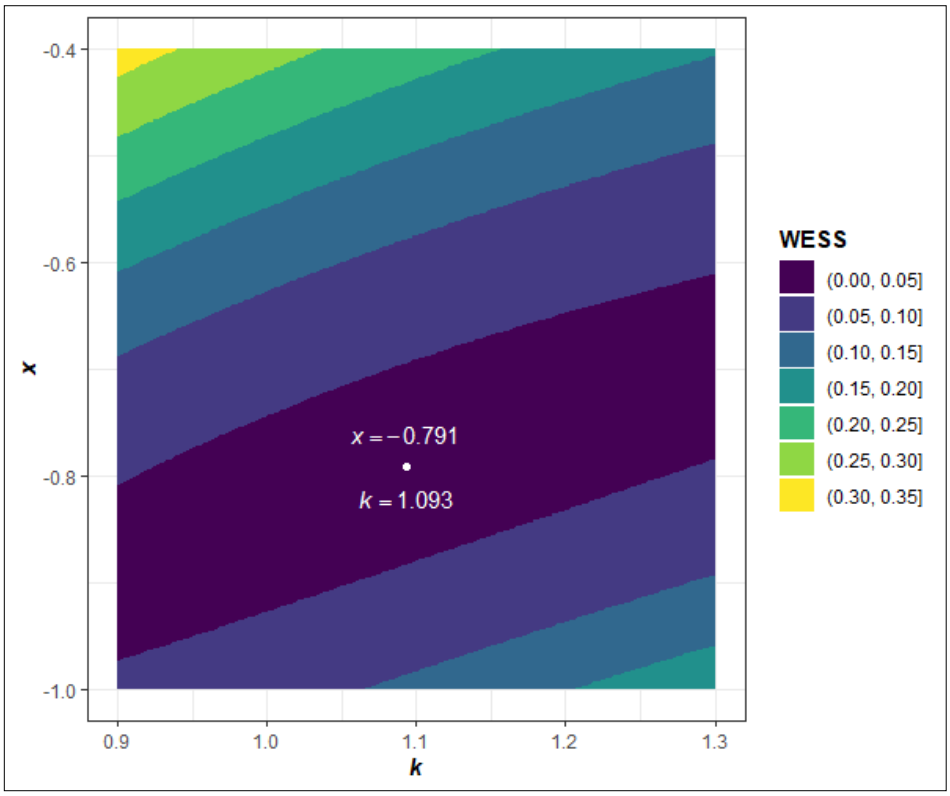

Figure 2. Sensitivity of the Lake Tuggeranong modified Vollenweider model to changes in *k* and *x* in terms of the resultant weighted error sum of squares (WESS). The white point indicates the optimal values.

resultant WESS with a range of k and x values. This analysis indicated that a relatively wide band of k and x values yielded similarly good fits (indicated by relatively low WESS values: Figure 2), which again was consistent with the findings of Brett & Benjamin 2008.

Using the fitted values of k and x, the modified Vollenweider model is represented in equation 8:

$$\mathrm{TP}_{\mathrm{lake}} = \frac{\mathrm{TP}_{\mathrm{in}}}{1+\left(1.093\times\tau_w^{-0.791}\right)*\tau_w} \qquad (8)$$

This yielded predicted $\mathrm{TP}_{\mathrm{lake}}$ values similar to observed values (Table 2, Figure 3).

Table 2. Comparison of observed annual average and predicted total phosphorus concentrations in Lake Tuggeranong (TP_{lake}) from 2005-2022.

	Observed $\mathrm{TP}_{\mathrm{lake}}$ (mg/L)	**Predicted $\mathrm{TP}_{\mathrm{lake}}$ (mg/L)**
Minimum	0.064	0.079
Median	0.086	0.090
Maximum	0.114	0.107

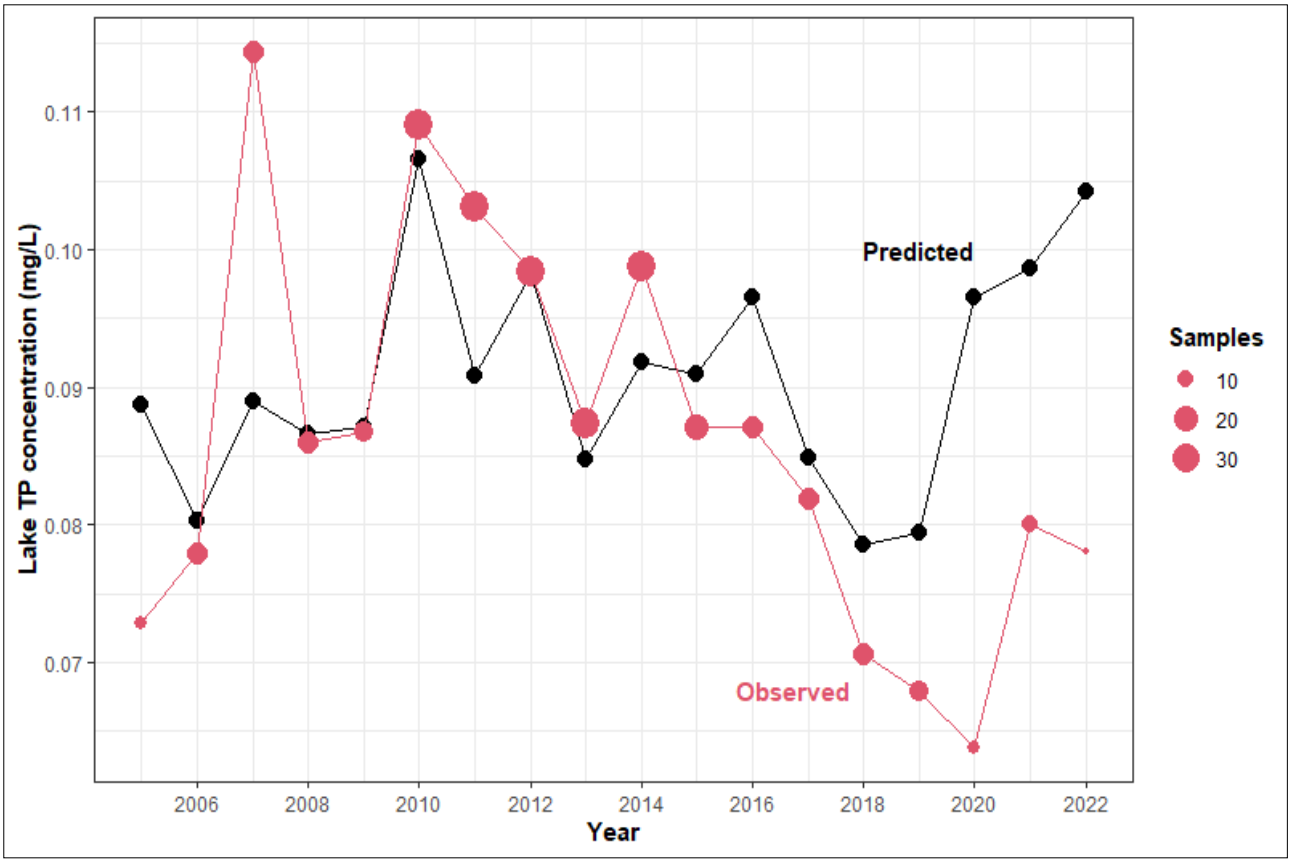

Figure 3. Comparison of observed (red) and predicted (black) annual total phosphorus (TP) concentrations in Lake Tuggeranong from 2005-2022 shows the modified Vollenweider model captures the centre and spread of observed values well with some mirroring of year-to-year trends. Observed values are averages of samples for each year, and data point size represents the number of underlying samples.

The predicted TP concentrations in Lake Tuggeranong had a very similar average and variability to observed TP concentrations, and for many years the two time-series followed similar up/down-wards trajectories (Figure 3). Overall, predicted and observed TP concentrations in Lake Tuggeranong were positively correlated. This was confirmed by a linear regression model relating the two (weighted based on annual sample number), which yielded a significant association between the two variables (ANOVA F-test of slope coefficient: F=8.5889, p=0.0098), and an adjusted r^2 value of 0.3086.

This model can be used to predict the chlorophyll a level using the power relationship described by Lawrence (1980) and applied in Beer *et al.* (1982) in their early work on Lake Tuggeranong:

$$\text{Chlorophyll a} = 0.367 * TP_{Lake}^{0.91} \qquad (9)$$

This relationship was derived from a comparison of several Canberra lakes.

3. Estimation of Lake Trophic State

Using 133 years of annually aggregated Source model output of TP load and inflow water volumes, the above-mentioned models were combined under a range of influent TP reduction scenarios ranging from current/business as usual (BAU: no reduction in TP load), and 100kg to 900kg reduction in annual TP load coming into the lake (with no change to inflow water volumes). Additionally, a predevelopment flow and TP load scenario was considered, which assumed a wholly undeveloped catchment. The Vollenweider model was used to predict annual TP concentrations in the lake for each year under each scenario. This was then converted to predicted chlorophyll a concentration using equation 9. Finally, these predicted concentrations were compared to published cut-offs (e.g. Neil 2012) of chlorophyll a concentration under different trophic states: Oligotrophic <5 µg/L, Mesotrophic <15 µg/L, Eutrophic >15 µg/L.

The predictions for the predevelopment scenario show that, in the absence of development within the catchment, Lake Tuggeranong would likely have experienced a wide range of trophic conditions. In some years the lake would not have received any inflow at all and would likely have reached an oligotrophic state. But in high rainfall years the lake's size and the inflow of TP would have pushed it towards a eutrophic state. This provides a good baseline for considering realistic futures for the lake.

Under the 'current' scenario (BAU), Lake Tuggeranong is predicted to (at the annual, average timescale) remain in a eutrophic state (Figure 4). To avoid a constant eutrophic state, the results of the TP reduction scenarios show that TP load reductions of 600kg or more into Lake Tuggeranong are predicted to result in conditions that are eutrophic less often than not (Figure 4). However, even under high TP load reduction scenarios there will be years of high TP inflow (wet years) where we probably cannot avoid eutrophic conditions developing (as with the pre-development scenario) simply because of the large total TP load entering the lake via stormwater (such that even a >600kg reduction in TP is proportionally fairly insignificant). Conversely, though, dry years with low TP inflows could yield oligotrophic conditions in scenarios with greater than 500kg TP reduction (Figure 4).

Overall, these modelling results suggest that an annual 700kg reduction in TP entering Lake Tuggeranong is an appropriate target for future lake management plans. This level of TP reduction is predicted to lead to

favourable conditions for human recreation in the lake in ~75% of years (~25% oligotrophic, ~50% mesotrophic; Figure 4).

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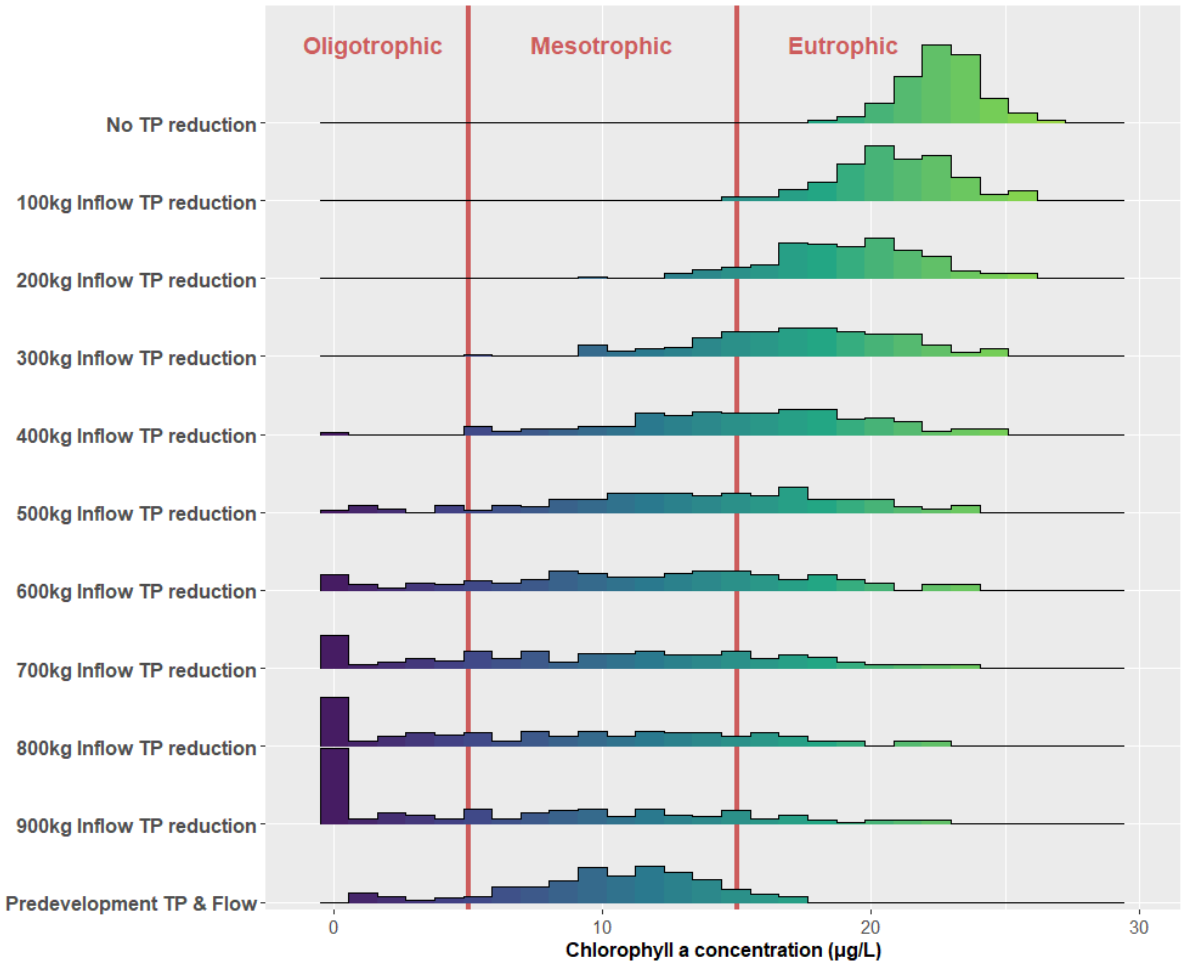

Figure 4. Distribution of annual predicted chlorophyll a concentration (i.e. trophic state) in Lake Tuggeranong under different scenarios of reductions in inflow total phosphorus (TP).

4. Conclusion

Vollenweider's mass-balance model is a simple, but useful, tool for predicting nutrient concentrations in lakes based on influent volumes and concentrations. Whilst they are typically used for comparisons between lakes, in this study the Vollenweider model was modified to derive Lake Tuggeranong specific total phosphorous concentrations. The model produced a reasonable fit with observed values over a 17-year period and could be used in conjunction with catchment model inputs to predict general trends in phosphorous levels in Lake Tuggeranong into the future. The model output was then used to provide an estimate chlorophyll a which is a measure of the trophic state. The estimated chlorophyll a concentration was used to determine the trophic state of the lake under different scenarios. The findings provide an approximate estimate of the target inflow TP load for Lake Tuggeranong to improve the lake trophic conditions, with a target annual reduction of ~700kg of TP yielding favourable predictions.

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Attachment I

ACT Government

Lake Tuggeranong Catchment Management Options Assessment

Technical report supporting the Healthy Waterways Plan for Lake Tuggeranong

Water Information Services, ACT Office of Water

December 2024

Environment, Planning and Sustainable Development Directorate

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ACT Government Disclaimer

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Executive Summary

Lake Tuggeranong is a small (57 ha) urban lake in southern Canberra. Lake Tuggeranong was constructed in the late 1980s on Tuggeranong Creek, a 66 km^2 catchment that is predominantly (62%) urbanised. In recent decades, Lake Tuggeranong has been plagued by poor water quality. Since 2017, there has been a concerted effort to improve water quality in the lake through the construction of Water Sensitive Urban Design (WSUD) infrastructure throughout the catchment, and a major research program to understand the causes of poor water quality, and sources of pollutants entering the lake. This work has been undertaken as part of the ACT Healthy Waterways program.

In 2022, the ACT Government commited to developing Healthy Waterways Plans for priority catchments in the ACT. The Lake Tuggeranong Healthy Waterways Plan provides a suite of potential management options to Government to further improve water quality in Lake Tuggeranong. To acheive this, modelling and analyses have been undertaken to examine a broad range of management scenarios and identify cost-effective options to improve water quality in Lake Tuggeranong, with a focus on reducing the annual load of phosphorus entering the lake.

This report documents the approach taken to assess the predicted performance and cost of 10 proposed catchment management options for reducing the load of phosphorus entering Lake Tuggeranong. For each management option identified, details of the data and information used to calculate the estimates of performance and cost are presented, and summarised in an assessment of cost-effectiveness. To provide a comparison of cost-effectiveness both across and within management options, the cost-effectiveness of four different levels of investment was calculated for each option, ranging from relatively low to relatively high investment. An evaluation of the quality of evidence supporting these estimates and its impact on our confidence in specific values is provided for each management option.

These assessments found that increasing the frequency of municipal street sweeping and the construction of additional WSUD infrastructure were the management options predicted to remove the greatest loads of phosphorus, with street sweeping the most cost-effective option at all levels of investment.

The assessments of management option cost-effectiveness were provided to the ACT Healthy Waterways team who chose options to combine into two proposed management scenarios, with the aim of reducing the phosphorus load entering Lake Tuggeranong (currently ~ 1440 kg/year) by approximately 700 kg/year. A reduction of this amount is predicted to maintain Lake Tuggeranong in a predominantly mesotrophic state, substantially reducing the frequency, extent and duration of blue-green algal blooms (Kahn & Dey, 2024). The proposed management scenarios were then implemented in the catchment model for the Lake Tuggeranong catchment (Dey, Stewart, Kahn, Booksmythe, & Starrs, 2024), to estimate their average annual phosphorus load reductions, accounting for interactive effects of the different options included in a scenario.

Modelling the proposed management scenarios revised down the estimated annual load of phosphorus they were predicted to remove,from 700-750 kg/year to 450-575 kg/year. This is mainly due to the large impact of street sweeping on reducing the concentration of phosphorus in stormwater, which alters the rate of phosphorus removal estimated for management options involving WSUD infrastructure.

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1. Introduction

Lake Tuggeranong is a small (57 ha) urban lake in southern Canberra. The lake was constructed in the late 1980s on Tuggeranong Creek, a 66 km^2 catchment that is predominantly (62%) urbanised. In recent decades, Lake Tuggeranong has been plagued by poor water quality, with high loads of nutrients (phosphorus and nitrogen) and sediments entering the lake, leading to frequent, extensive blue-green algal blooms that result in lake closures. Since 2017, there has been a concerted effort to improve water quality in the lake through the construction of Water Sensitive Urban Design (WSUD) infrastructure such as wetlands, bioretention swales and raingardens throughout the catchment, and a major research program to understand the causes of poor water quality, and sources of pollutants. This work has been undertaken as part of the ACT Healthy Waterways program.

In 2022, the ACT Government commited to developing Healthy Waterways Plans for priority catchments in the ACT. The Lake Tuggeranong catchment Healthy Waterways Plan aims to provide a suite of potential management options to Government to further improve water quality in Lake Tuggeranong (ACT Government, 2025). To achieve this, modelling and analyses have been undertaken to examine a broad range of management scenarios and identify cost-effective options to improve water quality in Lake Tuggeranong, with a focus on reducing the annual load of phosphorus entering the lake. The availability of phosphorus is the main controllable factor limiting blue-green algal growth (Ubrihien, et al., 2020). While large amounts of phosphorus are bound to sediments on the lake bottom, reducing the phosphorus inputs to the lake is necessary before this in-lake source of phosphorus can be effectively addressed.

This report documents the approach taken to assess the predicted performance and cost of proposed catchment management options for reducing the load of phosphorus entering Lake Tuggeranong. For each management option identified, details of the data and information used to calculate the estimates of performance and cost are presented, and summarised in an assessment of cost-effectiveness. An evaluation of the quality of evidence supporting these estimates and its impact on our confidence in specific values is provided for each management option.

Government experts identified a range of potential management options for mitigating phosphorus pollution. They then narrowed their consideration of options based on the availability of data to support cost-effectiveness analyses. In some instances, cost-effectiveness data were based on local trials of mitigation options.

Ten management options are assessed in this report:

- Construction of additional WSUD infrastructure
- Improved maintenance of existing WSUD assets
- Increased frequency of street sweeping
- Improved management of grass clippings from municipal mowing
- Management of public sports field fertilizer use practices
- Management of household fertilizer use practices
- Installation (retrofitting) of castellated kerbs
- Installation of in-lake floating wetlands

- Installation of stormwater recycling infrastructure for sports field irrigation
- Installation of household rainwater tanks

The assessments used to generate estimates of the cost-effectiveness of each of these management options is detailed in section 2 of this report. Sections 3.1 and 3.2 describe the process of comparing management options and combining them into proposed management scenarios with the aim of reducing the phosphorus load entering Lake Tuggeranong by approximately 700 kg/year. A reduction of this amount is predicted to maintain Lake Tuggeranong in a predominantly mesotrophic state, substantially reducing the frequency, extent and duration of blue-green algal blooms (Kahn & Dey, 2024). Section 3.3 outlines the results of implementing the proposed management scenarios in the catchment model for the Lake Tuggeranong catchment (Dey, Stewart, Kahn, Booksmythe, & Starrs, 2024).

1.1 Management option performance

The performance of each management option is assessed in terms of the amount of total phosphorus (TP) it is predicted to prevent from entering Lake Tuggeranong in a year. To facilitate comparison between different types of management option, we assume a 30-year lifecycle for each option. Total lifecycle performance is estimated by multiplying the annual TP removal by 30.

Phosphorus reduction has been chosen as the primary quantitative metric for management option performance due to its key role in promoting blue-green algal blooms in Lake Tuggeranong. Further assessment could consider other aspects of water quality improvement (e.g. the reduction of total nitrogen, TN, and total suspended solids, TSS), along with non-water quality benefits, as part of performance.

1.2 Management option costs

Costs are estimated in Australian Dollars (AUD) as at 2024. Costs are broken down into three components:

- Capital costs (in 2024 currency; assumed to be incurred in the first year of implementation)
- Annual operating costs (in 2024 currency)
- Total 30-year lifecycle costs (capital costs + annual operating costs over 30 years, using an annual discount rate of 7% after the first year (Infrastructure Australia, 2021))

We assume that management options have no residual value at the end of lifecycle, facilitating a like-for-like comparison between management options with vastly different cost profiles (e.g. infrastructure vs. non-infrastructure options).

1.3 Management option cost-effectiveness

By calculating an estimate of cost-effectiveness we aim to provide a metric allowing direct comparison of different management options. The cost-effectiveness of each management option is calculated by dividing the total lifecycle cost by the total lifecycle performance (TP removal). This produces a standardised metric for comparison between disparate management options in a consistent unit ($/kg). To provide a comparison of cost-effectiveness both across and within management options, the cost-effectiveness of

four different levels of investment was calculated for each option, ranging from relatively low to relatively high investment.

1.4 Quality of supporting evidence

With any process of estimation comes uncertainty. In assessing the cost-effectiveness of phosphorus-reducing management options in the Lake Tuggeranong catchment, uncertainty may arise through three main channels:

- Uncertainty about estimates of the cost of implementing a management option
- Uncertainty about estimates of the efficacy of the management option in removing phosphorus (e.g., uncertainty about the amount of leaf litter prevented from entering the stormwater system by street sweeping)
- Uncertainty about estimates of the amount of phosphorus available for removal by a particular management option (e.g., uncertainty about the pollutant load generated from leaf litter on roads)

We use both quantitative and qualitative approaches to address these sources of uncertainty in our assessment of management options.

1.4.2 Quantitative assessment of estimate uncertainty

A wide range of data and information were collated to estimate the phosphorus-removal performance and cost of each assessed option. In some cases, when incorporating multiple sources of information about the same aspects of performance or cost, a range of estimates was obtained. We assessed this range of estimates statistically, to understand whether it was likely to represent a realistic range of possible variability in outcomes, or to over- or under-estimate the expected variability.

1.4.2 Qualitative assessment of estimate uncertainty

We developed a rubric to systematically assess the quality of evidence sources contributing to the cost-effectiveness estimates of each management option (Appendix A). The data informing the calculations of predicted cost and performance were scored on nine criteria and the scores summed to give an overall uncertainty rating for the cost-effectiveness estimate.

Box 1. Key definitions and abbreviations used in this report

- Annual operating cost – the estimated annual cost of day-to-day operation of a management option, including routine maintenance and staff costs unless otherwise specified.
- Capital cost – the cost of capital works (i.e. construction planning, materials and delivery) of a management option, excluding operation and maintenance costs. Some management options do not have a capital cost (e.g. community partnership programs).
- Discount rate – the interest rate at which future dollar values are adjusted to represent their value in today's dollars. This adjustment is made to account for the fact that money today is more valuable than money in the future.
- EPSDD – Environment, Planning and Sustainable Development directorate, ACT Government
- Gross pollutant trap (GPT) – infrastructure installed upstream of stormwater management infrastructure to capture large debris and prevent it from causing blockage of the infrastructure.
- Model for Urban Stormwater Improvement Conceptualisation (MUSIC) – software that simulates rainfall, stormwater runoff, flows, and pollution. Used to simulate flow reduction and pollution removal through stormwater management infrastructure such as wetlands, bioretention, and sediment ponds.
- O&M – Operation and maintenance
- TCCS – Transport Canberra and City Services directorate, ACT Government
- Total lifecycle cost – the estimated cost of implementing and operating a management option over 30 years, with annual (O&M) costs discounted by 7% per annum after the first year.
- Total phosphorus (TP) – the sum of all forms of phosphorus present in a sample. In this report the term phosphorus refers to total phosphorus (TP) unless otherwise specified, and these terms may be used interchangeably.
- Water-sensitive Urban Design (WSUD) assets – infrastructure such as constructed wetlands, bioretention, and sediment ponds, for the management of stormwater and its pollutants using natural biological and physical processes including sediment settlement, filtration, and uptake by plants.

2. Management option assessments

2.1 Construction of additional WSUD infrastructure

2.1.1 Background

Stages 1 and 2 of the ACT Healthy Waterways program saw the construction of several different types of water-sensitive urban design (WSUD) infrastructure across urban Canberra waterways, including 8 assets in the Lake Tuggeranong catchment. WSUD infrastructure, including constructed wetlands, raingardens, and bioretention swales, can be situated directly on a branch of the stormwater network (online) or receive inflows diverted from the stormwater network (offline), or be positioned to intercept runoff before it enters the stormwater network (at-source). While water is within the infrastructure, a proportion of the nutrient and sediment pollutants in the water are removed through processes including natural settling, filtration, and uptake by plants. Outflows from the infrastructure are returned to the stormwater network. This section assesses the cost-effectiveness of installing additional WSUD infrastructure in the catchment.

The amount of total phosphorus (TP) available for removal by additional WSUD infrastructure is that which is intercepted by the infrastructure as it travels through the catchment. The catchment model for the Lake Tuggeranong catchment estimates the load of TP generated and entering the stormwater network in each subcatchment, allowing calculation of the accumulated load that would be received by a new WSUD asset depending on its location in the catchment (Dey, Stewart, Kahn, Booksmythe, & Starrs, 2024).

2.1.2 Phosphorus removal performance

We estimate the TP removal performance of additional WSUD infrastructure based on the performance of similar existing infrastructure. MUSIC models were developed for each of the WSUD assets constructed as part of Stage 1 of the ACT Healthy Waterways program. These models are configured to reflect the final design of each asset and model the predicted TP removal for each asset over a known climatic period, adopting MUSIC's default TP concentrations for stormwater runoff generated from different land uses in the catchment. The models for the 8 WSUD assets installed in the Lake Tuggeranong catchment were reviewed and updated by eWater (eWater Ltd, 2022), which estimated annual mean percentage reductions in TP of between 15-80% for these assets. These percentage reductions were applied in the Lake Tuggeranong catchment model (Dey, Stewart, Kahn, Booksmythe, & Starrs, 2024) to estimate the TP load removed by each asset. The total annual load of TP removed depends on the type, size, and location of assets. The two constructed wetlands in the Lake Tuggeranong catchment remove an estimated 0.003-0.01 kg TP per square metre of wetland per year. However, we excluded wetlands from the infrastructure used to estimate the performance of additional WSUD infrastructure, as there is very little scope to build further wetlands in the Lake Tuggeranong catchment, and modelling smaller assets is more realistic. For the 6 non-wetland assets (bioretention swales, raingardens, and channel restorations) in the catchment, the annual load of TP removed ranges between 0.0048-0.014 kg TP per square metre of asset area (Table 1).

The installation of additional WSUD infrastructure, and the size of infrastructure that can be built, is limited by the availability of suitable locations in the catchment. This means that specific asset designs, of known type, size, and location, are needed when estimating the impact of additional WSUD infrastructure on reducing the TP load entering Lake Tuggeranong. Here, the size and possible locations of additional WSUD infrastructure were determined from design reports for 10 proposed raingardens in the Lake Tuggeranong

catchment (Alluvium, 2015), undertaken as part of the ACT Healthy Waterways program Stage 1, that were not selected as priorities for construction during that project (Table 2). As there may be planning and feasibility constraints that determined why these particular raingardens were not built at the time, the estimates in this section should be read as an example of the kind of infrastructure that could be installed in the Lake Tuggeranong catchment, not a specific proposal.

Table 1. Summary statistics for the performance of 6 existing non-wetland WSUD assets in the Lake Tuggeranong catchment.

Parameter	Total annual TP removed (kg/m^2)
Minimum	0.0048
Median	0.0074
Mean	0.0081
Maximum	0.0142

We assigned each of these hypothetical assets an annual TP removal rate, assuming that raingarden performance efficacy improves with increasing treatment area. To implement this relationship, we ranked the raingardens by size, and applied the maximum TP removal rate from Table 1 to the largest two assets, the mean TP removal rate to the next three largest assets, the median TP removal rate to the next three largest assets, and the minimum TP removal rate to the two smallest assets (Table 2).

Table 2. Size, assigned rate of TP removal, and estimated total annual TP removed for 10 proposed raingardens in the Lake Tuggeranong catchment.

Asset	Asset size (m^2)[1]	Annual TP removed (kg/m^2)	Total annual TP removed (kg)
TG018	4,800	0.0142	68.16
TG014	2,700	0.0142	38.34
TG004	2,600	0.0081	21.06
TG013	2,600	0.0081	21.06
TG015	2,600	0.0081	21.06
TG016	2,600	0.0074	19.24
TG031	2,600	0.0074	19.24
TG005	2,459	0.0074	18.20
TG007B	1,500	0.0048	7.20
TG009	1,440	0.0048	6.91

1 Assets with no projected treatment area were assigned an area of 2,600 m^2, the average area for a raingarden in the catchment.

2.1.3 Costing

G2W Pty Ltd were engaged to review the capital and ongoing operation and maintenance costs associated with existing WSUD infrastructure in the Lake Tuggeranong catchment (G2W Pty Ltd, 2024). Bioretention assets (raingardens and swales) in the Lake Tuggeranong catchment ranged between 765 - 5,270m^2 in size, and between $774 - 2,532/m^2 in capital construction cost, with a strongly negative relationship between

size and cost such that on average, larger assets had a lower capital cost per square metre. We used this size - capital cost relationship to estimate the capital cost of constructing the 10 proposed raingardens based on the sizes presented in Table 2. We used the capital cost of the cheapest existing raingarden as a lower limit for the cost estimates of the proposed raingardens. Similarly, the annual operation and maintenance (O&M) cost of existing bioretention assets ranged between \$62 – 170/m^2, with larger assets having a lower O&M cost per square metre. We used the asset size - O&M cost relationship to estimate the annual maintenance cost of the 10 proposed raingardens, again using the lowest existing O&M cost as a lower limit for our estimates. We used the capital and O&M cost estimates to calculate the 30-year lifecycle cost of the 10 proposed raingardens, assuming an annual discount rate of 7% each year on the O&M costs.

2.1.4 Cost-effectiveness

We calculated the individual cost-effectiveness of each of 10 proposed raingardens based on the assigned rate of TP removal for each asset (Table 3).

Table 3. Capital costs, annual operation and maintenance costs, 30-year lifecycle costs, and individual cost-effectiveness of 10 proposed raingardens in the Lake Tuggeranong catchment.

Asset	Capital cost	Annual operation and maintenance cost	Total 30-year lifecycle cost[1]	Cost per unit TP removed ($/kg)
TG018	$4,882,560	$338,496	$13,025,856	$6,388
TG014	$4,226,310	$261,846	$8,878,356	$7,740
TG004	$4,137,640	$255,424	$8,620,664	$13,585
TG013	$4,137,640	$255,424	$8,620,664	$13,585
TG015	$4,137,640	$255,424	$8,620,664	$13,585
TG016	$4,137,640	$255,424	$8,620,664	$14,969
TG031	$4,137,640	$255,424	$8,620,664	$14,969
TG005	$4,003,746	$245,941	$8,248,021	$15,143
TG007B	$2,817,750	$168,150	$5,424,900	$24,882
TG009	$2,727,590	$162,513	$5,231,543	$24,995

1 Total lifecycle cost is calculated over 30 years using a discount rate of 7% per annum on O&M costs.

To provide four levels of investment in the additional WSUD infrastructure management option, we grouped the 10 proposed raingardens by their size and cost-effectiveness and created four tiers of installation: to either build the two, five, 8 or 10 most cost-effective of these assets. We re-calculated the overall 30-year lifecycle cost and cost-effectiveness for the group of assets included in each investment level (Table 4), incorporating additional cost scaling factors to account for total construction size, number of assets to be constructed and the number of gross pollutant traps required (we assumed that each asset would need one gross pollutant trap).

Table 4. Costing summary for four levels of investment in additional WSUD infrastructure in the Lake Tuggeranong catchment.

Investment level	Number of assets built	Total annual TP removed (kg/year)	Total 30-year lifecycle cost[1]	Cost per unit TP removed ($/kg)
1	Build 2 assets	106.21	$22,507,500	$7,064
2	Build 5 assets	169.67	$48,369,492	$9,502
3	Build 8 assets	226.22	$73,862,467	$10,884
4	Build 10 assets	240.46	$84,519,403	$11,716

1 Total lifecycle cost is calculated over 30 years using a discount rate of 7% per annum on O&M costs.

2.1.5 Quality of supporting evidence

Using the evaluation rubric (Appendix A), the above estimates of cost-effectiveness of installing additional WSUD infrastructure scored 13/14 for confidence in cost estimates, and 9/16 for confidence in performance estimates.

2.2 Maintenance of existing WSUD infrastructure

2.2.1 Background

WSUD infrastructure requires ongoing maintenance to function at its designed phosphorus removal efficiency. Transport Canberra and City Services (TCCS) undertake this maintenance for the 8 existing WSUD assets in the Lake Tuggeranong catchment.

2.2.2 Phosphorus removal performance

Six of the 8 WSUD assets in the Lake Tuggeranong catchment were visually assessed for their current level of maintenance and treatment efficacy in February 2024. Five of these assets were assessed as performing at between 20% and 70% of their designed efficiency due to maintenance shortfalls. The estimated reduction in performance of each asset was incorporated into the baseline run of the catchment model, used to calculate the current (business-as-usual) annual load of TP entering Lake Tuggeranong (Dey, Stewart, Kahn, Booksmythe, & Starrs, 2024). To estimate the amount of TP that could be removed if all existing assets were maintained to 100% of their designed efficiency, the catchment model was then run without applying the asset performance reductions. The total difference in TP load between the business-as-usual and optimal asset maintenance model runs was 88 kg/year (Table 5).

Table 5. Current asset total phosphorus (TP) removal performance efficiency as a percentage of designed performance, and the additional annual TP load that could be removed if assets were maintained to designed performance.

Asset	Current TP removal performance	Marginal increase in TP removed with optimal maintenance (kg/year)
TG011N – wetland	60%	23.28
TG029 – raingarden	20%	12.56
TG010 – raingarden	70%	25.94
TG011S – wetland	60%	18.15
TG008 – raingarden	50%	8.09

2.2.3 Costing

The costs provided for asset operation and maintenance are based on annualised operational cost estimates from TCCS budget requests, and incorporate costs of major renewal activities such as cleaning GPTs, mucking out sediment forebays and replacing raingarden filter media at regular intervals. We used the costs provided without modification, to calculate the 30-year lifecycle cost of each asset assuming an annual discount rate of 7% after the first year.

2.2.4 Cost-effectiveness

Our estimates of cost-effectiveness assume that there is currently no funding provided for WSUD asset maintenance, and that if the estimated O&M costs (Table 6) *were* to be spent on these assets, the marginal gains in TP removal (Table 5) would be achieved.

Table 6. Annual operation and maintenance costs, 30-year lifecycle costs, and cost-effectiveness of maintaining 5 existing WSUD assets to their designed performance.

Asset	Annual operation and maintenance cost	Total 30-year lifecycle cost[1]	Cost per unit TP removed ($/kg)
TG011N – wetland	$485,352	$6,508,917	$9,320
TG029 – raingarden	$221,091	$3,668,211	$9,735
TG010 – raingarden	$340,432	$8,909,451	$11,449
TG011S – wetland	$541,800	$7,265,925	$13,344
TG008 – raingarden	$235,739	$3,999,929	$16,481

1 Total lifecycle cost is calculated over 30 years using a discount rate of 7% per annum on O&M costs.

To provide four levels of investment in the WSUD maintenance management option, we grouped the five assets by the cost-effectiveness of their maintenance and created four tiers of implementation: to maintain either the two, three, four or five most cost-effective of these assets. We re-calculated the overall 30-year lifecycle cost and cost-effectiveness for the group of assets included in each investment level (Table 7).

Table 7. Costing summary for four levels of investment in maintenance of existing WSUD infrastructure in the Lake Tuggeranong catchment.

Investment level	Number of assets maintained	Total annual TP removed (kg/year)	Total 30-year lifecycle cost[1]	Cost per unit TP removed ($/kg)
1	Maintain 2 assets	35.84	$10,177,128	$9,465
2	Maintain 3 assets	61.78	$19,086,579	$10,298
3	Maintain 4 assets	79.93	$26,352,433	$10,990
4	Maintain 5 assets	88.02	$30,352,433	$11,495

1 Total lifecycle cost is calculated over 30 years using a discount rate of 7% per annum on O&M costs.

2.2.5 Quality of supporting evidence

Using the evaluation rubric (Appendix A), the above estimates of cost-effectiveness of maintaining existing WSUD infrastructure scored 4/14 for confidence in cost estimates, and 8/16 for confidence in performance estimates.

2.3 Increased frequency of street sweeping

2.3.1 Background

In the Lake Tuggeranong catchment, research by the University of Canberra (Ubrihien, et al., 2020) indicates that a large amount of nutrients enter the waterways from diffuse, rather than point, sources – i.e. from widespread land uses across the catchment such as residential blocks and roads. One potential contributing factor found across these land uses is leaf litter (here defined as fallen leaves and other plant and soil matter) on impervious surfaces like roads, footpaths and driveways. Water passing over this leaf litter can take up nutrients in both dissolved and particulate forms, and enter the stormwater system via street gutter sumps. Dissolved nutrients may be leached out of leaf litter by the passing water, while particulate nutrients are chemically bound to particles such as soil and leaf fragments. In addition, with sufficient flows intact leaf litter may be washed into the stormwater system and transported to the lakes and waterways where they will break down and release nutrients into the water.

The primary function of the municipal street sweeping program is to prevent blockage of the stormwater system and ensure its effectiveness in flood mitigation. While increasing the frequency of street sweeping is often raised as a possible action to reduce leaf litter as a source of nutrient pollution, the impact of street sweeping on reducing nutrient inputs into the urban waterways of the ACT has not previously been quantified.

Phosphorus generated from leaf litter on roads

The amount of TP available for removal by street sweeping is that which originates as leaf litter on roads. The Lake Tuggeranong catchment model estimates the total annual TP load that runs off roads in the Lake Tuggeranong catchment as 582 kg TP/year (Dey, Stewart, Kahn, Booksmythe, & Starrs, 2024), and we use this as an estimate of the maximum available load of TP generated by leaf litter on roads.

There is strong seasonal variation in leaf fall in *Eucalyptus* species, which are predominant among the street tree and other public tree assets in the Lake Tuggeranong catchment (Ubrihien, et al., 2024), with most leaves falling in the warmer months (Crockford & Richardson, 1998). This variation, as well as seasonal variation in rainfall, will affect the accumulated load of leaf litter on the roads at any given time, and means that not just the frequency but also the timing of street sweeping can impact the amount of TP removed by this management option.

2.3.2 Phosphorus removal performance

We created a simple build-up wash-off model ('leaf load calculator') to incorporate these sources of seasonal variation in TP load, and the influence of sweeping frequency and timing, into our estimate of the TP removal performance of street sweeping. The calculator is based on 24 years of daily rainfall data from the Tuggeranong (Isabella Plains) climatological station (Bureau of Meteorology station ID 070339). It allows manual adjustment of variability in leaf fall, and specification of the frequency and timing of street sweeping. Using these inputs it calculates the cumulative load of leaf litter each day:

Load today = load yesterday + new fall today – load swept today – load washed away by rain today.

We used data from University of Canberra research into the leaf fall and TP content of four *Eucalypt* species in urban Canberra (Ubrihien, et al., 2024) to generate an approximate seasonal leaf fall pattern for the Lake Tuggeranong catchment. We input this seasonal pattern into the leaf load calculator, scaling the daily maximum leaf fall rate to be consistent with the average annual load of 582 kg TP on roads in the catchment estimated by the catchment model (Dey, Stewart, Kahn, Booksmythe, & Starrs, 2024). We then compared different annual street sweeping schedules, from two sweeps per year (business-as-usual) to 48 sweeps per year. We explored schedules of sweeping evenly spaced throughout the year, as well as seasonally focused schedules with increased frequency during high leaf fall periods and reduced or no sweeping during low leaf fall periods. For all schedules we assumed a minimum of one week between sweeps.

To compare each sweeping schedule explored using the leaf load calculator, we calculated their monthly and annual statistics on the leaf litter load on roads, the load collected by street sweeping trucks (and the approximate number of truckloads), and the load washed away into the stormwater network, over the 24 years of rainfall data.

2.3.3 Costing

To find the cost of a single sweep event for the Lake Tuggeranong catchment, we multiplied the current daily cost of one street sweeping truck by the number of truck-days needed to sweep the entire catchment once. We then added the cost of transporting and disposing of the swept material in landfill. We assume an expansion of the current operational model based on leasing trucks, so no capital cost (e.g. outright purchase of trucks) is included in our costings for this management option.

Days needed for one catchment sweeping event A pilot experiment investigating the impact of frequent street sweeping on nutrient concentrations in stormwater included a 12-week period of fortnightly street sweeping in two subcatchments of the Lake Tuggeranong catchment, comprising 10% of the total catchment road area. From records of the number of shifts needed to complete sweeping of this area each

fortnight during the experiment, we calculate that on average 24.17 truck-days would be needed to sweep the entire Lake Tuggeranong catchment.

Daily truck cost An estimate of daily cost per truck, based on the current running costs of a truck in the ACT street sweeping fleet, was provided by the TCCS Street Sweeping team. The fleet runs 5 days per week, with up to two staff shifts per truck per day, allowing each truck to operate for up to 10 hours per day. At the maximum (2 shift/day) rate of operation, the cost of one truck, including leasing, staff, running and maintenance costs, is $1,200-$1,500/day. Here we conservatively use the higher cost estimate. Over 24.17 truck-days, the estimated truck cost to sweep the entire Lake Tuggeranong catchment is $36,255.

Disposal costs The total cost of disposing of material to landfill in 2024 currency is $181/tonne. Of this, tip fees comprise $171/tonne and the cost of transporting collected material to landfill sites is $10/tonne (both excluding GST).

From data provided by TCCS, the estimated tonnage of material removed in one year (260 weekdays) by the fleet of 6 trucks is 2,364 tonnes, or an average of 9.1 tonnes/day. Assuming that each truck spends about 10% of its time non-operational (due to breakdowns, time out for servicing, etc.), this equates to an estimated average of 1.7 tonnes of material removed per truck per day (9.1 / (6 * 0.9)). Given 24.17 truck-days per catchment sweeping event, the disposal cost per sweeping event is $7,437. The total combined truck and disposal cost to sweep the Lake Tuggeranong catchment is $43,692 per street sweeping event. These estimates assume a constant load of material collected at each sweeping event (i.e., no seasonality or decrease due to sweeping frequency is included in disposal cost estimates, due to a lack of data on these possible effects).

2.3.4 Cost-effectiveness

To provide four levels of investment in the street sweeping management option, we considered four sweeping schedules ranging between 12 - 48 sweeping events in a year (1 - 4 per month). The three lower-frequency schedules account for the seasonality of leaf fall to obtain the best performance for each level of investment. The 48-sweep schedule is essentially equivalent to sweeping every week, so no seasonal adjustment is made. We calculated the 30-year lifecycle cost of each schedule using an annual discount rate of 7% on annual program costs after the first year.

Table 8. Costing summary for four levels of investment in increased frequencies of street sweeping in the Lake Tuggeranong catchment.

Investment level	Sweeping schedule	Total annual TP removed (kg/year)	Annual program cost	Total 30-year lifecycle cost[1]	Cost per unit TP removed ($/kg)
1	12 sweeps – seasonal focus	203.7	$524,304	$7,030,414	$1,150
2	24 sweeps – seasonal focus	320.1	$1,048,608	$14,060,827	$1,464
3	36 sweeps – seasonal focus	372.5	$1,572,912	$21,091,242	$1,887
4	48 sweeps – weekly	395.8	$2,097,216	$28,121,656	$2,369

1 Total lifecycle cost is calculated over 30 years using a discount rate of 7% per annum on annual costs after the first year.

2.3.5 Quality of supporting evidence

Using the evaluation rubric (Appendix A), the above estimates of cost-effectiveness of increasing the frequency of street sweeping scored 10/14 for confidence in cost estimates, and 9/16 for confidence in performance estimates.

2.4 Management of grass clippings from municipal mowing

2.4.1 Background

Grass clippings resulting from mowing of public open space can be blown onto adjacent roads, from where they can enter the stormwater system. Public perception is that large amounts of clippings end up on the roads, and if so these clippings may be a sizeable contributor to nutrient pollution of the waterways. Preventing or reducing the input of phosphorus from this source could be achieved by installing catchers on lawnmowers, using blowers to return clippings to the verge, or running designated street sweeping trucks along mown roadsides.

Phosphorus export from municipal mowing activity

The total area of pervious, ground-level (i.e., likely grassed and subject to TCCS mowing) public open space in the Lake Tuggeranong catchment is 928.5 ha. We assume that clippings from areas within 2m of a road are likely to end up on the road - this is probably an overestimate, and gives an area of 98.1 ha of mown area from which grass clippings will reach the road.

The estimated amount of clippings generated from this area in a year is between 327,000 - 523,000 kg dry mass. This is based on a 2016 report for the South Australian Government investigating the effect of watering regime on turf grass yields (Barton, 2016). University of Canberra research (Ubrihien, et al., 2024) estimates the phosphorus content of grass clippings at 0.1% of the dry weight of clippings, which gives between 327 - 523 kg TP for the estimated annual load of clippings on roads in the Lake Tuggeranong catchment.

When considered in light of information from the street sweeping pilot experiment (see section 2.3), this estimate appears unrealistically high. At this rate, the TP load from 12 weeks' worth of grass clippings on the road in the subcatchments monitored in the experiment would comprise around 50% of the total TP load estimated from the experiment. Furthermore, the mass of these clippings would be around 100 times greater than the total mass of material collected during the experiment. Rough visual estimates suggest that only between 0-10% (by volume) of the swept material was grass clippings. To reconcile these different estimates, we assume that current mowing management practices are 90% effective in keeping clippings off the road, so clippings contribute 32.7 - 52.3 kg TP/year (at this rate, TP loads from clippings would comprise around 5% of the total TP load measured in the street sweeping experiment).

2.4.2 Phosphorus removal performance

Only two of the three suggested management methods for municipal grass clippings are assessed here. Through consultation with the Transport Canberra and City Services mowing team, the use of catchers has

been discounted – most of the current fleet of mowers cannot accommodate a catcher, and the team does not have the capacity (time or resources) to dispose of collected clippings.

Management method 1 is to adopt the use of electric blowers towed behind mowers to move clippings away from road edges. This option is assumed to improve current practices to be 95% effective at keeping clippings off the roads, reducing TP inputs by 50% (removing between 16.4 - 26.1 kg TP/year).

Management method 2 is to use street sweeping trucks to immediately remove all remaining grass clippings on roads. A suggestion to do this by coordinating with the current street sweeping program has previously been trialled and found to be logistically infeasible. This option would instead require the lease of a designated street sweeping truck(s) to run immediately after mowing and is assumed to remove the entire TP load from clippings (removing 32.7 - 52.3 kg TP/year).

2.4.3 Costing

Management method 1 To achieve the full reduction in phosphorus inputs estimated for this method would require enough blowers to provide operational coverage to current municipal mowing activities in the Lake Tuggeranong catchment. Based on consultation with the TCCS mowing team, the purchase of two blowers and their ongoing operation and maintenance are costed:

- Capital purchase (2 blowers) = $160,000
- Annual cost (2 staff at $65,000/year + maintenance at $5,000/year) = $140,000/year

Management method 2 Here we assume that operational coverage for current municipal mowing activities in the Lake Tuggeranong catchment would require the lease of one dedicated street sweeping truck running full time (2 shifts per day, 5 days per week). Costing is based on leasing and operational cost information provided by the TCCS street sweeping team:

- No capital cost
- Annual operational cost (truck lease, staff, fuel, and maintenance) = $108,996/year
- Additional annual cost (landfill charges at $171/tonne ex. GST, for 32,700-52,300 kg material) = $5,592-$8,943/year

2.4.4 Cost-effectiveness

These two methods for the management of grass clippings from municipal mowing are predicted to remove between 16 - 52 kg TP per year at a cost of between $998 - $4,103 per kg P removed, over 30 years. We use the high and low estimates of TP removal performance for each method to provide four levels of investment in this management option (Table 9).

2.4.5 Quality of supporting evidence

Using the evaluation rubric (Appendix A), the estimates of cost-effectiveness of managing grass clippings from municipal mowing scored 9/14 for confidence in cost estimates, and 7/16 for confidence in performance estimates.

Table 9. Estimated annual load of total phosphorus (TP) prevented from entering Lake Tuggeranong, total 30-year lifecycle cost, and cost-effectiveness of options for management of grass clippings from municipal mowing.

Investment level	Management method and level of TP removal	Total annual TP removed (kg/year)	Total 30-year lifecycle cost[1]	Cost per unit TP removed ($/kg)
1	Method 1 (blowers) – low TP removal estimate	16.4	$2,018,874	$4,103
2	Method 1 (blowers) – high TP removal estimate	26.1	$2,018,874	$2,578
3	Method 2 (sweeping) – low TP removal estimate	32.7	$1,521,462	$1,551
4	Method 2 (sweeping) – high TP removal estimate	52.3	$1,565,956	$998

1 Total lifecycle cost is calculated over 30 years using a discount rate of 7% per annum on annual costs after the first year.

2.5 Management of sports field fertilizer use practices

2.5.1 Background

The use of fertilizers containing phosphorus on sports grounds and other 'managed' green space is undertaken by both government and private managers. The Lake Tuggeranong catchment includes ~60 ha of actively managed (irrigated and fertilized) sports grounds, and a few additional privately managed assets: Vikings Club football ground, and three school sports grounds (Trinity Christian School, St Mary Mackillop College, Erindale College) with an estimated combined total of 7.5 ha.

Interviews with Canberra sports field and turf managers (Edmondson, 2022) suggest that in general, sports field managers are motivated to use fertilizer efficiently within the constraints of their management priorities. There is likely little to be gained in trying to further reduce fertilizer application rates. An additional option to address fertilizer export from sports fields is to install bioretention swales to intercept runoff from sports fields, and this is the management option we assess here.

Phosphorus application and export rates from sports field fertilizer use

TCCS provided information on the fertilizer application of the public sports grounds in the catchment. Estimates of fertilizer application regimes of privately managed sports grounds are based on information from interviews with Canberra sports turf managers (Edmondson, 2022). Export rates of phosphorus from different fertilizer products (Table 10) were estimated based on a review of experimental studies of TP export rates (Booksmythe, 2023).

Table 10. The amount of phosphorus (P) applied in fertilizers, and literature-derived rates of P export for the fertilizers applied, for three categories of sports field management in the Lake Tuggeranong catchment. Lower, medium, and upper estimates of P export rates are provided, based on the range of values reported for each fertilizer type in the literature.

Sports field type	TP applied (kg/year)	Lower TP export rate (kg/ha/year)	Medium TP export rate (kg/ha/year)	Upper TP export rate (kg/ha/year)
Public sports field	10	0.2	1.2	2.5
'Elite' public sports field	36	0.72	4.32	9
Private sports field	3	0.06	0.36	0.75

We multiplied the annual amount of P applied by the export rates given in Table 10 to calculate a range of estimates of the total P load exported from sports fields in the Lake Tuggeranong catchment (Table 11).

Table 11. The total area of three categories of sports field management in the Lake Tuggeranong catchment, and the estimated total annual load of total phosphorus (TP) exported from each category.

Sports field type	Total area (ha)	Lower total TP exported (kg/year)	Medium total TP exported (kg/year)	Upper total TP exported (kg/year)
Public sports field	58.7	11.74	70.44	146.75
'Elite' public sports field	2.3	1.66	9.94	20.7
Private sports field	7.5	0.45	2.7	5.63
Total	68.5	13.85	83.08	173.08

The median and upper estimates of the total TP exported from sports fields (based on the upper bound of estimates of TP export rate from the literature) are larger than the total TP load of 57.9 kg/year from sports field land use estimated by the Lake Tuggeranong catchment model (Dey, Stewart, Kahn, Booksmythe, & Starrs, 2024).

2.5.2 Phosphorus removal performance

We assess the TP removal performance of installing bioretention swales below public managed sports fields in the Lake Tuggeranong catchment based on the performance of similar existing WSUD infrastructure in the catchment (see Section 2.1.2). We calculated the swale area required to remove the total TP load from sports fields, 57.9 kg P/year, across the range of performance rates in Table 1. In the absence of explicit scoping work investigating possible locations and designs for swales, we made a simplified assumption of the range of TP removal performance: of the total infrastructure required to remove 57.9 kg TP/year, 25% would perform at the highest rate, 25% would perform at the lowest rate, and 50% would perform at the average rate (Table 12). Based on this assumed performance range, the total swale area required to remove the total TP load from sports fields is 7,882 m^2.

Table 12. Phosphorus removal performance bands assumed for bioretention swales installed below sports fields in the Lake Tuggeranong catchment

Performance band	Annual TP removal (kg/m^2/year)	TP load addressed (kg)	Swale area required (m^2)
High performance (25% of assets)	0.0142	14.93	1,016
Average performance (50% of assets)	0.0077	29.86	3,878
Low performance (25% of assets)	0.0048	14.93	2,988

2.5.3 Costing

G2W Pty Ltd were engaged to review the capital and ongoing operation and maintenance costs associated with existing WSUD infrastructure in the Lake Tuggeranong catchment (see section 2.1.3) (G2W Pty Ltd, 2024). Bioretention assets (raingardens and swales) in the Lake Tuggeranong catchment ranged between 765–5,270m^2 in size, and between \$774 - 2,532/m^2 in capital cost, with a strongly negative relationship between size and cost such that on average, larger assets had a lower capital cost per square metre. Similarly, the annual operation and maintenance (O&M) cost of existing bioretention assets ranged between \$62 – 170/m^2, with larger assets having a lower annual O&M cost per square metre. We used these asset size - cost relationships to estimate the capital and O&M costs of constructing between 4 and 24 swales with a total combined area of between 1,016 - 7,882 m^2, and used these capital and O&M cost estimates to calculate the 30-year lifecycle cost, assuming an annual discount rate of 7% each year for O&M costs.

2.5.4 Cost-effectiveness

To provide four levels of investment for this management option, we used the performance bands described in Section 2.5.2 to define four tiers of implementation: to build the best-performing 25%, 50%, 75% or 100% of the swales required to remove the TP load from sports fields (Table 13). Investment option 1 is to build all assets in the 'high performance' band, addressing 25% of the sports field TP load. Investment option 2 builds the assets from option 1, and additionally half the assets in the 'average performance' band, in total addressing 50% of the sports field TP load. Investment option 3 builds all the assets in the 'high' and 'average performance' band, addressing 75% of the sports field TP load, and investment option 4 builds all the assets in all performance bands, addressing 100% of the sports field TP load.

Table 13. Costing summary for four levels of investment in constructing bioretention swales below managed sports fields in the Lake Tuggeranong catchment.

Investment option	Costing level	Total annual TP removed (kg/year)	Total 30-year lifecycle cost[1]	Cost per unit TP removed ($/kg)
1	Build best 25%	14.93	$4,204,451	$9,387
2	Build best 50%	29.85	$11,817,327	$13,196
3	Build best 75%	44.78	$19,430,204	$14,463
4	Build all	59.70	$31,445,222	$17,557

1 Total lifecycle cost is calculated over 30 years using a discount rate of 7% per annum on O&M costs.

2.5.5 Quality of supporting evidence

Using the evaluation rubric (Appendix A), the above estimates of cost-effectiveness of installing bioretention swales below managed sports fields scored 13/14 for confidence in cost estimates, and 9/16 for confidence in performance estimates.

2.6 Management of household fertilizer use practices

2.6.1 Background

Household use of fertilizer products was investigated as a source of TP in the catchment that may be exported from residential blocks. The loss of fertilizer TP from residential blocks could be reduced by community partnership programs designed to alter how people use fertilizer on their block, and/or by legislating to reduce the TP content of fertilizer products, e.g. (Environmental Protection (Packaged Fertiliser) Regulations, 2010).

Concepts of Change were contracted to survey Canberra households on their fertilizer use (including purchased compost, manures, and 'chemical' fertilizer products). Based on the detailed information the survey obtained about the usage rates of different types of fertilizer products, Concepts of Change estimated the amount of phosphorus applied to residential properties (Concepts of Change, 2023). Export rates of phosphorus from different fertilizer products were estimated based on a review of experimental studies of TP export rates (Booksmythe, 2023).

Phosphorus application and export rates from household fertilizer use

Survey respondents lived on residential blocks with garden space - i.e. RZ1 or RZ2 -zoned blocks. The total per-household rate of TP application in fertilizer products estimated from the survey was 0.59 kg TP/year (Table 14).

Table 14. Average annual amounts of total phosphorus (TP) applied to residential blocks in the ACT from chemical fertilizers, commercial composts and raw manures, and literature-derived rates of TP export for these products. Lower, medium, and upper estimates of TP export rates are provided, based on the range of values reported for each fertilizer type in the literature.

Product type	TP applied (kg/household/year)	Lower TP export rate (% of applied)	Medium TP export rate (% of applied)	Upper TP export rate (% of applied)
Fertilizers	0.15	2%	12%	25%
Composts	0.36	0.2%	1%	2.5%
Raw manures	0.07	1%	9%	17%

There are ~21,000 RZ1 and RZ2 -zoned blocks (low to medium density residential, detached and semi-detached dwellings with garden) in the Lake Tuggeranong catchment comprising ~1030 hectares of permeable area (out of 1950 ha total area of RZ1 and RZ2 blocks). Chemical fertilizers account for about 25% of the TP applied to household gardens, but their higher export rates compared to composts and manures mean they are estimated to account for about 65% of the exported TP (Table 15).

Table 15. Annual amounts of total phosphorus (TP) from fertilizer products applied to and exported from residential blocks (RZ1 and RZ2) in the Lake Tuggeranong catchment.

Product type	Total TP applied in catchment (kg/year)	TP applied (kg/ha/year)	Lower total TP exported (kg/year)	Medium total TP exported (kg/year)	Upper total TP exported (kg/year)
Fertilizers	3192	3.10	0.06	0.37	0.78
Composts	7644	7.42	0.02	0.07	0.19
Raw manures	1533	1.49	0.02	0.13	0.25
Total	12369	12.01	0.09	0.58	1.21

The Lake Tuggeranong catchment model (Dey, Stewart, Kahn, Booksmythe, & Starrs, 2024) estimates the total TP load from suburban pervious land in the Lake Tuggeranong catchment to be ~0.12 - 0.16 kg/ha/year, or in the vicinity of the lower estimate from the survey data. The catchment model estimate includes all TP inputs from suburban pervious land (e.g. any TP from leaves & grass clippings, pet waste, etc.) so it suggests that our estimates from the survey data might be too high (even the lower value). Caveats to our current understanding of the TP inputs contributed by household fertilizer use include:

- Although the survey was very detailed and thorough, and estimates of fertilizer use included correction factors based on on-the-ground verification of reported product use, these estimates may still over-estimate the amount of fertilizer applied to residential blocks. Information on Bunnings' annual ACT fertilizer sales suggest rates of 'chemical' fertilizer use are between 12 - 20 times lower than survey estimates.
- Estimates of export rates obtained from the literature varied widely between studies and depend on a large number of factors (e.g. soil type, 'rainfall' intensity and duration, vegetation type and presence). The highest export rate reported in the literature for a given type of fertilizer product was used as the upper estimate in these calculations. This is similar to assuming a 1-in-10 year rain event occurring immediately after fertilizer is applied. The lower estimates may be more realistic, and are more

consistent with the catchment model estimates of the TP load generated by suburban pervious land use in the Lake Tuggeranong catchment.

- The reported rates of phosphorus application suggest that we should see far more phosphorus exported from residential blocks than current water quality data indicates. If the survey-derived estimates of phosphorus application are broadly correct, several further avenues of investigation are required to understand what is happening to this phosphorus, e.g.:
  - how long has phosphorus been applied at this rate?
  - how much phosphorus can be stored in the soil?
  - is excess phosphorus taken up by trees?

2.6.2 Phosphorus removal performance

The management option assessed here is to use specialised community partnership approaches to encourage households to reduce the amount of phosphorus fertilizer products they apply to residential blocks.

To estimate the potential TP reduction resulting from this approach, we assume a community partnership program that gets the top 20% of P-inputting households to reduce their inputs by 20% (this outcome is chosen based on advice from Concepts of Change). Using the fertilizer survey data and TP export rates from the literature, the amount of TP applied and exported by the top 20% of users can be calculated. Reducing these inputs by 20% and adding the unaltered inputs from the remaining 80% of users, gives a reduction of 17% of the current total household P exports.

To calculate the estimated TP load reduction of this option, we assume that household fertilizer TP exports occur in event flows, and any reduction will not affect the baseflow TP loads coming from suburban pervious areas in the Source catchment model. This baseflow TP load is estimated to be 0.018 kg/ha/year. This is subtracted from the total modelled TP load from suburban pervious areas (~0.12 - 0.16 kg/ha/year) to give the estimated event flow TP load, of between 0.103 - 0.142 kg/ha/year.

We also assume that the catchment model estimates represent the upper limit of current household fertilizer TP exports. This means that the median and upper TP export estimates (Table 13) based on the survey data and export rates from the literature are too large to be consistent with the model. In providing an estimated range of the TP load reduction from banning phosphorus in fertilizers, we use the lower TP export estimate from the survey and literature review as the lower bound, and the catchment model estimate of suburban pervious event flow load as the upper bound (Table 16).

To calculate the percent reduction in the suburban pervious TP load resulting from this community partnership program, we add the baseflow loads to the new event flow loads from fertilizer and divide this by the current total suburban pervious load. This gives an estimated maximum TP reduction of between 14 - 41% of the current load contributed by suburban pervious areas, or the removal of between 20 - 58 kg of the current 140.3 kg TP/year.

Table 16. Estimating the reduction in TP load from suburban pervious land use resulting from a 17% reduction in current TP inputs from household fertilizer use. The range of values in each cell reflects the range of estimated TP export rates from the fertilizer applied to residential blocks.

Total TP load from suburban pervious land use (kg/ha/year)[1]	Current event-flow TP load from fertilizer (kg/ha/year)[2]	Reduced event-flow TP load from fertilizer (kg/ha/year)	Reduced event-flow TP load from fertilizer, plus baseflow load (kg/ha/year)	Percent reduction in total TP load from suburban pervious land use (kg/ha/year)
Lower estimate: 0.121	0.092 – 0.103	0.076 – 0.085	0.094 – 0.103	14.5 – 22.2%
Upper estimate: 0.160	0.092 – 0.142	0.076 – 0.118	0.094 – 0.136	15.1 – 41.2%

1 Estimated from the catchment model for the Lake Tuggeranong catchment (Dey, Stewart, Kahn, Booksmythe, & Starrs, 2024).

2 Estimates for the event-flow TP load from household fertilizer use are capped at the model-estimated total event-flow TP load from all suburban pervious land use, 0.103 or 0.142 kg TP/ha/year.

2.6.3 Costing

The lower cost estimate is based on the cost of a 6-month Concepts of Change community partnership program implemented in 2024, scaled up to run over 5 years and reach all households in the Lake Tuggeranong catchment. The higher cost estimate is based on expert opinion provided by Concepts of Change for the cost of a 5-year intensive campaign to achieve the reductions described in this section across all of Canberra. 30-year costings use a discount rate of 7% per annum after the first year, and assume that the intensive 5-year campaign runs twice (years 0-4 and 15-19), and that for all intervening years, maintenance costs of $350,000/year are required for both costing levels.

2.6.4 Cost-effectiveness

Based on the above, management of household fertilizer use by way of a community partnership program aimed at reducing the TP inputs of the top 20% of users by 20% is predicted to remove between 20 - 58 kg TP per year at a cost of between $3,700 - $24,000 per kg TP removed, over 30 years (Table 17).

Table 17. Estimated annual program and maintenance costs, total 30-year lifecycle cost, and cost-effectiveness of options for management of household fertilizer use.

Costing level	Annual program cost (2 x 5-year programs in 30-year lifecycle)	Annual maintenance cost (non-program years)	Total 30-year lifecycle cost[1]	Cost per unit TP removed ($/kg) – low performance	Cost per unit TP removed ($/kg) – high performance
Lower cost estimate	$637,000	$350,000	$6,362,682	$10,604	$3,657
Higher cost estimate	$2,000,000	$350,000	$14,509,794	$24,183	$8,399

1 Total lifecycle cost is calculated over 30 years using a discount rate of 7% per annum on O&M costs.

However, how cost estimates relate to the efficacy of this option is uncertain. We have no information on whether cost-effectiveness would increase or decrease with the scale of investment in a community partnership program to manage household fertilizer use.

In providing four levels of investment for this management option, we therefore assumed a uniform cost-effectiveness of $10,000/kg TP removed at all four levels of investment. This value was chosen as it falls within the cost-effectiveness estimates generated from both cost estimates above, and results in a realistic range of total program costs (between $6 and $17 million) when applied to the lower and upper estimates of the reduction in TP achieved by such a program. We used the lower and upper estimates of TP removal as the amount that would be removed by the lowest and highest levels of investment in this management option, respectively, and interpolated two evenly-spaced levels of TP removal between these extremes (Table 18).

Table 18. Costing summary for four levels of investment in community partnership programs aimed at managing household fertilizer use to reduce TP inputs in the Lake Tuggeranong catchment.

Investment level	Assumed program implementation	Annual TP removed (kg)	Total 30-year lifecycle cost[1]	Cost per unit TP removed ($/kg)
1	Low implementation	20	$6,000,000	$10,000
2	Medium implementation	32.67	$9,800,000	$10,000
3	High implementation	45.33	$13,600,000	$10,000
4	Very high implementation	58	$17,400,000	$10,000

1 Total lifecycle cost is calculated over 30 years using a discount rate of 7% per annum on annual costs after the first year.

2.6.5 Quality of supporting evidence

Using the evaluation rubric (Appendix A), the above estimates of cost-effectiveness of community partnership programs aimed at managing household fertilizer use scored 9/14 for confidence in cost estimates, and 7/16 for confidence in performance estimates.

2.7 Installation of castellated kerbs

2.7.1 Background

The stormwater network of the Lake Tuggeranong catchment was designed and built to be extremely efficient at directing stormwater into the piped network. The prevailing paradigm at the time was to minimise flood risk by getting stormwater out of residential areas as efficiently as possible. Consequently, the Lake Tuggeranong catchment stormwater network is dominated by concrete drains and a significant underground stormwater pipe network.

Almost all stormwater that ends up on sealed roads is diverted directly into the underground stormwater pipe network via the sumps along the kerbs. A small number of sealed roads in the Lake Tuggeranong catchment divert stormwater directly to public open space.

Castellated kerbs are concrete kerbs that include engineered breaks or channels diverting water to adjacent pervious land. Retrofitting castellated kerbs on roads adjacent to public open space in the Lake Tuggeranong catchment has two potential benefits for improving water quality in the lake. Firstly,

stormwater diverted to public open space is able to infiltrate the soil, allowing the capture of nutrients and sediment from the water. Secondly, the flow of the portion of stormwater diverted to public open space is slowed, and the volume of water remaining in the stormwater network is reduced. These effects reduce the hydrological flashiness in downstream areas of the catchment, with benefits for the function of other WSUD infrastructure. Estimating these secondary effects on downstream hydrology is extremely complex and beyond the capability of this assessment. Here, phosphorus removal performance estimates are estimates of the amount of stormwater and pollution diverted from sealed roads.

The Lake Tuggeranong catchment model estimates that 582 kg TP/year is generated from the 388 ha of impervious road surface area in the catchment (Dey, Stewart, Kahn, Booksmythe, & Starrs, 2024). Using ACT Government GIS layers for land zoning and roads, the surface area of road that is adjacent to public open space is 166.15 ha, or 43% of the total road area. Assuming that pollutant generation is uniform, the amount of TP generated on roads adjacent to public open space is calculated as 249 kg/year (43% of the total road TP load). However, in some instances, the road will slope away from the adjacent open space – here we assume that on average, half of the road area adjacent to public open space has a slope suitable to allow drainage towards the open space, and so half of the TP generated on this road area – 124.5 kg TP/year – is currently received by the 1813 stormwater sumps located along kerbs bordering public open space.

2.7.2 Phosphorus removal performance

Not all of the TP currently received by stormwater sumps bordering open space would be diverted to castellated kerb outlets, as these outlets are not able to receive as much road runoff as stormwater sumps, and will be bypassed when the pervious land is saturated. Here we conservatively assume that a castellated kerb outlet can receive half as much runoff as a stormwater sump.

Under these assumptions, if a castellated kerb outlet was installed immediately ‘upstream’ of each of the 1813 stormwater sumps located on kerbs bordering public open space, intercepting half of the road runoff received by each sump, 62 kg TP/year would be diverted from the stormwater network. This represents an upper limit to the amount of TP removed, as it is likely an unrealistically high rate of installation, and does not take into account logistical considerations for construction or issues such as changes to the road flooding risk. Lower rates of installation result in proportionally lower rates of TP removal: installing a castellated kerb outlet for every second, third, or fourth sump would remove 31, 20.75, or 15.5 kg TP/year, respectively.

2.7.3 Costing

The cost to retrofit castellated kerb outlets was reported as $6,872 per outlet in the preliminary sketch plan (PSP) report by Construction Control Australia for a project to construct 36 outlets in the Lake Tuggeranong catchment as part of Stage 2 of the ACT Healthy Waterways project (Construction Control Australia Pty Ltd, 2022). We used this figure as our lower estimate of the cost of this management option. An alternative costing estimate of $10,000 per outlet is is derived from the estimated cost in 2024 for the construction of 51 outlets of $18,802 per outlet (GW2, 2024), and assumes an economy of scale to achieve a reduced per unit cost.

2.7.4 Cost-effectiveness

We assume a lifecycle of 30 years for castellated kerbs, consistent with other management options. However, no reliable estimate of the maintenance costs of castellated kerb outlets was obtained, and our estimates of cost-effectiveness of this management option are based solely on the capital cost of installation.

In calculating the cost-effectiveness of castellated kerbs as a management option, we incorporated a range of installation frequencies (an outlet for every sump – an outlet for every 4 sumps) and costs (between the lower and higher cost estimates obtained, above). We assumed an economy of scale such that installing outlets at the lower rate of one for every four sumps incurs the highest per-outlet cost of $10,000, but there is a marginal decrease in per-outlet costs as more outlets are installed (Table 19).

2.7.5 Quality of supporting evidence

Using the evaluation rubric (Appendix A), the estimates of cost-effectiveness of installing castellated kerb outlets scored 11/14 for confidence in cost estimates, and 7/16 for confidence in performance estimates.

Table 19. Estimated annual load of total phosphorus (TP) prevented from entering Lake Tuggeranong, cost per castellated kerb outlet installed, total 30-year lifecycle cost, and cost-effectiveness of for four levels of investment into retrofitting castellated kerb outlets to divert road runoff from the stormwater network.

Investment level	Number of outlets installed	TP removed (kg/year)	Cost per outlet	Cumulative total lifecycle cost[1]	Cost per unit TP removed ($/kg)
1	453 (1 per 4 sumps)	15.56	$10,000	$4,532,500	$9,708
2	604 (1 per 3 sumps)	20.75	$9,652	$5,990,823	$9,624
3	906 (1 per 2 sumps)	31.13	$8,957	$8,539,901	$9,146
4	1813 (1 per sump)	62.25	$6,872	$14,349291	$7,684

1 Cumulative total lifecycle cost is calculated based on the assumed marginal improvement in per-unit cost between installation tiers. For example, the total cost of installing 453 outlets (the lowest installation rate) is equal to 453 times the unit cost of $10,000. The total cost of installing 604 outlets (the second-lowest installation rate) is equal to the cost of installing 453 outlets at $10,000, plus 153 outlets at the unit cost of $9,652.

2.8 Installation of floating wetlands

2.8.1 Background

Once nutrients are transported into a waterbody, they may become available for uptake by plants, algae, and bacteria, including blue-green algae. Fringing and in-lake vegetation can help to limit blue-green algae blooms by competing with them for these nutrients, particularly phosphorus. One approach to increasing in-lake vegetation is to install floating wetlands.

Floating wetlands are floating structures supporting beds of emergent wetland vegetation, deployed in lakes and ponds to remove nutrients from the water. The plants take up the nutrients they need as they grow, and regular harvesting of the plants prevents the recycling of those nutrients back into the water. The ACT Healthy Waterways program contracted Atlan Stormwater to trial floating wetlands in Lake Tuggeranong in 2023 (Atlan Stormwater, 2023). Three floating platforms totalling 500m^2 were installed, with three species of wetland plants compared for their nutrient uptake rates. The data from this trial inform the estimates of TP removal performance and cost of this management option.

2.8.2 Phosphorus removal performance

In the trial, the floating wetland plants were harvested once, after a year of deployment, and the increase in their TP content was recorded as a measure of the amount of TP they removed from the lake. From this we can calculate the amount of TP removed from the lake per square metre of floating wetland area for each plant species separately. The worst-performing species removed 0.001kg TP/m^2/year, and the best-performing species removed 0.005kg TP/m^2/year. The average amount of TP removed by all three species was 0.003kg TP/m^2/year, and we used this as our estimate of floating wetland TP removal performance.

2.8.3 Costing

G2W Pty Ltd were engaged to review the costs associated with existing WSUD infrastructure in the Lake Tuggeranong catchment (G2W Pty Ltd, 2024). The average capital cost of the trialled floating wetlands was \$1,049/m^2, and the annual maintenance cost was \$13.24/m^2.

2.8.4 Cost-effectiveness

We calculated the cost-effectiveness of floating wetlands based on the above TP removal performance and costs over a 30-year lifecycle, as \$13,622.2/kg TP removed. We assume that both cost and performance scale linearly with floating wetland area, so cost-effectiveness remains the same for any size of wetland. To provide four levels of investment in this management option, we used four sizes of floating wetland area (Table 20).

Table 20. Wetland area, estimated TP removal performance, estimated capital cost and annual operation and maintenance costs, 30-year lifecycle costs and cost-effectiveness for four levels of investment in installation of floating wetlands in Lake Tuggeranong.

Investment level	Wetland area (m^2)	Total annual TP removed (kg)	Capital cost	Annual operation and maintenance costs	Total 30-year lifecycle cost[1]	Cost per unit TP removed ($/kg)
1	1000	3	$1,049,000	$13,240	$1,226,000	$13,622.2
2	2000	6	$2,098,000	$26,480	$2,452,000	$13,622.2
3	3000	9	$3,147,000	$39,720	$3,678,000	$13,622.2
4	4000	12	$4,196,000	$52,960	$4,904,000	$13,622.2

1 Total lifecycle cost is calculated over 30 years using a discount rate of 7% per annum on O&M costs.

2.8.5 Quality of supporting evidence

Using the evaluation rubric (Appendix A), the above estimates of cost-effectiveness of installing floating wetlands in Lake Tuggeranong scored 10/14 for confidence in cost estimates, and 9/16 for confidence in performance estimates.

2.9 Installation of stormwater recycling infrastructure

2.9.1 Background

Urban stormwater contains high concentrations of nutrients because the large area covered by impervious surfaces in the urban environment prevents water from soaking into the ground and being naturally filtered through the soil. Diverting some stormwater for use in the irrigation of public sports fields removes nutrients from the stormwater system. It also slightly reduces the volume of stormwater that continues through the system, reducing hydrological flashiness to the benefit of downstream WSUD infrastructure.

In the Lake Tuggeranong catchment, a stormwater recycling system for sports field irrigation has been installed at one publicly managed sports field (TCCS ID: Kambah 3). A further ten publicly managed sports fields at 8 sites in the Lake Tuggeranong catchment are currently irrigated using potable water, with a combined irrigation water demand of 194 ML/year, at an average cost of $5,478/ML. Here we assess the TP removal performance and cost of installing stormwater recycling infrastructure for sports field irrigation across these sites.

2.9.2 Phosphorus removal performance

As we assume that 100% of the P in stormwater is removed when water is used for irrigation, the amount of TP removed depends on the amount of stormwater used for irrigation. TCCS provided data on the average annual water demand for 10 irrigated sports fields at 8 sites in the Lake Tuggeranong catchment (Table 18). In wet years, irrigation water demand is low and stormwater is abundant, conditions that make it likely that 100% of demand can be met using recycled stormwater. In dry years, however, water demand is high and stormwater is relatively scarce. This, combined with the flashy nature of stormwater hydrographs, make it unlikely that all the irrigation demands will be met by stormwater. We therefore assume that overall, 75% of average annual potable water demands would be met using stormwater (Table

20). We assume a TP concentration of 0.15mg/L to calculate the potential load of TP removed by harvesting stormwater to irrigate these sports fields (Table 21). This value is the average median observed TP in the University of Canberra research data used to calibrate the catchment model (Ubrihien, et al., 2020).

Table 21. Annual irrigation demand, estimated demand met by recycled stormwater, and estimated annual TP load in recycled stormwater, for 8 sports field sites[1] in the Lake Tuggeranong catchment.

Sports field ID	Total annual irrigation water demand (ML)	Demand met by stormwater = 75% of total (ML)	TP load in stormwater used for irrigation (kg)
Calwell 1, 2, 3[1]	47.15	35.36	5.30
Kambah 1	31.18	23.38	3.51
Wanniassa 2	28.40	21.30	3.19
Greenway 1	27.70	20.77	3.12
Gowrie 1	18.68	14.01	2.10
Kambah 2	17.49	13.12	1.97
Chisholm 1	15.21	11.41	1.71
Isabella 1	7.76	5.82	0.87
Total	193.57	145.17	21.78

1 TCCS provided a combined irrigation demand for three Calwell sports fields, which are treated as a single site.

2.9.3 Costing

The estimated costs of installing stormwater recycling infrastructure are based on the realised cost of the infrastructure installed at Kambah 3 (GW2, 2024) and assume that each system will include the same components, namely:

- Stormwater treatment train (gross pollutant trap, sediment forebay, and wetland/pond/raingarden)
- Pumps and pipe infrastructure
- Water treatment plant (sand filter and UV filter)
- Water holding tanks (1 ML capacity)
- Operation and maintenance

These costs will be offset by the savings accrued as a result of the 75% reduction in the use of potable water and its associated cost of $5,478/ML.

The infrastructure installed at sports field Kambah 3, which has an average annual water demand of 26.6 ML, had capital costs of approximately $1,500,000, and annual operation and maintenance costs of $65,000. This site had existing water tanks for irrigation, which is not the case for all of the sites costed here. We therefore take these as the lower bound of cost estimates, and assign this minimum cost to sports fields with an average annual water demand equal to or less than that of Kambah 3. We assume that more infrastructure will be required to divert, filter, store, and irrigate more water, and that operation and maintenance of larger facilities will increase similarly. Both the capital costs and O&M costs for stormwater

recycling infrastructure installed at sports fields with larger water demands than Kambah 3 are scaled up in proportion to their demand (Table 22).

2.9.4 Cost-effectiveness

While sports fields with the highest annual irrigation demands have the highest capital and O&M costs, they also experience the largest savings from reduced potable water expenses and remove the largest TP loads, representing the most cost-effective options (Table 22).

Table 22. Capital cost, annual operation and maintenance cost, savings from reduced potable water use, 30-year lifecycle cost, and cost-effectiveness for the installation of stormwater recycling infrastructure for irrigation at 8 sports field sites in the Lake Tuggeranong catchment.

Sports field ID	Capital cost	Annual operation and maintenance cost	Savings from potable water expenses	Total 30-year lifecycle cost[1]	Cost per unit TP removed ($/kg)
Calwell 1, 2, 3	$2,661,034	$115,311	-$193,726	$1,609,575	$10,115
Kambah 1	$1,759,537	$76,247	-$128,096	$1,064,288	$10,115
Wanniassa 2	$1,602,639	$69,452	-$116,681	$969,446	$10,115
Greenway 1	$1,563,316	$67,744	-$113,811	$945,600	$10,115
Gowrie 1	$1,500,000	$65,000	- $76,748	$1,342,472	$21,295
Kambah 2	$1,500,000	$65,000	- $71,868	$1,407,903	$23,850
Chisholm 1	$1,500,000	$65,000	- $62,496	$1,533,578	$29,875
Isabella 1	$1,500,000	$65,000	- $31,887	$1,994,008	$74,221

1 Total lifecycle cost is calculated over 30 years using a discount rate of 7% per annum on both annual O&M costs and savings from reduced potable water expenses.

To provide four levels of investment in this management option, we grouped the 8 sports field sites by size and cost-effectiveness and created four tiers of installation: either build the best two, best four, best six, or all 8 stormwater recycling systems (Table 23).

Table 23. Costing summary for four levels of investment in installing stormwater recycling infrastructure for sports field irrigation in the Lake Tuggeranong catchment.

Investment option	Costing level	Total annual TP removed (kg/year)	Total 30-year lifecycle cost[1]	Cost per unit TP removed ($/kg)
1	Build best 2	8.81	$2,673,863	$10,115
2	Build best 4	15.12	$4,588,909	$10,115
3	Build best 6	19.19	$7,339,284	$12,748
4	Build all 8	21.78	$10,816,870	$16,558

1 Total lifecycle cost is calculated over 30 years using a discount rate of 7% per annum on O&M costs.

2.9.5 Quality of supporting evidence

Using the evaluation rubric (Appendix A), the above estimates of cost-effectiveness of installing stormwater recycling infrastructure for sports field irrigation scored 10/14 for confidence in cost estimates, and 10/16 for confidence in performance estimates.

2.10 Installation of household rainwater tanks

2.10.1 Background

Residential properties make up a large proportion of the Lake Tuggeranong catchment area, and consist of large areas of impervious surface in the form of rooftops. Residential properties are therefore expected to be a significant contributor to the generation of nutrient pollutants and runoff in the catchment.

Encouraging the installation of plumbed household rainwater tanks on residential properties, by covering some or all of the associated costs to property owners, is a potential approach to reducing this source of runoff. Installation of plumbed rainwater tanks at residential properties diverts runoff, and the phosphorus it carries, from the stormwater system, instead directing it to non-potable household uses and on to the wastewater (sewage treatment) system, or to garden uses from where it completes the water cycle either via evapotranspiration or by entering the groundwater. When properly plumbed in and used, household rainwater tanks help to reduce the intensity of rises in water level and flow during rainfall events (i.e. flatten the hydrograph), which should be beneficial for the TP removal performance of downstream WSUD infrastructure. Rainwater tanks provide some opportunity to directly capture phosphorus when particulate forms are deposited within the tanks, although this effect is likely to be small.

2.10.2 Phosphorus removal performance

To calculate the amount of TP diverted from the stormwater system by rainwater tanks we used estimates of the annual amount of water captured and used by plumbed rainwater tanks, from a study that modelled the savings in potable water offered by residential rainwater tanks in Canberra (Imteaz, Yilmaz, Santos, & Ahsan, 2023). Their estimates account for seasonal variability in rainfall, the typical non-potable water demands of a household, and the spillover of water to the stormwater system when tanks are over capacity, and are broadly summarised for a range of roof and tank sizes in Table 24.

Table 24. Potable water savings from plumbed household rainwater tanks, estimated by Imteaz et al. 2023.

Roof size (m^2)	Tank size (L)	Water saved – dry year (L/year)	Water saved – average year (L/year)	Water saved – wet year (L/year)
100	2,500	35,000	50,000	55,000
200	5,000	40,000	55,000	60,000
100	2,500	50,000	60,000	65,000
200	5,000	60,000	75,000	80,000

These estimated water savings represent the amount of residential runoff diverted from the stormwater system by plumbed rainwater tanks. By multiplying these by the estimated concentration of TP in runoff from suburban roof area in the Lake Tuggeranong catchment (from the calibrated catchment model) we can calculate the approximate load of TP removed per household (Table 25).

Table 25. Estimated loads of TP diverted from the stormwater system by plumbed household rainwater tanks.

Roof size (m^2)	Tank size (L)	TP removed – dry year (L/year)	TP removed – average year (L/year)	TP removed – wet year (L/year)
100	2,500	3.82	5.45	5.99
200	5,000	4.36	5.99	6.54
100	2,500	5.45	6.54	7.09
200	5,000	6.54	8.18	8.72

While the annual load of TP removed from the stormwater system per household is small, ranging between approximately 4-8 g/year, multiplying by the number of residential properties in the Lake Tuggeranong catchment (~21,000 RZ1- and RZ2-zoned blocks) gives an upper estimate of annual TP removal of between 84-168 kg/year.

However, this assumes 100% uptake in rainwater tank installation, which is unlikely for several reasons. An estimated 36% of households in the ACT already have rainwater tanks installed, and therefore do not contribute to this source of TP (Schirmer & Dale, 2023). Some households may not be willing or able to install rainwater tanks, and others may not make full use of the water captured by their tanks, which increases spillover and reduces the amount of water diverted from the stormwater system. In costing this option we assume that the highest rate of uptake of new household rainwater tanks would be 10,000 households, or around 50% of residential properties in the Lake Tuggeranong catchment.

2.10.3 Costing

For this management option we estimate costs for a government grant scheme that covers the capital cost of rainwater tank installation for residential properties in the Lake Tuggeranong catchment. Rainwater tanks installed on suburban residential properties are typically of 1,000 - 3,000 L capacity, and cost between $1,000 - $2,000. Adding the costs of installation and plumbing, here we assume a total cost per household of $5,000 that would be provided by government funding. Rainwater tanks are fairly low maintenance, and we assume any operation and maintenance costs would be left to property owners in costing this management option.

2.10.4 Cost-effectiveness

We assume an average rainwater tank TP removal performance of 6 g/year, at a cost of $5,000 per tank installed. Over a 30-year lifecycle, this gives a cost-effectiveness estimate of $27,778 per kg TP removed. To provide four levels of investment in this management option, we costed rates of uptake of rainwater tank installation of between 2,500 and 10,000 households (Table 26).

Table 26. Costing summary for four levels of investment in installing household rainwater tanks on residential properties in the Lake Tuggeranong catchment.

Investment level	Number of households	Total TP removed (kg)	Total 30-year lifecycle cost[1]	Cost per unit TP removed ($/kg)
1	2,500	15	$12,500,000	$27,778
2	5,000	30	$25,000,000	$27,778
3	7,500	45	$37,500,000	$27,778
4	10,000	60	$50,000,000	$27,778

1 30-year lifecycle cost is the capital cost of tank installation, as we assume no operation and maintenance costs for this option.

2.10.5 Quality of supporting evidence

Using the evaluation rubric (Appendix A), the above estimates of cost-effectiveness of a government grant scheme that covers the capital cost of rainwater tank installation for residential properties in the Lake Tuggeranong catchment scored 6/14 for confidence in cost estimates, and 9/16 for confidence in performance estimates.

3. Designing management scenarios

3.1 Comparing the cost-effectiveness of management options

Table 27 presents the annual load of TP removed, the 30-year cost, and the cost-effectiveness of the four levels of investment for the management options assessed in Section 2. We plotted the range of TP removal performance and cost of each management option across the levels of investment to provide a visual comparison of the management options and the range of cost-effectiveness for each option (Fig. 1). Increasing street sweeping frequency and constructing additional WSUD infrastructure were estimated to remove the largest amounts of phosphorus annually, in the range of 100-400 kg/year. Street sweeping was the more cost-effective of these two approaches, estimated at $1,000-2,500 per kg TP removed, while constructing WSUD infrastructure had costs of between $7,000-12,000 per kg P. The remaining options all had lower total annual TP removal performances and ranged in cost-effectiveness up to $28,000 per kg TP.

Table 27. Summary of phosphorus removal performance, total cost, and cost-effectiveness for four levels of investment for each of 10 management options assessed in this report. See Section 2 for details of the investment levels for each management option.

Management option and level	TP removed (kg/year)	30-year cost ($)[1]	Cost-effectiveness ($/kg TP)
Install additional WSUD 1	106.21	$22,507,500	$7,064
Install additional WSUD 2	169.67	$48,369,492	$9,502
Install additional WSUD 3	226.22	$73,862,467	$10,884
Install additional WSUD 4	240.46	$84,519,403	$11,716
Maintenance of existing WSUD 1	35.84	$10,177,128	$9,465
Maintenance of existing WSUD 2	61.78	$19,086,579	$10,298
Maintenance of existing WSUD 3	79.93	$26,352,433	$10,990
Maintenance of existing WSUD 4	88.02	$30,352,433	$11,495
Increase street sweeping 1	203.7	$7,030,414	$1,150
Increase street sweeping 2	320.1	$14,060,827	$1,464
Increase street sweeping 3	372.5	$21,091,242	$1,887
Increase street sweeping 4	395.8	$28,121,656	$2,369
Manage grass clippings 1	16.4	$2,018,874	$4,103
Manage grass clippings 2	26.1	$2,018,874	$2,578
Manage grass clippings 3	32.7	$1,521,462	$1,551
Manage grass clippings 4	52.3	$1,565,956	$998
Sports field fertilizer management 1	14.93	$4,204,451	$9,387
Sports field fertilizer management 2	29.85	$11,817,327	$13,196
Sports field fertilizer management 3	44.78	$19,430,204	$14,463

Management option and level	TP removed (kg/year)	30-year cost ($)[1]	Cost-effectiveness ($/kg TP)
Sports field fertilizer management 4	59.70	$31,445,222	$17,557
Household fertilizer management 1	20	$6,000,000	$10,000
Household fertilizer management 2	32.67	$9,800,000	$10,000
Household fertilizer management 3	45.33	$13,600,000	$10,000
Household fertilizer management 4	58	$17,400,000	$10,000
Install castellated kerbs 1	15.56	$4,532,500	$9,708
Install castellated kerbs 2	20.75	$5,990,823	$9,624
Install castellated kerbs 3	31.13	$8,539,901	$9,146
Install castellated kerbs 4	62.25	$14,349,291	$7,684
Install floating wetlands 1	3	$1,226,000	$13,622.2
Install floating wetlands 2	6	$2,452,000	$13,622.2
Install floating wetlands 3	9	$3,678,000	$13,622.2
Install floating wetlands 4	12	$4,904,000	$13,622.2
Stormwater recycling for irrigation 1	8.81	$2,673,863	$10,115
Stormwater recycling for irrigation 2	15.12	$4,588,909	$10,115
Stormwater recycling for irrigation 3	19.19	$7,339,284	$12,748
Stormwater recycling for irrigation 4	21.78	$10,816,870	$16,558
Household rainwater tanks 1	15	$12,500,000	$27,778
Household rainwater tanks 2	30	$25,000,000	$27,778
Household rainwater tanks 3	45	$37,500,000	$27,778
Household rainwater tanks 4	60	$50,000,000	$27,778

1 Total lifecycle cost is calculated over 30 years using a discount rate of 7% per annum on annual (O&M) costs after the first year.

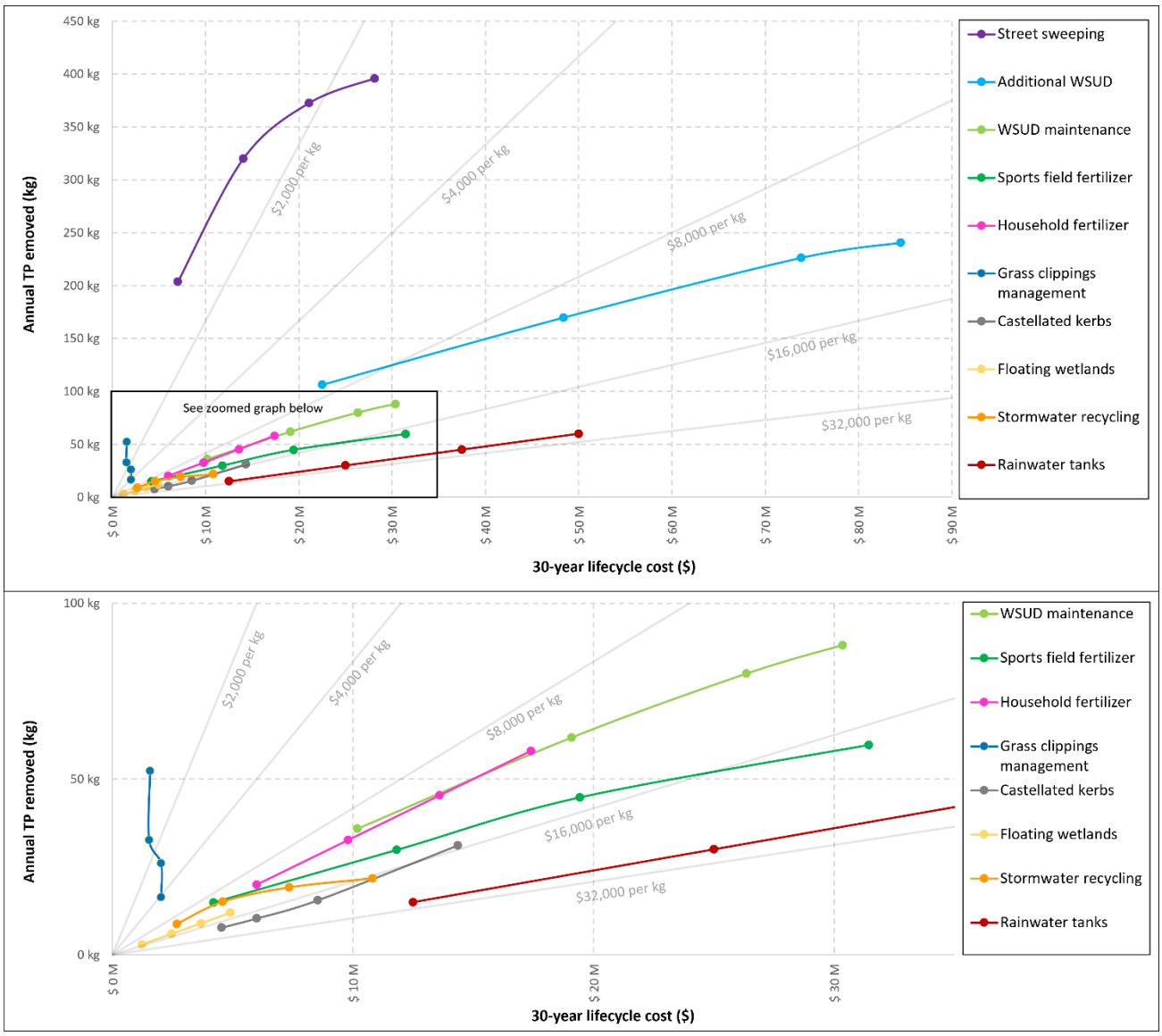

Figure 1. Annual total phosphorus load removed, and 30-year lifecycle cost, of each investment level for the 10 management options assessed in Section 2. Coloured lines connect the four estimates for each management option. Grey lines are a guide indicating the cost-effectiveness (cost per kg TP removed) of the estimates. The top panel shows all estimates; the bottom panel shows a zoomed in view of the estimates within the inset box.

The results of the management option assessments show that there is no single option capable of achieving the estimated ~700 kg reduction in annual phosphorus load required to maintain Lake Tuggeranong in a predominantly mesotrophic state (Kahn & Dey, 2024). To approach this target reduction, a combination of several management options aimed at reducing and intercepting catchment sources of phosphorus will be necessary.

3.2 Combining options to build management scenarios

The Healthy Waterways planning team used the information in Section 2, Table 27 and Figure 1 to create two scenarios, consisting of different combinations of management options, that achieved a reduction in the total annual phosphorus load entering Lake Tuggeranong of around 700 kg (Table 28).

Table 28. Comparison of the investment levels of management options selected for inclusion in the Cost-effective and Broad benefits scenarios designed to achieve a 700 kg reduction in the annual phosphorus load entering Lake Tuggeranong.

Management option	Cost-effective scenario	Broad benefits scenario
Install additional WSUD infrastructure	Investment level 1	Investment level 2
Maintenance of existing WSUD infrastructure	Investment level 3	Investment level 4
Increase frequency of street sweeping	Investment level 4	Investment level 3
Manage grass clippings from municipal mowing	Investment level 3	Investment level 3
Sports field fertilizer management	Investment level 1	Investment level 3
Household fertilizer management	Investment level 4	Investment level 1
Install castellated kerbs	n/a	Investment level 1
Install floating wetlands	n/a	Investment level 4
Stormwater recycling for sports field irrigation	Investment level 2	Investment level 3
Sum of annual TP removed	702.65 kg	766.62 kg
Total 30-year cost	$104,696,482	$143,540,616

The **Cost-effective scenario** systematically ranked the investment levels of each management option by cost-effectiveness, and selected the most cost-effective investment level of the most cost-effective options until the total annual phosphorus load removed met the 700 kg target. This scenario prioritized management options that prevent pollutants from entering the stormwater system, such as street sweeping and fertilizer management, as these have high cost-effectiveness. Options involving WSUD infrastructure were given lower priority under this approach, as they tend to have high costs for more limited phosphorus removal capacity. Some options, including rainwater tanks, floating wetlands, and castellated kerbs, were not considered to be sufficiently cost-effective for inclusion in this scenario.

The **Broad benefits scenario** considered additional information, as well as cost-effectiveness, when selecting management options to meet the 700 kg phosphorus removal target. This approach took into account the quality of evidence underlying each management option assessment, avoiding large investments into options with less certainty around their cost or performance estimates. Broader community and government values, including wellbeing, climate resilience, and public amenity, were also considered when selecting options to include in this scenario. This led to a wider variety of options being

selected for the broad benefits scenario compared to the cost-effective scenario, including more options involving WSUD infrastructure (Table 28).

The TP removal and cost-effectiveness estimates obtained for each management option do not consider the way that options may interact and affect each other's performance. For example, decreasing the load of phosphorus entering stormwater by frequent street sweeping in the catchment should result in lower phosphorus concentrations in the stormwater intercepted by a raingarden further downstream, reducing the phosphorus available for the raingarden to remove. Some of these interacting effects can be estimated by implementing combinations of management options in the catchment model, and calculating the total reduction in the phosphorus load entering Lake Tuggeranong under different combinations.

3.3 Modelling management scenarios

The two scenarios summarised in Table 28 were implemented in the catchment model, to generate estimates of the total annual load of phosphorus entering Lake Tuggeranong under each scenario, while accounting for interactive effects of different management options (Dey, Stewart, Kahn, Booksmythe, & Starrs, 2024).

Different management options are implemented in different ways in the catchment model. Some options are explicitly represented by the addition or modification of specified links and nodes in the model:

- **Additional WSUD infrastructure** Proposed raingardens were represented in the catchment model by new storage nodes placed at the locations indicated in the original plans for the raingardens. The raingarden nodes were configured using the size indicated in the original plans, and the performance details of similar existing WSUD assets.
- **Maintenance of existing WSUD infrastructure** The catchment model includes storage nodes representing each WSUD asset in the Lake Tuggeranong catchment, with the performance of each asset configured to reflect its current phosphorus removal efficiency. To represent maintenance of these assets to their designed performance, the performance details were reconfigured to the phosphorus removal rates given in the detailed design reports for each asset.
- **Sports field fertilizer management** For each scenario we modelled sufficient bioretention swales to intercept the required amount of sports field-generated phosphorus (i.e., 25% or 75% of all sports field generated phosphorus). We modelled one swale per subcatchment, with swale size proportional to the area of sports field in each subcatchment. Bioretention swale performance was configured using the performance details of similar existing WSUD assets. As the scale of the catchment model does not delineate sports fields from their subcatchments, a controlled splitter was used to divert water to the node representing each swale, in proportion to the swale : subcatchment area ratio.
- **Stormwater recycling infrastructure for sports field irrigation** Each sports field with stormwater recycling infrastructure was represented by a storage node and an irrigator node. A maximum of 1 ML water was diverted to the storage node via a controlled splitter during event flows. The water in the storage node was used to meet the irrigation demand specified by the irrigator node. Excess water was returned to the stormwater system downstream of the sports field.
- **Floating wetlands** To represent floating wetlands in the catchment model, a storage routing link was added just upstream of the Lake Tuggeranong storage node. This was configured using a decay model to reduce the phosphorus concentration in the water passing through the routing link.

The remaining options were implemented in the model by calculating the percentage phosphorus removal attained by each option, compared to the current load of phosphorus available to be intercepted by that option, and adjusting phosphorus concentrations within the catchment model based on these percentage reductions:

- **Increase street sweeping frequency** The percentage reduction in phosphorus concentration due to increased street sweeping was applied to all area classified as road, and calculated based on the difference in total phosphorus load generated from roads across the catchment with and without an increase in street sweeping frequency.
- **Manage grass clippings from municipal mowing** The percentage reduction in phosphorus concentration due to management of grass clippings from municipal mowing was applied to all area classified as road, and calculated based on the difference in total phosphorus load generated from roads across the catchment with and without management of grass clippings.
- **Install castellated kerbs** The percentage reduction in phosphorus concentration due to the installation of castellated kerbs was applied to all area classified as road, and calculated based on the difference in total phosphorus load generated from roads across the catchment with and without the installation of castellated kerbs.

  As street sweeping, grass clipping management, and castellated kerbs all act to reduce the load of phosphorus generated from roads, the combined effects of these management options were modelled using a build-up wash-off model as described in 2.3.2 and used to predict the total percentage reduction in the phosphorus load from roads due to the selected combination of these options in each scenario.
- **Household fertilizer management** The percentage reduction in phosphorus concentration due to management of household fertilizer use was applied to all area classified as suburban and permeable, and calculated based on the difference in total phosphorus load generated from suburban pervious land across the catchment with and without household fertilizer management.

The catchment model for the Lake Tuggeranong catchment estimates the current load of phosphorus entering Lake Tuggeranong at 1,442 kg/year (Dey, Stewart, Kahn, Booksmythe, & Starrs, 2024). Under the cost-effective scenario, the model estimates that this load would be reduced to 992 kg TP/year (a reduction of 450 kg/year) and under the broad benefits scenario, the model estimates that the load would be reduced to 868 kg TP/year (a reduction of 574 kg/year; Figs. 2, 3).

The estimated reductions in TP load for each proposed management scenario generated by the catchment model are substantially lower than the reductions calculated by adding the individual estimated reductions for each management option (~ 450-575 kg/year vs. ~ 700-750 kg/year, respectively). The major interactive effects explaining this difference are those between management options that prevent TP from entering the stormwater system, such as street sweeping and household fertilizer management, and options that intercept and remove TP from stormwater, such as WSUD infrastructure. Options that prevent TP from entering stormwater have the effect of reducing TP concentrations in the stormwater that will be intercepted by WSUD-type options, which lowers the rate at which these can remove P. Considering management options that act to reduce runoff generation and flatten the peaks of storm flows, might help to improve the performance of WSUD management options in these scenarios.

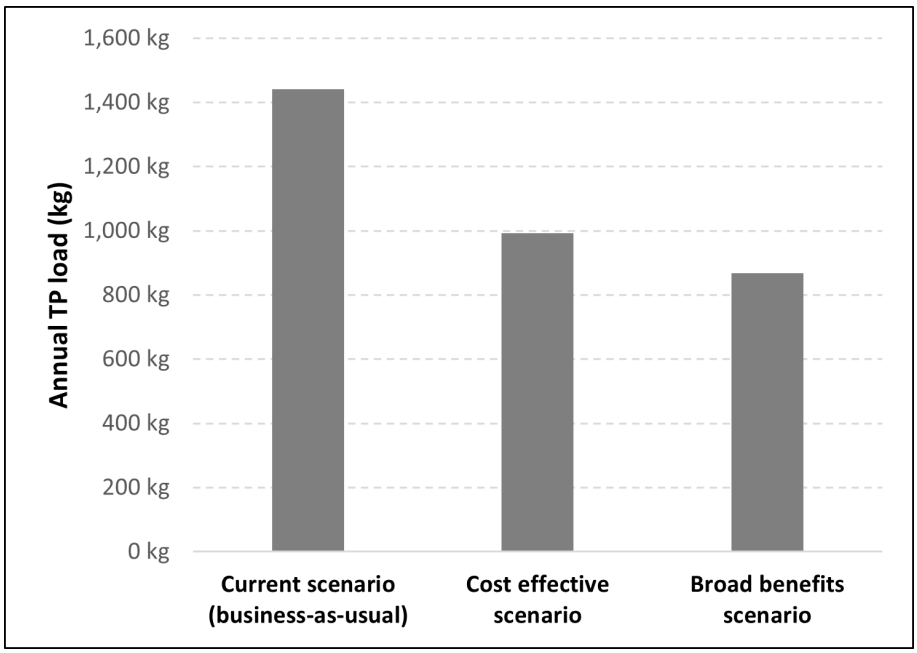

Figure 2. Modelled average annual load of total phosphorus (TP) generated in the Lake Tuggeranong catchment under three management scenarios.

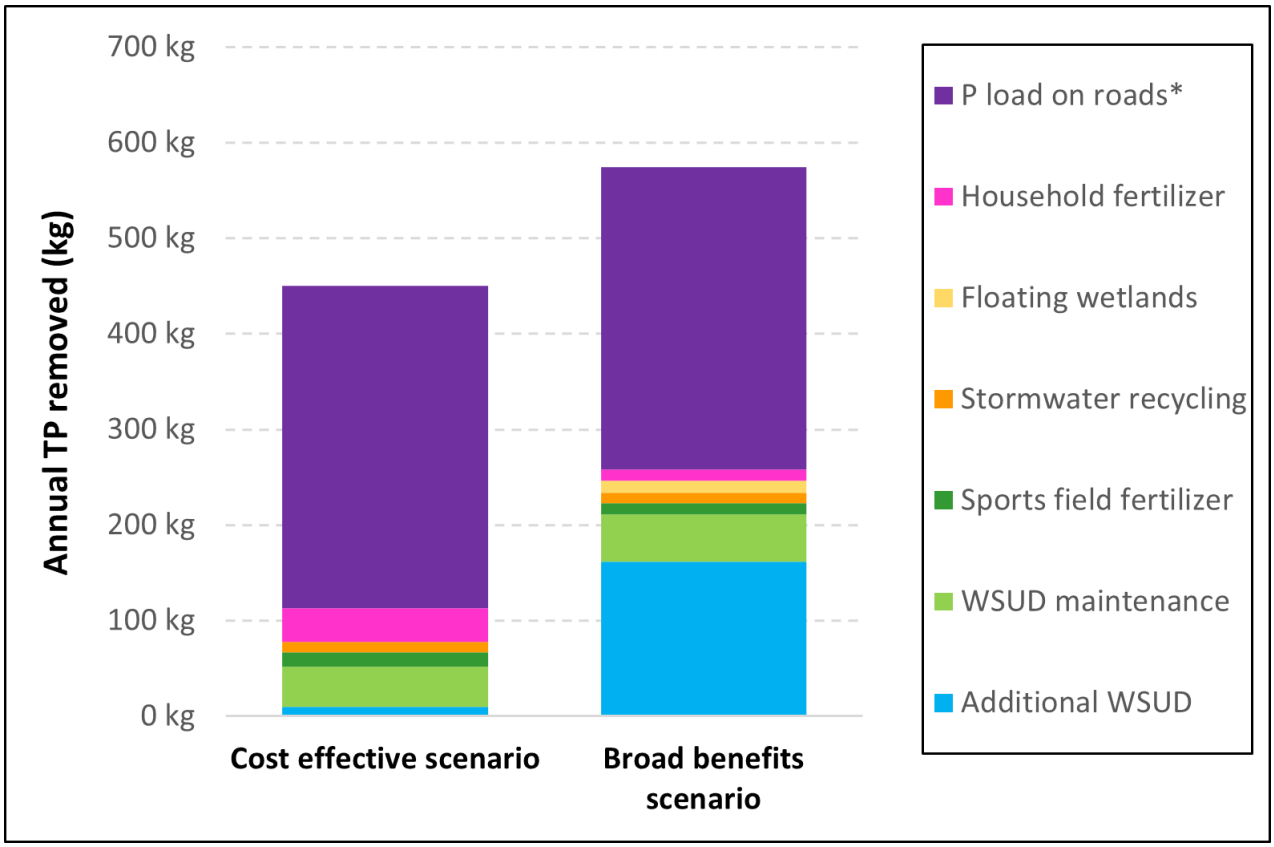

Figure 3. Modelled average annual reduction in the load of total phosphorus (TP) generated in the Lake Tuggeranong catchment, under the cost effective and broad benefits management scenarios. Colours indicate the reduction due to different management options in each scenario. * P load on roads includes the reductions in TP load due to street sweeping, grass clippings management and installation of castellated kerbs.

3.4 Summary

This report has described the approaches used to estimate the phosphorus removal performance and implementation cost of proposed management options for the Lake Tuggeranong catchment. These estimates were used to compare the cost-effectiveness of different management options, and create combinations of options aimed at achieving a ~700 kg reduction in the annual phosphorus load entering Lake Tuggeranong. The Lake Tuggeranong catchment model was used to simulate the effects of these combinations of management options and estimate long-term mean annual inflows and phosphorus loads to Lake Tuggeranong under each scenario.

The management option assessments aimed to provide evidence-based estimates of cost-effectiveness:

- Estimates of the phosphorus removal performance and implementation costs of management options were based on multiple sources, including local implementation of similar management options wherever possible.
- Estimates of the cost of implementation were calculated over a 30-year lifespan for all management options, to allow for the comparison of options with disparate cost distributions.
- A range of estimates was produced for both performance and cost wherever possible, to understand and incorporate uncertainty in the predicted cost-effectiveness of each management option.
- Cost-effectiveness was calculated for each option at four levels of investment to allow its assessment within as well as between management options.
- Confidence in the estimates provided by these assessments was evaluated systematically using a rubric to score the quality of supporting evidence for both the performance and cost estimates for each management option.

Key results of the management options assessment exercise include:

- Increasing the frequency of street sweeping and installing additional WSUD infrastructure are the management options with the largest predicted impacts on reducing phosphorus loads entering Lake Tuggeranong each year.
- Increasing the frequency of street sweeping is estimated to be the most cost-effective management option of those assessed.
- Management scenarios created by combining management options with the aim of achieving a 700 kg reduction in the annual load of phosphorus entering Lake Tuggeranong are estimated to have a total 30-year cost of between $100-145 million.
- Simulating these management scenarios in the Lake Tuggeranong catchment model allows estimation of the predicted reduction in phosphorus entering the lake while accounting for interactions between the different management options included. The model estimates that the average annual phosphorus load to Lake Tuggeranong would be reduced to between 868-992 kg, a 33-44% decrease compared to current catchment conditions.

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5. Appendices

5.1 Appendix A: Quality of evidence assessment rubric

To evaluate the sources of evidence used to inform our assessments of the cost-effectiveness of catchment management options, we designed a rubric to score each option against 9 criteria addressing the information on option cost (4 criteria) and option efficacy (5 criteria) (Table A1).

Table A1. Rubric used to score the quality of evidence informing the assessments of cost-effectiveness of the 10 catchment management options included in this report.

Criterion	Maximum score	1 (weak)	2 (fair)	3 (good)	4 (very good)
Estimates of cost	14				
C1: How recent are cost estimates?	4	Based on implementation 5-10 years ago; **not** 2024 currency	Based on implementation 5-10 years ago; 2024 currency	Based on implementation within the last 5 years; **not** 2024 currency	Based on implementation within the last 5 years; 2024 currency
C2: Source of cost estimates?	4	Not based on previous implementation	Based on implementation overseas	Based on implementation in Australia	Based on implementation in the ACT
C3: Number of independent sources of cost estimates?	3	Costs inferred, from a single source	Based on implementation, from a single source	Based on implementation, from multiple independent sources	
C4: How is variability in cost estimates considered?	3	Based on a single point estimate (+/- 50% or more)	Based on a limited range of estimates (+/- 20-50%)	Based on a substantial range of estimates (+/- 20% or less)	
Estimates of performance	16				
P1: Source of pollutant estimates?	4	Poorly understood	Indirectly inferred from Australian/ overseas data	Indirectly inferred from local empirical data	Directly quantified from local empirical data
P2: Source of performance estimates?	3	Not based on empirical data	Indirectly inferred from local data, or quantified elsewhere	Directly quantified from local empirical data	

Criterion	Maximum score	1 (weak)	2 (fair)	3 (good)	4 (very good)
P3: Is the option explicitly modelled?	3	Represented indirectly in the catchment model, conceptually inconsistent	Represented indirectly in the catchment model, conceptually consistent	Represented explicitly in the catchment model	
P4: Confidence in scaleability of performance?	3	Not understood or not explicitly represented	Inferred from conceptual understanding, explicitly represented	Based on empirical data, explicitly represented	
P5: How is variability in performance estimates considered?	3	Based on a single point estimate (+/- 50% or more)	Based on a range of estimates (+/- 20-50%)	Based on statistical analysis of empirical/ modelled data (+/- 20% or less)	

CABINET

ACT Government

City and Environment Directorate

Ministerial Brief

To:	Minister for Climate Change, Environment, Energy and Water	**Tracking No.: 25/222**
Date:	30/7/2025	
From:	Executive Group Manager, Climate Change, Energy and Water	
Subject:	Final lodgement of 'Options for restoring Lake Tuggeranong', a draft of the 'Healthy Waterways Plan for Lake Tuggeranong'	
Critical Date:	**18/08/2025**	
Critical Reason:	The final submission must be lodged with Cabinet Office on or before 18/08/2025 for Cabinet consideration	

- DDG …/…/…

Recommendations

That you:

1. Sign and agree to lodge the final Cabinet Submission at Attachment 1 and associated documents with the Cabinet Office;

Signed / Not Signed / Please Discuss

2. Annotate if a CED official is required to attend Cabinet.

Required / Not Required / Please Discuss

3. Note that changes have been made in *the Options for Restoring Lake Tuggeranong (the draft Plan)* to recognise Traditional Custodian connection to Country and support planned consultation;

Noted / Not agreed / Please Discuss

4. Note that ongoing consultation with Traditional Custodian on catchment management will include some high-level consultation on Plan implementation approaches – but **not** distribution of the draft Plan – prior to Cabinet consideration.

Noted / Not agreed / Please Discuss

Suzanne Orr MLA 12/08/25

Minister's Feedback

Background

1. Since 2014, the ACT Government has invested approximately $44 million in Lake Tuggeranong through Stages 1 and 2 of the Healthy Waterways Program (the Program) to address ongoing water quality issues.
2. In the 2023-24 Budget the Government committed to developing catchment plans that would consolidate learnings from the Program and present options to Government to address water quality in four urban lakes and ponds, and in the Naas/Gudgenby rural catchment (2023-24 Business Case EPSDD C02 – Expanding Healthy Waterways – Consolidating Gains).
    a. The Naas/Gudgenby catchment plan was delivered in 2023 and is informing investment under the Restoring the Upper Murrumbidgee River Program, a joint program between the Commonwealth and ACT Governments.
    b. The Lake Tuggeranong plan is the first of the four urban plans to be developed, to be followed by Lake Burley Griffin (Q4 2026), Lake Ginninderra (Q2 2027) and Yerrabi Pond (Q2 2027).
3. For this term, the Government priority (208) is to Develop and deliver a 10-year plan for a healthier Lake Tuggeranong.
4. Options for restoring Lake Tuggeranong (the draft Plan) is a draft of the Healthy Waterways Plan for Lake Tuggeranong (the final Plan), which will be finalised following public consultation and consideration by Cabinet.
5. This submission seeks Cabinet approval to take the draft Plan to community consultation to inform the development of the final Plan.

Issues

6. Through the Program and its productive collaboration with researchers from the University of Canberra, we now know that algal blooms are being driven by excessive amounts of phosphorus entering the lake through stormwater inflows from many diffuse sources.
7. Modelling has been used to:
    a. Model water quality and quantity for the Tuggeranong catchment (Attachment G);
    b. Develop an in-lake model to set the target phosphorus reduction amount (Attachment H); and
    c. Assess the cost-effectiveness ($/kg phosphorus reduced) of different mitigation options (Attachment I).
8. According to water quality models, seven of the recently built water quality assets are intercepting only 13% of the nutrient pollution destined for Lake Tuggeranong. This demonstrates that water quality assets are necessary to intercept unavoidable pollution, but on their own won't remove enough phosphorus to solve the problem. The draft Plan

identifies and assesses a range of other ways to reduce phosphorus which can be used to improve on the reductions achieved by water quality assets.

9. Modelling indicates that measures to prevent phosphorus entering stormwater in the first place are more cost-effective than removing it through water quality infrastructure like wetlands. Increasing the frequency of street sweeping is the most cost-effective of all the options assessed.

10. No individual management options are a 'silver bullet'. Multiple options will need to be implemented to achieve a meaningful decrease in the incidence of algal blooms in Lake Tuggeranong.

11. The draft Plan provides two indicative scenarios for investment: one based only on cost-effectiveness, and one including more costly options like wetlands which provide broader benefits like improving biodiversity and amenity.

What can be achieved in Lake Tuggeranong

12. In managing Lake Tuggeranong, we want to reduce the amount of phosphorus in the lake by 700kg/year as that will, based on our modelling, allow the lake to be suitable for contact-based activities on average in three out of four years (Attachment H).

13. Following Cabinet and agency feedback and community consultation on the options, the final Plan will be developed.

14. The final version of the Plan will be brought to Cabinet at the first available opportunity in 2026 and published on the CED website as soon as practicable after Cabinet consideration.

15. Business cases will then be developed to implement the Plan.

Financial Implications

16. Improving water quality in Lake Tuggeranong requires significant investment by Government over the longer term, estimated at $105-$144 million over 30 years (Attachment I).

17. You supported a business case for ERC's consideration in the 2025-26 budget Improving Lake Tuggeranong (EPSDD E16). The business case requested funding for $2.6 million for one year only: for 'no-regrets' options to start to implement the recommendations in the draft Plan, including retaining staff required to do necessary planning.

18. You may consider bringing forward a more substantial business case to the 2026-27 budget. That business case would provide costings for a detailed plan of implementation, informed by community and Government feedback on the approach proposed in this draft Plan.

Consultation

Internal

19. The Office of Water - Water Information Services Team provided extensive modelling to underpin the draft Plan, including three supporting technical reports detailing methodologies (Attachments G, H, I) that will be published on CED's website alongside the draft Plan.

20. The CED Communications and Engagement team developed the Communications and Engagement Strategy (Attachment D), an At-a-glance Snapshot of the draft Plan and the proposed community consultation (Attachment E).

Cross Directorate

21. The Healthy Waterways Team met with CMTEDD (Finance and Budget Group) on 5 March 2025 to discuss the Cabinet Submission and associated 2025-26 Business Case. The Group encouraged finalisation of the Plan to support future business case development and sought clarity on any funding overlap with the Water Efficiency Business Case. This information was provided on 18 March, confirming no overlap.

22. The Healthy Waterways Team worked closely with the former TCCS in developing the draft Plan:

    a. With Roads ACT to carry out the street sweeping trial. Roads ACT also provided estimated costs of street sweeping to be included in cost modelling.

    b. ACT Sport and Recreation provided input on sports field fertiliser management practices.

    c. Place Management provided estimated costs for the mitigation option around improving open space mowing to reduce the impact of grass clippings.

    d. With ACT NoWaste, discussing the potential for street sweeping trucks and green bins to have Healthy Waterways messaging on them.

23. The ACT Chief Health Officer provided advice on current understanding of the potential links between cyanobacteria (from blue-green algae) and motor neurone disease.

24. Access Canberra (Environment Protection Authority EPA) provided formal comment through exposure round circulation including requesting that the Plan better acknowledge the role the EPA and other agencies play in supporting healthy waterways. The Cabinet package has been amended to address this.

25. The EPA provided informal feedback in a meeting with the Healthy Waterways Team on 28 May 2025, expressing their desire to:

    a. Collaborate more closely in the development of the final Plan to make greater use the regulatory framework to reduce phosphorus pollution, and

b. Provide input into activities as part of the public consultation process on the draft Plan, and Healthy Waterways community partnership program generally, to ensure that educational messaging also informs the community and businesses of their regulatory obligations regarding waterways.

The proposed response to EPA requests is discussed in the 'Sensitivities' and 'Communications, media and engagement' sections below.

External

26. The draft Plan has been reviewed by two expert reviewers, Prof Fiona Dyer (University of Canberra) and Prof Tim Fletcher (University of Melbourne).

27. From mid-2023 the Healthy Waterways team delivered presentations on the research findings and proposed direction of the draft Plan to the Tuggeranong Community Council, ACT and Region Catchment Management Coordination Group, and Upper Murrumbidgee Catchment Network.

28. Initial Ngunnawal Traditional Custodian input on the draft Plan was gained through an Aboriginal Water Assessment undertaken in 2022, facilitated by the Office of Water's Ngunnawal Water Policy Officer.

29. As a part of an ongoing program of consultation with Ngunnawal Traditional Custodians and other Aboriginal and Torres Strait Islander people with connections to the lands and waters of the ACT and Region, facilitated conversations on catchment management and Plan implementation approaches will occur ahead of formal community consultation, and before the Plan is considered by Cabinet.

    a. The draft Plan itself will not be shared. Consultation will draw on public commitments with the aim of helping us understand key cultural values and considerations for working with Traditional Custodians as a part of future implementation.

    b. Consultant Paul Knight will lead this process in August, as part of an Office of Water project to strengthen engagement with First Nations on water issues.

    c. The implementation phase of the Plan, once agreed, will provide additional opportunity for continuing engagement with Traditional Custodians on delivery of the Plan.

30. Note that since you last reviewed the draft Plan, minor edits have been made to several leading paragraphs of the draft Plan to raise the profile of Traditional Custodian connection to Country and aid consultation with Traditional Custodians, as per consultant advice.

Work Health and Safety

31. Nil.

Benefits/Sensitivities

32. Improving the water quality in the lake will have wellbeing benefits in the environment and climate domain, as well as economic benefits. The Wellbeing Impact Assessment is at Attachment C.

Inclusion of the cost estimates in the draft Plan

33. The plan includes the estimated costs of different mitigation options, and the estimated cost to implement the Plan over 30 years. Including the figures in this public facing document transparently conveys to the community the level and timeframe of investment needed to fix the problem.

Potential use of algicides

34. The draft Plan notes that in the future treatment options such as algicides (chemical treatment to kill algae) may be required to control severe blooms. There may be community opposition to their use because of environmental impacts.

    a. The draft Plan proposes further investigations to assess the effectiveness and potential environmental impacts of using algicides to control algal blooms in Lake Tuggeranong.

    b. As these investigations are yet to occur, community consultation on the draft Plan will not include consulting on potential algicide use.

Blue-green algae and motor neurone disease

35. The draft Plan discusses potential health risks associated with blue-green algae and motor neurone disease. There's a growing body of evidence on the issue and it has had media attention. In 2023, the NSW Government announced $2 million for urgent research into motor neurone disease and its connection with blue-green algae, including in the Riverina irrigation district where the incidence is seven times the national average (Media release).

36. A causal link and level of exposure risk has not yet been conclusively established by the scientific community. However, if aerosolized exposure to bloom-affected lake water is considered as a risk, as suggested in the draft Plan, this presents an elevated health risk for Tuggeranong residents living by the lake or using the lake surrounds, not just those who use it for primary and secondary contact activities.

Use of the regulatory framework to achieve phosphorus reduction

37. The EPA provided informal feedback that the Plan misses the potential to utilise the regulatory framework more strongly to address Lake Tuggeranong's algal bloom problems, and that a regulatory approach was not included in the modelled solutions.

38. The nature of the problem does not lend itself to a regulatory solution. Non-point source pollution is typically difficult to regulate because it is coming from many diffuse sources and is difficult to monitor and enforce.

39. The Healthy Waterways team undertook preliminary investigation into regulating the sale, or use of, fertiliser, but based on internal advice on costs and resourcing required to develop new or amended regulation, the Healthy Waterways Team considered other approaches to be 'lower-hanging fruit', and did not explore this, or other, regulatory solutions further.

40. While new or amended regulation wasn't included as a modelled management option, the modelled options all implicitly reflect the existing regulatory landscape and level of compliance with it.

41. The Healthy Waterways Team will engage with the EPA to better understand the scope of regulatory options currently available to support implementation of the Plan but does not intend to pursue new regulatory options (new or amended legislation) at this stage for the Tuggeranong catchment.

Communications, media and engagement implications

42. The draft Plan presents information about the underpinning science and modelling that may be too detailed for many in the community. However, it's important to include this information to convey the problem and solutions accurately, to provide confidence in the findings and conclusions, and to set community expectations about what is realistically achievable for Lake Tuggeranong and expected timeframes for change.

    a. The three technical reports underpinning the draft Plan (Attachments G, H, I) provide even more detail and, subject to your approval, will be published on the EPSDD website.

43. The Communications and engagement strategy (Attachment D) has been developed to provide community with the opportunity to have their say and allows for an eight-week consultation period.

44. Communications consultants 'Communications Link' have been engaged to help facilitate engagement with the community.

45. Consultant Paul Knight has been engaged to facilitate targeted engagement with First Nations in the first two weeks of August.

a. This timing is necessary to align with the Office of Water's broader consultation process with First Nations, established to reduce the burden of consultation on First Nations communities on water issues.

b. Engagement will be in the form of facilitated conversations on the management options: the draft document will not be shared.

c. The EPSDD Communications and Engagement team will seek your approval on any additional supporting materials developed for the purpose of First Nations consultation.

46. An 'At a Glance snapshot' document will form part of the communications materials, giving Community a snapshot of what the consultation is about and how they can participate (Attachment E).

Signatory Name: Tom Nilsen

Action Officer: Katie Miller

Attachments

Attachment	Title
Attachment 1	A – Table of Comments B – Open Access Assessment: Cabinet Decision and Wellbeing Impact Assessment Summary C – Wellbeing Impact Assessment D – Communications and Engagement Strategy E – 'At a Glance' Snapshot F – Options for Restoring Lake Tuggeranong (draft Plan) G – Technical report #1 – Dey et al (2024) H – Technical report #2 – Kahn and Dey (2024) Report supplement – Lake Tuggeranong In-lake model I – Technical report # 3 – Booksmythe et al (2024) – Lake Tuggeranong Catchment Management Options Assessment Report
Attachment 2	Cabinet brief

CABINET SUBMISSION

Cabinet number	**25/222**	
Title	**Healthy Waterways Plan for Lake Tuggeranong**	
Meeting Type	Cabinet	
Minister	Suzanne Orr MLA Minister for Climate Change, Environment, Energy & Water	
Co-Sponsoring Minister/s	N/A	
ERC date	Tuesday, 8 July 2025	
Cabinet date	Wednesday, 30 July 2025	
Status	FINAL	
Relationship to previous decisions	2023/24 ERC EPSDD CO2 Expanding Healthy Waterways – Consolidating Gains	
Submission type	Agree to public consultation	
Purpose	To approve release of 'Options for Restoring Lake Tuggeranong' (draft Plan) for public consultation	
Category	Category 2 - Government business	
Financial Impact	No	
Treasury Agreement	Yes	28/04/2025
	Date of Treasury agreement:	13/05/2025
Technology Impact	No	
Digital, Data & Technology Solutions Consultation	No	Click or tap to enter a date.
Service delivery impact	No	
Access Canberra Consultation	No	Click or tap to enter a date.
Legislative change	No - change to legislation not required	
PCO/JACS Human Rights	N/A	Click here to enter a date.
	N/A	Click here to enter a date.
Regulatory impact	No	Click here to enter text
Wellbeing Impact Assessment	Yes	
Primary Wellbeing Domain	Environment and climate	
Closing the Gap - Priority Reforms	Not in Scope for Closing the Gap Priority Reform	

Minister's signature_____ Date 12/08/2025

RECOMMENDATIONS

1) I recommend Cabinet agree:

   a. To release the report 'Options for Restoring Lake Tuggeranong' (the draft Plan) (Attachment F) and the 'At a glance snapshot' (Attachment E) for public consultation using the Communications Strategy outlined in Attachment D, and

   b. that the Minister for Climate Change, Environment, Energy and Water finalise any minor amendments to the draft Plan prior to releasing for public consultation.

   c. Supporting communications materials will be approved by the Minister for Climate Change, Environment, Energy and Water.

2) I recommend Cabinet note:

   a. The final 'Healthy Waterways Plan for Lake Tuggeranong' (the final Plan) will be brought to Cabinet following the public consultation, likely early 2026.

   b. The final Plan will deliver on a 2024 election commitment to *'develop and deliver a 10-year plan for a healthier Lake Tuggeranong'*.

   c. The draft Plan is underpinned by three comprehensive technical reports detailing modelling and other analyses. These will be made publicly available on the EPSDD website at the time of the draft Plan's public release (Attachments G, H, I).

   d. The proposed release of the following Cabinet Decision and Wellbeing Impact Summaries as required under Section 23 of the *Freedom of Information Act 2016*:

      i. Cabinet agreed to the release of the draft Healthy Waterways Plan for Lake Tuggeranong for public consultation. The draft Plan describes current knowledge about what's causing blue-green algal blooms in Lake Tuggeranong, and, using modelling of catchment hydrology and mitigation costs, presents management options for addressing them.

      ii. Lake Tuggeranong's frequent blue-green algal blooms have negative visual and smell impacts, present health risks, and prevent people from recreating in and around the lake. Using current scientific understanding of what's causing Lake Tuggeranong's algal blooms, the draft Plan presents a ten-year vision to improve water quality in the catchment to reduce the frequency and severity of blooms. This will have positive wellbeing benefits for the Tuggeranong community through reducing health risks, providing access to blue-green space, and enhancing cultural and biodiversity values.

   e. The Minister for Climate Change, Environment, Energy and Water has brought forward a proposal relating to the implementation of the draft Plan for consideration in the 2025-26 budget (*Healthy Waterways – Improving Lake Tuggeranong – election commitment).*

SUPPORTING ARGUMENT

BACKGROUND

1) For at least the past decade Lake Tuggeranong has experienced poor water quality and regular blue-green algae blooms in summer, reducing the amenity and recreational values provided by the lake. This has been a consistent, high-profile issue for the Tuggeranong community and a complex problem to address.

2) The ACT Healthy Waterways program (Healthy Waterways) was established in 2014 to address water quality problems in Canberra —including in Lake Tuggeranong—through planning and on-ground actions. There have been two stages to the program:

   a. Stage 1 (2014-2021), a $94 million joint initiative of the Australian and ACT Governments

   b. Stage 2 (2021-June 2025) 'Expanding Healthy Waterways', to fulfil the Parliamentary and Governing Agreement for the 10th Legislative Assembly commitment to *Expand Healthy Waterways: $30 million over 4 years*. This commitment is to investigate water quality and plan and deliver pollution mitigation works for Lakes Tuggeranong, Burley Griffin and Ginninderra, Yerrabi Pond and the Nass/Gudgenby rural catchment. The outputs will be finalised through 2027.

3) Across the two stages approximately $44 million has been invested to better understand Lake Tuggeranong water quality issues and how to solve them, as well as on-ground works to begin to improve water quality in Lake Tuggeranong. These include:

   a. Building nine water quality assets

   b. Education programs

   c. Research and monitoring

   d. Catchment hydrological and water quality modelling and data analyses.

ISSUES AND OPTIONS

Plan scope - a water quality plan focusing on blue-green algae

4) The draft Plan presents, for the first time, a comprehensive suite of management options to reduce the nutrients coming off the catchment contributing to the formation of algal blooms, drawing on lessons learned from the past ten years of investment.

5) The draft Plan focuses on one aspect of water quality - nutrient pollution, and specifically the nutrient phosphorus, because of its key role driving algal blooms which most heavily impact the amenity of the Lake.

6) A ten-year timeframe is proposed to implement the Plan, with interim goals set for 2030. This timeframe is needed to implement management interventions and to evaluate their effectiveness.

Public Consultation Plan

7) The public consultation process described in this submission is an important way to confirm community support (or otherwise) for the proposed mitigation options. Feedback from this process will inform the final Plan along with technical and budget considerations.

8) The Communications and engagement strategy (Attachment D) has been developed to provide community with the opportunity to have their say and allows for an eight-week consultation period.

9) An 'At a glance snapshot' document (Attachment E) will form part of the communications materials, giving community a snapshot of what the consultation is about and how they can participate. The snapshot is designed to complement the data rich and technically detailed draft Plan (Attachment F).

10) Communication consultants will be engaged to help facilitate engagement with the community, and with First Nations.

The options presented to reduce phosphorus to prevent algal blooms

11) Modelling suggests that the level of phosphorus reduction required to reduce the incidence of algal blooms in Lake Tuggeranong is 700 kg phosphorus/year (phosphorus reduction target). This target was derived using an in-lake model (Attachment G).

12) Modelling indicates that achieving the phosphorus reduction target would shift the lake away from a state of being primed for an algal bloom most summers to a state where algal blooms form in just one out of every four years on average.

13) Detailed analyses were undertaken of the cost and benefit (kg phosphorus removed/year) of ten management options for reducing phosphorus pollution, including:

    a. Increasing street sweeping to remove leaf litter from roads
    b. Using behaviour change strategies to encourage high-fertiliser-using households to use less fertiliser
    c. Implementing extra measures to prevent grass clippings from open space mowing operations ending up in waterways
    d. Subsidising the installation of household rainwater tanks
    e. Building stormwater recycling on sportsfields
    f. Retrofitting outlets into road kerbs (castellated kerbs) to divert stormwater to open green space
    g. Building bioretention swales on sportsfields (using vegetation to filter surface flow of nutrients)
    h. Building more large water quality assets low in the catchment (e.g. raingardens – a type of constructed wetland)
    i. Improving maintenance of existing water quality assets, built via the Healthy Waterways program, to optimise their phosphorus removal performance
    j. Building more floating wetlands.

14) The costs and phosphorus reduction benefits of each option are summarised in the draft Plan and detailed further in a supporting technical report (Attachment I).

15) Key conclusions are:

    a. The most effective way to reduce phosphorus is through increased street sweeping.
    b. There is no 'silver bullet' for solving the problem. Multiple management options will need to be implemented to reach the phosphorus reduction target and so reduce the incidence of algal blooms.

c. Building additional large wetlands low in the catchment—the focus of Healthy Waterways investment to date—is necessary but not the answer on its own.

16) Two packages of mitigation options were developed to demonstrate how combinations of options might reach the target, and the cost of doing this: a 'cost-effective' package and a 'broad benefits' package. These were developed for indicative purposes only, with the intention that they would be informed by feedback from the community on the different options.

Alignment with other Territory planning priorities

17) The draft Plan aligns with community feedback heard during the development of the Tuggeranong District Strategy, in which the Tuggeranong community expressed that they value the lake for a range of recreational activities throughout the year, including walking, cycling, swimming, fishing and windsurfing (ACT Government, 2023).

18) Building and maintaining large water quality assets like wetlands and raingardens can also help achieve Territory Planning objectives to improve Biodiversity Sensitive Urban Design, enhance the Blue-Green network, and promote urban cooling.

a. Large water quality assets have an urban cooling effect, contributing to the implementation of Canberra's Living Infrastructure Plan: Cooling the City.

i. A recent study on ACT living infrastructure found two sites (Crace stormwater basin, and Bonner wetland) were 2-2.5^{0}C cooler than the overall average of sites measured (CSIRO. 2024. *Measuring the Cooling benefits of Living Infrastructure– report for EPSDD*).

b. Constructed wetlands and raingardens help to restore aquatic habitat to degraded urban channels, supporting the implementation of the ACT Nature Conservation Strategy and Connecting Nature Connecting People initiative.

FINANCIAL IMPACT

19) There are no financial impacts from this paper, there will be financial impacts arising from implementing actions under the Healthy Waterways Plan which will be subject to future budget processes. Cost modelling indicates that fully implementing the plan to achieve target phosphorus reductions would cost between $105-$144 million over ten years (Attachment I).

20) The Minister for Climate Change, Energy, Environment and Water has brought forward a business case for consideration in the 2025-26 budget for one year of investment to undertake trials into in-lake treatment in Isabella Ponds and plan for capital works.

TECHNOLOGY IMPACT

21) There is no technology impact from this proposal.

SERVICE DELIVERY IMPACT

22) One management option presented in the draft plan is to increase the frequency of street sweeping. This would impact on service delivery by Roads ACT. Funding for increased service delivery would be sought through the budget process.

WELLBEING IMPACT SUMMARY

23) Lake Tuggeranong's frequent blue-green algal blooms have negative visual and smell impacts, present health risks, and prevent people from recreating in and around the lake. Using current scientific

understanding of what's causing Lake Tuggeranong's algal blooms, the draft Plan presents a ten-year vision to improve water quality in the catchment to reduce the frequency and severity of blooms. This will have positive wellbeing benefits for the Tuggeranong community through reducing health risks, providing access to blue-green space, and enhancing cultural and biodiversity values.

CLOSING THE GAP - PRIORITY REFORMS

24) Not in scope for Closing the Gap – Priority Reforms.

CONSULTATION

External stakeholders

25) The draft Plan has been reviewed by two external experts, Prof Fiona Dyer (University of Canberra) and Prof Tim Fletcher (University of Melbourne).

26) The Healthy Waterways team have delivered presentations on the research findings and proposed direction of the draft Plan to the Tuggeranong Community Council, ACT and Region Catchment Management Coordination Group, and Upper Murrumbidgee Catchment Network.

27) Initial Ngunnawal Traditional Custodian input on the draft Plan was gained through an Aboriginal Water Assessment undertaken in 2022, facilitated by the Office of Water's Ngunnawal Water Policy Officer. To gain further perspectives of Ngunnawal Traditional Custodians and other Aboriginal and Torres Strait Islander people with connections to the lands and waters of the ACT, Aboriginal consultant Paul Knight will lead facilitated conversations in the first half of August on options for Lake Tuggeranong as part of an Office of Water project to strengthen engagement with First Nations on water issues.

ACT Government Agencies

28) The Healthy Waterways team worked closely with TCCS on asset designs, street sweeping, sports field fertiliser management and grass clipping management on road verges in preparing the draft Plan.

29) The ACT Chief Health Officer provided advice on current understanding of the links between cyanobacteria (from blue-green algae) and motor neurone disease.

MEDIA AND COMMUNICATIONS

30) The Communications and Engagement Strategy is at Attachment D. A draft 'At a Glance' snapshot is at Attachment E.

IMPLEMENTATION

31) The final Plan will be presented to Cabinet in early February 2026, with more refined options based on community feedback from the draft, and in consultation with ACT Government agencies including the EPA. Further implementation will depend on ERC's consideration of future business cases.

Table 2: **Implementation milestones and timeframes to publishing of final Plan**

Milestones	Date complete
1. Public consultation on draft Plan (including with First Nations)	24 September 2025
2. Listening/consultation report published	24 October 2025
3. Consultation with other ACT government agencies to develop implementation approach in final plan	November 2025
4. Final Plan brought to Cabinet	Early February 2026

5. Plan published	March 2026
Final completion date:	March 2026

HUMAN RIGHTS IMPACT

32) The right to a healthy environment is enshrined in the *Human Rights Act 2004*, with the right applying to all relevant policies and legislation. The Healthy Waterways Program aims to improve water quality for the Territory, contributing to healthy environments.

ATTACHMENTS

A	Table of comments
B	Open Access Assessment: Cabinet Decision and Wellbeing Impact Assessment summary
C	Wellbeing Impact Assessment
D	Communications and Engagement Strategy
E	'At a Glance' snapshot
F	*Options for Restoring Lake Tuggeranong* (draft Plan)
G	Technical report #1 – Dey et al (2024) Lake Tuggeranong Catchment Model Calibration Report
H	Technical report #2 – Kahn and Dey (2024) Report supplement – Lake Tuggeranong In-Lake model
I	Technical report #3– Booksmythe et al (2024) Lake Tuggeranong Catchment Management Options Assessment Report

ACT Government

MINISTER'S CABINET BRIEF

Cabinet Number	**25/222**
Title	Healthy Waterways Plan for Lake Tuggeranong
Minister	Suzanne Orr MLA
Portfolio	Minister for Climate Change, Environment, Energy & Water
Co-Sponsoring Ministers	N/A
Cabinet date	Wednesday, 10 September 2025
Recommended position	SUPPORT

Submission recommendations

That you support all recommendations.

Issues/comment

During exposure circulation, formal comments were received from CMTEDD (Access Canberra, Environment Protection Authority (EPA)). The comments (Attachment A) relate to acknowledgment of the role of the EPA in protecting Lake Tuggeranong, and implications for resourcing regulatory compliance. The Submission was amended to address the comments.

All other agencies supported the exposure draft with nil formal comment. Minor edits were made in response to informal comment.

Wellbeing Impact Assessment

Implementation of the Healthy Waterways Plan will have a positive impact on the wellbeing of residents in Tuggeranong and visitors to Tuggeranong by improving water quality in the lake and its catchment.

Context and consultation

The draft Plan responds to the Government priority for this term (208) to develop and deliver a 10-year Plan for a healthier Lake Tuggeranong. The Government committed to developing catchment plans to improve water quality in the ACT's rural and urban catchments in the 2023-24 budget. Lake Tuggeranong has the worst water quality, receives the greatest amount of community feedback, and is the first urban plan to be developed.

The purpose of releasing the draft Plan now is to gain community feedback on management options to inform development of the final Plan.

ACT Government directorates and community stakeholders have been consulted throughout the draft Plan's development. Stakeholders are supportive of the Government taking action to address longstanding water quality issues in the lake. The EPA and TCCS wish to be consulted during the implementation planning phase, which will occur in late 2025, (i.e. once public consultation has occurred).

Implementation of the Plan supports Government priorities around blue-green space and urban cooling.

Prepared by: Katie Miller
Cleared by: Kieran Lawton

ACT Government

TABLE OF COMMENTS

Attachment A

EXPOSURE DRAFT COMMENTS – 25/222

Exposure circulation undertaken: Full exposure circulation

Dates circulated: 19-26 May 2025

Directorate	Comment	Response
CMTEDD	Support with comment The Environment Protection Authority (EPA) suggests that the cabinet submission, draft plan and attachments be amended to: • provide formal acknowledgment of the role of government agencies including the EPA in the protection of lake Tuggeranong to date and into the future. • formally acknowledge and include the EPA and other government agencies in the development of the consultation process • highlight and address resourcing implications for additional regulatory work that will result from the proposed activities	Text has been added to the draft plan (Attachment F - p16) noting the role of the EPA administering the *Environment Protection Act 1997,* and *Lakes Act 1976.* A summary of agency responsibilities regarding management of Lake Tuggeranong has been added to the draft plan (Attachment F - p17). The Cabinet Submission has been amended to note proposed consultation with other agencies in the development of the final plan (Para 31 – Implementation). Text has been added to the 'Cross-portfolio collaboration and partnerships' section of the Wellbeing Impact Assessment to note collaboration with the EPA (Attachment C p4). No changes to Cabinet Submission regarding resourcing implications for additional regulatory work since additional regulatory work has

		not yet been identified. This will be discussed with EPA at the stage of budget bid development and implementation planning and.
JACS	Supported.	
HD	Supported.	
CHS	Supported.	
EDU	Supported.	
TCCS	Supported.	
CSD	Supported.	
EPSDD	Supported.	
MPC	Supported.	
Statutory Office Holder	Supported.	

FINAL COMMENTS – 25/222

Final circulation undertaken: Choose an item.

Dates circulated: Provide dates circulated

Directorate	**Comment**	**Response**
CMTEDD	Choose an item. [Provide comments.]	[Drafting directorate to provide response]
JACS	Choose an item. [Provide comments.]	[Drafting directorate to provide response]
HD	Choose an item. [Provide comments.]	[Drafting directorate to provide response]
CHS	Choose an item. [Provide comments.]	[Drafting directorate to provide response]
EDU	Choose an item. [Provide comments.]	[Drafting directorate to provide response]

TCCS	Choose an item. [Provide comments.]	[Drafting directorate to provide response]
CSD	Choose an item. [Provide comments.]	[Drafting directorate to provide response]
EPSDD	Choose an item. [Provide comments.]	[Drafting directorate to provide response]
MPC	Choose an item. [Provide comments.]	[Drafting directorate to provide response]
Statutory Office Holder	Choose an item. [Provide comments.]	[Drafting directorate to provide response]

OPEN ACCESS ASSESSMENT

CABINET DECISION AND WELLBEING IMPACT ASSESSMENT SUMMARY

Attachment B

The Chief Minister must proactively release the information described in section 23 of the *Freedom of Information Act 2016* (the FOI Act) unless the information is contrary to the public interest in accordance with sections 16 and 17, and schedules 1 and 2 of the FOI Act. Please refer to the **Cabinet SharePoint Site** for further guidance on what is within the scope of Open Access requirements.

If you believe that release of this information is within the scope of Open Access requirements and would be contrary to the public interest, please complete Part B.

Cabinet Number and title: 25/222 - Cabinet - [ERC 08-07-25] Draft Healthy Waterways Plan for Lake Tuggeranong - Public Consultation

Please select one of the following:

Proposed Release of Cabinet Decision Summaries - Please Complete Part A Only

PART A: Proposed Release or Delayed Release

Proposed Summary of the decision for public release

Cabinet agreed to the release of the draft Healthy Waterways Plan for Lake Tuggeranong for public consultation. The draft Plan describes current knowledge about what's causing blue-green algal blooms in Lake Tuggeranong, and, using modelling of catchment hydrology and mitigation costs, presents management options for addressing them.

Proposed summary of the Wellbeing Impact Assessment for public release

Lake Tuggeranong's frequent blue-green algal blooms have negative visual and smell impacts, present health risks, and prevent people from recreating in and around the lake. Using current scientific understanding of what's causing Lake Tuggeranong's algal blooms, the draft Plan presents a ten-year vision to improve water quality in the catchment to reduce the frequency and severity of blooms. This will have positive wellbeing benefits for the Tuggeranong community through reducing health risks, providing access to blue-green space, and enhancing cultural and biodiversity values.

If a Wellbeing Impact Assessment is not required, please select from the following:

Choose an item.

Other releases – how will the community be informed of the decision of Cabinet?

Expected Milestone for Release	Consultation through YourSay
Expected milestone completion date	14 August 2025

Wellbeing Impact Assessment (WIA)

Resources and support

The Wellbeing Toolkit provides a range of resources to support you to complete a WIA, including the WIA Drafting Guide and details of the Wellbeing Domains. The Drafting Guide includes definitions, prompting questions, examples and other advice related to each section of the WIA.

Support is available from Wellbeing Champions in each directorate. The Wellbeing Team can review and provide advice on draft WIAs where capacity allows – contact the team at WellbeingFeedback@act.gov.au.

Healthy Waterways Plan for Lake Tuggeranong

EPSDD

Purpose of proposal

This proposal seeks Cabinet approval to release the 'Options for Restoring Lake Tuggeranong (draft Healthy Waterways Plan for Lake Tuggeranong) for public comment. The Plan's purpose is to address the problem of blue-green algal blooms in Lake Tuggeranong to improve amenity for Tuggeranong residents and the lake's ecological health.
The Plan summarises current knowledge and scientific understanding about why blooms occur in Lake Tuggeranong and describes alternative ways to reduce nutrients in the catchment, a key contributor to algal blooms.

Wellbeing domains and impact description

Access and connectivity	Economy	Education and life-long learning	Environment and climate	Governance and institutions	Health
Housing and home	Identity and belonging	Living standards	Safety	Social connection	Time

Primary domain	Impact description
Environment and climate	By reducing the frequency and intensity of algal blooms, this proposal will improve the lake's ecological health as severe blue-green algal blooms can impact fish populations and other aquatic biota. There will also be improved urban ecosystem function locally throughout the catchment where non-polluting practices are adopted, and water quality assets are built.
Other domains	
Health	There are health risks to humans and pets associated with contact and/or ingestion of water from lakes affected by toxic blue-green algal blooms. This is why the Government closes lakes when algal populations rise above a threshold level. There are also potential health risks (neurological disorders) associated with aerosolised exposure to the cyanotoxins present in blue-green algae. This proposal aims to reduce the frequency of algal blooms, reducing the potential health risks. This proposal will also significantly improve Lake Tuggeranong's recreational and amenity value and the associated wellbeing of residents and visitors by reducing the frequency of algal blooms and providing access to blue-green spaces.
Social connection	Improved blue-green network (by improving the health of the lake and its catchment's waterways, including building new wetlands) will create more opportunities for increased social connection as people walk, run, cycle, and picnic near the waterways.
Economy	Businesses operating on and near the lake will benefit from reduced algal blooms - a recent literature review found there was a drop in property values of 2-22% for residences nearby waterways that experienced toxic algal blooms (NC Economics 2021).
Governance and institutions	The proposal will improve trust in Government because the Tuggeranong community will see the Government acting on an issue of longstanding concern.

Evidence base and data

Provide evidence that your proposal will have the wellbeing impacts described above. Note that it is not enough to only provide evidence that the issue exists.

Evidence	Source	Type of evidence

• Ecological impacts of blue-green algal blooms	• Potter et al (1983) Blue-green algae and fish population changes in a eutrophic estuary. *Marine Pollution Bulletin* V14 I6: 228-233.	National data or research
• Ecological impacts of blue-green algal blooms	• Sharma et al (2011) Freshwater cyanobacterial (blue-green algae) blooms: causes, consequences, and control. Impact Monitoring and Management	International data or research
• Reduced urban heat and risks of heat stress where water quality assets are built	• Tapsuwan, S, Ingleton, G & Capon, T (2024). Measuring the cooling benefits of living infrastructure in urban Canberra: a report of findings. Canberra.	ACT government data or research
• The importance of blue-green spaces for wellbeing	• Dushkova et al (2021). Human Dimensions of Urban Blue and Green Infrastructure during a pandemic. Case study of Moscow (Russia) and Perth (Australia). *Sustainability* 13: 414-4172	National data or research
• The importance of blue-green spaces for wellbeing	• UK Environment Agency (2020) The social benefits of blue space: a systematic review	International data or research
• Residents want an improved blue-green network and improved water quality in Lake Tuggeranong	• Tuggeranong District Strategy Planning System Review and Reform Project (Listening Report)	ACT government data or research
• Residents want an improved blue-green network and improved water quality in Lake Tuggeranong	• Tuggeranong Community Council 2024 survey of residents	ACT government data or research
• Residents want an improved blue-green network and improved water quality in Lake Tuggeranong	• Schirmer and Mylek (2016) Water Quality and the community: understanding the views, values and actions of residents of the ACT and surrounding region.	ACT government data or research
• Residents are willing to pay up to $280/pp/year to *greatly improve* the amenity of Lake Tuggeranong	• Natural Capital Economics 2023. Economic values of ACT Urban Lakes.	ACT government data or research
• Potential human health risks associated with exposure to blue-green algae	• Cox et al 2003 Biomagnification of cyanobacterial neurotoxins and neurodegenerative disease among the Chamorro people of Guam.	International data or research
• Potential human health risks associated with aerosolised exposure to blue-green algae	• Plaas, H & Paerl, H (2021). Toxic cyanobacteria: a growing threat to water and air quality. Environmental Science and Technology 55:44–64.	International data or research
• Economic impacts (property values reduced by 2-22% for residences nearby waterways that experience toxic algal blooms)	• Natural Capital Economics 2021 Economic impacts of blue-green algae for urban lakes: a literature review.	ACT government data or research

What don't we know?

- We don't have specific data on the links between Tuggeranong's natural spaces—green corridors between suburbs, ponds and lakes—and Tuggeranong residents' wellbeing.
- The causal links between toxins in blue-green algae and neurological disease have not been definitively established, and the scientific community does not agree on the level of risk posed through aerosolised exposure.

Measuring wellbeing outcomes

How will the Government know this proposal has achieved the anticipated wellbeing impacts?

Your thinking on this does not need to be finalised – this is an opportunity to set out ideas about what may need to be measured in order to understand whether this proposal has had the anticipated impact.

What is the measurable outcome?	How will you measure it?
• Decreasing phosphorus concentrations in stormwater	• Water quality monitoring (sampling)
• Decreasing lake closures due to blue-green algal blooms	• EPA monitoring data on lake closures

- Reduced frequency, intensity and or duration of blue-green algal blooms
- Improved ecological outcomes
- Contribution to urban cooling
- Residents' and visitors' wellbeing due to access to 'blue' spaces in the Tuggeranong catchment.

- Water quality monitoring
- CHIP reports
- WSUD assets to be included in ongoing studies as part of Living Infrastructure Plan
- Survey of residents, potentially through Omnibus survey.

Evaluation

- The impacts of this proposal will be evaluated as part of evaluating the implementation of the (draft) Healthy Waterways Plan for Lake Tuggeranong.

Who is impacted?

The population of Tuggeranong was approximately 87, 680 in 2021.People who use the lake for recreation (walking, running, picnicking, cycling, swimming, boating, fishing), as well as businesses and clubs nearby to the lake, will be most impacted.

Table 1.1 – Lake Tuggeranong lake user characteristics, from survey of 316 people who said they visit the lake once or more a year. Source: NC Economics, 2023.

Gender	
Male	48.7%
Female	50.6%
Non-binary/use other term	0.6%
Area of residence in Canberra	
Tuggeranong	35.7%
Other parts of Canberra	64.3%
Age	
18-34	34.1%
35-54	27.4%
55-74	33.1%
75 and over	5.4%
Aboriginal and Torres Strait Islander	2.5%

Will the proposal have a different or disproportionate impact (positive or negative) on any groups?

- The proposal will not have a disproportionate impact on any specific groups, using Tuggeranong District population data and the results of the lake user survey data shown in Table 1 above.

Gendered impacts

- To understand whether there are gendered impacts of this proposal, we would need data on to what extent cisgender, transgender, gender diverse and non-binary people use lake Tuggeranong. This data does not currently exist and would need to be collected through a survey of lake users.

Impacts on Aboriginal and Torres Strait Islander people

- The proposal will not explicitly support commitments under the National Agreement on Closing the Gap or the ACT Aboriginal and Torres Strait Islander Agreement 2019-2028. It is not predicted to have a disproportionate impact on Aboriginal and Torres Strait Islander people.
- The Healthy Waterways program has attempted to gain Ngunnawal perspectives in planning for the Tuggeranong catchment through undertaking a Healthy Waterways-funded Aboriginal Waterway Assessment, facilitated by the EPSDD Ngunnawal Water Policy Officer. This is undertaken by the Ngunnawal community on country, and as part of the assessment, Ngunnawal community members went on country in the Tuggeranong catchment to assess it for culturally significant values. The outcomes of the Aboriginal Waterway Assessment have not yet been shared with the Healthy Waterways team.
- Broader consultation with other Traditional Custodians and groups on cultural values and aspirations for the Tuggeranong catchment is planned to occur through an Office of Water First Nations engagement procurement in Q1 2025.

Impacts on future generations

- The proposal will positively impact future generations by securing their ability to enjoy a healthy Lake Tuggeranong and blue-green network.

Will the proposal have an impact on or be impacted by climate change?

Emissions reduction

- The proposed activities are unlikely to have a significant positive or negative impact on carbon emissions.

Adaptation and risk management

- Susceptibility to algal blooms will be impacted by projected changes to rainfall, storm intensity, and temperature because these influence nutrient dynamics in the catchment and lake. These effects have not yet been quantified in the Tuggeranong context, but it is expected that the net impact will be to increase the lake's susceptibility to algal blooms.
- The proposal will help support a more climate resilient waterbody, by reducing its susceptibility to algal blooms.
- The proposal helps support an adaptation response by contributing to urban cooling and providing people with access to blue spaces as temperatures increase.

Cross-portfolio collaboration and partnerships

- The Healthy Waterways Team has been collaborating with Transport Canberra and City Services (City Services) on how increasing street sweeping can help to address the problem of algal blooms, and with ACT No Waste on how we can support the community to more effectively pick up leaf litter from their properties (a source of nutrients causing algal blooms), and exploring options for recycling green waste collected from street sweeping.
- The Healthy Waterways Team will collaborate with the EPA to maximise any opportunities to use the regulatory framework to improve the health of waterways.

Open Access Wellbeing Impact Summary (Cabinet Submission WIAs only)

Lake Tuggeranong's frequent blue-green algal blooms have negative visual and smell impacts, present health risks, and prevent people from recreating in and around the lake. Using current scientific understanding of what's causing Lake Tuggeranong's algal blooms, the draft Plan presents a ten-year vision to improve water quality in the catchment to reduce the frequency and severity of blooms. This will have positive wellbeing benefits for the Tuggeranong community through reducing health risks, providing access to blue-green space, and enhancing cultural and biodiversity values.

Communications Plan

Project: Community consultation – Options for Restoring Lake Tuggeranong
Directorate: Environment, Planning and Sustainable Development Directorate
Release date: August 2025 **Attachment D**

What is government's involvement/interest?	The ACT Government is seeking feedback from Tuggeranong residents and Canberrans who use, or take an interest in, Lake Tuggeranong on proposed options to restore the Lake.
Why are we communicating on this issue?	• **To inform and educate** the Tuggeranong community about the importance of improving water quality in Lake Tuggeranong and how they can help. • **To engage** with a range of stakeholders who may be substantially impacted by the water quality of Lake Tuggeranong and/or the proposed methods to improve the lake. • **To drive participation** throughout the engagement process to make sure the Healthy Waterways Plan for Lake Tuggeranong has incorporated feedback from the community, experts and First Nation's people. The condition of Lake Tuggeranong has been a contentious issue for many years. We need to engage with the community as early as possible, acknowledge the community and stakeholder feedback that has been received to date, and ensure that they feel their voice is being heard. It will be important to demonstrate that long-term action has been undertaken but there needs to be more work done. The new plan seeks to take more preventative action at the source. The community will also have an important role to play in implementing the plan to improve the water quality of Lake Tuggeranong.
Background/research/insights	• **The Planning Act (2023)** prioritises management objectives for all public land (including waterways) as (1) prevent and control floods, (2) prevent and control pollution, (3) provide for public recreation and (4) habitat for flora and fauna. Since there is little urban infrastructure downstream of Lake Tuggeranong to protect from floods, the highest priority management objective for Lake Tuggeranong under the Planning Act is to prevent and control pollution. • **The ACT Water Strategy 2024–2044 Striking the Balance** sets a 20-year vision for ACT water management as: 'A community working together, managing water wisely to support a vibrant, sustainable and thriving region'. Outcome 1 of the Strategy—Healthy Catchments and Waterbodies—aims to achieve 'Well managed, functioning catchments that provide sufficient clean water for the environment and human consumption, support healthy waterbodies, and contribute to liveability of the ACT community'. • **The ACT and Region Catchment Strategy 2016-2046**. This Strategy establishes a 30-year vision to guide priority actions for a healthy Upper Murrumbidgee River region (upstream of Burrinjuck Dam to Tantangara Dam in NSW).

	• **A 2002 Legislative Assembly commitment** to manage downstream water quality through an agreed motion that the water leaving the ACT via the Murrumbidgee River should be of no less quality than the water flowing into the ACT (ACT Legislative Assembly motion 5 June 2002 9.1(b)). • **The Canberra Urban Lakes and Ponds Land Management Plan's** vision is to 'enrich local communities through the aesthetic, recreational, sporting, tourism, cultural and ecological values of lakes and ponds, and to provide opportunities for people to be involved in their use, care, and management'. Under this Plan, 'recreation' and 'visual landscape' are listed as Lake Tuggeranong's highest values (Figure 3, ACT Government, 2022b). • **The ACT's Water Resource Plan,** developed under the Murray-Darling Basin Plan, contains a Water Quality Management Plan that sets locally relevant water quality targets. • **A 2016 survey of** over 7000 people on Canberra's urban lake use found that the lake use activity most often rated as 'highly important' was walking with other people, followed by picnics/barbeques, cycling, and using playground areas (Schirmer & Mylek, 2016). • In community engagements as part of developing the **Tuggeranong District Strategy**, the Tuggeranong community expressed that they value the lake for a range of recreational activities throughout the year, including walking, cycling, swimming, fishing and windsurfing (ACT Government, 2023). • In the findings of an **ACT 'Better Suburbs' community survey** from 2018, the citizen forum's first recommendation (out of 14) was to increase funding for lakes, ponds, wetlands, stormwater and water quality. This was ranked as more important for community members than issues such as street trees, roads, footpaths and public libraries (ACT Government, 2018). • A **report commissioned by the ACT Government in 2023** explored ACT residents' willingness to pay for environmental amenity and recreational use of Canberra's lakes (NCEconomics, 2023). ACT residents surveyed indicated that they were prepared to pay up to $70/pp/quarter (or $280/pp/year, to greatly improve the environmental—visual and smell—amenity of Lake Tuggeranong (NCEconomics, 2023). • In a 2024 **Tuggeranong Community Council annual community survey,** 'improved water quality in Lake Tuggeranong', was one of the top four priorities for the general community, and the number one priority for young people		
Does it cross over other Directorates/ agencies?	Transport Canberra and City Services Environment Protection Authority ACT Health	**Spokesperson**	Ms Suzanne Orr, Minister for Climate, Change, Environment, Energy and Water Fiona Wright, Executive General Manager, Climate Change, Energy & Water Kieran Lawton, Executive Branch Manager, Office of Water

Commented [EC1]: Amended spokesperson

			Dr Ralph Odgen, Director, Healthy Waterways Program
Communications tier	Tier 2		

Engagement areas of influence	The research shows that the water quality can be improved in Lake Tuggeranong and the instances of lake closures due to algae blooms can be significantly reduced by employing a range of nutrient pollution mitigating actions.
	
	• The focus areas of these actions are:
	  ○ Stop pollution at the source
	  ○ Treat stormwater before it reaches the lake
	  ○ Treat the lake itself
	
	• The strongest focus and area of influence for this consultation falls within the 'Stop pollution at the source' area.
	
	• This focus area is the most effective at preventing algae blooms but also has the most impact on community members as it will require residents to take action to reduce pollution entering the lake.
	
	• A lesser focus will be on 'Treat stormwater before it reaches the lake', and even less feedback needed for 'Treat the lake itself'. The former will be a focus of engagement during implementation of the plan. The latter will be a focus of awareness raising—that we need to curb pollution from the catchment before considering lake treatments.
	
	• The engagement will also seek to educate community on what actions can be taken to improve the health of the lake and how they prioritise and value the water quality of the lake.		

EPSDD Strategic Indicators	**Deliver a compact, efficient and sustainable city to be enjoyed now and into the future** (*Access and connectivity, Economy, Environment and climate, Health, Housing and home, Identity and belonging, Governance and institutions, Time)* **Enhance Canberrans wellbeing by conserving and experiencing nature and culture** (*Environment and climate, Social Connection, Health, Education and life-long learning, Identity and belonging, Governance and institutions, Safety)* **Create our climate-ready city** (*Economy, Environment and climate, Social Connection, Health, Education and life-long learning, Housing and home, Governance and institutions, Safety*) **Respect our Ngunnawal Traditional Custodians' history, knowledge and aspirations and work in partnership with Ngunnawal people to build a strong and shared future that respects and values Ngunnawal Country. Acknowledge and celebrate the diverse First Nations peoples and their unique cultures through shared opportunities, respecting and valuing their knowledge and contributions to the work we do** (*Economy, Environment and climate, Education and life-long learning, Housing and home, Identity and belonging, Governance and institutions, Safety*)		

Target audiences

A detailed stakeholder engagement matrix is included at the end of this document.

Primary	• Residents that live near the lake • Tuggeranong District residents • Lakeside residents, businesses, and other organisations. • Lake users including Tuggeranong Sea Scouts, Rowing Club
Key influencers/stakeholders	• **Tuggeranong Community Council** • **Lake users:** Tuggeranong Sea Scouts, Rowing Club, Park Run, Seniors Centre, Leisure Centre, Arts Centre • **Entities that operate near the lake:** Lake Tuggeranong College, Seniors Centre, Leisure Centre, Arts Centre, businesses, Playgroups and childcare centres on lake edge • **Aboriginal and Torres Strait Islander community:** Representative Aboriginal Organisations (RAOs), United Ngunnawal Elders Council, Aboriginal and Torres Strait Islander Elected Body. • **Water catchment groups:** Southern ACT Catchment Group (primary), Ginninderra Catchment Group, Molonglo Conservation Group, Upper Murrumbidgee Catchment Group • **Environmental groups:** Conservation Council ACT Region, Landcare ACT, ACT Australian Conservation Foundation Community, SEE Change. • **ACT Government advisory bodies and reference groups:** ACTNRM Advisory Group, ACT and Region Catchment Coordination Group, Environment and Planning Forum, Office of the Commissioner for Sustainability and the Environment, ACT Climate Change Council • **Tuggeranong residents** that live near the lake and further afield. • **Wider Canberra community** who may use the lake or take an interest in the health of Lake Tuggeranong**.** • **Academics and universities** who research water quality and take an active interest in water quality strategies and plans.
ACTPS (if relevant)	• Transport Canberra and City Services • Treasury • Traditional Custodian Engagement (EPSDD) • ACT Health

Key Messages

General about the consultation

- ACT Government is inviting the community to have their say to help develop the ACT's first 10-year dedicated plan to improve water quality in Lake Tuggeranong. This is a key priority for Government.
- ACT Government will be consulting with the Tuggeranong community, residents and stakeholders who live, work and use Lake Tuggeranong to seek their feedback on options that ACT Government is proposing to improve the water quality and restore the health of Lake Tuggeranong.
- This consultation is open from [XX to XX] for an 8-week period.
- The Tuggeranong District Strategy envisions Tuggeranong Town Centre as a thriving hub for jobs, shopping, and services, supported by a clean and healthy lake that enhances the area's appeal, attracts visitors, boosts local businesses, and strengthens the ACT economy.
- Lake Tuggeranong is at the heart of the region, and the ACT Government has been working to improve the lake's water quality and is committed to ongoing investment to creating a long-term plan to restore Lake Tuggeranong.
- The proposed options build on previous ACT Government work including the construction of nine wetlands and other water quality assets, funded research and community engagement and education that has already seen a reduction in nutrient pollution entering the lake.
- Our vision is that by 2035, Lake Tuggeranong is more consistently free of blue-green algal blooms and, when they do occur, they are short-lived so the Tuggeranong community can enjoy the lake most of the year.
- But there is more for us to do. We know that there continues to be several sustained periods of poor water quality caused by blue-green algae blooms. This means that the lake is unable to be used and enjoyed by the Tuggeranong community, as well as impacting the environmental sustainability which helps protect local ecosystems.
- We know that the community has provided significant feedback to Government already on initiatives and challenges over a number of years.
- Our goal is to gauge the community's support for restoring Lake Tuggeranong and to explore any concerns they may have regarding the process.
- This consultation focuses on the new proposed options to restore Lake Tuggeranong, as well as seeking feedback on how we maintain existing wetland infrastructure.

Commented [EC2]: To be settled following cabinet

What are we consulting on

- An excess of plant nutrients (fallen leaves, grass clippings and fertilisers) makes its way down drains via our stormwater systems and pollute our lakes, stimulating algal blooms.
- The consultation will provide 10 options along the journey of stormwater where nutrient reduction can occur:
  - **At its source** - by preventing nutrient pollution from occurring in the first place
  - **Within the stormwater system** - by slowing the flow and filtering pollution from the stormwater
  - **In the lake** - we can build wetlands or use substances that compete with algae, or use chemicals that kill algae

- We now understand that the most effective option for preventing algal blooms is to stop nutrient pollution from entering the stormwater system in the first place followed by the construction of more wetlands.
- The ACT Government have taken steps to improve the water quality of Lake Tuggeranong, with projects delivered through nine constructed wetlands. This has greatly improved the health of the lake, but more must be done.
- The proposed new options focus on what we can do to prevent nutrient pollution occurring in the first place, such as increasing the frequency of street sweeping, new street kerb designs, and changing how we manage leaf and grass litter and fertiliser use.
- Research and modelling indicate that Lake Tuggeranong can be improved over the next 10 years and experience fewer lake closures if the ACT Government can work with the local community to reduce these nutrients entering the lake.

Why we are consulting

For Tuggeranong residents

- Every option presented may impact the local community. It could mean temporarily moving cars for more frequent street sweeping, adjusting gardening habits, or the construction of local wetlands.
- As a Tuggeranong resident, you are likely to benefit from a clean and healthy lake that can provide enhanced recreational space, decreased health risks, help to boost local economy and community pride.
- You will also continue to have in important role to play in keeping the lake clean by keeping leaves and fertilisers out of the stormwater system.

For lake users

- Every option presented may impact you, the consultation is your opportunity to provide your input to shape the Plan.
- As a lake user, you'll benefit from a cleaner, fresher environment with little to no unpleasant odours and fewer health risks.
- With time the lake will be available for recreational activities most of the time throughout the year and if we do have lake closures, they will be short lived.

For lakefront residents and businesses and other entities operating on the lakefront

- Every option presented may impact you, the consultation is your opportunity to provide input to shape the Plan.
- As someone who is close to the lake, you are likely to benefit from the implementation of the plan.
- A clean lake has the potential to attract more visitors, boost local businesses and make the Tuggeranong town centre a prime location for jobs, shopping, and services.

Public consultation action plan

Date	Communications tactic and collateral	Distribution	Responsibility
Pre-launch of consultation			
June/July	**Engage Ngunnawal Water Policy Officer and First Nations consultant**, and co-design engagement approach to ensure the voice of First Nations people is included.		Office of Water CED Comms
Early September	**Set up YourSay page** - Survey - Quick comments - Cost allocation sliders - Written submissions (using consultation/survey questions).		CED Comms
Week prior to launch	**Key Stakeholder pre-briefing** 4-5 key stakeholders pre-briefing to get an outline of what the consultation process will look like and key areas of influence. This would include the Tuggeranong Community Council. Briefings of other ACT MLAs and local MPs will occur as requested. - Powerpoint presentation - Media release - Talking points - At a glance		Option for Office of Water CED Comms
Day prior to launch	**Media pre-briefing** A pre-briefing is recommended to ensure media are able to understand the subject matter within the consultation. - Powerpoint presentation - Media release - Talking points - At a glance - Q&A		Office of Water CED Comms
Day of Consultation launch			
September (Date TBC)	**Media release** with supporting talking points and Q&As		CED Comms
September (Date TBC)	**YourSay project page** published YourSay conversations		CED Comms
September (Date TBC)	**Social media post** on ACT Government social media channels		CED Comms

Commented [TM3]: Also could be worth including Brindabella MLA's and David Smith MP

September	**Direct emails** to stakeholder list and EPF to formally notify of the consultation being launched. This will include a partnership pack which will allow them to share promotional material through their owned channels.		Office of Water
During the Consultation period – 8 weeks			
September – November	**Community Events** - 1 x in-person information session for Tuggeranong Community Council (provide option for a second session) - 2 x Stakeholder information workshops - 1 x online (and recorded) information session for Tuggeranong residents and general public - 2-4 pop-ups at different areas around the lake and broader Tuggeranong district. **Targeted stakeholder events** - Workshop/s with Tuggeranong Community Council, Southern ACT Catchment Group, Landcare, ACT NRM, ACTCMCG **First Nations** - Facilitated engagement with Ngunnawal and other Family Groups with connections to the ACT and Region		Office of Water CED Comms
September – November	**Communications** - Development and distribution of a range of print collateral: o Poster for community noticeboards and lakeside businesses o Postcards at businesses o Temporary Corflutes installed around lake		CED Comms

Commented [TM4]: Worth flagging dates and times with Brindabella MLA's or proactively providing event comms to to Brindabella MLA's as they all have decent coverage and exposure.
David Smith also?

Commented [EC5R4]: Noted, but not included in the comms plan.

Commented [TM6]: Worth offering these to lakeside businesses too?

	- Article in the October edition - OurCanberra print, online and digital newsletter - Social media posts, including geotargeted dark posts for Tuggeranong district - Physical display at Tuggeranong Library - Stakeholder emails - Letterbox drop for homes near the lake - Easy English translation		
Following consultation			
November	**Media Release** wrapping-up the consultation (if appropriate)		CED Comms
November	**Direct emails** to the stakeholder list and EPF including the Listening Report.		Office of Water
December	**Listening Report** – upload the to the YourSay project page		CED Comms

Commented [TM7]: Can't happen for Sept, would need to be in for October

Stakeholder Engagement Matrix

Community or Stakeholder Group	Level of impact on policy direction (low, moderate, high)	Level of interest (low, moderate, high)	Engagement needs or expectations	Level of engagement (inform, involve, collaborate)	How we will engage	Responsibility (line area/comms team)
Tuggeranong Community Council	High	High	Participate in workshops, be presented a detailed draft plan and be provided an opportunity to provide feedback on proposed options.	Collaborate	Will write to council and invite the opportunity to present the Plan at council meeting and seek feedback from council members.	Office of Water
Southern ACT Catchment Group	High	High	Participate in workshops, be presented a detailed draft plan be provided an opportunity to provide feedback to the Healthy Waterways team.	Collaborate	Contact the SACG and host a workshop with members of the group to run through details of the Plan and consultation.	Office of Water
Lake users e.g. Tuggeranong Sea Scouts, Rowing Club	Low	High	Opportunity to participate in YourSay or take part in a "Pop up" event to talk about the consultation. They like to be kept informed about health risks, likelihood of future blooms under Plan and how the plan might impact lake usage.	Involve (YourSay)	Email targeting these groups with information about the consultation, link to YourSay provide snap-shot doc and provide information about upcoming pop-up events.	EPSDD Comms
Around the lake users	Low	High	To provide input by YourSay, to be kept informed about	Involve (YourSay)	Email targeting these groups with	EPSDD Comms

e.g. Park Run, Seniors Centre, Leisure Centre, Arts Centre,			health risks. May want to participate in a pop-up event.		information about the consultation, link to YourSay provide snap-shot doc and provide information about upcoming pop-up events.	
Lake Tuggeranong College	Low	High	To provide input via YourSay, to be kept informed about health risks and any future blooms under plan. May take part in a pop-up event to understand the consultation better.	Involve (YourSay)	Email targeting the college with information about the consultation, link to YourSay provide snap-shot doc and provide information about upcoming pop-up events as well as links to learning resources.	EPSDD Comms
Playgroups and childcare centres on lake edge	Low	High	To provide input by YourSay, to be kept informed about health risks, they would like to know about algae blooms in future. They would like information and resources about how to care for Lakes and Waterways to aid teaching.	Involve (YourSay)	Email targeting this group with information about the consultation, link to YourSay provide snap-shot doc and provide information about upcoming pop-up events as well as links to learning resources.	EPSDD Comms
Lakeside businesses	Low	High	To provide input by YourSay, and to be kept informed about health risks, and future blooms under the Plan. Could provide information on how their businesses have	Involve (YourSay)	Email targeting local business. Provide information about the consultation, link to YourSay provide snap-shot doc and provide	EPSDD Comms Office of Water to hold workshops.

			been impacted by blooms over years. May want to participate in a pop-up event.		information about upcoming pop-up events.	
Ngunnawal people	High	Moderate	This group will want to participate in design of assets to enhance cultural values.	Collaborate (targeted workshops, Aboriginal Waterway Assessments)	Engage with a consulting firm who specialises in first nation consultations.	Office of Water to manage First Nations engagement
Residents that live near the lake [need to define boundary]	Moderate	High	To provide input into YourSay, to be kept informed about health risks, to understand how they can participate in waterway friendly gardening	Involve	Letterbox drop postcards that contain a snapshot of the consultation and QR code linking to YourSay.	EPSDD Comms
Tuggeranong Residents and Canberra residents further afield	Moderate	Moderate	To provide input by YourSay, information about how they can participate and be interested in waterway friendly gardening	Involve	Dark posts on social media geo-targeting Tuggeranong residents with links to YourSay.	EPSDD Comms
Other Catchment groups	Low	Moderate	Will be keen to understand approach in Tuggeranong and how it may be rolled out in other catchments in future	Collaborate	Email targeting Catchments groups to participate in pop-up events or in a dedicated workshop.	Office of Water
Landcare ACT	Moderate	Moderate	Membership is Ngunnawal community, rural landholders, catchment groups. May be helpful to coordinate input from these interests.	Collaborate	Email with information about the Plan and consultation. Provide information to take part in You-Say or attend a workshop.	Office of Water

ACTNRM Advisory Group	Moderate	Moderate	Membership includes various experts, landholders, urban parks volunteering. May be helpful to coordinate input from these interests.	Collaborate	Email with information about the Plan and consultation. Provide information to take part in You-Say or attend a workshop.	Office of Water
ACT and Region Catchment Coordination Group	Moderate	Moderate	Membership includes ACT, NSW Government, water experts. Dr Maxine Cooper is Chair.	Collaborate	Email targeting Catchments groups to participate in pop-up events or in a workshop	Office of Water
University of Canberra ANU, CSIRO and other academics in the sector	High	High	Participate in workshops, be presented a detailed draft plan be provided an opportunity to provide feedback to the Healthy Waterways team.	Collaborate	Contact academics and host a workshop to run through details of the Plan and consultation.	Office of Water

‘At a glance’: A 10-year plan to restore Lake Tuggeranong

The ACT Government invites the community to be an active partner in reducing nutrients entering Lake Tuggeranong, to improve the water quality in the Lake for everyone.

The Government has some infrastructure options and other potential methods to improve water quality such as increased street sweeping. But none of these can be truly successful without the community also taking action in their own homes to help reduce nutrients from leaf and grass clippings and fertiliser from entering the storm water system. ~~local residents changing their gardening methods and reducing both fertiliser use and grass and leaves entering stormwater.~~

The ACT Government is developing a 10-year plan to improve the water quality in Lake Tuggeranong. This will include options for community action in homes and gardens, as well as additional ACT Government work ~~as well options for community action in homes and gardens to supplement community gardening changes =~~ that we want you to have your say on. ~~on these options.~~

The challenge

Lake Tuggeranong is closed when blue-green algal blooms occur and the lake becomes unsafe, particularly for swimming and boating.

Most years, the lake is closed for recreation for several months due to blue-green algae blooms.

The same nutrients that help our gardens and plants grow help algal blooms grow too. Those nutrients are in residential fertiliser products, fallen leaves, and grass clippings. Stormwater carries them from ke~~cu~~rbs, paved areas and our ~~yards~~ gardens down drains and eventually into our lakes, polluting the water.

The changing climate contributes to the challenge as the warmer temperatures expected will lead to warmer lake temperatures, which help ~~causing~~ the algae grow.

Explainer: Algal blooms and nutrients

What are nutrients?

Nutrients refer to things like nitrogen and phosphorus that help plants (and people) grow. In our urban waterways, these nutrients come from sources such as leaf and grass litter, fertilisers (including composts and manure), sewage leaks and agricultural runoff. In big amounts they become pollutants.

What causes algal blooms?

Algal blooms can grow rapidly when there are high levels of nutrients, warm water, slow-moving water bodies and plenty of sunlight.

Algal blooms can make the water smell and look green and can sometimes be harmful because they produce toxins that can hurt animals and people. The blooms can also impact the lake's ecosystem.

What's been done so far?

To improve the water quality of Lake Tuggeranong, the ACT Government has delivered 9 constructed wetlands and several other water quality improvement features. This has greatly improved the health of the lake and recreational opportunities in Tuggeranong, but more must be done.

[This will be designed as an infographic in the style of a waterway leading to the Lake]

2017/18	2019	2021	2022	2023	2024
Wetlands built flanking the north and south sides of Isabella Pond A raingarden built at Isabella Plains	Three raingardens built at Gowrie Playing Fields, Fadden Pines, Wanniassa. A concrete drain naturalised in Monash. A pond built below Kambah Shops.	A set of floating wetland platforms deployed in the north arm of Lake Tuggeranong 'Leaf Collective' community education program launched in Tuggeranong	Four bioretention swales installed in drains around Playing Fields in Kambah	ACT Healthy Waterways public information campaign on managing leaves commences 45 Roadside kerb outlets to water green space created in Kambah	'Love the Lakes' community education program targeting Tuggeranong A major concrete drain naturalised in Calwell. A filtration unit added to Kambah Playing Fields to recycle stormwater to irrigate the fields.

What else can we do?

During the 'journey of the stormwater', it's possible to remove nutrients from the system, or to treat algae directly, at three stages:

- **At its source** by preventing nutrient pollution from occurring in the first place.
- **Within the stormwater system** by slowing the flow and filtering nutrient pollution from the stormwater.
- **In the lake** by promoting natural competitors of blue-green algae or using chemicals to kill the algae.

The research shows there is not one single solution. A range of options will be needed to stop the blooms in addition to community efforts.

The most effective way~~most important method~~ to reduce nutrients in the lake is to ~~entering the lake~~prevent nutrient pollution at its source. Households can greatly contribute to this by reducing fertiliser use and ensuring grass clippings and leaves end up in green bins, not in the gutters.~~, is to reduce the amount of fertiliser used in the gardens of Tuggeranong, closely followed by ensuring grass clippings and leaves end up in green bins, not in stormwater. This is the most effective way to improve water quality in Lake Tuggeranong.~~

The ACT Government is developing a 10-year plan to improve the water quality in Lake Tuggeranong. ~~While these community efforts are the key, the~~The Government has additional options which will support these important efforts by the community.

Your feedback will help the ACT Government to understand the level of support for the additional options to improve the lake. For example:

- which options you prefer
- what you think are the benefits or drawbacks of each option
- how the options would affect you
- ~~which management scenario you prefer?~~

The consultation will be open from XX to XX for 8 weeks. There will be several ways you can have your say both in-person and online.

The Vision

By 2035, Lake Tuggeranong is more consistently free of blue-green algal blooms and, when they do occur, they are short-lived so the Tuggeranong community can enjoy the lake most of the year.

What are the options?

Here are the additional options we are consulting on:

At its source:	**More street sweeping** Increase the amount of street sweeping in the Lake

	Tuggeranong catchment to remove more organic material from roads. **Better open-space mowing practises** Reduce grass clippings from municipal mowing ending up on the road. **Rainwater tanks** Capture stormwater from roofs for reuse on residential blocks. **Stormwater recycling** Divert and filter more stormwater to storage tanks at sports fields for use in irrigating the fields. **Improved kerbs** Replace standard road kerbs with specially designed castellated kerbs that divert some of the stormwater to open green space and allow it to filter into the ground. **New water quality infrastructure at sports fields** Build swales around sports fields to capture nutrients from fertiliser.
Within the stormwater system 	**New water quality infrastructure** Construct more wetlands at suitable locations in the Lake Tuggeranong catchment.
In the lake 	**Floating wetlands** Install more floating wetlands on Lake Tuggeranong to draw nutrients out of the lake water and shade algae. ~~**Anti-algal agents**~~ ~~Promote natural competitors of blue-green algae or use chemicals to kill algae.~~

What you can do

The ACT Government wants your feedback on the additional options that will form part of the 10-year plan to restore Lake Tuggeranong.

Each option may impact the local community. It could mean temporarily moving cars for more frequent street sweeping~~, adjusting gardening habits~~ or constructing local wetlands.

Commented [KM1]: Not consulting on anti-algal agents option

Commented [KM2]: Removed as we are no longer consulting on community action options.

[Engagement activities both digital and in-person will be added following cabinet agreement on consultation plan]

Find out more at [YourSay URL and QR Code].

Attachment F

Options for Restoring Lake Tuggeranong

August 2025

ACT Government

ACT Healthy Waterways

Acknowledgement of Country

Yuma
Dhawura nguna ngurumbangu gunanggu Ngunnawal. Nginggada dindi dhawura Ngunnawalbun yindjumaralidjinyin.
Mura bidji mulanggaridjindjula.
Naraganawaliyiri yarabindjula.

Hello,
This country is Ngunnawal (ancestral/spiritual) homeland. We all always respect elders, male and female, as well as Ngunnawal country itself.
They always keep the pathways of their ancestors alive.
They walk together as one.

We acknowledge the Ngunnawal people as traditional custodians of the ACT and recognise any other people or families with connection to the lands of the ACT and region. We acknowledge and respect their continuing culture and the contribution they make to the life of this city and this region.

Privacy

Any personal information provided during your submission will be used solely for the purpose of this community engagement process. Submissions may be partially or fully published on an ACT Government website or incorporated into a subsequent consultation report. As the ACT operates under a pro-release policy, citizens and others have the right to access information obtained through this engagement process under the Freedom of Information Act 2016. While the names of organisations may be disclosed, individuals' identities will be de-identified unless explicit prior consent has been obtained.

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Options for Restoring Lake Tuggeranong

Executive summary

There is a rich history of Aboriginal use of the Tuggeranong valley and its waterways, with evidence of the Ngunnawal people occupying the valley for more than 20,000 years. The name 'Tuggeranong' comes from a Ngunnawal word for 'cold place' or 'cold plains'.

The valley has changed dramatically in the past 200 years~~.~~, shifting the traditional life patterns that Traditional Custodians have understood and worked with for thousands of years. Sheep and cattle stations were established in the early 1800s. Since suburban development started in the 1970s, around 50% of the water catchment has been urbanised. Lake Tuggeranong was built in 1987 as a focal point for the growing town centre and to protect the downstream Murrumbidgee River from the water quality effects of development. Around the same time, a stormwater system was built to manage flood risk by converting natural creek lines such as Tuggeranong Creek into concrete channels.

Lake Tuggeranong has experienced elevated nutrient levels for more than ten years, which has led to frequent blue-green algal blooms. The algal blooms smell unpleasant, are unsightly and require the government to close the lake to activities such as swimming and water sports due to health risks. They also may pose health risks to residents of suburbs surrounding the lake who are exposed to aerosolised lake water on windy days.

These nutrient levels and algal blooms can be reduced to a manageable level using current knowledge.

Several key conclusions can be drawn from the analyses in this report:

- There is sufficient knowledge to have confidence that better water management can lead to a substantial reduction in the frequency of blue-green algal blooms in Lake Tuggeranong.
- A suite of pollution mitigation options to prevent nutrients entering the lake will be needed for success.
- There will be a limit to what can be done to prevent algal blooms; the best that can be achieved is to prevent algal blooms in three out of four years on average.
- Water managers may need to develop options to treat algal blooms when they do arise.

This report presents the best ways to apply our current knowledge in terms of impact and cost-effectiveness. This report builds on previous Healthy Waterways work in the Lake Tuggeranong catchment that saw the construction of nine important wetlands and funded research and community engagement to reduce the sources of nutrient pollutants.

Following consideration of community feedback on the report, the Government will present its preferred options for achieving a healthier Lake Tuggeranong as a *Healthy Waterways Plan for Lake Tuggeranong* (the Plan).

The vision

This report and the Plan that will follow, address an ACT Government commitment for the 11th Assembly to *Develop and deliver a 10-year plan for a healthier Lake Tuggeranong*.

The 10-year vision is:
By 2035, Lake Tuggeranong is more consistently free of blue-green algal blooms and, when they do occur, they are short-lived so the Tuggeranong community can enjoy the lake most of the year.

Aquatic ecosystems in the ACT are highly valued by Traditional Custodians and the broader community as living systems that embody the interconnectedness of all life. Achieving this 10-year vision will support Traditional Custodian responsibilities to care for Country for future generations, as practiced for tens of thousands of years. This reflects Traditional Custodian understanding of water as an interconnected part of Country.

The underpinning research and analyses

Research and modelling funded through the ACT Healthy Waterways program over the past decade has greatly improved understanding of blue-green algal blooms in Lake Tuggeranong. It is now well established that the inflow of phosphorus and other nutrients from the catchment is the main factor driving the blooms. They effectively feed the blooms.

There is currently far more phosphorus entering the lake from its catchment than is released to the water column from lake-bottom sediments. Phosphorus is generated from many diffuse sources across the urban catchment such as leaves, grass clippings, fertiliser products (including composts and manures), soil and sewage. Roughly half of it is in a dissolved form that is readily taken up by algae.

The stormwater flowing off the catchment carries an average annual generation of 1,656 kg phosphorus/year. The seven constructed wetlands built in Stage 1 of Healthy Waterways have reduced this by about 214 kg a year (to 1,442 kg). However, under current flow and levels of phosphorus supply, Lake Tuggeranong will remain in a eutrophic state—which means it is primed for algal growth.

Research shows that blue-green algal blooms can be significantly reduced if the supply of phosphorus to the lake is curbed or 'mitigated' by about 50%, or around 700 kg a year. Once this happens, any further algal blooms can be prevented through in-lake actions.

If the average annual amount of phosphorus entering the lake can be reduced by another 700 kg, the water quality models predict a eutrophic state can be avoided for an average of three out of four years. The 700 kg target is based on annual averages. In very wet years the reductions in phosphorus will need to be higher, while in dry years they can be lower. Some blue-green algae will be present in all years, but if the 700 kg target can be achieved, the likelihood of problem blooms would be lower than at present and the lake should usually be available for contact-based activities.

Options for removing phosphorus

It is possible to remove phosphorus from the system, or to treat algae directly, at three stages during the 'journey of the stormwater':

1. At the sources of pollution, by preventing pollution from occurring in the first place.

2. Within the stormwater system, by slowing the flow and filtering pollution from the stormwater.
3. In the lake, by using agents that compete with algae for nutrients, or by using algicides.

Potential options are presented for reducing or mitigating phosphorus levels (pollution mitigation options) or directly treating algal blooms. A subset of ten options are examined in detail. These were chosen for discussion because their costs and effectiveness could be well characterised based on local trials or the scientific literature.

The analyses clearly show that the most effective options for reducing phosphorus pollution are an increased frequency of street sweeping and building extra water quality assets, such as wetlands, which cleanse stormwater of pollutants. Street sweeping is by far the most cost-effective mitigation measure, decreasing phosphorous by 200–400 kg per year, depending on the frequency of sweeps. Constructing more water quality assets would decrease phosphorous by 100–200 kg per year, depending on the scale of the wetlands and other water quality assets already in the system.

However, the analyses highlight that no single option is a 'silver bullet' that has the potential to reach the phosphorus mitigation target on its own. Multiple options will be needed. Notably, options to prevent stormwater from getting polluted in the first place will be needed to substantially reduce the frequency of blue-green algal blooms.

Management scenarios

After outlining the options, this report investigates solutions by defining two management scenarios that are comprised of multiple pollution mitigation options:

1. A 'cost-effective' scenario that represents the most cost-effective set of options to reach the 700 kg target.
2. A 'broad benefits' scenario that recognises that some options that rank lower for cost-effectiveness, such as constructed wetlands, should nevertheless still be included in the solution because they provide additional values to the community beyond water quality improvement, such as wellbeing.

The management scenarios reflect reality; water managers implement pollution mitigation options concurrently (at the same time). However, the water quality models estimate that concurrent implementation would result in a lower amount of phosphorus being removed than when the options are implemented in isolation from one another. For example, the combination of street sweeping, additional wetlands and eight other options (the 'broad benefits' scenario) was modelled as decreasing phosphorus by just under 600 kg per year compared with 746 kg per year when the options were considered in isolation from one another. This makes sense. For example, campaigns to get residents to remove leaves from roadside gutters will reduce the volume of leaves collected by increased street sweeping, but the sweeping will still be needed.

Despite the result of just under 600 kg per year being slightly lower than the 700 kg per year target, there are reasons to suggest the ACT Government could successfully curb algal blooms in the lake if it implements a program to reduce phosphorous pollution.

- First, reducing phosphorus pollution by just 500–600 kg/year would represent a substantial improvement and would significantly lower the frequency of blue-green algal blooms in Lake Tuggeranong.

- Second, the options to mitigate pollution have only been represented in models in a simple way and their refinement, both during implementation planning and in models, should both decrease their cost and increase their effectiveness.
- Last, there are several promising options that have yet to be tested that may help meet the phosphorus mitigation target of 700 kg/year, such as in-lake phosphorus adsorption materials.

The main cautionary note is about how quickly algae in Lake Tuggeranong will respond to reduced supplies of phosphorus from the catchment. If the phosphorus already in the lake sediments is able to sustain the blooms, it may take longer than the goal of a decade to fix the problem. However, there are options that the government can explore through research and trials for directly dealing with both phosphorus in lake sediments and algal blooms. This increases the likelihood of good progress over the next decade.

The costs

The analyses suggest the cost of mitigating phosphorus pollution in stormwater by 500–600 kg/year (or by the target 700 kg per year with refinement of the mitigation options) is $105 million over 30 years, or $146 million over 30 years for the broad benefits management scenario. However, refinement of the pollution mitigation options should not only increase the effectiveness of the management solutions but may reduce their costs.

Future research and monitoring

An active research and monitoring program has played a central role in the work to date. Ongoing research and monitoring will be critical to refining pollution mitigation options to maximise their effectiveness and minimise their costs. New evidence and knowledge can be incorporated into future versions of the Plan, and its implementation plans.

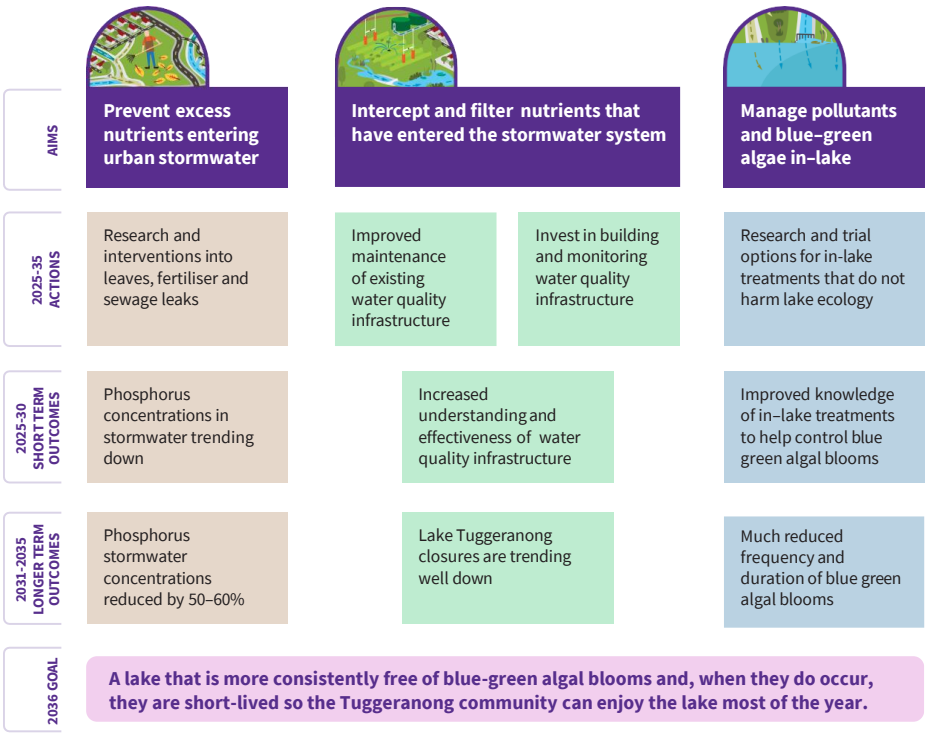
The highest research priorities are trials of promising options and investigations to better understand the fate of fertilisers applied to residents' blocks and to determine whether sewage (either through cross-connections or by other mechanisms) is a significant source of phosphorus in stormwater. It will be critical to continue to monitor the effectiveness of wetlands and other water quality assets, as well as other interventions.

Additional research will continue to refine knowledge and understanding of how to reduce phosphorus in the catchment. However, there is enough evidence already to identify priorities for restoration. Substantial improvements should occur in the lake within several years of the commencement of a material pollution mitigation program.

Next steps

Version 1 of the Healthy Waterways Plan for Lake Tuggeranong will be created based on this report and incorporating further inputs from First Nations people and feedback from the community and experts on the proposed approach. An implementation plan will then be developed to set out how the vision will be achieved over the next 10 years, including how it will be monitored and evaluated.

Healthy Waterways Plan for Lake Tuggeranong
Program Logic



Aerial view of Lake Tuggeranong. Source: MetroMap

Part 1 Context

The ACT Healthy Waterways Program

Addressing water quality in our urban lakes, and specifically the issue of blue-green algae, is a major challenge. The ACT Healthy Waterways Program (Healthy Waterways) was created to address the issue of declining water quality in ACT's rivers and urban lakes.

Stage 1 Healthy Waterways (2014–21) was a joint Australian Government and ACT Government investment, while the ACT Government is fully funding Stage 2 (2021–25).

Over the last decade, Healthy Waterways has delivered a comprehensive suite of activities to help improve water quality and improve our understanding of the problem. It has built water quality assets (such as wetlands and raingardens); invested in research, monitoring and data analyses; built water modelling capability; and initiated community partnership programs to uplift catchment management practices.

Through this work, we have greatly improved our understanding about how ACT's urban catchments operate, the different sources of nutrient pollution that enter waterbodies and lead to algal blooms, the in-lake processes that promote algal blooms, and how the community wishes to participate in caring for waterways.

Of the urban lakes, Lake Tuggeranong has suffered the most chronically from water quality issues in recent years and has been the primary focus of investigative efforts to date. This report will underpin a *Healthy Waterways Plan for Lake Tuggeranong* (the Plan; Figure 1), which is the first of four Healthy Waterways plans for urban waterways.

Objective and scope of the report

The objectives of this report are to:

1. determine whether it is feasible to achieve a substantial reduction in the incidence of algal blooms in Lake Tuggeranong
2. evaluate various options for mitigating stormwater pollution that drives algal blooms.

The Government will finalise the report as a *Healthy Waterways Plan for Lake Tuggeranong* once the community has provided feedback on the options (Figure 1). Subsequently, funding will be investigated for the Plan to be implemented. Funded restoration activities will be monitored and evaluated, and further research and stakeholder engagement will be conducted. The Government will periodically update the Plan as new knowledge comes to hand to ensure the plan achieves maximum value for the community at least cost.

This report and the Plan prioritise focussing on algal blooms over other water quality issues because the ACT Government believes they are the highest priority for the Tuggeranong community (for example, TCC, 2024, Draft). Reducing the incidence of blue-green algal blooms in Lake Tuggeranong should improve its amenity and recreational values for residents and reduce health risks.

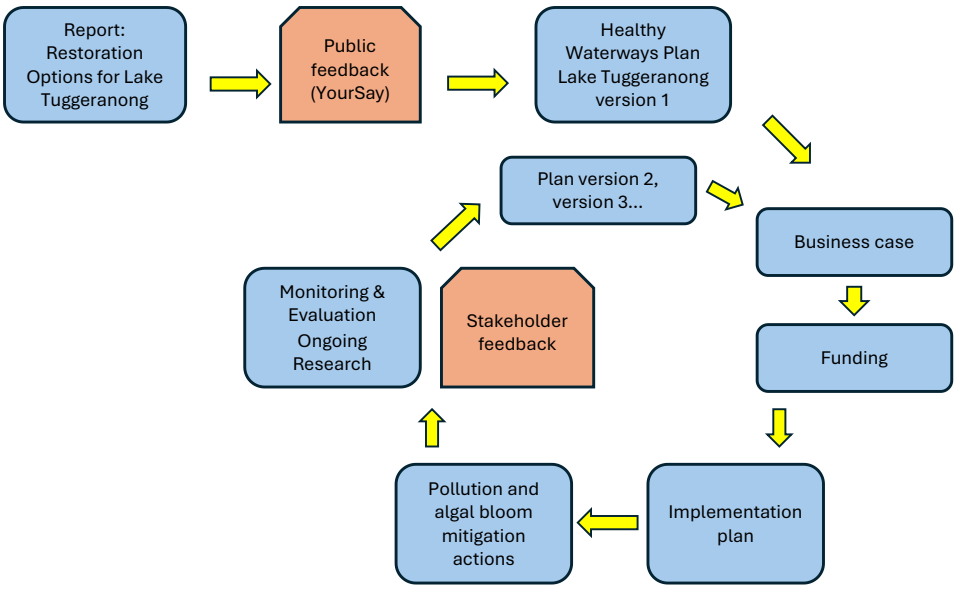


Figure 1. Role of Restoration Options for Lake Tuggeranong *in the adaptive management cycle for mitigating algal blooms in the lake.*

Vision

This report and the subsequent Plan address an ACT Government commitment for the 11th Assembly to *Develop and deliver a 10-year plan for a healthier Lake Tuggeranong*.

The 10-year vision is:
By 2035, Lake Tuggeranong is more consistently free of blue-green algal blooms and, when they do occur, they are short-lived so the Tuggeranong community can enjoy the lake for most of the year.

We need a 10-year time frame because new infrastructure assets will take time to build and become fully functional, and to allow enough time to assess the effectiveness of interventions while considering the background influence of year-to-year climate variability. Nevertheless, fulsome implementation of the Plan should lead to substantial improvements in water quality within several years.

Lake values

Lake Tuggeranong provides multiple social, economic and environmental values for the ACT and region community. However, the lake does not provide all these values consistently. The 2022 State of the Lakes and Waterways highlights that there are tensions between the competing values of urban lakes and waterways—for example the amenity of Lake Tuggeranong versus its role as a pollution trap—and widely differing expectations of urban water management (OCSE, 2022).

Mitigating downstream pollution

Canberra's lakes reduce downstream pollution by acting as sediment and pollution filters. NCEconomics (2023) estimated the market value of this function, known as 'avoided abatement cost', which describes how much it would cost to provide the equivalent pollution abatement if the lakes were not serving that function. They estimated value of Canberra's urban lakes as pollution filters using a hypothetical comparison of water quality outcomes 'with' and 'without' the lake, where water quality upstream of the lake was used as a proxy for water quality 'without' the lake (NCEconomics, 2023). Total nitrogen was used as the water quality indicator. This was used because pollution abatement assets can reduce multiple pollutants at the same time, so only the highest-cost pollutant for each lake was used, to avoid the risk of double counting. The abatement costs were based on the cost of creating equivalent abatement capacity by building water quality assets. The cost of water quality assets was derived from construction costs in the ACT in the six years from 2017 to 2023. The study estimated the net present value associated with Lake Tuggeranong's pollution abatement value is $133–144 million (over 30 years). As discussed in Part 7, water quality assets are not the most cost-effective option for mitigating phosphorus pollution, so this is likely an overestimate of Lake Tuggeranong's pollution abatement value.

However, Lake Tuggeranong is not always effective as a pollution filter. The 2023 State of the Environment Report concludes, 'Lake Tuggeranong does not appear to be consistently mitigating the effects of urbanisation for the downstream waters with periods of higher phosphorus and nitrogen concentrations within and downstream of the lake compared to upstream of the lake'.

Providing opportunities for recreation and amenity

Canberra's urban lakes and their catchments provide important social values for Canberra residents. Access to blue spaces also contributes to improving people's physical, mental and spiritual wellbeing (UK Environment Agency, 2020; Dushkova et al., 2021; Lal and Akhikari, 2024). It follows that when algal blooms require the government to close the lake for long periods, there may be negative consequences for people's health and wellbeing.

The high value that Canberra residents place in their waterways is reflected in several surveys and community engagements undertaken from 2016 to 2023:

- A 2016 survey of more than 7000 people on Canberra's urban lake use found that the activity most often rated as 'highly important' was walking with other people, followed by picnics/barbeques, cycling and using playground areas (Schirmer & Mylek, 2016).
- In community engagements as part of developing the Tuggeranong District Strategy, the Tuggeranong community said they value the lake for a range of recreational activities throughout the year, including walking, cycling, swimming, fishing and windsurfing (ACT Government, 2023b).
- In the findings of a 2018 ACT 'Better Suburbs' community survey, the citizen forum's first recommendation (out of 14) was to increase funding for lakes, ponds, wetlands, stormwater and water quality. This was ranked as more important for community members than issues such as street trees, roads, footpaths and public libraries (ACT Government, 2018).
- A report commissioned by the ACT Government in 2023 explored residents' willingness to pay for environmental amenity and recreational use of Canberra's lakes (NCEconomics, 2023). The report found that the total annual non-market economic value of the lakes based on pollution control and amenity was approximately $159 million a year for Lake Tuggeranong, with the economic value

from benefits to the community significantly outweighing the benefits attributable to water quality management (pollution abatement) provided by the lakes (Figure 2). (The much lower value of Lake Tuggeranong for pollution abatement in Figure 2 compared with its net present value is because Figure 2 reports annualised data whereas net present value is assessed for a 30-year period.)

- A 2023 survey of ACT residents indicated they were prepared to pay up to $70/per person/quarter (or $280/per person/year) to greatly improve the environmental (visual and smell) amenity of Lake Tuggeranong (NCEconomics, 2023). Across all lakes, the survey found that most lake users are infrequent, casual users who draw more value from lake amenity and lakeside facilities than from primary and secondary contact activities like swimming and boating. This finding is also consistent with findings from the earlier survey of Schirmer & Mylek (2016).

Environmental values

There is limited information on the ecological values of the lake. The Waterwatch Catchment Health Indicator Program (CHIP) 2023 report notes the lake has poor riparian condition with little native vegetation, but Eastern Long-necked Turtles, water dragons and occasionally Rakali (Australian native water rats) are present in the wetlands at the southern end of the lake (Upper Murrumbidgee Waterwatch, 2023).

The 2023 State of the Lakes Report found that the aquatic health of the lake supported ecological values to a 'fair' degree, noting limited information to determine a trend. This conclusion was based on the CHIP assessments and because water quality and ecosystem health of the lake are sufficient for the survival of stocked native fish (OCSE, 2022). Murray Cod and Golden Perch are stocked, primarily to support recreational fishing, it also to improve biodiversity and help balance the fish composition by adding native predators to the system. There are a lot of carp in the lake; surveys in 2015 and 2018 showed carp comprised around 90% of all biomass caught. This decreased to 60% in 2024 due to increased stocking of native fish (ACT Government, unpublished data, 2025).

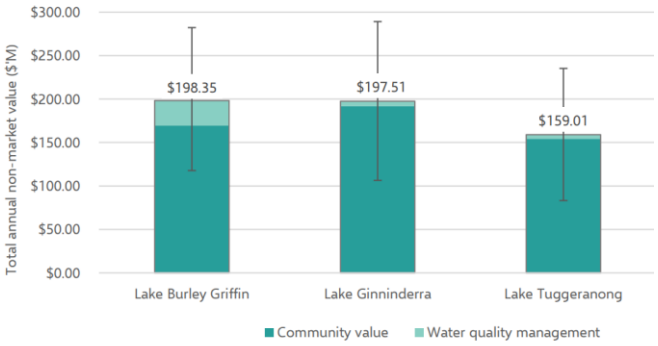


Figure 2. Total annual non-market value from ACT urban lakes. The community value is based on surveyed residents' willingness to pay for good water quality within the lakes through increases in rates. The water quality management value is based on the avoided cost of building water quality assets that provide the same level of treatment as the lake. Source: NCEconomics (2023).

Cultural values

~~In 2023 the~~Cultural values mapping can help to identify what First Nations cultural values and uses are associated with the lake, its tributaries and catchment. This should be undertaken with Traditional Custodians as part of implementation planning to guide an integrated design approach that supports and enhances place-based management actions.

This would build upon a Ngunnawal ~~Water Policy Officer with the Office of Water conducted an~~ Aboriginal Waterway Assessment (AWA~~) with the Ngunnawal community in the Tuggeranong catchment to assess~~), which assessed the health of Country and the waterways in the Tuggeranong catchment from a cultural perspective. The Assessment stressed the importance of:

- recognising Ngunnawal people as a part of the solution to restoring the health of Lake Tuggeranong
- reintroducing and respecting cultural practice in catchment management such as cultural burning and cultivation of pointer and keeping trees
- establishing Ngunnawal rangers
- continuing to conduct AWAs
- introducing more native plants to the creek and surrounding riparian and dry landscapes, including natives of cultural significance such as reeds for weaving
- restoring key features such as naturalising concrete drains
- creating a fully connected cultural way from the headwaters of Tuggeranong Creek to its confluence with the Murrumbidgee River~~; concerns were raised about pollution, including blue-green algae, entering the Tuggeranong Creek reach below Lake Tuggeranong~~
- concerns about pollution, including blue-green algae, entering the Tuggeranong Creek reach
- considering river health and Country health as intertwined
- exploring opportunities for an entitlement to water for cultural purposes.

Lake Tuggeranong looking north towards Mount Taylor (photo: Jennifer Smits)

Legislative and policy context for managing water quality in Lake Tuggeranong

Lake Tuggeranong's management is prescribed by the *Planning Act 2023 (ACT),* which prioritises management objectives for all public land (including waterways) in the following order:

- Prevent and control floods by providing a reservoir to receive flows.
- Prevent and control pollution of waterways.
- Provide for public use for recreation.
- Provide habitat for fauna and flora (Schedule 3 [Part 3.2]).

Since there is little urban infrastructure downstream of Lake Tuggeranong to protect from floods, the primary management objective for Lake Tuggeranong under the Planning Act is to prevent and control pollution.

The Plan aligns with and supports the implementation of other ACT legislative and policy commitments on water quality, specifically the following:

- The *Lakes Act 1976,* administered by the Environment Protection Authority (EPA), which provides for the administration, control and use of urban lakes in Canberra (other than Lake Burley Griffin).
- The ACT Water Strategy 2024–2044 Striking the Balance sets a 20-year vision for ACT water management as: *'A community working together, managing water wisely to support a vibrant, sustainable and thriving region'.*
  Outcome 1 of the Strategy—Healthy Catchments and Waterbodies—aims to achieve 'Well managed, functioning catchments that provide sufficient clean water for the environment and human consumption, support healthy waterbodies, and contribute to liveability of the ACT community'.
- Focus on improved water quality standards to support identified environmental values and permitted uses for Lake Tuggeranong. Environmental values and permitted uses are defined through the Water Use and Catchment General Code (the Code), a subordinate instrument of the *Water Resources Act 2007* (ACT). Under the Code, Lake Tuggeranong and its catchment is defined as drainage and open space with the following environmental values and permitted uses of:
  - discharge of stormwater
  - irrigation water supply
  - waterscape view
  - aquatic habitat (lowland streams, urban lakes and ponds, urban wetland)
  - water-based recreation (boating).
- Water quality standards are set through the Environment Protection Regulation 2005 (ACT) Schedule 4, a subordinate instrument under the *Environment Protection Act 1997* (ACT), and support the policies, management objectives and values of the Code. Access Canberra (EPA) ensures compliance with the Environment Protection Regulation, including s44 that 'a person must not place, or permit to be placed, a pollutant in a waterway if the pollutant is likely to cause environmental harm.'
- The ACT and Region Catchment Strategy 2016–2046 establishes a 30-year vision to guide priority actions for a healthy Upper Murrumbidgee River region (upstream of Burrinjuck Dam to Tantangara Dam in NSW). Developed in partnership with the Australian Government, ACT Government, NSW Government, local councils, Icon Water and the community, it is currently undergoing a 5-yearly review.

- The 2002 Legislative Assembly committed to manage downstream water quality through an agreed motion that the water leaving the ACT via the Murrumbidgee River should be of no less quality than the water flowing into the ACT (ACT Legislative Assembly motion 5 June 2002 9.1[b]).
- The Canberra Urban Lakes and Ponds Land Management Plan's vision is to: *enrich local communities through the aesthetic, recreational, sporting, tourism, cultural and ecological values of lakes and ponds, and to provide opportunities for people to be involved in their use, care and management*. Under this plan, 'recreation' and 'visual landscape' are listed as Lake Tuggeranong's highest values (Figure 3, ACT Government, 2022b).
- The ACT's Water Resource Plan, developed under the Murray–Darling Basin Plan, contains a Water Quality Management Plan that sets locally relevant water quality targets.

None of these legislative and policy commitments consider whether and how to reduce the problem of blue-green algal blooms in Lake Tuggeranong, but they do underpin this report, which fills that gap.

Management of the ACT's lakes and ponds represents a collaborative effort across government, the private sector and the community (residents). ACT Government agencies and other organisations with responsibilities include:

- City and Environment Directorate
  - delivers the Healthy Waterways Program, undertakes water science, monitoring and modelling, implements the ACT Aquatic and Riparian Strategy,
  - implements Murray-Darling Basin commitments,
  - undertakes planning to include water sensitive urban design,
  - owns, manages, maintains the stormwater system and water sensitive urban design assets,
  - manages urban open spaces, water quality services (dredging, street sweeping, GPT cleaning) recreation services on lakes and ponds, and dam safety.
  - includes the Environment Protection Authority – the statutory decision maker under the *Water Resources Act 2007* and *Environment Protection Act 1997,* administers Environment Protection Regulations on environment, water quality and waterway health.
- Health and Community Services Directorate– monitors water quality of recreational water sites.
- ACT Emergency Services Agency – undertakes strategic and emergency flood risk management.
- Icon Water – owns, operates, maintains drinking water supply and wastewater system, undertakes long-term water resource planning.
- National Capital Authority – manages Lake Burley Griffin's water quality and waterway health.

Commented [KL1]: Have updated to show post July 1 responsibilities

Lake Tuggeranong and its catchment

Three major tributaries deliver inflows to Lake Tuggeranong—Kambah and Village creeks in the north (draining a fully urban area) and Tuggeranong Creek in the south (draining urban and rural areas)—as do several minor drains (Figure 4). Tuggeranong Creek runs through a series of settling ponds to improve water quality—Isabella Pond then Lake Tuggeranong wetlands—before discharging into Lake Tuggeranong (Figure 4). Key lake statistics are shown in Table 1 and Figure 5.

Geographical setting and early history

Before it was developed, the Tuggeranong Creek catchment featured hills and valleys with a large, shallow gravel aquifer with 1.5 times the current lake's volume. Tuggeranong Creek would have had a hydrology consistent with a 'chain-of-ponds' system (Lawrence, 2012). Chain-of-ponds systems usually occur in shallow, alluvial valleys where a river doesn't carry flow under baseflow conditions; instead of a continuous channel the river forms a series of irregularly spaced ponds (Mould and Fryirs, 2016). The other tributaries may originally also have been damp valleys, chains of ponds or small creeks.

There is evidence to suggest Ngunnawal people have occupied the Tuggeranong Valley for more than 20,000 years. The name 'Tuggeranong' comes from a Ngunnawal word for 'cold place' or 'cold plains'. Tuggeranong Creek would have provided an important source of water. Important cultural sites in the valley include scarred trees found at Lanyon (canoe tree) and the Wanniassa–Kambah area (ACT Heritage Council, 2024). Axe-grinding grooves have been found in a sandstone outcrop in what is now the suburb of Theodore (Flood, 1996). Tuggeranong Creek remains a culturally and spiritually important part of country for Ngunnawal people today, and undertaking cultural values mapping would help provide us with a better understanding of this.

Europeans began grazing the valley with sheep and cattle in the late 1820s and homesteads were established close to watercourses, including Tuggeranong Creek. Lanyon Station was established in 1835 and the Tuggeranong and Lanyon Homesteads, which remain today, are reminders of this period.

Values

Value	Ecological	Fish	Visual landscape	Aboriginal	Historic	Recreation	Sporting	Tourism	Commercial	Flood management
Icon										
Status	Moderate	Moderate	High	Moderate	Moderate	High	Moderate	Low	Low	Moderate

Figure 3. Canberra Urban Lakes and Ponds Land Management Plan values for Lake Tuggeranong (ACT Government, 2022b).

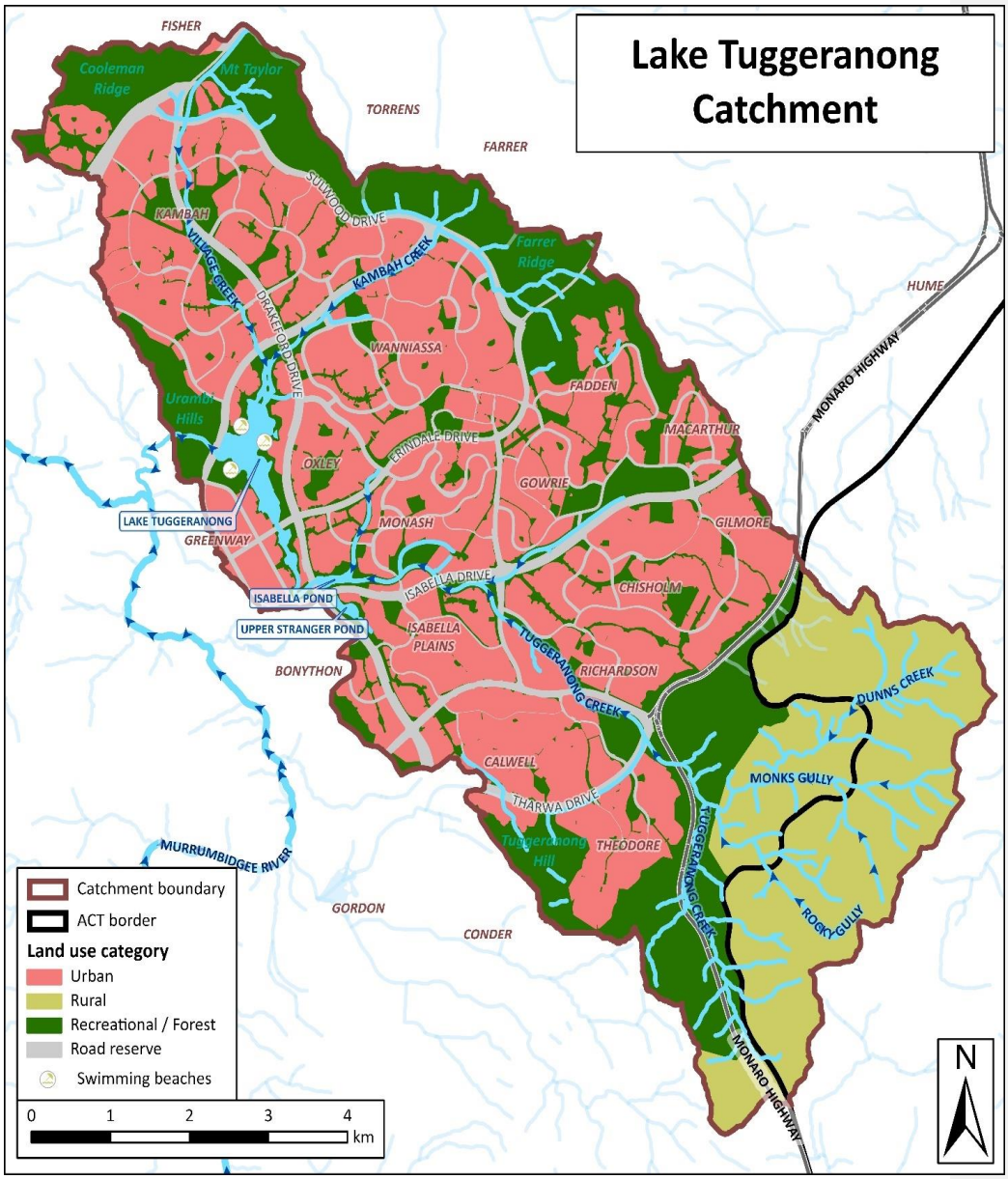


Figure 4. Lake Tuggeranong catchment showing its tributaries. The lake discharges into a short section of Tuggeranong Creek via an outflow channel and weir at the west corner of the lake. This creek then flows into the Murrumbidgee River.

Table 1. Lake characteristics and Tuggeranong climate. Source: (GHD, 2024) and www.bom.gov.au

Lake characteristic	
Size	**57 hectares**
Volume	**1790 megalitres (at normal operation)**
Average depth	**2.9 metres**
Maximum depth	**12.2 metres**
Average residence time of water	**58 days**
Average annual inflows	**9000 megalitres**
Minimum inflows (dry year)	**3000 megalitres**
Maximum inflows (wet year)	**18000 megalitres**
Tuggeranong climate	
Summer mean maximum temperature	**28.1 ^{0}Celcius**
Summer mean minimum temperature	**13.6 ^{0}Celcius**
Winter mean maximum temperature	**14.4 ^{0}Celcius**
Winter mean minimum temperature	**0.7 ^{0}Celcius**

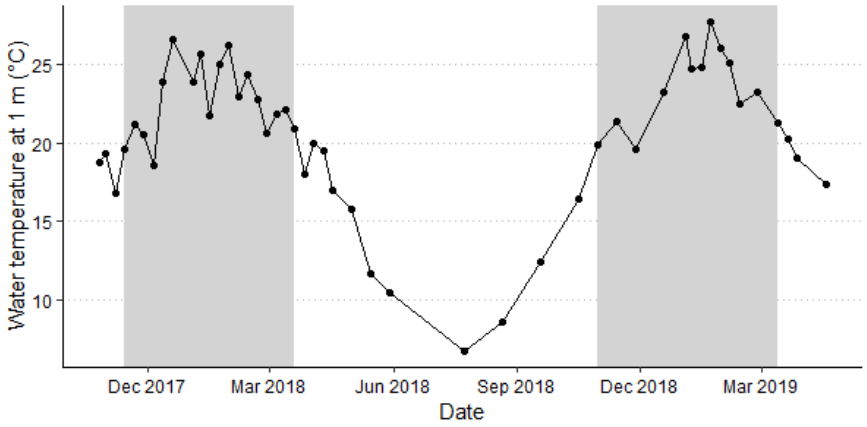


Figure 5. Surface water temperature in Lake Tuggeranong: Mean water temperature at a depth of 1 metre in the central basin of the lake. The grey rectangles that overlay the plot indicate the period from the first detected stratification to the final breakdown of stratification in the lake for the year. (Source: Figure 4-2 in Ubrihien et al., 2019, p.77).

An urbanised catchment—a new lake to filter sediment and concrete drains to channel flows

Tuggeranong was earmarked to be the third town centre of Canberra and was rapidly developed into suburbs throughout the 1970s and 1980s. Much of the shallow aquifer was drained using agricultural drains, stormwater pipes and concreting of the channel bed inset into the aquifer (Lawrence, 2012). To manage the flood impacts of urban runoff, most of the catchment's tributaries have been modified to become a constructed stormwater system of concreted open channels and underground pipes. Lake Tuggeranong was built in 1987 by damming the Tuggeranong Creek at Athllon Drive. While some rural land still exists within the Tuggeranong catchment, it now has a built-up area of more than 50% (Table 2).

Urbanisation changes flow regimes by increasing the impervious surface area (Walsh et al., 2012). Dey et al. (2024) estimated that runoff is four times higher in the Lake Tuggeranong catchment now than when it was a natural catchment. This is because roads, buildings and concrete are water-resistant materials that prevent water from being absorbed into the landscape. This leads to high surface water runoff that makes its way to the stormwater system (Ladson et al., 2006), carrying pollutants with it.

Table 2. Land use in the Tuggeranong catchment

Built-up area		Green space area	
Urban	**41.2%**	**Rural land**	**28.3%**
Roads/transport	**8.9%**	**Urban open space**	**10.2%**
Commercial land use	**1.8%**	**Natural bushland**	**9.5%**
Approx total	**52%**	**Approx total**	**48%**

Part 2 Water quality problems in Lake Tuggeranong

Lake Tuggeranong currently experiences frequent blue-green algal blooms and periods of elevated bacteria levels. Other water quality issues in the lake or its tributaries include high turbidity and industrial pollution events; for example, from paint (Upper Murrumbidgee Waterwatch, 2022).

This report and the subsequent Healthy Waterways Plan focus primarily on addressing algal blooms over other water quality issues. This is because of the higher potential health risk associated with blue-green algal blooms, the fact they contribute to a large proportion of lake closures, and the significant visual and odour impact on the community during severe blooms, such as reported in TCC (in draft).

Blue-green algae

Blue-green algae (Cyanobacteria) are a group of bacteria present in virtually all aquatic environments worldwide. Blue-green algae are not plants but are photosynthetic bacteria, reproducing rapidly when given sunlight and warm, nutrient-rich conditions (Joehnk et al., 2008). They are buoyant, forming surface scums known as a blue-green algal bloom. When this happens, they block the light that would otherwise be available for favourable plant growth, discolour the water and may release a range of toxins. Such blooms are a growing problem in Lake Tuggeranong, especially in summer. Algal blooms reduce visual amenity, release foul odours, pose a health hazard to residents and visitors and require the ACT Government to close the lake to recreational use.

Blue-green algae and human health

Some types of blue-green algae produce toxins (cyanotoxins) that can be harmful for humans, domestic animals and livestock that drink or make contact with the water, and for fish and other organisms living in the water.

There is increasing research and community interest in Australia and overseas into potential associations between cyanobacteria and neuro-degenerative diseases in humans (as noted, for example, by NSW Health, 2023). For example, studies have found an increased incidence of motor neurone disease in people living near waterbodies with blue-green algal blooms (Cox et al., 2003; Caller et al., 2009; Andrew et al., 2017; ABC Online, 2023; Torbick et al., 2018), although most of these studies could not confirm whether direct exposure to cyanobacteria had occurred.

The link between exposure to blue-green algae through primary or secondary contact and neuro-degenerative diseases has not been proven, except where foods have been grown in the presence of blue-green algae (Cox et al. 2003). Clusters of residents with motor neurone disease might be caused by a myriad of factors unrelated to blue-green algae blooms. However, researchers have yet to fully evaluate all plausible cause–effect mechanisms related to blue-green algae blooms and there is an argument for adopting the precautionary principle to mitigate potential risks to human health (Dunlop et al., 2021; Cox, 2021). This is particularly important while investigating airborne exposure pathways such as chronic exposure to aerosolised cyanotoxins downwind of affected waterbodies (Sutherland et al., 2021; Schaefer et al., 2020; Plaas & Paerl, 2021).

Lake Tuggeranong experienced a significant blue-green algae bloom over the summer of 2019/20 (photo: Alica Tschierschke)

Blue-green algae monitoring and lake closures

The Environment Protection Authority (EPA) monitors five sites in Lake Tuggeranong during the recreational season, which runs from October to April. The lake is closed to recreational use if either blue-green algae or faecal bacteria concentrations exceed the levels specified in the ACT Guidelines for Recreational Water Quality. Data analysed from 2015 to 2024 shows frequent closures throughout the recreational season with at least one swimming beach closed for more than 50% of the time for seven of those nine years (Figure 6).

In the 2022–23 season, EPA monitoring showed that all three swimming beaches were closed for almost the entire recreational season. In addition, blue-green algal blooms kept the lake closed to primary contact recreation from mid-January 2023 through to the beginning of June 2023, well beyond the recreational season.

Information about how water quality in Lake Tuggeranong is monitored, and current alerts and closures, is published on the ACT City Services website www.cityservices.act.gov.au.

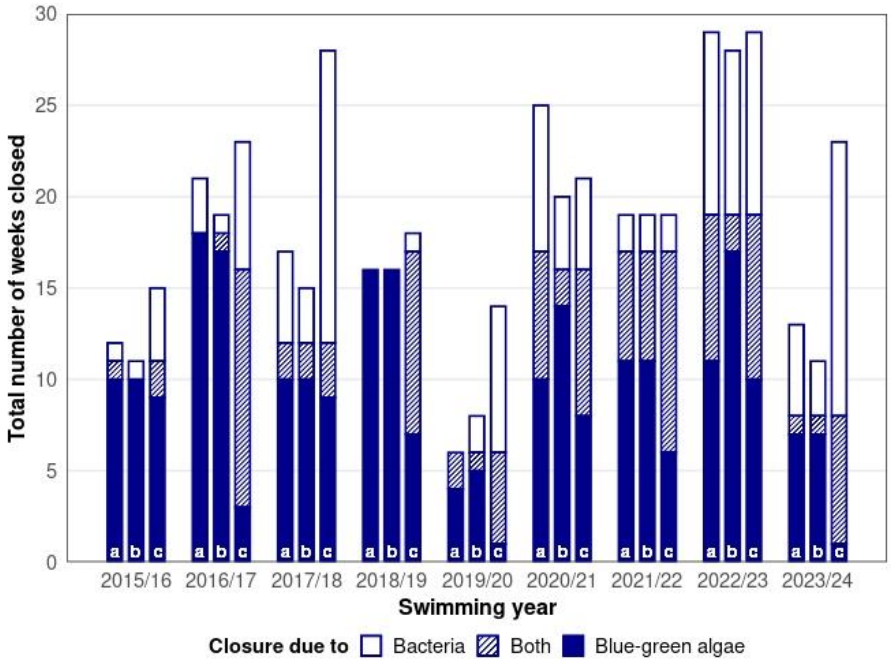


Figure 6. Number of weeks of the swimming season (30 weeks from Oct–April) that Lake Tuggeranong was closed to swimming at one or more beaches due to blue-green algae or bacteria between 2015 and 2024. Column a: Ngadyung Beach, Column b: Nguru Beach, Column c: Tuggeranong Town Beach

Faecal indicator bacteria

As Figure 6 shows, lake closures can also be due to the presence of faecal indicator bacteria, with Tuggeranong Town Beach showing a higher incidence of closures due to this cause.

ACT Health routinely tests ACT lakes for faecal contamination using the faecal indicator bacteria enterococci. These are a group of bacteria found in the intestines of humans and animals; their presence in water may indicate domestic sewage leaks or contamination from diffuse sources of human and animal waste. Water managers use enterococci as the standard faecal indicator bacteria to test water quality in recreational waters in Australia because they are well understood, easy to detect and their presence reliably predicts health risks associated with exposure to waterborne bacterial pathogens.

Monitoring work using Microbial Source Tracking is currently underway to understand the extent the faecal matter is coming from human or animal sources. Findings from this work will inform future iterations of the Plan. In the meantime, many of the interventions proposed to reduce algal blooms will also remove bacteria and other pollutants, such as excess carbon, nitrogen and total dissolved solids, that are potentially causing issues in the catchment.

Part 3: The cause of algal blooms

Drivers of algal blooms

The prevalence of blue-green algae is linked to the trophic state of a water body. Trophic state is a description of the biological productivity of a water body and depends on factors such as the concentration of nutrients used by plants (and blue-green algae) such as phosphorus and nitrogen (South Dakota State University Extension, 2022).

Water bodies in an oligotrophic state have very low nutrient concentrations and tend to have very clear water with little plant or algal growth and high oxygen concentrations that depress the release of algal nutrients stored in lake-bottom sediments. Hence, oligotrophic lakes are not prone to algal blooms. Water bodies in a mesotrophic state have a moderate amount of nutrients, moderately clear water, some algal blooms in late summer and oxygen depletion at bottom of lake as biomass decomposes. Most of the time, the water quality is within an acceptable limit to provide recreation, amenity and ecological benefits. Finally, water bodies in a eutrophic state are nutrient rich, with highly productive plant growth and high turbidity. They are seasonally deficient in oxygen, which may lead to fish kills. Eutrophic lakes may experience regular algal blooms.

When a waterway is in a eutrophic state, nutrient concentrations are so high that blue-green algae blooms are likely to occur whenever the conditions are stable (low flow), the water is warm enough and there is enough light penetrating through the water column (Paerl, 1988). These have been the conditions in Lake Tuggeranong for more than a decade, with blooms occurring every summer.

Nutrient overload in Lake Tuggeranong

It is widely accepted that phosphorus is the main nutrient that drives algal blooms in freshwater systems; without it, algal growth is severely limited (Carvalho et al., 2013). While nitrogen is also essential for algal growth, its absence in lake water does not limit algal growth in the same way as phosphorus because blue-green algae can source nitrogen from the atmosphere (a process called nitrogen fixing) as well as from the water. Therefore, to reduce the incidence and severity of algal blooms, we need to reduce the availability of phosphorus in the system. However, most management options to reduce phosphorus in stormwater will also reduce nitrogen.

In 2019, Healthy Waterways funded research into the conditions leading to algal blooms in Lake Tuggeranong (Ubrihien et al., 2019). This research found high concentrations of both dissolved phosphorus and nitrogen in the lake and determined that a large proportion of these nutrients were being delivered to the lake through the stormwater system. The research, conducted during a significant algal bloom, also demonstrated the importance of controlling phosphorus for limiting the severity of algal growth in Lake Tuggeranong.

Supply of phosphorus: catchment versus lake sediments

To reduce the phosphorus available to blue-green algae in the lake, and therefore the risk of severe algal blooms, we need to know where the phosphorus is coming from; whether it's mainly coming from the Tuggeranong catchment and reaching the lake via stormwater inflows, or if it is mainly coming from

phosphorus already trapped within the lake bottom sediments (Lawrence et al. 2000; e.g. Nikolai and Dzialowski, 2014).

Phosphorus is transported to the lake in stormwater, either in a dissolved or particulate form. Particulate forms are small pieces of plant matter containing phosphorus or phosphorus bound to sediments. Sediment-bound phosphorus is often a result of erosion in the catchment or is blown into drains as dust and dirt. In its dissolved forms, phosphorus, especially phosphate, is more readily available for use by blue-green algae (bioavailable; Lawrence et al. 2000), making it more immediately problematic in causing algal blooms.

Much of the particulate phosphorus that is washed by storms into Lake Tuggeranong settles on the bottom of the lake and creates a nutrient-rich sediment layer. This creates an internal supply of phosphorus in the lake that can be released in a dissolved form later to become bioavailable through in-lake processes (Box 1).

Research by the University of Canberra (Ubrihien et al., 2019) found that the concentration of phosphorus observed in the surface water of Lake Tuggeranong was more than three times that required to support an algal bloom, with further significant amounts detected in sediments at the bottom of the lake. The internal supply of phosphorus—released from lake-bottom sediments—was enough to drive an algal bloom. However, the research found that the external supply of phosphorus to the lake from its catchment was five times the internal supply of phosphorus from lake sediments.

These findings suggest that internal supply of phosphorus is not driving most algal blooms in Lake Tuggeranong. Therefore, to mitigate blooms, water managers need to address catchment sources of phosphorus pollution before dealing with sources within Lake Tuggeranong.

Catchment sources of phosphorus

There are many potential sources of nutrients and other pollutants from urban catchments (as shown, for example, by Muller et al. 2020). Recent research and water quality monitoring in the Tuggeranong catchment has found that:

- phosphorus is mainly coming from urban, not rural, areas (Ubrihien et al., 2020; Upper Murrumbidgee Waterwatch, 2023)
- phosphorus is coming from many small sources across the whole catchment (diffuse sources), rather than from one or two large, concentrated locations (point-source) (Ubrihien et al. 2019)
- around 50% of the catchment-based phosphorus is in dissolved, bioavailable forms (Ubrihien et al., 2019), meaning it is available for uptake by blue-green algae
- leaves, grass clippings, fertiliser products (including composts and manures), soil and sewage are all likely contributing to catchment-based phosphorus (Ubrihien et al., 2019; Concepts of Change, 2023).

Soil

Soil can contain phosphorus both in its crystalline structure and adsorbed to soil particles. Sediments can release the adsorbed portion of phosphorus to water, after which algae can take it up. Because this is a

slow process, most of the adsorbed phosphorus is not immediately bioavailable. However, sediments may release phosphorus over time once they are deposited in a lake.

Phosphorus adsorbed to clays suspended in the water column can take hours to weeks or longer to be released into water and available for uptake by algae.

Development sites

Tuggeranong District's population is predicted to be stable between 2022 and 2060, but there is still a potential future housing demand of 1100 dwellings by 2050 in the district forecast (ACT Government, 2022c, 2023b). While there are no greenfield suburbs planned, there are plans to redevelop existing areas through infill, and smaller-scale construction projects like knock-down rebuilds or major home renovations will also occur.

Development sites might contribute phosphorus to the stormwater system as phosphorus bound to the sediments in drainage or from roads that construction vehicles track mud onto. The University of Canberra examined the overall effect of urban development sites on the stormwater system in Lake Tuggeranong catchments in 2024 (Ubrihien et al., 2024b). They found that during storms, stormwater concentrations of total suspended solids were significantly higher downstream of development sites compared to upstream. However, levels of total and dissolved phosphorus did not vary significantly between stormwater sampled above and below development sites. The sediments from development sites are likely to be subsurface soils and thus low in phosphorus.

Leaf litter and grass

Phosphorus from plant materials can make up a substantial portion of the total phosphorus inputs in an urban catchment (Duan et al., 2014; Janke et al. 2017; Selbig, 2016; Muller et al. 2020). Plant materials have different amounts of phosphorus depending on the plant species and part of the plant (blossoms, fruits or leaves; Hill, et al., 2022).

Leaf litter (leaves, sticks, nuts, flowers) and grass clippings release nutrients as they decompose or are wet. This can happen quickly; research in the Tuggeranong catchment by the University of Canberra suggests that leaves will leach out most of their phosphorus within two days of either continuous or periodic inundation (Ubrihien et al., 2024a). In an urban environment with lots of impervious surfaces, leached, dissolved phosphorus cannot soak into the soil where soil particles could absorb it, or vegetation take it up. Instead, it enters the stormwater system where concrete channels and pipes convey it rapidly to lakes and waterways.

While much of Canberra is known for its deciduous street trees, nearly 80% of street trees in the Tuggeranong catchment are eucalypts (ACT Government, 2022a). From December 2022 to November 2023 the University of Canberra investigated the potential contribution of street trees' leaves to nutrients in the Tuggeranong catchment (Ubrihien et al. 2024a). They measured the deposition rate of leaves for the four most common eucalypt species onto impervious surfaces to determine their potential nutrient leaching rates, and then extrapolated this across the catchment by using estimates of tree canopy hanging over impervious surfaces. They found:

- the amount of leaf fall from these species was greatest in summer
- the phosphorus leached from leaves differed greatly between eucalypt species, with *Eucalyptus sideroxylon* leaching the most phosphorus
- the annual supply to Lake Tuggeranong of dissolved nitrogen, phosphorus and organic carbon contributed by leaves across the catchment as 25, 43 and 6,748 kg per year, respectively. They note

these are probably underestimates because they only capture litter that falls directly from the overhanging canopy, not any that is blown or washed onto roads.

Box 1. Why did dry weather in 2019–2020 limit algal blooms?

The Tuggeranong catchment experienced a dry period from September 2019 to January 2020, with only 6 mm of rain falling in the catchment. In Lake Tuggeranong, no blooms occurred and there were no lake closures due to blue-green algae during that time.

Dry conditions impact the lake's susceptibility to algal blooms by impacting in-lake processes. During the warmer months, Lake Tuggeranong experiences thermal stratification. This is where a marked, stable zone of cooler water forms at depth in the lake where daylight does not penetrate and a warmer, light-filled, less-dense layer of water sits on top. In this top layer the light allows for photosynthesis to occur and bacteria, algae and other micro-organisms consume the available nutrients, most of which are washed in from the catchment. During dry periods, these top-layer nutrients are not replenished as they are consumed, which prevents blue-green algae from blooming.

Catchment phosphorus can also end up in the cool lower layer, with much of it bound to sediment on the lake floor where it's not bioavailable. Carbon also gets washed into the lake from the catchment as organic matter such as leaves. As bottom-dwelling bacteria feed on the carbon, they use up oxygen in the water; if the lake is stratified for a long time, this process creates an oxygen-depleted (anoxic) environment. Under anoxic conditions, phosphorus can be released from the sediment to become bioavailable. The released, bioavailable phosphorus can be brought to the top layer by diffusion or by mixing of bottom and surface waters as stratification later weakens or breaks down with winds, cool weather or rainfall.

In autumn in Lake Tuggeranong, the top layer of water cools and eventually sinks, forcing the bottom water, with its bioavailable phosphorus, to the surface. This is known as turnover and can cause a late season blue-green algal bloom. These are often of a shorter duration and less severe than summer blooms.

Blue-green algae can also access nutrients in bottom waters by modifying their buoyancy to move up and down through the water column.

University of Canberra researchers monitored phosphorus concentrations in the lake over the 2019/20 dry period and hypothesised that blooms didn't occur during this time because low baseflows meant there was a limited supply of nutrients in the top layer of the lake (Ubrihien et al., 2020). Their data also suggested that lack of carbon inputs may have led to reduced bacteria in the bottom layer, meaning less oxygen was consumed and the phosphorus remained bound to the sediments rather than becoming bioavailable.

One implication of this is that removing sources of phosphorus *and* carbon in the catchment may have a greater combined impact on reducing the incidence of algal blooms. The influence of dry vs wet weather conditions is also a key part of understanding year-to-year variability in the number, duration and intensity of blue-green algal blooms in Lake Tuggeranong.

The phosphorus content of *E. sideroxylon* leaves as measured here is comparable to the average phosphorus content of leaves from a variety of deciduous trees measured in northern hemisphere studies (Duan et al. 2014; Hill et al. 2022). The average phosphorus content of leaves from all the eucalypt species studied in the Tuggeranong catchment was generally slightly lower than the average for deciduous leaves.

In the same study the University of Canberra also measured grass clippings deposition (Ubrihien et al. 2024a). It found:

- nutrient deposition from grass clippings varies between seasons (with higher releases in summer) and between different mowing events
- an average 'mowing event' releases 33–76 mg of phosphorus for each square metre of impervious surface next to a mown area. The average varied depending on the season and whether clippings were continuously or intermittently soaked during the experiments.

Booksmythe et al. (2024) extrapolated these estimates to all the road surface within two metres of mown open space in the Lake Tuggeranong catchment, multiplied by the around 11 mowing events per year undertaken by ACT City Services, and found that this equates to clippings contributing between 85–200 kg of phosphorus per year to the lake.

Together, according to these estimates, leaves and grass contribute around 130–240 kg phosphorus per year on average to Lake Tuggeranong.

Urban open space mowing

ACT City Services manage the mowing of all urban open spaces in accordance with Canberra's Lakes and Ponds Land Management Plan and the complementary Urban Open Space Land Management Plan. Together, these plans require that:

- mowing programs aim to improve the ACT's water quality outcomes
- verge managers remove cut vegetation from guttering
- mowing cannot occur within five metres of waterbodies
- verge managers seek the Conservator of Flora and Fauna's advice on mowing areas next to certain waterbodies including Lake Tuggeranong District Park (south) and Isabella Ponds grassland.
- However, some cut vegetation will still end up blowing into gutters. The government is exploring ways to minimise this impact.

Fertiliser

Some residents and businesses use fertilisers to enrich soils with nutrients important for plant growth and health, including phosphorus, nitrogen and potassium. They fertilise residential lawns and gardens as well as public and private green spaces like sports fields, golf courses and gardens. Fertilisers can be a major source of phosphorus pollution of stormwater (Muller at al. 2020).

Fertiliser products come in different forms (manure, compost, chemical/synthetic) and have different release rates. The type of fertiliser used, how much is applied and when it is applied determine how well the plants can take it up, and whether it will stay in (or on) the soil or be transported out of the lawn, turf or garden bed and into waterways.

Nutrients can end up being 'exported' from residences to waterways either in dissolved or particulate form if too much fertiliser is applied (more than can be taken up by soils and plants), it is applied just before rain, or it is applied to soils that don't absorb water well.

Household fertiliser use

A Healthy Waterways funded survey in 2023 heard from 400 Canberra residents about the type and quantity of fertiliser they use (Concepts of Change, 2023). The findings of this survey were that:

- households use an average 84 kg of garden nutrient boosters (fertilisers, manures, compost) annually, which equates to 0.59 kg of phosphorus per household
- 6% of households use a paid gardening service and these accounted for 0.11 kg of annual phosphorus use by households, making a total of 0.70 kg phosphorus applied per household
- around half of Canberra residents use no fertiliser at all, with most of the fertiliser applied by the top 20% of users
- by volume, compost and manure are the most used fertiliser.

There are 21,000 low to medium density residential, detached and semi-detached dwellings with gardens in Tuggeranong (Booksmythe et al. 2024). Survey data on the amount of fertiliser applied by Canberra householders to their blocks combined with data from a literature review on the proportion of phosphorus that leaks into stormwater from different fertilisers (Booksmythe et al. 2024) yields a wide-ranging estimate of around 90–1,200 kg of phosphorus per year entering stormwater from fertilisers applied by householders, with an intermediate estimate of around 550 kg per year. The wide range is because of significant uncertainty in the export rates for phosphorus in fertilisers applied by residents or their gardeners.

Sports field fertiliser use

The Tuggeranong catchment includes approximately 70 hectares of managed sports grounds. Most of these are public grounds managed by ACT City Services Sport and Recreation, with about 7 hectares being privately managed.

The University of Canberra's research in the Tuggeranong catchment found that water samples taken near sports fields had slightly elevated phosphorus concentrations (total and dissolved) (Ubrihien et al., 2020). While they still represent a relatively small component of overall catchment phosphorus, they warrant further investigation.

More work is needed to understand the nutrient transport pathways around sports fields**.** Soil moisture testing and on-ground observations of public sports fields don't indicate high volumes of surface water runoff, so it's possible the elevated concentrations detected represent historical fertiliser use (going back decades) that is leaching out through the system at a subsurface level.

In general, both public and private sports field managers practice careful application of fertiliser as it represents a significant input cost. In 2022 several private sports field managers were surveyed about their fertiliser application practices (Edmonson, 2022). The survey found that private managers had a detailed knowledge of turf nutrient requirements and, as fertiliser is a major expense, were managing fertiliser application as efficiently and effectively as possible.

ACT City Services Sport and Recreation manage public sports fields in Tuggeranong using practices to improve irrigation efficiency and water retention, prevent surface water runoff and manage the chemical composition of the soil profile to improve nutrient uptake. These help prevent nutrients being exported from sports fields in runoff.

Installing additional bioretention swales between a sports field and the stormwater channel would help intercept and filter any nutrients exported from the sports fields.

Leaky sewerage pipes

Leaking sewers can be a major contributor to water quality issues in urban areas, causing increased nutrients, suspended solids and microbial pollutants to enter waterways. Sewers can become defective and leak from structural problems (broken joints, cracks, fractures and holes), operational problems (root intrusion, sediment accumulation and grease build up) and hydraulic capacity failures (Nguyen & Venohr, 2021). As holes are drilled in urban catchments for a variety of purposes, pipes can be damaged and leak into the stormwater system.

Healthy Waterways has commissioned a study to help characterise how large a problem sewage leaks might be, noting that they might affect not only nutrient concentrations but levels of faecal pollution, which can also result in lake closures. Results will be delivered in 2025 and will be incorporated into later versions of the Plan.

Part 4: Identifying solutions to the algal bloom problem

This report presents a series of analyses to identify and evaluate potential solutions to the problem of algal blooms in Lake Tuggeranong. The analyses were designed to achieve the following:

1. Model the effects of phosphorus inputs from the catchment on in-lake algal responses to help establish a target for reducing phosphorus pollution in Lake Tuggeranong (Part 5).
2. Identify options to either reduce levels of phosphorus in waterways or directly lower algal concentrations within the lake (Part 6).
3. Formulate potential water management scenarios made up of various pollution mitigation options that together reduce the level of phosphorus entering Lake Tuggeranong to the target level (Part 7):
    a. Estimate the costs, effectiveness and cost-effectiveness of a subset of the most feasible pollution mitigation options to help achieve the phosphorus mitigation target.
    b. Define two water quality management scenarios or combinations of workable pollution mitigation options that together reach the phosphorus mitigation target (and thus a substantial reduction in the incidence of blue-green algal blooms in Lake Tuggeranong):
        i. The most cost-effective option to achieve the phosphorus mitigation target.
        ii. A broader benefits option that not only achieves the target but provides stronger benefits than the cost-effective option in relation to supporting health outcomes, amenity and biodiversity, promoting climate resilience by reducing urban heat and recycling stormwater to irrigate sports fields.
    c. Re-configure the catchment water quality model to reflect the two management scenarios to understand the effect of implementing the pollution mitigation options together.
    d. Consider aspects of the feasibility and likelihood of being able to reach the required phosphorus mitigation target.

Based on the analyses, Part 8 plots a path forward.

Form of phosphorus

The models and other analyses presented below predict total phosphorus or its effects. There are not enough data to inform what proportion of the particulate fraction of phosphorus in Tuggeranong stormwater is bioavailable, so total phosphorus is used to predict algal responses—and total phosphorus data used in model calibrations—rather than dissolved or bioavailable phosphorus. So, even though algae actually take up dissolved phosphate, in these analyses, 'phosphorus' refers to total phosphorus.

Part 5: The target – how much phosphorus to mitigate?

Water quality modelling approach

Dey et al. (2024) developed two coupled water quality models to help estimate how much the supply of phosphorus from the catchment to the lake needs to drop to substantially decrease the incidence of algal blooms in the lake.

The first model is a catchment model that predicts how much water and phosphorus will reach Lake Tuggeranong and how this changes with daily variations in rainfall. The researchers initially used pollution generation rates from different types of land use, derived from the scientific literature, which they then calibrated with observations of water quality and flow in storm events that came from research by the University of Canberra (Ubrihien at al. 2019, 2020).

The second model is a simple in-lake model that predicts how phosphorus concentrations in the lake will change in response to varying runoff and inflow of phosphorus, and then the amount of algae that will grow in response to this. Kahn and Dey (2024) predicted the algal response indirectly using chlorophyll *a* concentration. Chlorophyll *a* is a pigment in many plants and algae that helps them absorb light and is used to assess the amount of algae (ANZECC and ARMCANZ, 2000). They then assigned predicted concentrations of chlorophyll *a* concentration to trophic states: Oligotrophic <5 µg/L, Mesotrophic <15 µg/L, and Eutrophic >15 µg/L.

Inputs of phosphorus from the catchment

The water quality modelling has shown that that the stormwater flowing off the catchment carries very high levels of phosphorus, with an average annual supply to the lake of 1,656 kg phosphorus/yr (Dey et al., 2024; Table 3). This is greater than the annual estimate of 500 kg estimated by Ubrihien, et al. (2019), which was based on data collected in a dry period, with reduced inflows from the catchment.

Table 3. Modelled annual total phosphorus (TP) supply to Lake Tuggeranong (kg/yr) generated for each combination of functional land use and surface type imperviousness: road, hardstand, roof and pervious (from Appendix 5 in Dey et al., 2024).

FUNCTIONAL LAND USE	Road TP (kg/yr)	Hardstand TP (kg/yr)	Roof TP (kg/yr)	Pervious TP (kg/yr)	Total TP (kg/yr)
Suburban	**322**	**169**	**314**	**140**	**945**
Commercial	**17**	**45**	**30**	**16**	**108**
Open space	**243**	**76**	**5**	**88**	**412**
Rural	**0**	**0**	**1**	**132**	**133**
Sports field	**0**	**0**	**0**	**58**	**58**
Total annual supply (kg/yr)	**582**	**290**	**350**	**434**	**1,656**

Based on research data (Ubrihien et al., 2019, 2020), about 50% of this input is in a dissolved form, with most of it ready for uptake by algae. Dey et al. (2024) predict that the seven constructed wetlands built in Stage 1 of Healthy Waterways have reduced the amount of phosphorus entering the lake annually by 214 kg, from 1,656 kg to 1,442 kg.

Current and target supply of phosphorus to the lake

Current supply

Kahn and Dey (2024) used an in-lake algal response model to determine the phosphorus mitigation target (Figure 7). Under current flow and levels of phosphorus supply (Figure 7, 'No P reduction'), their modelling clearly indicates that Lake Tuggeranong will remain in a eutrophic state, with chlorophyll *a* concentrations over 15 μg/L, even in years with relatively little rainfall when smaller amounts of nutrient are transported to the lake. This fits with observations of consistently high levels of phosphorus and frequent blue-green algal blooms in the lake in recent years. It also supports the findings of a 1982 hydrological study of the catchment, which predicted that based on nutrient levels at the time, the lake would exist in a eutrophic state for most of the time (Beer et al., 1982).

A suitable and realistic chlorophyll *a* concentration target range to aim for in Lake Tuggeranong, correlating to a mesotrophic state, is in the range of 5–15μg/L. This target range is based on the following considerations:

- The model predicts that in a predevelopment scenario (when the area was entirely native bushland), Lake Tuggeranong would typically have been in a mesotrophic state, with a chlorophyll *a* concentration in the range of 0–18 μg/L (Figure 7: 'Predevelopment') (Dey et al., 2024).
- The ANZECC guidelines specify a range of 5–15 μg/L for mesotrophic conditions (see Table 8.2.1 in ANZECC and ARMCANZ, 2000).
- In the nearby Googong Reservoir, a water supply with a reduced level of disturbance, chlorophyll *a* concentrations are typically in the range of 0–28 μg/L, with annual averages consistently in the range of 4–10 μg/L.
- The Australian Environment Council recommends that chlorophyll *a* concentrations in recreational waterbodies be kept below 20 μg/L for recreational lakes and 5 μg/L for water supply reservoirs (AEC, 1987). In the ACT, the Environment Protection Regulation sets a more stringent target of less than 10 μg/L for contact-based activities (noting that direct observations of algal counts rather than chlorophyll *a* concentrations are used to determine when to close lakes in the ACT).

Target supply to mitigate algal blooms

Kahn and Dey (2024) predict that a mesotrophic state can be achieved in Lake Tuggeranong for most the time if the average annual phosphorus supply to the lake is reduced by 700 kg, having already accounted for the effect of the seven constructed wetlands built in Stage 1 of Healthy Waterways (Figure 7). They did not adopt a higher target because the further reduction in phosphorus would not significantly reduce algal blooms but would cost a lot more to achieve.

A target of 700 kg represents approximately 50–60% of the total supply of phosphorus to the lake from the catchment.

Note that these targets are indicative only, developed for the purpose of supporting the modelling exercise and communicating the benefits of different management scenarios. While the 700 kg target is based on annual averages, the required reductions will be higher in very wet years and lower in dry years.

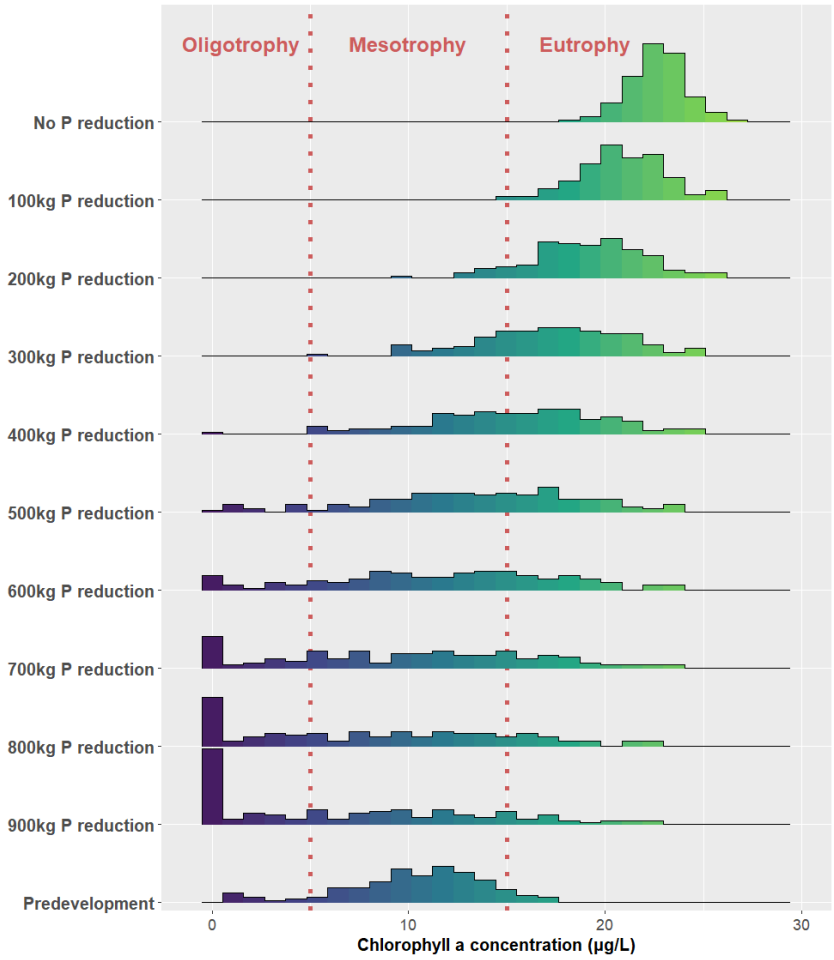


Figure 7. Modelled distribution of predicted chlorophyll a concentrations (an indicator of trophic state) in Lake Tuggeranong under varying supply of phosphorus (P). The top row 'No P reduction' shows the lake in its current, eutrophic state. The bottom, 'Predevelopment' row shows the predicted chlorophyll a concentrations if there were no urban development upstream of the lake, indicating that it would have been in a mesotrophic state in most years, but still occasionally have reached a eutrophic state, supporting algal blooms.

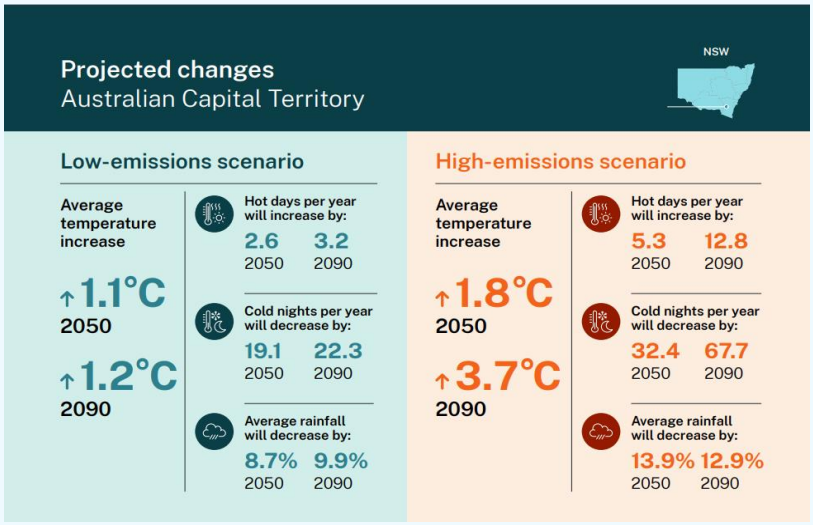
Box 2. How will climate change affect nutrient dynamics and algal blooms?

In the future, the ACT will experience hotter average temperatures, more hot days per year and decreased average rainfall, particularly in spring (NSW Department of Climate Change, the Environment and Water, 2024). Across Australia, including the ACT, extreme rainfall events (storms) will become more intense. The Australian Rainfall and Runoff Guidelines project the biggest increases for very short storms. For example, under scenario SSP3-7.0, storms of under one hour will increase in intensity by 18% by 2030, and by 29% by 2050 (Wasko et al., 2024). More intense localised storms may increase the frequency of 1% Annual Exceedance Probability (AEP) (in layman's terms, 1 in 100 year storms) flooding events in the ACT. The ACT Government's ACTMapi website shows the extent of riverine flooding that would be expected during a 1% AEP flood event.

These changes to temperature, rainfall averages and storm intensity will likely impact nutrient dynamics in the Tuggeranong catchment, for example:

- higher storm intensity will impact streamflow and the way that nutrients are mobilised in, and transported through, the catchment
- hotter temperatures will affect when eucalypt species drop their leaves, how much they drop and the phosphorus content of the leaves
- higher water temperatures will affect in-lake processes like thermal stratification and turnover.

These effects are anticipated but have not yet been studied or quantified in the Lake Tuggeranong context. However, a response framework developed for Victoria's waterbodies argues that climate change will exacerbate blue-green algal blooms through factors including increased temperatures, stronger stratification, increased nutrient levels due to extreme wet/dry periods, longer residence times of water in water bodies and storm events (HydroNumerics, 2020).



Climate change projections for the ACT (NARCliM 2024)

How will the lake behave if the target phosphorus reduction is achieved?

With a 700 kg annual reduction in phosphorus, modelling by Kahn and Dey (2024) suggests the lake will be in a mesotrophic state—or better, in an oligotrophic state—in approximately 75% of years (Figure 7). Under these conditions, some blue-green algae would be present, but the likelihood of problem blooms would be lower than now, and the lake should mainly be in a condition suitable for contact-based activities. Closures may still occur due to elevated levels of faecal indicator bacteria.

The modelling also reveals there will likely always be considerable variation in the concentration of phosphorus in Lake Tuggeranong over time, driven by variation in climatic conditions. Specifically, in very wet years the significant amount of phosphorus coming off the catchment will likely overwhelm any attempts to reduce nutrient levels in the lake, leading to eutrophic conditions.

For example, with a target 700 kg annual reduction in phosphorus, the modelling predicts that in about 25% of years (the wettest years) the lake will still be in a eutrophic state, with sufficient nutrients to promote algal blooms. However, wet years also tend to be relatively cooler, which would reduce the likelihood of severe blooms. Some algae would also flush from the lake in wet years.

Conversely, in relatively dry years, any phosphorus removed from the system represents a relatively larger proportion of the total supply reaching the lake. So, for a target 700 kg annual reduction in phosphorus, modelling by Kahn and Dey (2024) suggests about 25% of years (the driest years) will experience oligotrophic conditions in the lake, with very low concentrations of nutrients, relatively clear water and very little risk of algal blooms occurring.

Reconciling some estimates based on research and modelling

There are two notable instances where the predictions from catchment water quality modelling and results from catchment research are not fully aligned.

The first relates to the contribution that fertiliser applied on residential gardens makes to phosphorus levels in stormwater. The Lake Tuggeranong catchment water quality model predicts that only around 140 kg/year of phosphorus is generated from pervious suburban land use (Table 3). This is the land use category representing residential yards and gardens, which would include fertiliser use by residents or their gardeners and other sources of phosphorus from residential blocks. The model is based on published literature of phosphorus draining from household blocks and was calibrated to the observed data on phosphorus concentrations in runoff and waterways around the catchment.

In Part 3, the amount of phosphorus entering stormwater from residences, based on surveys of residents, is conservatively estimated at around 90–1,200 kg of phosphorus per year, with an intermediate estimate of around 550 kg per year. The model prediction of around 140 kg/year leakage is within, but at the very lower end, of the estimate of around 90–1,200 kg of phosphorus per year based on the surveys of residents. Since 140 kg/year is well below the middle estimate of 550 kg/year, the difference between the prediction based on modelling and the estimate based on research warrants further investigation.

The second instance where the catchment water quality model and research yield different results relates to the contribution of phosphorus due to leaves and grass. The effect of nutrients leaching from leaf and grass litter—and soils and other road detritus—on roads was assessed through the catchment model as 582 kg/year (Table 3). This is greater than the research estimate of around 130–240 kg/year based on leaf-fall patterns plus biomass

of grass on road verges in Part 3 (Ubrihien et al., 2024a). However, there are reasons to believe that the estimates for leaf-fall biomass are underestimated (see Part 3). To date there have been no independent estimates for how much soil and non-leaf debris is on the roads and how much extra phosphorus this contains.

Further research is required to ensure fertilisers applied to household blocks are not making a larger contribution than suggested by the modelling, and to clarify the contribution of leaves and grass. However, both sources of phosphorus pollution are likely to be significant and are preventable so consideration needs to be given to reducing both sources of pollution.

Part 6: Options to mitigate phosphorus pollution

Previous research and programs in the ACT and elsewhere have identified and trialled a range of potential phosphorus mitigation options. For this report, options were shortlisted based on the availability of data to support cost-effectiveness analyses. In some instances, cost-effectiveness data were based on local trials of options. The Healthy Waterways team has yet to evaluate some other very promising options because of a lack of relevant data on which to base cost-effectiveness. These options will be evaluated as data on their cost-effectiveness becomes available through ongoing research and trials.

Conceptually, there are three stages in the 'journey of the stormwater' where phosphorus might be removed from the system or algae may be directly treated through various options (Table 4 and Figure 8). This section describes these options.

Table 4. Pollution mitigation options to remove phosphorus in the 'journey of the stormwater'.

	Where to remove phosphorus/treat algae	Mechanism
1	**At the source/s**	Reduce the amount of phosphorus before it enters the stormwater system (phosphorus pollution prevention).
1.1	Enhanced street sweeping	Increase the frequency that streets are swept.
1.2	Pollution prevention partnerships	Promote waterways-friendly gardening practices by working with community and business.
1.3	Water sensitive urban design (WSUD)	Adopt suburb designs—or retrofit elements to existing suburbs—that minimise the impacts of urban development on the natural water cycle and better integrate suburbs into the natural landscape.
2	**In the stormwater system**	Use water sensitive urban design infrastructure to divert runoff in storms, allowing it to slow down, be filtered naturally by wetlands and/or to seep slowly back into the landscape.
2.1	Infrastructure that reduces stormwater peaks	Retain stormwater in green belts, detain it in tanks and/or recycle it.
2.2	Infrastructure that improves stormwater quality	Create various types of constructed wetlands.
2.3	Maximised effectiveness of water quality infrastructure	Sequentially place constructed wetlands and other water quality/quantity assets along drainage lines and waterways to reach end-of-system targets and maintain the infrastructure in good condition.
3	**In the lake**	Use anti-algal agents that either compete with algae or treat the algae once it grows to bloom proportions.
3.1	Reduction of nutrient levels and/or competition with blue-green algae	Deploy materials or processes that remove nutrients from surface waters, where algae live, or promote natural competitors to algae.
3.2	Direct treatment of algae	Apply algicides or physical mechanisms to destroy or remove algae.

Reduce the amount of phosphorus entering stormwater at the source

There are several ways to prevent waters from becoming polluted in the first place, rather than allowing them to become polluted and then treating the pollution or its effects within the stormwater system.

Street sweeping

The ACT Government's street sweeping program removes leaves and debris from kerbs and gutters along Canberra's urban roads. Every street in Canberra receives at least two full sweeps each year, with additional local sweeps between April and September during the heavy period of leaf-fall (See: https://www.cityservices.act.gov.au/roads-and-paths/road-infrastructure-and-maintenance/street-sweeping).

One option is to increase the frequency of sweeps. As described in Part 4, leaf litter and grass clippings release nutrients quickly as they decompose or are wet. They lose most of their phosphorus within two days of either continuous or periodic inundation (Ubrihien et al., 2024a). The intent of increasing the frequency of street sweeping is therefore to remove leaf and grass litter from gutters before the phosphorus and other nutrients have had a chance to leach out of the litter.

Pollution prevention partnerships

Canberra's residents affect waterway health in the way they manage leaves, grass and fertilisers on their blocks. Through Healthy Waterways, the ACT Government has been building expertise in supporting households to prevent stormwater pollution since 2016. It is working with the community to improve awareness and to support households to adopt practices that promote waterway health, like collecting leaves from the road verge.

Since the evidence began to point strongly to leaf litter in gutters and on paved surfaces as one of the top pollutants, programs have been developed and tested that target leaves directly.

From 2020–23, the government partnered with Griffith University and community stakeholders to test numerous interventions under the project title 'The Leaf Collective'. Three iterations of the program were run—two during autumn and one during summer. In all three campaigns householders reported an increase in the volume of leaf litter they collected from areas draining to stormwater. On average, they collected 20% more than the control groups collected. Attitudes towards the value of leaf litter also changed, with more people adding leaves to compost or using them to create leaf mould, and fewer people disposing of them inappropriately in their general waste bins.

From 2023–25, the government has delivered a smaller program. It features the most popular elements of the earlier pilots, such as the leaf-bag giveaway and leaf cages in schools and is gradually building in more offerings. Community stakeholders and individual community members consistently give positive feedback about these initiatives.

While our understanding of the impacts of fertiliser use on phosphorus pollution in stormwater is less advanced, the ACT Government piloted a 'Love the Lakes' program in May 2024 that aimed to reduce garden fertiliser use in households that use high amounts. Concepts of Change (2023) interviewed 600 households across Tuggeranong and coached householders (via telephone or in-person) about ways they could reduce fertiliser use. When the householders were contacted again in late 2024, they reported an average 36% decrease in fertiliser use during spring.

Through the **Healthy Waterways Plan for Lake Tuggeranong**, we can at look to how to remove phosphorus at three distinct stages in the 'journey of the stormwater'.

Reduce the amount of phosphorus entering the stormwater system:

1. Support the community to help stop leaves and grass from accumulating along our verges and street drains.
2. Work with government, businesses and the community to minimise the amount of fertiliser entering urban stormwater.
3. Work with government and universities to better understand and manage the link between street tree leaves and grass clippings and the amount of nutrients in the stormwater.

Slow the flow and filter – reconnect water back into the landscape and filter nutrients out of the stormwater:

4. Intercept and treat nutrient–laden stormwater running off sports fields. Also reuse stormwater from elsewhere to water the sports fields. This will reduce the amount of runoff and amount of nutrients flowing into Lake Tuggeranong.
5. Provide opportunities for stormwater to be absorbed and treated in the landscape while improving habitat connectivity, through green infrastructure like swales, raingardens and wetlands.

Manage the in-lake environment

6. Investigate the drivers, habitat enhancements and possible in–lake treatments to reduce the incidence of blue green algal blooms.

ACT Government

Figure 8. Conceptual model showing where phosphorus can be removed from its source to the lake.

Garden service providers were also contacted. They reported applying an average 1.78 kg of phosphorus per garden per year, which accounts for about 15% of the total amount of phosphorus applied across Canberra. Working with garden service providers offers another potential avenue to reduce fertiliser use.

Water Sensitive Urban Design

For many decades, town planning adopted engineering solutions aimed at flood mitigation that turned many ACT waterways into straight pipes and concrete drains. These engineered systems are very efficient at conducting stormwater, and the nutrients it carries, rapidly and directly out of urban landscapes to the natural waterways without opportunities for treatment by catchment soils and vegetation. Studies into urban runoff in storms suggest it has fewer adverse impacts on water quality in natural waterways if there is less direct flow from impervious surfaces, such as roads, to natural waterways (Ladson et al 2006, Walsh et al. 2022).

Water Sensitive Urban Design (WSUD) planning, landscaping and infrastructure promote infiltration of urban stormwater into the soil, increase water retention, reduce flow rates and filter out nutrients from stormwater in the catchment. Using WSUD helps reduce runoff and improve water quality before stormwater enters natural waterways such as Lake Tuggeranong (for example, see Ubrihien et al. 2020).

WSUD infrastructure has been a key feature of Healthy Waterways over its 10 years to date. The program has built 27 water quality assets, predominantly ponds, wetlands, rain gardens and channel restorations across urban Canberra since 2014.

In developing these assets, Healthy Waterways worked across government to ensure the asset designs were either approved against Municipal Infrastructure Standards (MIS) or Municipal Infrastructure Technical Standards (MITS) or are new and effective designs. The new designs allow for an expansion of the MIS and MITS standards, which means there are now more options in the infrastructure toolkit that water managers can use to improve stormwater quality.

Infrastructure that reconnects storm runoff with its catchment

WSUD infrastructure may target either reducing the amount of runoff in storms or improving stormwater quality or both. Features can be added to an urban area to retain water in the landscape or route small streams of stormwater back into green space, such as castellated kerbs and landscape contours (Table 5). This allows stormwater to soak back into natural catchment areas where it is mostly retained (for example, it evaporates or is taken up by plants) or is cleansed by surface vegetation and soils. At one end of the spectrum these features are capital works; for example, Healthy Waterways built some small runoff infrastructure assets such as castellated kerbs to reduce the volume of water in the stormwater system. At the other end of the spectrum, landcare groups can improve stormwater retention simply by roughening drainage lines (Alluvium, 2023). In the case of stormwater recycling, water is diverted from pipes, drains or WSUD infrastructure and usually treated before being used, sometimes to irrigate green space like sports fields and golf courses, and sometimes for other purposes, such as in construction.

Table 5. Types of runoff infrastructure built in the ACT.

Type of infrastructure	How it works
Castellated kerbs	Roadside drains have gaps in them where some of the stormwater is diverted into adjacent green space where the stormwater can be absorbed into the soil.
Landscape roughening	Small mounds are dug into slopes to temporarily capture runoff and allow it to sink into the soil (Alluvium, 2023).
Rainwater tanks	Hold water in the landscape using above or below ground storage tanks for rainwater usually sourced from roofs.
Detention tanks	Built underground to temporarily store stormwater sourced from drains and often used to irrigate sports fields.
Stormwater recycling	Stormwater is diverted to tanks before being cleaned and used instead of potable water; for example, to irrigate sports fields. It may be cleaned by a combination of constructed wetlands, groundwater aquifers, and/or a filtering unit in a shipping container.

Slow the flow and filter the stormwater

Infrastructure that reduces stormwater peaks

Tanks can be used to temporarily store stormwater before the water is either used (for example, to water resident's gardens) or released back into the stormwater system. The delayed release of stormwater reduces peak flows and allows downstream wetlands and ponds more time to process and treat a greater volume of the stormwater.

Infrastructure that improves stormwater quality

WSUD infrastructure is built with a primary function of treating pollutants and improving water quality. This infrastructure includes a variety of constructed wetlands, where plants and soil media filter nutrients and fine sediment particles from the stormwater. Different types of constructed wetlands are shown in Table 6. Constructed wetlands can also have several added benefits such as providing riparian (waters-edge) and aquatic habitat for wildlife within urban areas, reducing urban heat, enhancing Traditional Owner values and contributing to urban amenity. The wetlands, ponds and raingardens built in the Healthy Waterways program are examples of WSUD infrastructure that target improving stormwater quality by removing pollutants.

In the Tuggeranong catchment, research by the University of Canberra has shown that most nutrients are mobilised and transported during big storm events where flow volumes are high (Ubrihien et al., 2020). In this situation, wetlands are only able to treat a small proportion of the nutrient-laden flows, with the remainder bypassing the wetlands. Part 7 further considers the implications of this.

Maximising the effectiveness of WSUD infrastructure

Treatment trains

The effectiveness of water quality assets can be maximised through careful design and sequential placement of different types of assets. A series of assets working in sequence to reduce and improve stormwater quality is known as a treatment train**.**

Box 3. Urban catchments create more runoff in storms

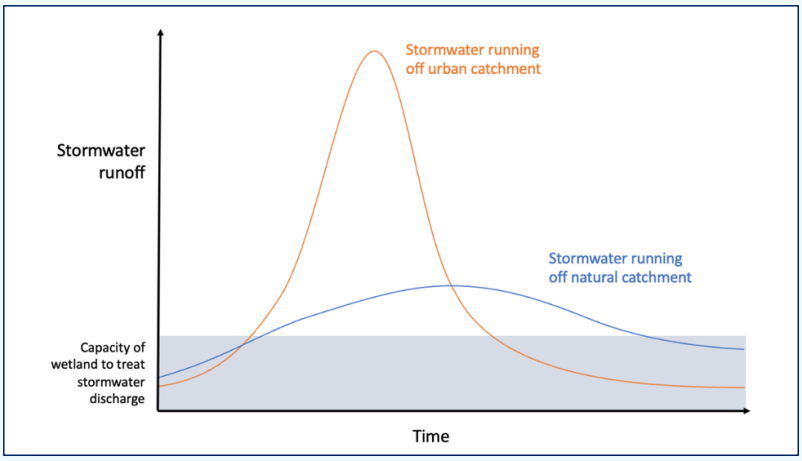
Phosphorus pollution in Lake Tuggeranong is, in large part, a result of urbanisation. Water that flows over the land surface is known as runoff, which in urban areas quickly enters the engineered stormwater system.

In a natural catchment, rain falls on trees and vegetation, which take energy out of the water and allow it to be absorbed into the soil and bedrock. When the ground is saturated, water will eventually start to run off, but at lower volumes and speeds than in an urbanised catchment. When the runoff ceases, water will be slowly released from the landscape, allowing waterways to flow at a gentler rate over a longer period.

The highly urbanised nature of the Lake Tuggeranong catchment means that much of the catchment is covered by buildings, roads, concrete paving and other surfaces that water can't soak into, known as impermeable surfaces (Codner et al., 1988). Rain therefore runs off impermeable surfaces. This runoff washes lots of phosphorus from these impermeable surfaces into the stormwater system, which is also highly impermeable, and on to Lake Tuggeranong. Models estimate that the volume of runoff from the Lake Tuggeranong catchment is three times higher than that of a natural catchment (Dey et al., 2024). Consequently, urban stormwater systems are very 'flashy' waterways, with water levels rising quickly after rainfall, and falling back to baseflow levels almost as quickly (see the hydrograph in the figure below).

Large amounts of runoff in an urban system make it difficult to treat the high levels of phosphorous in stormwater. A wetland only has the capacity to treat a limited amount of stormwater per hour, so the smaller the volume and longer the duration of flow from a storm event, the greater the proportion of stormwater that will be treated.

By reconnecting more runoff and stormwater back into the landscape, we can start to return the catchment to a more natural flow state. This would provide more opportunities for water to be absorbed into the landscape, and for wetlands and their plants to better capture phosphorus from the remaining stormwater and prevent it from reaching Lake Tuggeranong.



Stormwater flow in an urban vs natural catchment and the capacity of a wetland to treat the stormwater. The grey area indicates the volume of water that a wetland can treat over a given period and shows the 'flashy' nature of stormwater coming off an urban catchment.

For example, placing runoff infrastructure such as castellated kerbs higher up in the catchment can divert water back onto grassy areas, which reduces the volume of phosphorus-laden stormwater running down the drains. Detention tanks, like rainwater tanks connected to roofs of houses, can capture stormwater peaks and either release some of the stormwater slowly after the storm has passed (for example, by using a specially designed 'leaky tank') or be used for watering gardens. Around playing fields, smaller swales and raingardens filter out coarse sediments and some nutrients from the stormwater before it flows downstream to bigger wetlands and ponds.

Using a treatment train in this way is particularly effective during big storm events by allowing bigger wetlands downstream to more effectively treat more of a storm event's runoff (and for longer) because flow volumes have been reduced upstream and the first pass through smaller filtering infrastructure that has already filtered some nutrients and sediments, reducing the pressure on the bigger downstream wetland.

Maintenance

When sediments do build up in a constructed wetland and the water plants absorb all the nutrients they can, the wetland needs to be maintained to retain its ability to clean the stormwater. This is an often-overlooked part of managing them for optimal effectiveness. Maintenance can include removing built-up sediments, which reduce the wetland's capacity to hold and filter stormwater and harvesting water plants regularly to remove the nutrients they contain from the system and prevent them from decaying back into the water.

Raingardens are renowned within the stormwater industry as particularly sensitive to poor maintenance. They can become completely dysfunctional if their inlets become blocked and their surface sediments clogged and overgrown with trees or weeds that disrupt their ability to function properly. Operational and maintenance requirements are a key design feature of WSUD infrastructure. The choice of assets and the level of maintenance funding need to be considered before committing to such projects.

Table 6. Types of constructed wetlands built in the ACT.

Type of infrastructure	How it works
Ponds	Stormwater is routed to one or more settling ponds fringed with emergent aquatic plants. The overflow is returned to the stormwater channel.
Traditional wetlands	Stormwater is diverted from channels and routed through a sequence of pools and shallower beds of emergent aquatic plants before being returned to the stormwater drain.
Raingardens	Stormwater floods the soil surface, which has dense growth of emergent aquatic plants, then percolates downwards through the soil and is collected in pipes and returned to the stormwater drain.
Bioretention swales	These smaller, vegetated drains operate in the same way as raingardens and are often targeted at point sources of pollution such as sports fields.
Subsurface wetlands	Stormwater is routed horizontally through gravel beds overlain by soils and emergent aquatic plants. Plant roots extend into the gravel beds. The overflow is returned to the stormwater drain. The aquatic plants remove dissolved nutrients, as in a hydroponic garden.

Channel re-naturalisations	Concrete stormwater open drains or channels are replaced with various combinations of pools, riffles, runs and beds of aquatic plants. In the process, the channels may be reconnected with surrounding floodplain sediments and aquifers.

Box 4. Examples of Water Sensitive Urban Design (WSUD) in Tuggeranong

WSUD infrastructure has been a key feature of Healthy Waterways. Twenty water quality assets, predominantly ponds, wetlands, rain gardens and channel restorations, were built in Healthy Waterways Stage 1. Seven of eight assets have been built in Stage 2, with the final asset slated to be built in 2025.

1. Bioretention swale at Kambah District Playing Fields
2. Pond at Kett St near the Kambah shops
3. Drain naturalisation at Tuggeranong Creek in Calwell – before
4. Drain naturalisation at Tuggeranong Creek in Calwell – after (but before plantings have grown)

Treat the polluted water in-lake

Alongside pollution reduction programs and infrastructure, in-lake treatments are a complementary management tool to further reduce nutrient levels in the system and curb blue-green algal blooms. Blue-green algal blooms are an issue across Australia and globally, affecting drinking water catchments, recreational water bodies and the agricultural industry. Governments, industry and the research community have invested heavily in trying to find solutions and a range of in-lake treatments have been developed (see Table 7).

Broadly, these in-lake treatments try to address blue-green algal bloom by either:

- reducing nutrient levels in a waterbody (adsorptive materials, lake water treated by a lakeside bioretention, biological competitors, water treatment plant) or
- treating the algae directly with chemicals such as algicides or through physical actions or with water treatment plant.

Trials of in-lake treatments—past and future

In 2019–2020 the ACT Government engaged the University of Canberra to conduct in-lake mesocosm experiments using Phoslock™ (adsorptive material), Diatomix™ (modifies the nutrient composition of the water to favour species that promote the growth of diatoms at the expense of blue-green algae) and peroxide (an algicide). The experiments found these methods to be ineffective at reducing established blue-green algal blooms in Lake Tuggeranong. However, the timing of their application, after a bloom was established, may have limited the effectiveness of at least the Phoslock and peroxide treatments. The experiment report suggests that Phoslock offers a promising way to limit internal phosphorus loading, provided catchment sources can be controlled first. It recommends further trials that apply treatments before the onset of a bloom (Ubrihien et al., 2019).

Two floating wetlands have been deployed; one in Lake Tuggeranong and the other outside the Tuggeranong catchment at Yerrabi Pond. The floating wetlands directly compete with algae for light and nutrients. They have yet to be evaluated for their performance.

A range of existing and emerging technologies and methods to treat phosphorus in the lake have been identified, including filtration, sedimentation, floatation, biological and chemical removal (GHD, 2024). This work pointed to potential opportunities to use a combination of bioretention basins and phosphorus adsorptive (chemically binding) material. For example, Poseidon Pellets™ are a patented product made of magnesium carbonate beads, which adsorb phosphorus and ammonia from water. They could be used in a variety of ways; a water-permeable bag containing the beads can be placed in stormwater or suspended in the surface waters of the lake or in a bioretention basin. Once the pellets become saturated with phosphorus they need to be replaced.

Other in-lake treatments may also be trialled in the future through the Healthy Waterways research program, but the immediate priority will be to reduce catchment sources of phosphorus.

Table 7. Different types of in-lake treatments. All have potential adverse environmental impacts and most are likely to have low effectiveness until pollution from the Lake Tuggeranong catchment is reduced. Only a small number of these treatments have been trialled in Canberra, where the focus has been on reducing pollution in the catchment.

Treatment type	How it works
	By reducing nutrient levels and/or competing with blue-green algae
Adsorptive materials	Materials deployed to the lake bind phosphorus strongly, removing dissolved forms from water so the phosphorus is not available for uptake by blue-green algae.
Bubblers	Bubblers increase levels of dissolved oxygen in the water column, which encourages the formation of iron and manganese precipitates that bind dissolved phosphorus. The precipitates then sink and are stored in the lake sediments.
Bioretention	Water from the lake is circulated through raingardens at the edges of the lake, which partially filter the phosphorus by binding it to soil media and incorporating it into plant biomass.
Biological competitors	Competitors promote the growth of water plants or beneficial algae or bacteria that compete with blue-green algae, suppressing their growth.
	By treating algae directly, either in-lake or with water treatment plant
Algicides	Chemical agents aim to selectively kill algae.
Physical	Physical methods either physically break up blue-green algal cells or force them to the surface of the lake where they can be removed by skimming.

Conclusion for in-lake treatments

Unfortunately, there is no treatment that is effective in all contexts or that does not adversely affect the aquatic environment. Since in-lake treatments are unlikely to ever be effective enough to curb nutrient levels that fuel algal blooms, and the excessive use of algicides would present a heightened risk of impacts to non-target organisms, they do not represent a sustainable, stand-alone solution. However, water managers may need to use them both as an interim measure over the next decade, while we work to mitigate the sources of catchment loads, and then as a periodic solution when algal blooms arise despite best efforts to prevent them.

Selection of options for consideration

Booksmythe et al. (2024) analysed a subset of options for mitigating phosphorus pollution for their potential to contribute to solving the algal bloom problem in Lake Tuggeranong (Table 8). They only analysed options if their costs and effectiveness could be well characterised based on local trials or scientific literature. Of the nine selected options to remove phosphorus, five prevent phosphorus entering the stormwater system and four treat it once it's in the system.

They did not select any options for directly treating algae in-lake and selected only one in-lake treatment for reducing nutrient levels and/or competing with blue-green algae (floating wetlands). This is because the initial focus is to mitigate the phosphorus pollution that is driving algal blooms. Other in-lake options will be considered in future once their costs and benefits (and risks) are better understood and phosphorus pollution to Lake Tuggeranong has been reduced.

Table 8. Options considered in this report to reduce phosphorus pollution of stormwater (Booksmythe et al., 2024).

Option	Description
Street sweeping	Increase the amount of street sweeping in the catchment to remove more organic material from the roads, preventing it from leaching phosphorus into the stormwater drains. The implementation level reflects sweeping frequency ranging from 12 to 48 sweeps per year.
Fertiliser management	Identify and target the relatively small number of households that use excessive amounts of fertiliser to help them use either low-phosphorus fertiliser or no fertiliser at all. The implementation level reflects the reach of the program.
Open space mowing	Reduce the amount of grass clippings from municipal mowing that end up on the road, preventing them from leaching phosphorus into the stormwater drains. The implementation level reflects different management approaches, from having designated street sweeping trucks follow immediately after mowing events to towing electric blowers behind mowers to divert clippings away from the road.
Rainwater tanks	Capture stormwater from roofs for reuse on residential blocks. This may aid in removing some phosphorus in the system as well helping to reduce urban runoff. The implementation level reflects the number of houses that would have a tank installed.
Stormwater recycling	Divert and filter stormwater to storage tanks at sports fields for use in irrigating the fields. The implementation level reflects the number of sports field sites at which water managers would install this infrastructure.
Castellated kerbs	Retrofit outlets into road kerbs to divert some of the stormwater to open green space and allow it to filter into the ground. The implementation level reflects the number of outlets installed (water managers are limited by availability of suitable places in the Tuggeranong catchment; that is, areas adjacent to green space).
New water quality infrastructure—sports fields	Build swales around sports fields to potentially capture any phosphorus leaching out from fertiliser. Sports field managers are attempting to use fertiliser optimally and the leaching is more a legacy issue. The investment level reflects the number of sports field sites at which water managers would install this infrastructure.
New water quality infrastructure	Construct more wetlands at suitable locations in the catchment to treat phosphorus in the stormwater. The implementation level reflects the number of wetlands constructed, ranging from the two most effective builds to the ten most effective builds
Maintenance of existing water quality infrastructure	Ensure maintenance (such as dredging out built-up sediment and harvesting plants) of existing WSUD infrastructure in the Lake Tuggeranong catchment to maximise its performance and capture the largest amount of nutrients possible. The implementation level reflects the number of assets maintained.
Floating wetlands	Install more floating wetlands on Lake Tuggeranong to draw phosphorus out of the lake water. The implementation level reflects the number and size of wetlands installed.

Part 7: Identifying solutions to the problem

Booksmythe et al. (2024) derived potential solutions to the problem of phosphorus pollution that drives algal blooms in Lake Tuggeranong by comparing the cost-effectiveness of mitigation options in two ways: first separately and secondly together using the catchment water quality model. The former provides an indication of the most promising pollution mitigation options. The latter is important because it mirrors what will happen in the real world; that is, water managers will implement options together, not in isolation from each other, and implementing one option may affect the cost-effectiveness of other options.

Estimated cost-effectiveness of options

Method for determining cost-effectiveness of options

Booksmythe et al. (2024) defined four investment levels for each pollution mitigation option (Table 8). For example, for the option 'increased street sweeping', the investment levels were 12, 24, 36 and 48 sweeps a year.

They then derived data for costs and effectiveness (in terms of phosphorus reduction) of the investment levels from the scientific literature and the results of local trials. They estimated the benefits (kg phosphorus removed), costs (Net Present Value or 'NPV' over a 30-year period) and cost-effectiveness ($/kg phosphorus removed) of all investment levels. Cost-effectiveness represents the cost/effectiveness ratio of each investment level and was calculated as marginal annual benefit (kg phosphorus removed/year) / marginal annual cost (NPV to implement over 30 years divided by 30).

The researchers used a 30-year timeframe to calculate total costs because it allows for the comparison of options with very different cost schedules. For example, some options have large upfront costs, but low ongoing costs (for example, castellated kerbs) and some options have lower upfront costs, but higher ongoing costs (for example, street sweeping).

Results

Table 9 and Figure 9 present the annual load of phosphorus removed (effectiveness), the 30-year cost and the cost-effectiveness of each option's four levels of investment to mitigate phosphorus pollution. Note that the 30-year cost in Table 9 is the total cost of this option/investment level and any previous investment levels of the option.

It is clear from these data that street sweeping and adding extra water quality assets are the most effective options for reaching the 700 kg target, with the rest of the options bunched below these two in their effectiveness. Street sweeping is the standout option for cost-effectiveness; only the management of grass clippings comes close to the cost-effectiveness of street sweeping. The different pattern of the curve for grass clippings management in Figure 9 is due to the nature of the investment levels, which are effectively a matrix of two levels of assumed cost-effectiveness (low and high) by two separate types of removal, blowers and street sweeping (Booksmythe et al., 2024).

Table 9. Summary of phosphorus (P) removal performance, total cost and cost-effectiveness for four levels of investment for each of ten pollution mitigation options assessed independently (Booksmythe et al., 2024).

P mitigation option and level	Unit	P removed (kg/year)	30-year cost ($)[1]	Cost-effectiveness ($/kg P)
Install additional WSUD 1	Build 2 new WSUD assets	106.21	$22,507,500	$7,064
Install additional WSUD 2	Build 5 new WSUD assets	169.67	$48,369,492	$9,502
Install additional WSUD 3	Build 8 new WSUD assets	226.22	$73,862,467	$10,884
Install additional WSUD 4	Build 10 new WSUD assets	240.46	$84,519,403	$11,716
Maintenance of existing WSUD 1	Enhanced maintenance of 2 assets	35.84	$10,177,128	$9,465
Maintenance of existing WSUD 2	Enhanced maintenance of 3 assets	61.78	$19,086,579	$10,298
Maintenance of existing WSUD 3	Enhanced maintenance of 4 assets	79.93	$26,352,433	$10,990
Maintenance of existing WSUD 4	Enhanced maintenance of 5 assets	88.02	$30,352,433	$11,495
Increase street sweeping 1	12 street sweeps per year	203.70	$7,030,414	$1,150
Increase street sweeping 2	24 street sweeps per year	320.10	$14,060,827	$1,464
Increase street sweeping 3	36 street sweeps per year	372.50	$21,091,242	$1,887
Increase street sweeping 4	48 street sweeps per year	395.80	$28,121,656	$2,369
Manage grass clippings 1	Blow clippings into verge, low P removal estimate	16.40	$2,018,874	$4,103
Manage grass clippings 2	Blow clippings into verge, high P removal estimate	26.10	$2,018,874	$2,578
Manage grass clippings 3	Sweep clippings in verge, low P removal estimate	32.70	$1,521,462	$1,551
Manage grass clippings 4	Sweep clippings in verge, high P removal estimate	52.30	$1,565,956	$998
Sports field fertilizer management 1	Protect 25% of sports fields with bioretention swales	14.93	$4,204,451	$9,387
Sports field fertilizer management 2	Protect 50% of sports fields with bioretention swales	29.85	$11,817,327	$13,196
Sports field fertilizer management 3	Protect 75% of sports fields with bioretention swales	44.78	$19,430,204	$14,463
Sports field fertilizer management 4	Protect 100% of sports fields with bioretention swales	59.70	$31,445,222	$17,557
Household fertilizer management 1	Low P target (assume cost is $10,000/kg P/year)	20.00	$6,000,000	$10,000
Household fertilizer management 2	Medium P target (assume cost is $10,000/kg P/year)	32.67	$9,800,000	$10,000
Household fertilizer management 3	High target (assume cost is $10,000/kg P/year)	45.33	$13,600,000	$10,000
Household fertilizer management 4	Very high target (assume cost is $10,000/kg P/year)	58.00	$17,400,000	$10,000
Install castellated kerbs 1	Install 1 kerb outlet for every 4 sumps (or 453 outlets)	15.56	$4,532,500	$9,708
Install castellated kerbs 2	Install 1 kerb outlets for every 3 sumps (or 604 outlets)	20.75	$5,990,823	$9,624
Install castellated kerbs 3	Install 1 kerb outlets for every 2 sumps (or 906 outlets)	31.13	$8,539,901	$9,146
Install castellated kerbs 4	Install a kerb outlet for every sump (or 1813 outlets)	62.25	$14,349,291	$7,684
Install floating wetlands 1	Deploy 1000 m^2 of wetland	3.00	$1,226,000	$13,622
Install floating wetlands 2	Deploy 2000 m^2 of wetland	6.00	$2,452,000	$13,622
Install floating wetlands 3	Deploy 3000 m^2 of wetland	9.00	$3,678,000	$13,622

P mitigation option and level	Unit	P removed (kg/year)	30-year cost ($)[1]	Cost-effectiveness ($/kg P)
Install floating wetlands 4	Deploy 1000 m^2 of wetland	12.00	$4,904,000	$13,622
Stormwater recycling for irrigation 1	Build best 2	8.81	$2,673,863	$10,115
Stormwater recycling for irrigation 2	Build best 4	15.12	$4,588,909	$10,115
Stormwater recycling for irrigation 3	Build best 6	19.19	$7,339,284	$12,748
Stormwater recycling for irrigation 4	Build best 8	21.78	$10,816,870	$16,558
Household rainwater tanks 1	2,500 new households to install water tanks	15.00	$12,500,000	$27,778
Household rainwater tanks 2	2,500 new households to install water tanks	30.00	$25,000,000	$27,778
Household rainwater tanks 3	2,500 new households to install water tanks	45.00	$37,500,000	$27,778
Household rainwater tanks 4	2,500 new households to install water tanks	60.00	$50,000,000	$27,778

[1]Total lifecycle cost is the estimated cost of implementing and operating a mitigation option over 30 years, with annual operation and maintenance costs discounted by 7% per annum after the first year.

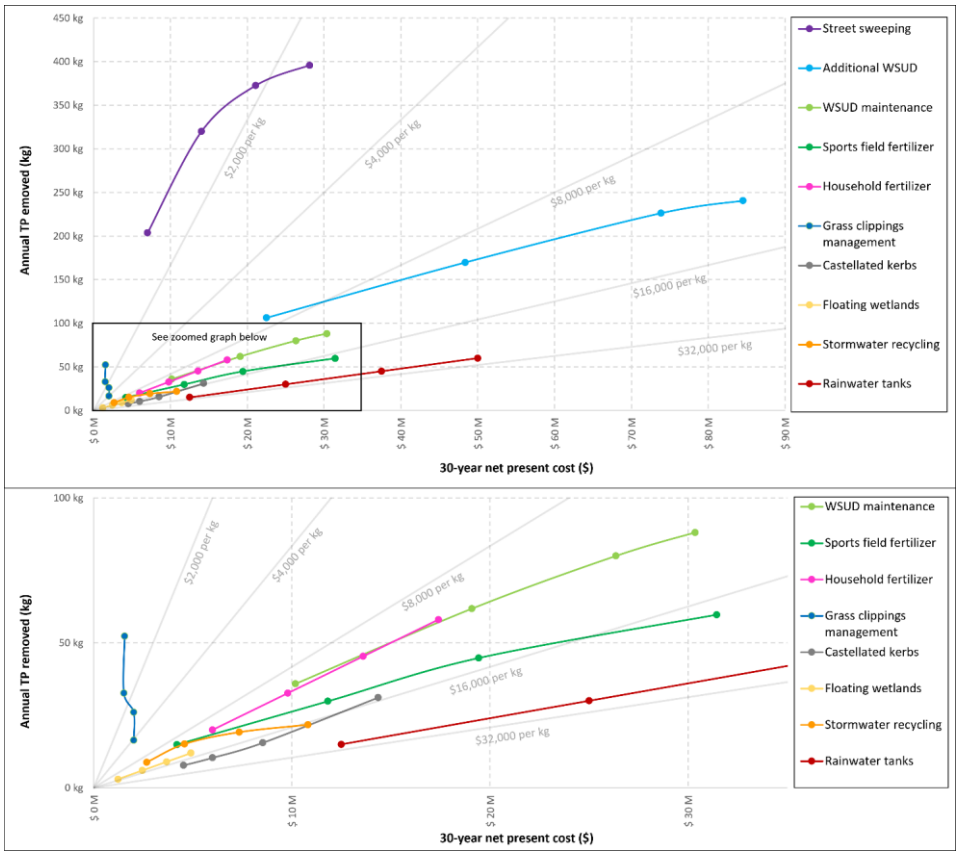


Figure 9. Annual total phosphorus load removed and 30-year lifecycle cost of each incremental investment level for the 10 assessed options for mitigating phosphorus pollution (Booksmythe et al., 2024). Coloured lines connect the four estimates for each option. Grey lines are a guide indicating the cost-effectiveness (cost per kg phosphorus removed) of the estimates. The top panel shows all estimates; the bottom panel shows a zoomed in view of the estimates within the inset box.

An important conclusion of this work is that options to prevent waters from becoming polluted in the first place—street sweeping and ensuring grass clippings from road verges do not enter drains—are more cost-effective than all other options, most notably, the construction of water quality assets. Thus, the most cost-effective way to improve water quality is to prevent waters from becoming polluted rather than relying on water treatment to achieve clean water.

Management scenarios to solve the problem

Booksmythe et al. (2024) define two water quality modelling scenarios: 'cost-effective' and 'broad benefits'. These scenarios are packages of various levels of investment in pollution mitigation options that would theoretically reach the target phosphorus reduction needed to achieve a mesotrophic lake in three out of four years (Dey et al., 2024). These are not the only management scenarios they could imagine but

represent two common ways of approaching water management. If water managers can successfully implement either of these scenarios, we can expect the lake to be more consistently free of blue-green algal blooms and thus open for the Tuggeranong community to use and appreciate for most of the year. In three out of four years, on average, we would expect no blue-green algal blooms. In the one out of four years where blooms arise, we will develop ways to clear the blooms.

Cost-effective scenario

The cost-effective water management scenario ranked the investment levels of each pollution mitigation option/investment level by its cost-effectiveness and selected the most cost-effective option/investment levels until the total annual phosphorus load removed met the 700 kg target. An increment of an option that represented a higher level of investment was excluded if the increments of lower investment were not also included in the list; that is, managers cannot double a $100,000 investment if they have not already invested $100,000. This resulted in the selection of nine pollution mitigation options (Table 10).

Broad benefits scenario

The 'broad benefits' management scenario started by taking the most cost-effective options and investment levels, as above, but recognised that some lower ranking options should still be included because they provide additional benefits to the community beyond water quality. For example, constructed wetlands can provide:

- Ngunnawal cultural benefits as identified in the Aboriginal Water Assessment (see Part 1), for example:
    - ensuring the locations of living infrastructure—drain re-naturalisations and other constructed wetlands—promote the creation of a cultural and ecological corridor that connects the Lake Tuggeranong catchment, its waterways and areas downstream of the dam at least to the Murrumbidgee River
    - considering the re-naturalisation of concrete drains as options for water quality assets
    - including reeds for weaving among the native seedlings added as water quality plantings
- foundations for residents' wellbeing including opportunities to improve physical and mental health (Lal and Adhikari, 2024)
- greater climate resilience by reducing urban heat (NC Economics, 2019, Tapsuwan et al 2024)
- enhanced amenity of suburbs
- support for urban biodiversity
- a source for recycled stormwater to irrigate sports fields, which relieves pressure on ACT's potable water supply (for example, as implemented at Kambah playing fields).

Under the broad benefits scenario, Booksmythe et al. (2024) considered the level of confidence in their estimates of cost-effectiveness for each pollution mitigation option. They developed confidence criteria for each option based on whether the information and data are robust, from a local source and from a single source or confirmed by multiple sources. Then, to create the broad benefits scenario, they adjusted the cost-effective scenario by increasing levels of investment in options with broader benefits and reducing investment in options with less certainty about their costs or effectiveness.

Compared with the cost-effective scenario, the broad benefits scenario:

- includes a wider variety of pollution mitigation options
- has slightly less street sweeping

- invests less in fertiliser management (because of lower confidence in the estimates of its contribution to phosphorus removal)
- has more investment in WSUD infrastructure because of its broader benefits to the community; for example, a benefit–cost ratio conservatively estimated as 1.66 (NCEconomics, 2019) is conservative because the analysis could not evaluate all benefits including Ngunnawal cultural benefits.

Table 10. Pollution mitigation options for reducing phosphorus in stormwater and levels of investment in these options modelled in the cost-effective and broad benefits scenarios.

	Level of investment	
Mitigation option	***Cost-effective scenario***	***Broad benefits scenario***
Increase street sweeping	48 sweeps uniformly over the year	36 sweeps, seasonally optimised
Improve open space mowing practices	Dedicated street sweeper to sweep after mowers go through	Dedicated street sweeper to sweep after mowers go through
Castellated kerbs	Not included in this scenario	Castellated kerbs retrofitted to replace every 4th sump along roads adjacent to open space (total 453 kerbs)
Improve fertiliser management in households through behaviour change program	Very high investment in program—$17.4 million (NPV, 30 years)	Lower investment in program—$6 million (NPV, 30 years)
Improve maintenance of water quality assets built in Stage 1 of Healthy Waterways	Improve maintenance of four most cost-effective water quality assets	Improve maintenance of five most cost-effective water quality assets
Build and maintain new large constructed wetlands or raingardens, e.g. drawn from the reserve list of assets proposed but not built under Healthy Waterways	Add the two most cost-effective assets	Add the five most cost-effective assets
Build and maintain water quality assets (bioretention swales) on sportsgrounds to capture fertiliser runoff	Add 1,000m^2 of bioretention swales at the biggest four sportsgrounds	Add 5,000 m^2 of bioretention swales at the biggest seven sportsgrounds
Install stormwater recycling tanks at sports fields for irrigation	Tanks installed at four sports fields (Greenway, Calwell, Kambah, Wanniassa)	Tanks installed at six sports fields (Greenway, Calwell, 2 x Kambah, Wanniassa, Gowrie)
Build new floating wetlands	Not included in this scenario	Build new 4000 m^2 of floating wetland in Lake Tuggeranong that is harvested once annually

Analysis of management scenarios

The overall performance of the two scenarios in mitigating phosphorus pollution is analysed in two ways:

1. Summing the costs (net present value, $ over 30 years) and effectiveness (kg phosphorus mitigated) of the pollution mitigation options/investment levels as if they were implemented in isolation, independently of one another. This provides an indication of which are the most promising pollution mitigation options.
2. Summing the costs and effectiveness of the options/investment levels as if they were implemented together at the same time. This is important because, in the real-world, water managers would implement options concurrently, not in isolation from each other, and the implementation of one option may affect the cost-effectiveness of another. Dey et al. (2024) used the catchment water quality model to estimate the combined effects of the options/investment levels on phosphorus supply to or availability in Lake Tuggeranong.

Performance of two scenarios to solve the problem

Options considered independently

The effects of the two scenarios, where the pollution mitigation options/investment level are considered independently of one another, are illustrated in Table 9 and Figures 9 and 10.

The cost-effective scenario is dominated by various investments in pollution prevention options that help prevent stormwater from getting polluted in the first place, such as street sweeping and fertiliser management (Table 9 and Figure 10). Options such as rainwater tanks, floating wetlands and castellated kerbs were less cost-effective (based on available data) than alternatives, so were not included in this scenario.

Only two constructed wetlands were included in the cost-effective scenario because wetlands are only moderately cost-effective in reducing phosphorus (Table 9). In older suburbs like Tuggeranong, there is limited space and it is expensive to retrofit large infrastructure. For example, during Stage 1 of Healthy Waterways, seven different types of constructed wetlands were built in the Lake Tuggeranong catchment at a cost of $30 million. The Lake Tuggeranong catchment water quality model estimates these assets remove 214 kg of phosphorus/year (Dey et al., 2024), approximately 13% of the catchment phosphorus load. While not insignificant, it highlights that wetlands alone will not remove enough phosphorus to reach the target. Even if enough space could be identified to build them, it appears that building more wetlands in the catchment could not reduce total phosphorous by more than 200 kg/year (Figure 9). The cost to attempt to use water quality assets alone to reach the phosphorus mitigation target would be prohibitive and, in medium to large storms, a significant amount of stormwater bypasses them and flows directly to Lake Tuggeranong untreated.

The cost of the cost-effective scenario for mitigating phosphorus pollution in stormwater by 700 kg per year is estimated at around $105 million over 30 years (Table 11).

A broad benefits scenario would remove 64 kg or 9% more phosphorus (Figure 10 and Table 11), while costing $141 million, which is $36 million or 34% more than the cost-effective scenario (Table 11). In both

scenarios, street sweeping, water quality assets and WSUD maintenance account for the greatest phosphorus mitigation. In the broad benefits scenario, fertiliser management by households contributes

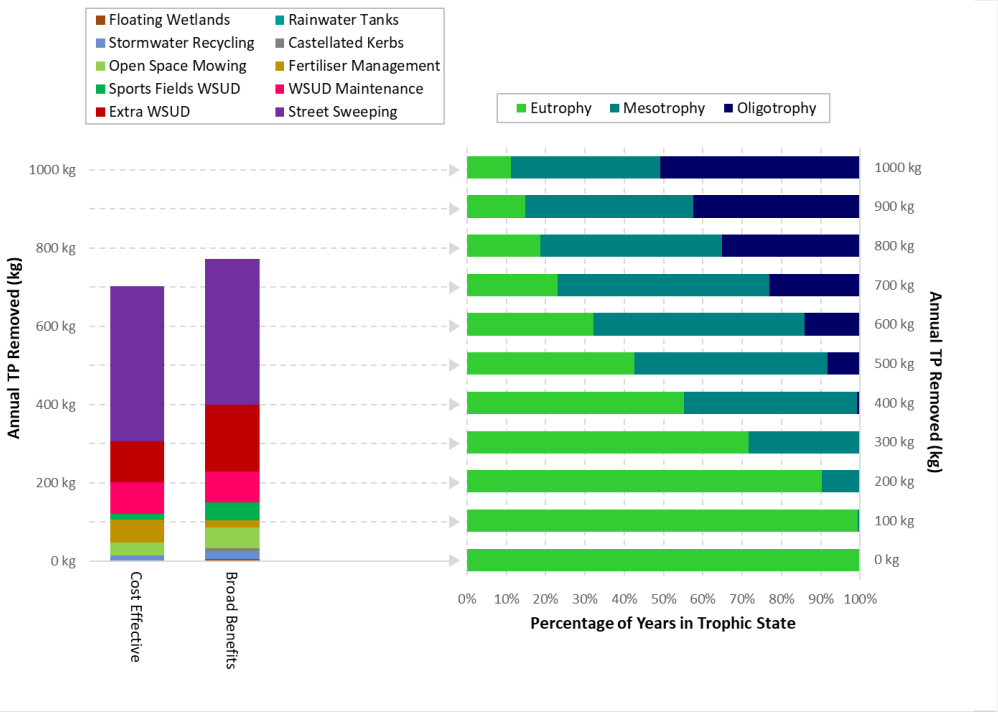


Figure 10. Two scenarios offering of a range of possible phosphorus-reducing options and increments of intensity of implementation, packaged up to reach the 700 kg target for phosphorus mitigation. This will enable Lake Tuggeranong to mostly exist in a mesotrophic state. The effects of the option increments have been analysed independently of one another.

Table 11. Comparison of the cost of two different management scenarios for mitigating phosphorus pollution. NPV is net present value.

Management scenario	Number of pollution mitigation options included	Cost (NPV – $ million over 30 years)	Benefit (kg phosphorus removed / year)	Cost-effectiveness $ / year / kg phosphorus removed
Cost-effective	**7**	**105**	**703**	**4,967**
Broad benefits	**9**	**141**	**767**	**6,241**

less than at sports fields, and open-space mowing and stormwater recycling contribute more to phosphorus mitigation. Five large water quality assets such as raingardens were included in the broad benefits scenario due to the other benefits they provide in addition to phosphorous removal, as described above.

Options implemented concurrently

In practice, water managers will implement various pollution mitigation options in either of the two scenarios concurrently, and this will affect their combined performance. Dey et al. (2024) used the catchment water quality model to model the two management scenarios to predict any impact to overall phosphorus reduction due to this interactive effect.

Their modelling indicates that when all pollution mitigation options are implemented together, the interactive effect reduces the total phosphorus removed by 14% under the cost-effective approach and by 12% under the broad benefits approach (Table 12, Figure 11). This decrease arises in part because the models assume that the cleaner the stormwater becomes, the less the water quality assets will filter out whatever pollutants remain. Monitoring of asset performance over time at different levels of stormwater flow will help to confirm or clarify this assumption. The decrease is also because some pollution mitigation options partially offset the effects of others. For example, having a dedicated street sweeper follow mowers of road verges would diminish some of the effect of sweeping suburbs 36–48 times a year. However, the uncertainties inherent in all estimates based on research and modelling (see Booksmythe et al. 2024 for details) probably mean that this reduction in supply is indistinguishable from the target of 700 kg (or from a lower level of performance of 400 kg).

Implications

Several key findings emerge from these results:

- There are no silver bullets; no pollution mitigation option has the potential to reach the 700 kg/year phosphorus mitigation target on its own. Managers will need to implement multiple options to reduce phosphorus pollution to a substantial extent and thus restrict the incidence of algal blooms.
- Street sweeping is the most cost-effective option in both scenarios and removes the largest amount of phosphorus (as also indicated in figures 9 and 10).
- Large water quality assets placed low down in catchments are necessary to treat unavoidable pollution but are not sufficient on their own to achieve the target reduction in phosphorus pollution of stormwater. Managers will need to implement options that prevent stormwater from getting polluted in the first place to substantially reduce the incidence of blue-green algal blooms in Lake Tuggeranong.

Table 12, Effects of implementing phosphorus pollution mitigation options together as determined by water quality modelling compared with the sum of benefits when multiple options are considered independently. Source: (Dey et al., 2024). Figures are for average kg phosphorus per year entering Lake Tuggeranong, or percentage decrease in the amount of phosphorus entering Lake Tuggeranong per year.

Average kg phosphorus/year entering Lake Tuggeranong						
Scenario	**Before Stage 1 assets were built**	**Current (with Stage 1 assets)**	**Current + added pollution mitigation options considered independently**	**% decrease from before Stage 1 assets were built**	**Current + added pollution mitigation options considered together (water modelling)**	**% decrease from before Stage 1 assets were built**
Cost-effective	**1656**	**1442**	**739**	**55%**	**979**	**41%**
Broad benefits	**1656**	**1442**	**662**	**60%**	**859**	**48%**

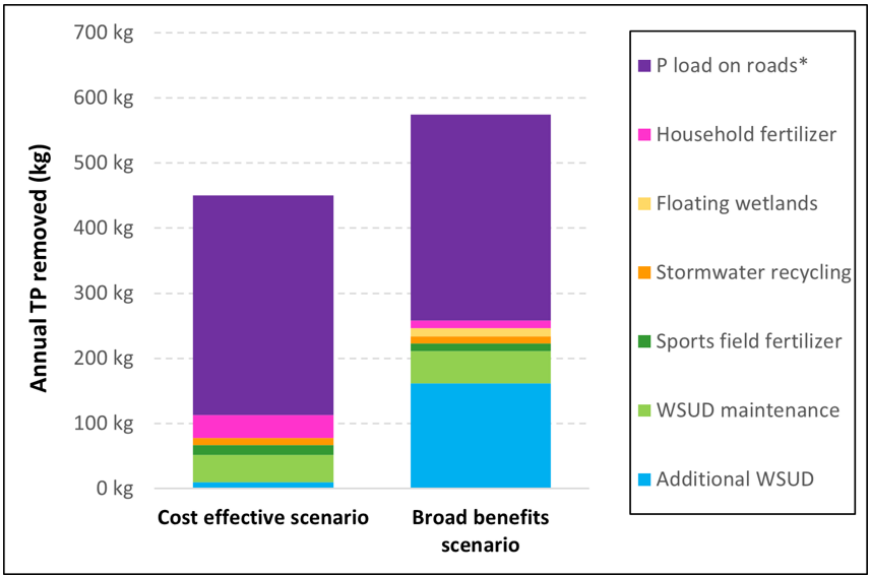


Figure 11. Modelled average annual reduction in the load of total phosphorus (TP) generated in the Lake Tuggeranong catchment under the cost effective and broad benefits management scenarios. Colours indicate the reduction in phosphorus due to different mitigation options in each scenario.
** 'P load on roads' includes the reductions in TP load due to street sweeping, grass clippings management and installation of castellated kerbs.*

Box 5. Street sweeping pilot

Based on the research findings that leaves contribute to stormwater pollution (see Part 3), a pilot street sweeping program was conducted over the summer of 2023/24 to better understand how much the leaves and other organic matter from streets contribute to the amount of nutrients in urban stormwater, and to begin to understand the efficacy of increasing the frequency of street sweeping as an option to mitigate pollution.

Over three months, two sub-catchments in the Lake Tuggeranong catchment were swept every fortnight and two sub-catchments were left unswept. Stormwater samples were collected during storm events to see if the fortnightly-swept catchments showed a reduction in nutrient concentrations. Samples of the material swept off the roads by the trucks were also taken to a lab for analysis.

The results indicate that leaves and other organic material on the roads are contributing significant amounts of phosphorus to stormwater in the catchment. Analysis of the material collected by street sweeping trucks (which included leaves, soil, grass clippings, gravel and road material) estimated that 39.2 kg of phosphorus was removed from the roads in the swept sub-catchments during the experiment. Scaled up to the Tuggeranong catchment, this pilot suggests that a fortnightly program of street sweeping could intercept around 300 kg a year of phosphorus, which is more than 40% of the target of 700 kg/year.

Analysis of the stormwater samples showed a modest decrease in phosphorus concentrations in stormwater from the swept sub-catchments over time, compared to the unswept sub-catchments. As there are many other factors that can influence nutrient concentrations in stormwater, the project was repeated in the summer of 2024/25 to strengthen our understanding of how much leaves contribute to phosphorus in the stormwater. Analysis of this second trial is underway.

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Can we reach the phosphorus reduction target?

The analyses suggest that the ACT Government can succeed in curbing algal blooms in the lake if it implements a program to reduce phosphorous pollution.

Firstly, a reduction of 500–600 kg/year in phosphorus pollution in the two scenarios presented would substantially reduce the frequency of blue-green algal blooms in Lake Tuggeranong (Figure 7).

Secondly, the management options to mitigate pollution are currently conceived, and thus modelled, in a simple way. Refinement of the options, both during implementation planning and in models, should both decrease their cost and increase their effectiveness. For example, street sweeping in winter, when cold temperatures limit algal growth, may have little impact on lake closures. Eliminating winter street sweeping will reduce costs. Conversely, targeting sweeping efforts in summer, and adding a complementary community program for collecting leaves, may intercept a greater amount of pollution from leaves and grass on verges, reducing the nutrient pollution from these sources beyond that predicted by Dey et al. (2024) for the most intense investment level of this option in the model. There are many nuances to the design of community partnerships and the design and siting of water quality assets that could increase their effectiveness above the average value used in the modelling.

Thirdly, several promising pollution mitigation options have yet to be explored that may help to meet the phosphorus mitigation target. Apart from floating wetlands, in-lake treatments have not been included in the modelled options, and these could contribute to further phosphorus reduction. For example, new products are emerging that draw and capture phosphorus out of stormwater, both in the catchment and in the lake itself. One potential intervention that has shown promising results in trials overseas is Poseidon Pellets™. These pellets consist of porous granules that adsorb dissolved phosphorus from water. They promise a high rate of phosphorous adsorption at a relatively low cost but remain untested locally.

The uncertainty about the extent that fertilisers applied to residents' gardens contribute to stormwater pollution (Part 5) does not preclude taking action now. If it turns out from further research that the fraction of phosphorus attributed to fertiliser use is more than is currently estimated, and the fraction due to leaves and grass is less, there would be a shift in emphasis from options that target leaves to ones that target fertilisers. The same is true if sewer leaks turn out to be an important source of phosphorus; the leaks would need to be fixed but it would still be necessary to deal with leaves, grass and fertilisers.

The main cautionary note is about how quickly algae in Lake Tuggeranong will respond to reduced supplies of phosphorus from the catchment. Algal blooms may persist if the phosphorus in the sediments is able to sustain the blooms. This may mean it takes longer than the goal of a decade to fix the algal bloom problem. The long-term research focus should include investigations into in-lake treatments that reduce the supply of phosphorus from the sediments or compete with algae for phosphorus, such as Poseidon Pellets™.

Key conclusions can be drawn from the analyses in this report:

- There is sufficient knowledge to have confidence that a suite of actions can lead to a substantial reduction in the frequency of blue-green algal blooms in Lake Tuggeranong. Inflows of phosphorus pollution can be reduced by up to 700 kg/year within ten years, but whether this would significantly reduce algal blooms in the same time frame may depend on the development of in-lake treatments to deal with phosphorus stored in lake sediments.

- Algal blooms probably cannot be prevented from forming altogether. The analyses carried out for this report suggest the best that can be achieved is for algal blooms to be prevented in three out of four years on average.
- This means that the ACT Government may need to consider developing ways to treat algal blooms as they arise in the years where pollution levels may permit their formation. These may range from the promotion of algal competitors to the use of algicides (see Part 6).

Part 8: The path forward

The research findings and modelling work presented in this report provide confidence that the ACT Government can make real progress in addressing the problem of algal blooms in Lake Tuggeranong. The target level of phosphorus reduction is achievable and this would reduce the impacts of blue-green algal blooms. Figure 12 shows a high-level plan for how this could be achieved, from which funding for implementation can be investigated.

Research agenda

Ongoing research and monitoring is critical to refining options to mitigate pollution, to maximise their effectiveness and minimise their costs. The ACT is one of only a small number of jurisdictions in the world actively monitoring constructed wetlands. This is important for testing how well wetland assets perform against design model expectations (including as stormwater entering them becomes cleaner over time) and for informing how the assets are operated and maintained.

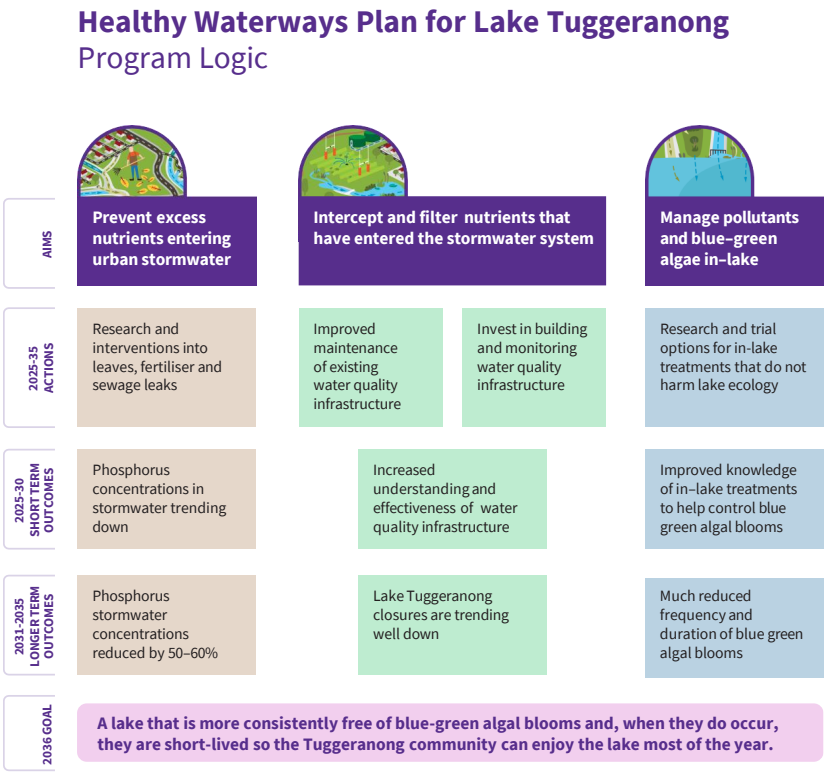

Figure 12. Draft program logic to guide more detailed implementation plan.

The highest priorities for research are to:

- trial promising pollution mitigation options
- investigate, to better understand, the fate of fertilisers applied to residents' blocks
- determine whether sewer cross-connections are a significant source of phosphorus in stormwater.

Table 14 describes the Healthy Waterways research program up to the summer of 2025/26.

Current priorities for restoration

Additional research will continue to refine knowledge and understanding of how to reduce phosphorus in the Lake Tuggeranong catchment, but there is enough evidence already to investigate funding for several priority actions.

Expand street sweeping program to be more often and seasonally optimised

Research by the University of Canberra (Ubrihien et al., 2019) plus the street sweeping pilot by the University of Canberra, Healthy Waterways and City Services demonstrated that leaves contribute a significant amount of phosphorus to catchment loads in the Tuggeranong catchment. Modelling by Booksmythe et al. (2024) indicates that an expanded street sweeping program would remove a significant amount of phosphorus from the catchment. If, for example, streets were to be swept 36 times a year, this would remove up to 316 kg/year or 53% of the target phosphorus reduction amount of 700 kg/year and cost up to around $1.4 million annually (Table 10, noting that the cost of investment level 3 has been annualised).

The Healthy Waterways team and ACT City Services ran a street sweeping pilot again in the summer of 2024/2025 to strengthen findings and inform how best to optimise a future street sweeping program to capture seasonal leaf fall.

New community pollution prevention programs

A successful community pollution prevention program that encourages communities to collect leaves and reduce fertiliser use will complement increased street sweeping by reducing the volume of leaves that make it onto roads. This will reduce the green waste going to landfill and disposal costs since, at present, all waste from streetsweeper trucks is deemed contaminated waste and goes to landfill.

The Leaf Collective and Love the Lakes pilot programs received positive feedback from the community and provide valuable insights into how to engage the community to change their practices around fertiliser use and leaves. In late 2024 a new program that builds upon the successes of the pilots was rolled out as the Waterways Friendly Gardening program.

Build new WSUD infrastructure

WSUD infrastructure cannot solve the problem of blue-green algal blooms on its own and is relatively costly to build and maintain (Table 10). However, there is value in building some additional water quality assets in the Tuggeranong catchment because there will always be some unavoidable pollution of stormwater, which these assets will help to intercept before the pollution reaches the lake. Constructed wetlands also

provide other benefits to the community including habitat for native plants and animals, urban cooling (Tapsuwan et al., 2024), public amenity (NC Economics, 2023) and cultural value.

Table 14. Healthy Waterways forward research agenda to 2026 for Lake Tuggeranong.

Area of research	Description	Estimated start date
Investigate potential leaks from sewerage—caffeine tracking study	Use caffeine in stormwater samples from across the catchment as an indicator of sewerage ingress.	Underway
Performance of constructed wetlands	Monitor the performance of four Stage 1 assets: two wetlands and two raingardens.	Underway
Street material content analysis	As part of the street sweeping project, run a study to understand what proportion of road matter phosphorus comes from non-leaf matter sources (e.g. from car tyres).	Summer 2024/ 2025
Maintenance of channel naturalisations	Develop methods to remove sediments accumulated in plant beds without destroying the plants.	Mid 2025
Investigate potential leaks from sewerage—Microbial Source Tracking	Test and compare the location, quantity and type of faecal matter (animal or human) found in different catchments after rain events, including Lake Tuggeranong.	Mid 2025
Investigate contribution of leaves on roofs to nutrient loads in stormwater	Examine how much leaves that fall on roofs are contributing to stormwater pollution given roofs are the biggest impervious area in the ACT.	Mid 2025
Circular economy—enhancing cost effectiveness of bioretention	Investigate income-generating potential from harvesting of vegetation from stormwater treatment ponds, floating wetlands etc., including when it's combined with swept material being used for biochar feedstock.	Mid 2025
Trial of Poseidon Pellets™	Run small-scale laboratory and field trials to test viability of Poseidon Pellets in the Lake Tuggeranong context.	Spring/Summer 2025/2026
Phosphorus content in leaves and soil	Investigate whether urban street trees of Tuggeranong shed unusually high levels of phosphorus in their leaves and where they access phosphorus from (soil or other sources such as the sewerage network).	Spring/Summer 2025/2026
Fertiliser leaching rates	Investigate runoff from residential blocks or gardens to estimate export rates of nutrients from fertiliser.	Spring/Summer 2025/2026
Maintenance of constructed wetlands	Develop approaches to harvesting macrophytes to increase the export of nutrients from wetlands and stimulate further uptake of nutrients.	Spring/Summer 2025/2026

As with all existing suburbs, space constraints and underground services limit the locations where new water quality assets can be built. However, Healthy Waterways feasibility studies have identified several potential locations that could be investigated further.

Improve maintenance of existing water quality assets

The ongoing performance of all water quality assets relies on good operation and maintenance practices. Modelling by Booksmythe et al. (2024) indicates that improving the maintenance of existing Stage 1 and 2 water quality assets would deliver substantial phosphorus reduction benefits (Table 10). The Healthy

Waterways and ACT City Services teams are exploring several ideas for facilitating the operation and maintenance of water quality assets to improve their performance.

Next steps to finalise the Plan

Version 1 of the Healthy Waterways Plan for Lake Tuggeranong will incorporate further inputs from First Nations people and feedback from the community and experts on the proposed approach. An implementation plan will then be developed to set out how the vision will be achieved over the next 10 years~~, including~~. This will consider how ~~it~~the plan will be monitored and evaluated, and include indicators for cultural values.

~~Glossary~~

Glossary

Term	As defined in the Plan
Adsorption, adsorbed	The adhesion of a substance (e.g. charged phosphorus ions) to a surface (such as charged clay particles in soil or Poseidon Pellets™).
Bacterial pathogen	Bacteria that can lead to illness.
Baseflow	Streamflow continues between rain events.
Bioavailable	(for plant nutrient–algae relationship) Plant nutrients that are in a form that can be absorbed and used by algae to support growth and metabolism.
Bioretention	Infrastructure (for example, swales or raingardens) comprised of soil, plants and microbes to treat and filter stormwater. Stormwater is spread through the surface of the infrastructure, percolates vertically and is collected in outlet pipes at the base of the asset, leaving behind filtered pollutants.
Bioretention basin	Landscaped depression to manage and treat runoff. See 'Bioretention'
Bioretention swale	Type of bioretention system using linear, vegetated drains in a landscape to capture and filter runoff.
Blue-green algae	A group of photosynthesising, algae-like bacteria that live in freshwater, estuarine and marine environments. Also known as cyanobacteria.
Calibrate, calibration (models)	Adjusting water quality models so they provide a good description of the water quality in Tuggeranong's waterways. This is achieved by comparing model predictions with actual measurements of water quality in the stormwater system and making adjustments to the model to minimise its differences with the observed data.
Catchment	Area of land where precipitation collects and drains to a common outlet (for example, a river or waterbody). May also be known as a drainage basin.
Chlorophyll *a*	A pigment in many plants and algae that helps them absorb light energy and convert it to chemical energy in a process called photosynthesis. Chlorophyll *a* is often used as a proxy to assess algae biomass as it is easier to measure than biomass.
Constructed wetlands	Both a general term for water quality assets comprised of soil, plants and microbes to treat and filter urban runoff, and a reference to a specific type of asset where stormwater that is diverted to the wetland flows laterally to an outlet at its downstream end (as compared to 'bioretention'; see definition above).
Cyanobacteria	See blue-green algae.
Diffuse source	A non-point source, where pollutants are generated from many sources across the catchment.
Deposition rate	(for leaves) The volume of leaves that fall from trees for a given area/time.
Enterococci	Bacteria commonly found in the intestines of humans and animals, used to indicate faecal pollution in waterbodies.
Eutrophic	Water bodies in a eutrophic state are nutrient rich, with highly productive plant growth and high turbidity. They are seasonally deficient in oxygen, which may lead to fish kills. Eutrophic lakes may experience regular algal blooms.
Export rate	% of nutrient (in this case phosphorus) in applied fertilisers lost to runoff.
Hydrograph	A way to display the flow of water over time.
Impervious surface	Water-resistant surface that is a partial or total barrier to water, such as concrete, roofs, roads.
Management scenarios	Packages of phosphorus pollution mitigation options that together are intended to achieve a desirable water quality outcome.
Mesocosm	Enclosure set up in the lake to study aquatic responses under controlled conditions.

Term	As defined in the Plan
Mesotrophic	Water bodies in a mesotrophic state have a moderate amount of nutrients, moderately clear water, some algal blooms in late summer and oxygen depletion at bottom of lake as biomass decomposes. If they do experience algal blooms, it is typically in late summer.
Microbial Source Tracking	Method to identify the sources of faecal contamination in water bodies; that is, whether it comes from humans or animals (domestic pets, wildlife, livestock).
Net Present Value (NPV)	The difference between the present value of cash inflows and outflows over time.
Nitrogen	Key nutrient essential for the growth of aquatic plants and algae. Excess nitrogen can lead to nutrient pollution which can cause algal blooms.
Nutrient load	Refers to the amount of nutrients entering a waterbody in a given time period; for example, kg phosphorus entering Lake Tuggeranong per year.
Oligotrophic	Water bodies in an oligotrophic state have very low nutrient concentrations and tend to have very clear water with little plant or algal growth. High oxygen concentrations depress the release of algal nutrients stored in lake-bottom sediments. Hence, oligotrophic lakes are not prone to algal blooms.
Phosphorus	Key nutrient essential for the growth of aquatic plants and algae. Excess phosphorus can lead to nutrient pollution which can cause algal blooms. Can be either particulate (sediment-bound) or present in dissolved forms. Total phosphorus (TP) is the sum of all forms of phosphorus present in a sample. In this report, phosphorus refers to total phosphorus unless otherwise stated and these terms are used interchangeably.
Phytoplankton	Photosynthesising microscopic organisms that live suspended in water. Blue-green algae/cyanobacteria are a type of phytoplankton.
Point-source	Where pollutants are generated from specific sources in the catchment such as nutrients from a sewage treatment plant outlet.
Pollutant, Pollution (of water)	A substance (like phosphorus) that is present at levels that can cause harm to life. Phosphorus is not directly harmful but is a pollutant at high concentrations or supply because it promotes the growth of harmful algae.
Pollution mitigation options	Individual approaches to reducing the level of phosphorus in stormwater such as increasing the frequency of street sweeping or building water quality assets.
Raingarden	A water quality asset using bioretention technology in a shallow, landscaped depression to capture and filter urban runoff.
Runoff	Water that flows over the surface of the ground when it cannot sink into the ground.
Runoff infrastructure	Infrastructure or landscaping that holds, redirects and/or slows runoff to allow it to sink into the landscape.
Sediments	In this context, sediments are bits of soil and organic matter eroded from the catchment into stormwater and lake water. Sediments may become deposited in the bottom of lakes.
Stormwater	Water generated through rain that has made its way into the stormwater system.
Stormwater runoff	Rain that isn't absorbed into the ground and flows over the landscape.
Stormwater system	Concrete channels and pipes designed to direct stormwater away from built up areas to reduce flood risk.
Stratification	Formation of distinct thermal layers in the water column, which affect the distribution of oxygen and nutrients within the lake.
Suspended solids	Small particles that remain suspended in water, affecting water quality and aquatic life by reducing light penetration and temperature.
Total dissolved solids	The inorganic and organic substances dissolved in water. They are used as an indicator of water quality.
Treatment train	Water quality infrastructure working in sequence to remove pollutants and manage water flow to a target level.

Term	As defined in the Plan
Trophic state	Describes the biological productivity of a water body and depends on factors such as the concentration of nutrients like phosphorus and nitrogen (see oligotrophic, mesotrophic, eutrophic).
Turnover	Seasonal process where water layers mix resulting in the redistribution of oxygen and nutrients throughout the lake.
Water Sensitive Urban Design (WSUD)	WSUD seeks to minimise impacts of urban development on the natural water cycle by integrating developments with a site's natural features and promoting the integration of stormwater, water supply and sewage management.
Water quality assets	Infrastructure solutions that aim to filter water of pollutants, such as constructed wetlands, raingardens and ponds. Water quality assets are also commonly referred to as 'WSUD infrastructure'.

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Attachment G

ACT Government

Lake Tuggeranong Catchment Model

Technical Report: Configuration and Calibration of the Water Quantity and Quality Model

Water Information Services, ACT Office of Water

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Environment, Planning and Sustainable Development Directorate

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Executive Summary

Lake Tuggeranong is a small (57 ha) urban lake in southern Canberra. Lake Tuggeranong was constructed in the late 1980s on Tuggeranong Creek, a 66 km^2 catchment that is predominantly (62%) urbanised. In recent decades, Lake Tuggeranong has been plagued by poor water quality. Since 2017, there has been a concerted effort to improve water quality in the lake through the construction of Water Sensitive Urban Design (WSUD) infrastructure throughout the catchment, and a major research program to understand the causes of poor water quality, and sources of pollutants entering the lake. This work has been undertaken as part of the ACT Healthy Waterways program.

The ACT Government has commited to developing Healthy Waterways Plans for priority catchments in the ACT. The draft Lake Tuggeranong plan aims to provide a suite of potential management options to Government to further improve water quality in Lake Tuggeranong. To acheive this, modelling and analyses have been undertaken to examine a broad range of management scenarios and identify cost-effective options to improve water quality in Lake Tuggeranong. To support these analyses, a catchment model was developed in the eWater model platform Source to support the testing of water quality management scenarios, and rank these scenarios based on cost-effectiveness.

This report presents an overview of the development, calibration and outputs of the Lake Tuggeranong catchment model. The underlying rainfall-runoff model chosen for this task was a Sacremento daily timestep model, implemented in Source. Fine-scale delineation of subcatchments, land use and imperviousness, flow regulation infrastructure and WSUD infrastructure were included in the model, to provide a complete, current assessment of the Lake Tuggeranong catchment. A total of 75 subcatchments were delineated to key infrastructure within the catchment, existing monitoring locations, and other features of interest. LIDAR data captured in 2020 was used to quantify surface imperviousness within subcatchments, facilitating an explicit representation of imperviousness in the model.

A comprehensive compilation of water quality data and streamflow data collected in the catchment from 2014 to the present was used to calibrate the Source model. The initial flow calibration is rated as suitable for estimating long-term catchment mean annual flow and long-term mean annual pollutant loads. The water quality model is parameterised against observed end-of-catchment median event concentrations of total phosphorus, total nitrogen, and total suspended solids, in the absence of load-based water quality data. The model estimates pollutant loads generated in the catchment based on land use and imperviousness data.

The parameterised model was used to simulate daily flows and pollutant loads generated in the Lake Tuggeranong catchment between 1889 and 2023, the period for which observed rainfall and climate data was available. Under current catchment land use and management conditions, the modelled average annual inflow to Lake Tuggeranong is 8.8 GL/year. The modelled mean annual loads of pollutants entering Lake Tuggeranong are 1,442 kg/year total phosphorus, 11,894 kg/year total nitrogen, and 397,064 kg/year total suspended solids.

The results provide a robust foundation for future catchment management plans and strategies.

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1. Introduction

Lake Tuggeranong is a small (57 ha) urban lake in southern Canberra. The lake was constructed in the late 1980s on Tuggeranong Creek, a 66 km^2 catchment that is predominantly (62%) urbanised. In recent decades, Lake Tuggeranong has been plagued by poor water quality, with high loads of nutrients (phosphorus and nitrogen) and sediments entering the lake. Since 2017, there has been a concerted effort to improve water quality in the lake through the construction of Water Sensitive Urban Design (WSUD) infrastructure such as wetlands, swales and raingardens throughout the catchment, and a major research program to understand the causes of poor water quality, and sources of pollutants. This work has been undertaken as part of the ACT Healthy Waterways program.

The ACT Government has commited to developing Healthy Waterways Plans for priority catchments in the ACT. The Lake Tuggeranong draft plan aims to provide a suite of potential management options to Government to further improve water quality in Lake Tuggeranong. To acheive this, modelling and analyses have been undertaken to examine a broad range of management scenarios and identify cost-effective options to improve water quality in Lake Tuggeranong. To support these analyses, a catchment model was developed in the eWater model platform Source (Argent, et al., 2005) to support the testing of water quality management scenarios, and rank these scenarios based on cost-effectiveness.

This report documents the development of a new, daily timestep water quantity and quality model for the Lake Tuggeranong catchment. The purpose of the model is to simulate long-term mean annual flows and associated pollutant loads entering Lake Tuggeranong, to inform and support catchment improvement studies and associated management strategies.

The model builds upon and extends previous models describing the Lake Tuggeranong catchment by:

- Including long-term, gap-filled climate data to extend the time period over which simulated results are available (1889-2023);
- Incorporating and combining up-to-date spatial data on land use and land surface imperviousness in the catchment;
- Undertaking hydrological model calibration;
- Adopting a model structure delineated to
    - water quality monitoring points to facilitate water quality model parameterisation;
    - existing and potential water quality improvement infrastructure (i.e., WSUD infrastructure) to facilitate estimation of pollutant load reduction from this infrastructure.

1.1 Overview of previous modelling and monitoring studies in the catchment

The model presented in this report builds on several published and unpublished modelling and monitoring studies undertaken in the Lake Tuggeranong catchment to describe flows and water quality in Lake Tuggeranong. These studies are reviewed briefly below, highlighting how the data has been used to inform the current study.

1.1.1 Modelling studies

Lake Tuggeranong catchment MUSIC 6 model, GHD (2015)

To inform the early stages of the Basin Priority Project, GHD developed a model of the Lake Tuggeranong catchment using the software MUSIC (Model for Urban Stormwater Improvement Conceptualisation) to aid in identifying sources of pollutant loads entering Lake Tuggeranong (GHD, 2015). The Lake Tuggeranong catchment was delineated based on contour information and the ACT stormwater network. Existing WSUD infrastructure in the catchment at the time comprised only gross pollutant traps (GPTs) with or without sedimentation basins, as well as Lake Tuggeranong, Isabella Pond, and Upper Stranger Pond. These assets were each represented as GPT, sedimentation basin, or wetland nodes in the MUSIC model. Land use classification in the model was based on ACT Government land zoning data aggregated to six broad categories, and imperviousness was based on values for each land use category from the published literature. Likewise, water quality parameters (event mean concentration, EMC, and dry weather concentration, DWC, of pollutants) were taken from the literature, rather than derived from existing data in the Lake Tuggeranong catchment.

The MUSIC model simulated flows and pollutant loads in the catchment under rainfall and evaporation conditions for the 10-year period from 1968-1977. It predicted an annual flow volume of 20,600 ML in the Lake Tuggeranong catchment, with an annual average of 2.7 tonnes TP, 31.5 tonnes N, and 2230 tonnes TSS generated given the existing WSUD infrastructure in the catchment at the time.

Lake Tuggeranong catchment MUSIC X model, eWater Ltd (2022)

eWater developed another MUSIC model of the Lake Tuggeranong catchment to assess the potential pollutant load reductions associated with WSUD assets that were constructed up to June 2019 as part of the ACT Healthy Waterways project (eWater Ltd, 2022). The Lake Tuggeranong catchment was delineated to 11 subcatchments, 7 of which drained through WSUD assets. The model operated on a 6-minute time step for the period 2010-2015. Published or MUSIC default values for hydrology and water quality parameters were applied to the model, which adopted a land use -based stochastic EMC/DWC approach to water quality modelling.

Land use was derived from 0.5m LIDAR coverage mapping impervious surfaces in the catchment and was divided into 6 classes (roof, road, hardstand, pervious, bushland, and rural). WSUD assets were incorporated in the model by importing and combining the 7 existing MUSIC models representing the detailed design configurations of each asset. Design configurations are expected to differ slightly from works-as-executed configurations.

The MUSIC model predicted an annual flow volume of 14,284 ML, with an annual average of 4.8 tonnes P, 39.8 tonnes N, and 2320 tonnes TSS generated in the Lake Tuggeranong catchment. However, the model was uncalibrated and over the period 2010-2015 overestimated flows by 57.2%, compared to observed data from the gauge immediately downstream of Lake Tuggeranong (Tuggeranong Creek upstream of Sewer Crossing, gauge 410779). The model is therefore also likely to overestimate pollutant loads in the catchment. However, the percentage removal of pollutants associated with each WSUD asset may be used as a starting point in the current modelling study to represent the treatment performance of existing assets.

Upper Murrumbidgee catchment Source models, Alluvium (2017) and eWater Ltd (2019)

Alluvium (Alluvium, 2017) developed an Upper Murrumbidgee catchment model in Source with the best available data and methods as a part of a project to meet requirements for the Murray-Darlin Basin Plan and the ACT Water Resource Plan. Alluvium's model delineated the Upper Murrumbidgee catchment into 440 subcatchments, using a 20 m digital elevation model (DEM), water management and hydrological boundaries, and stream gauging locations. Current ACT and NSW land use classifications, consistent with the Australian Land Use Mapping (ALUM) codes, were combined into 20 functional units for use in the model. The model used climate data from 1980-2016 and a combination of SIMHYD and GR4J rainfall-runoff models, assigned to urban and agricultural subcatchments, respectively. Observed discharge and water quality data from storages (dams and lakes) and sewage treatment plants (STPs) were used to parameterise the model. The model calibration was moderate for most of the gauges, with missing data at both hydrology and water quality monitoring gauges constituting a major limitation of the model. Moreover, due to the large number of subcatchments, model performance was very slow.

Alluvium's Source catchment model did not estimate flows and pollutant loads entering Lake Tuggeranong, instead providing estimates for the outlet of the Lake Tuggeranong catchment, including the effect of the lake itself on these parameters. The model predicted an annual flow volume of 5,868 ML for the outflow from the Lake Tuggeranong catchment, with an annual average load of 0.29 tonnes P, 5.63 tonnes N and 128.9 tonnes TSS.

In 2019, eWater identified a number of potential improvements to Alluvium's Upper Murrumbidgee catchment model and rebuilt the model (eWater Ltd, 2019). Their updated catchment model defined fewer subcatchments outside the ACT, delineating a total of 163 subcatchments, to improve model performance. eWater's model retained the climate data, land use and functional unit classifications used in Alluvium's model, but used the LASCAM rainfall-runoff model across all subcatchments to enable assessment of the hydrological impacts of land use change. The updated catchment model also incorporated Canberra's water supply, with storages configured to operate, albeit without implementation of operating rules.

Water quality parameters (EMC and DWC) in this model used values taken from the literature, rather than being fitted to observed data. While flow parameters were calibrated to observed data from 32 gauges across the Upper Murrumbidgee catchment, the model did not calibrate end-of-catchment values for the Lake Tuggeranong catchment to the downstream gauge Tuggeranong Creek at Sewer Crossing (410779). Therefore this model configuration cannot provide reliable estimates of the total flow and loads generated from the Lake Tuggeranong catchment.

1.1.2 Monitoring studies

University of Canberra Lake Tuggeranong research project, Stage 3 report (2020)

The University of Canberra's Lake Tuggeranong research project has demonstrated the importance of external sources of nutrients to water quality in Lake Tuggeranong. Stage 3 of the Lake Tuggeranong research project analysed the nutrient contribution from different subcatchments, in order to understand the relative influence of different land uses on nutrient inputs to the lake (Ubrihien, et al., 2020). Water sampling during rainfall events was undertaken in the Kambah Creek and Village Creek subcatchments over two years (2018 – 2020), with more than 2000 grab samples collected and analysed. The monthly total

phosphorus (TP), total nitrogen (TN) and total suspended solids (TSS) loads to Lake Tuggeranong were calculated for each subcatchment.

It was found that event discharge and loads of TP, TN, and TSS were much greater than those from baseflow. Event samples from urban areas of the subcatchments had high concentrations of nutrients with an unexpectedly high proportion in dissolved form. This study was constrained by extremely dry weather conditions over the spring and summer of 2019-20, which limited opportunities to collect event samples in a season of key interest. The movement of water and associated nutrients measured during these extreme conditions are unlikely to be representative of wetter years. Additionally, the lack of streamflow gauging at water quality sampling sites made it difficult to accurately estimate the nutrient loads entering the lake. Flow-weighted mean concentrations of nutrients from event samples were essential to calculate the load.

Despite these limitations, Stage 3 of the Lake Tuggeranong research project provides a significant water quality dataset including manual grab-sampling as well as data from 6 autosamplers at fixed locations on inflows to Lake Tuggeranong. The median measured concentrations of TP, TN and TSS from this work have been used in the parameterisation of our water quality model.

ACT Government water quality data

Several water quality monitoring programs supported or contracted by the ACT Government have measured pollutant (nutrient and sediment) concentrations at sampling sites across ACT waterways, including in the Lake Tuggeranong catchment. These have been collated into a single dataset and used in the parameterisation of our water quality model.

Waterwatch

This dataset includes water quality samples collected from eight different sampling sites in the Lake Tuggeranong catchment from 2017 to the present. The water quality parameters recorded include concentrations of TP and nitrates. Waterwatch data are publicly accessible at https://biocollect.ala.org.au/actwaterwatch. Following review and a focus on event flow water quality samples for model configuration, Waterwatch data were not used in the parameterisation of our water quality model.

Land Use Monitoring program (LUM)

Water quality data was collected from a single site in the Lake Tuggeranong catchment over 2018 and 2019. The water quality parameters recorded include concentrations of TP, TN and TSS.

Basin Plan Phase 1 (BPP1)

Under this program grab-samples were collected from 20 sampling sites in the Lake Tuggeranong catchment and analysed for water quality parameters including concentrations of TP, TN, and TSS.

ACT Lakes and Rivers water quality monitoring program

The ACT Lakes and Rivers water quality monitoring program has maintained two grab-sampling locations on Lake Tuggeranong. While these data were not used explicitly in the Source model calibration, they are

relevant to the in-lake modelling described in the supplement to this report, *Predicting phosphorus concentration and trophic state of Lake Tuggeranong* (Kahn & Dey, 2024).

1.2 Key gaps addressed by this study

The brief review above highlights the considerable amount of new water quality data that is now available for the Lake Tuggeranong catchment, including some event-based concentration data. The new data can be used to refine model water quality parameters that were previously based on values derived from the published literature. The modelling studies described above are limited in their utility as catchment models in the current planning context, as they either did not have the tools or resources available to calibrate model hydrology or were calibrated over a spatial resolution too coarse to investigate detailed catchment management strategies. Additionally, these previous studies simulated results over relatively short timeframes (6 – 36 years).

This study therefore aims to address these gaps by:

1. Preparing a high spatial resolution catchment model that uses a long-term historical climate observations dataset to simulate results over the 133-year period 1889-2023.
2. Calibrating the catchment model to ensure that end-of-catchment observed flows match modelled flows over the long term, so that the model accurately represents long-term water yield.
3. Using available event-based and baseflow water quality data to parameterise land use -based water quality models and derive new estimates of mean annual pollutant loads to Lake Tuggeranong.

Section 2 of this report collates and summarises the input data used to build and parameterise the model including terrain models, land use, water quality assets, hydrological and water quality data. Section 3 describes the model construction and parameterisation procedures and associated results and limitations. Section 4 presents the results of long-term flow and load estimates for the catchment under the current conditions including spatial results and estimated loads to Lake Tuggeranong. Section 5 presents the predevelopment and current scenario analysis of the catchment. Section 6 provides the conclusions and recommendations for next steps to improve model performance through additional data collection or by upgrading the model techniques.

2. Model input data

The Source modelling framework allows the simulation of catchment hydrology and pollutant generation in response to rainfall and climatic processes, catchment characteristics, land use and imperviousness, and waterway management. This requires the input of data describing each of these elements, enabling the catchment to be represented as a connected patchwork of areas for which the conversion of rainfall to runoff, the generation of pollutants, and the flow of surface waters between areas, can be calculated. Dividing the catchment into subcatchments for which flow and water quality data are available allows finer-scale calibration of the model to observed data in the catchment.

This section describes the input data sets used for model creation and parameterisation including:

- Subcatchment delineation;
- Land use classification and imperviousness;
- Water quality data;
- Climate data;
- Lake configuration;
- Streamflow and storage level data;
- WSUD asset configuration.

2.1 Subcatchment delineation

The Lake Tuggeranong catchment is approximately 6,600 hectares and is mostly (62%) urbanised. The southeastern part of the catchment is rural and extends across the ACT border into NSW. Catchment development began in the 1980s (Beer, Young, Humphries, & Burgess, 1982) and continued into the early 1990s. The Lake Tuggeranong catchment is the smallest Water Management Area in the ACT, and also encompasses a small component of the Upper Murrumbidgee water management area due to diversion of the upper Stranger Pond catchment to Lake Tuggeranong at Isabella Pond.

Because the subcatchments delineated to WSUD assets for the eWater (2022) study contained some discrepancies with the ACT Government stormwater network map, a new subcatchment map was created using a pit-filled, 1 m DEM based on high-resolution LIDAR data (ACT Government, 2016) and the ACT Government stormwater network map. Subcatchments within the Lake Tuggeranong catchment were delineated to:

- known water quality monitoring locations;
- known streamflow monitoring locations;
- existing WSUD assets;
- ponds and storages.

This resulted in 75 subcatchments, shown in Figure 1. When identifying water quality monitoring sites for catchment delineation, University of Canberra water quality monitoring sites based on the stormwater network were prioritised.

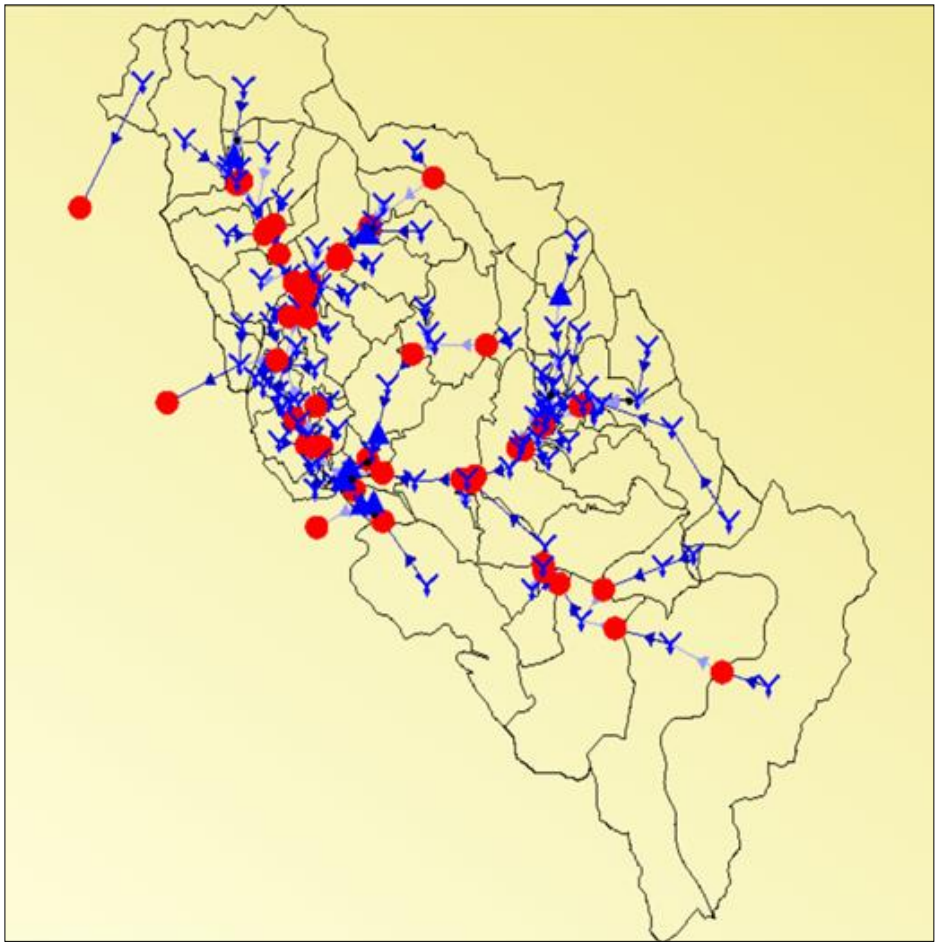

Figure 1. Screenshot of the Source model-generated Lake Tuggeranong subcatchment map, showing nodes defined by flow and water quality monitoring locations (large red points) and WSUD infrastructure (large blue triangles). Blue 'Y' symbols represent flow and pollutant generation within subcatchments and small blue arrows indicate the direction of flow.

2.2 Land use classification and imperviousness

Land use classification for the Lake Tuggeranong catchment model aims to represent a wide range of land uses that could be subject to different structural and non-structural catchment management actions, such as suburban street sweeping, construction of additional WSUD assets, or education around private household fertilizer use. To this end, broad land use classifications adopted for previous modelling studies (eWater Ltd, 2022) were disaggregated to a more granular set of classifications based on ACT Government land zoning. These were combined with data on land surface imperviousness to derive land use for the Lake Tuggeranong catchment model as follows:

1. Aerometrix (2020) LIDAR data at 0.5m pixel resolution was trimmed to the Lake Tuggeranong catchment, mapping 5 land surface imperviousness classes:
    - Impermeable ground level (i.e., roads and hardstand)
    - Impermeable above ground level (i.e., roofs)
    - Permeable ground level (i.e., pervious, unpaved ground)
    - Permeable above ground level (i.e., tree canopy)

- Water

2. The LIDAR data was converted to shapefile and intersected with the 2023 ACT Government land zoning GIS layer trimmed to the Lake Tuggeranong catchment, consisting of 17 land use zones consistent with ALUM codes:
   - Business zone
   - Community Facilities
   - Core zone
   - Leisure and accommodation
   - Local centre
   - Services
   - Services zone
   - Medium density residential
   - Suburban
   - Suburban core
   - Transport
   - Urban open space
   - Restricted access recreation zone
   - Hills ridges and buffer areas
   - Designated
   - River corridor
   - Rural

   The entire NSW portion of the catchment was classed as 'Rural' land use.
3. This cross-classified land use layer was intersected with the ACT Government road edges GIS layer, to identify road area within each land use zone. Areas classified as impermeable ground level that fell outside of the roads boundary were deemed hardstand, and areas classified as permeable above ground level that fell within the roads boundary (i.e. where trees overhung road) were reclassified as road (impermeable ground level). This approach yields a more precise classification of road area than the approach of eWater (eWater Ltd, 2022), where road centrelines buffered by 5m were used to estimate the area of impermeable road surface within the transport classification of the land zoning map, which includes the entire road corridor consisting of largely permeable open space.
4. Finally, visual inspection of aerial imagery was used to identify and manually delineate irrigated sports fields based on their "greenness" relative to nearby open spaces, and assign them a specific land use classification.
5. The land use and imperviousness layer was converted to a 0.5m grid, which was intersected with the Lake Tuggeranong subcatchment map to obtain the area of each land use - imperviousness combination within each subcatchment.
6. The detailed land use types were grouped into six major functional units for incorporation into the Source catchment model: suburban, commercial, open space, rural, bushland and sports field, each containing imperviousness classifications of road, hardstand, roof, permeable ground level, permeable above ground level, and water. The final land use and imperviousness classification schedule, and the area associated with each land use functional unit in the model domain is provided in Appendix C.

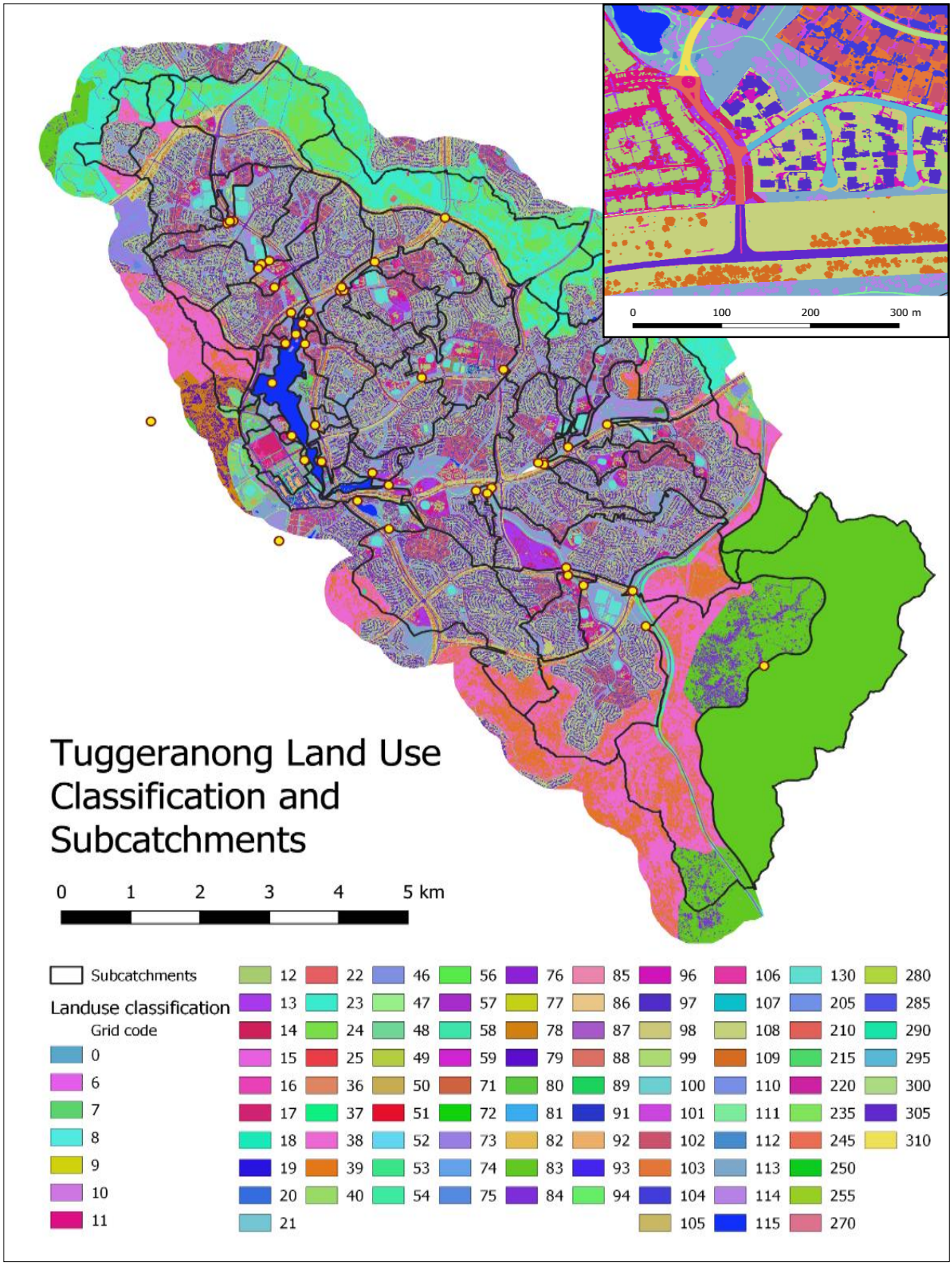

Figure 2. Land use map of the Lake Tuggeranong catchment with colours representing the unique code for each land use - imperviousness combination. Yellow dots indicate water quality or streamflow monitoring locations. **Inset:** close-up detail of a section of the map showing roads, rooftops and open space.

2.3 Water quality data

Water quality data from within the Lake Tuggeranong catchment was collected by a range of programs between 2014 and 2021 (Table 1). Some of the programs entailed event-based monitoring of specific land uses whilst others were focussed on grab sampling from many sites throughout the catchment to try and understand spatial variation of water quality and how it may relate to land use.

Table 1. The number of water quality samples collected across five monitoring programs and analysed for 3 pollutants used in model calibration. TP, total phosphorus; TN, total nitrogen; TSS, total suspended solids.

Monitoring program	Years active	Number of sites	TP	TN	TSS
Basin Plan Phase 1 (event sampling)	2014-2015	19	93	93	93
ACT Government Land Use Monitoring program (event sampling)	2018-2019	1	93	93	93
Lake Tuggeranong Research Project (event sampling)	2017-2018	7	1385	1376	1071
University of Canberra (grab sampling)	2018-2020	29	315	315	316
Upper Murrumbidgee Waterwatch (grab sampling)	2014-2021	8	585		
Total			2471	1877	1573

Table 1 shows there is a large amount of historical water quality data potentially available for use. However, no study in the catchment has converted the measured pollutant concentrations to loads, which requires simultaneously monitoring of flows in order to calculate flow-weighted mean concentrations.

Catchment models typically adopt a land use based EMC/DWC approach to estimate mean annual pollutant load, with model calibration achieved by matching observed loads to modelled loads. As no observed load data is currently available, we adopted the following model parameterisation approach:

1. All pollutant concentration data from the available water quality studies was compiled into a single data frame. For days where multiple samples were collected from a site, the mean of these samples was calculated as an approximation of the mean concentration occurring on that day.
2. Modelled daily flows and modelled pollutant concentrations were compiled into a single data frame and the event flow threshold, defined as the flow threshold that is exceeded in the top 10% of all modelled flow days, was identified.
3. For each day that observed pollutant concentration data was available, we retrieved the modelled flow and associated modelled concentration for the pollutant and monitoring site in question. We split this date-matched data between event and baseflow conditions and calculated the medians of the observed and modelled data for each site.

The median observed pollutant concentration value was compared to the median modelled pollutant concentration value for sites at the six major lake inlet points and a scaling factor estimated to scale the EMC values for that pollutant. The scaling factor was applied across all land uses for that pollutant.

Parameterisation steps 1-3 above were then re-run to test the model fit. This model parameterisation approach preserves the typical difference between land use-based EMC/DWC combinations whilst date-matching median observed lake inflow concentrations to the median modelled concentrations.

Figure 3 provides example plots and data for the monitoring point at the Village Creek inlet to Lake Tuggeranong. Modelled median event-based concentrations of TP exceed observed concentrations, however across all observed data (event and baseflow), median modelled concentrations match observations (n = 275). The time series of modelled concentrations can never attain the variability of observations due to the fixed nature of the EMC/DWC modelling method.

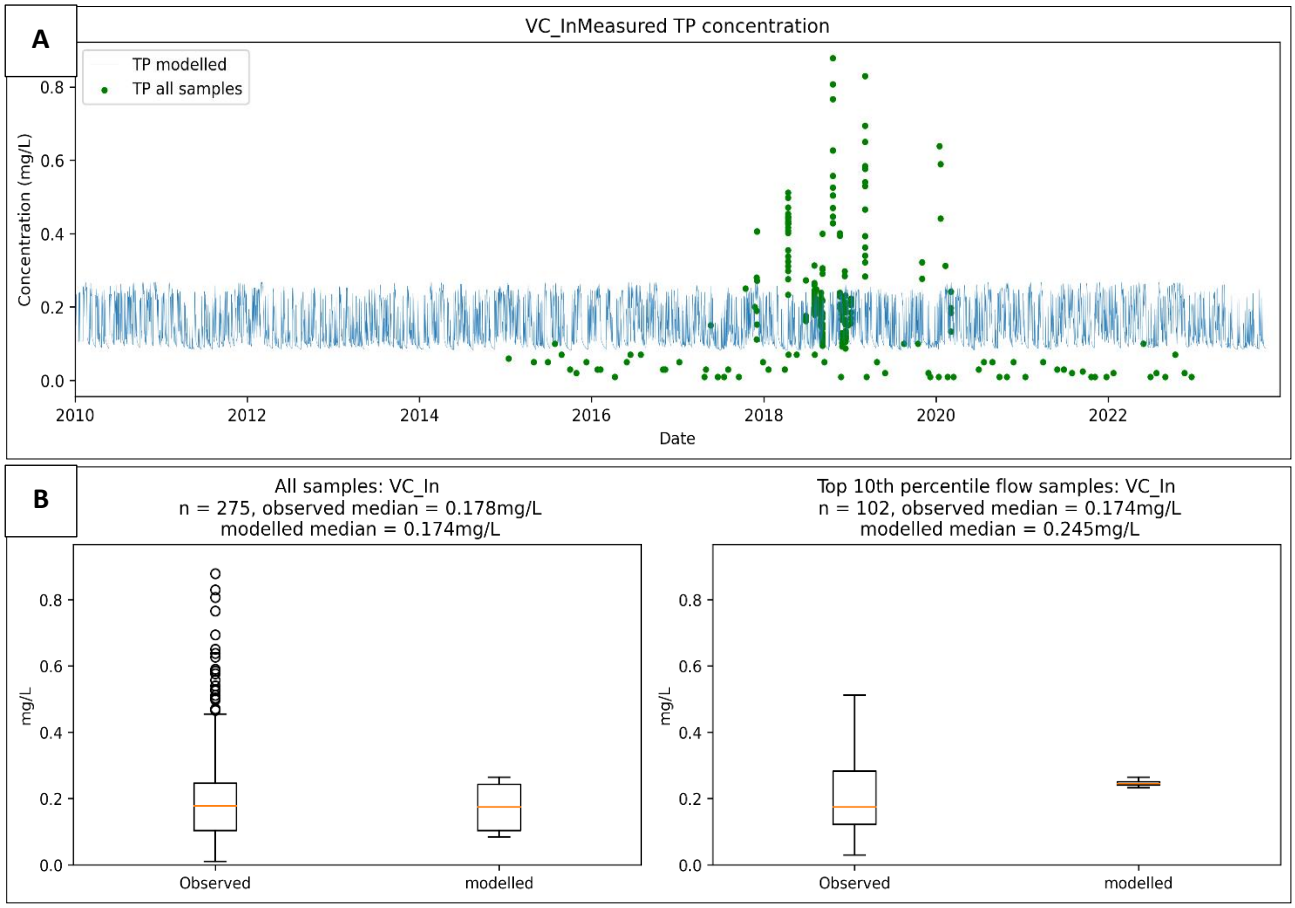

Figure 3. Example of the comparison of observed vs. modelled pollutant concentration data for a single water quality monitoring point. A) Time series of modelled total phosphorus (TP) concentrations (blue line) and date-matched observed median TP concentrations (green points) for the monitoring point at the Village Creek inlet to Lake Tuggeranong. B) Boxplots showing the distributions of modelled and observed median TP concentrations for all samples (left panel) and samples from the top 10th percentile of flow events (right panel) for the monitoring point at the Village Creek inlet to Lake Tuggeranong.

2.4 Climate data

Several climatological stations located within the Lake Tuggeranong catchment could provide data for sub-daily rainfall-runoff modelling. However, to meet the aims of the current model a long-term daily rainfall record without gaps is required. We therefore used patched daily data from the Tuggeranong (Isabella Plains) climatological station (Bureau of Meteorology station number 070339). This station is located within

the Lake Tuggeranong catchment (Figure 4) and has been open since May 1996 - present with 99% completeness of the data record. For this post-1996 period we were able to provide complete observed climate data to the model. To cover the entire period 1889-2023, we used patched data for the pre-1996 period from the SILO (Scientific Information for Land Owners) patch point dataset for this station (https://www.longpaddock.qld.gov.au/silo/).

The following climate variable time series associated with this site were used for catchment modelling:

- Rainfall (mm/d) for rainfall-runoff modelling and water body water balance modelling;
- Morton's wet-environment areal evapotranspiration over land (mm/d) for rainfall-runoff modelling (MWet);
- Morton's shallow lake evaporation (mm/d) for water body water balance modelling (MLake);
- Maximum and minimum temperature for experimental stormwater and lake temperature modelling (Tmax and Tmin) ;
- Evapotranspiration (mm/d) of short crop for irrigation modelling.

2.5 Lake Tuggeranong storage configuration

Lake Tuggeranong is modelled as a completely mixed storage, taking inflows from the whole catchment and releasing flows according to the stage (water level) -discharge relationship of its outflow point at Lake Tuggeranong weir. The lake is also subject to daily rainfall and daily evaporation (MLake), modelled using the SILO daily time-series for the Tuggeranong (Isabella Plains) climatological station (station ID 070339). As Lake Tuggeranong does not have any water supply requirements, no water use is modelled for this storage.

To configure the Lake Tuggeranong storage node, a rating curve was derived from the bathymetry data and imported into the model. This was calculated from the observed water level measured at the Lake Tuggeranong weir (gauge 410784), using the level-volume-area (LVA) relationship for Lake Tuggeranong obtained from bathymetry data collected in 2015 by Steger and Associates Registered Land Surveyors under the Basin Priority Project (data provided in Appendix A).

The lake outlet was configured as an ungated spillway, using the stage-discharge rating table for the Lake Tuggeranong weir (gauge 410784) supplied by ALS Hydrographics via their HYDSTRA database. The stage-discharge data is provided in Appendix B.

2.6 Streamflow and storage level data

2.6.1 Gauge 410779: Tuggeranong Creek upstream of Sewer Crossing

The key streamflow data available for this catchment comes from the gauge at Tuggeranong Creek upstream of Sewer Crossing (gauge 410779; Figure 4) which is located a short distance below the Lake Tuggeranong outflow. Recorded streamflow data is available from 1986 and the gauge remains current. Gauge records show that the maximum recorded flow rate is approximately 200 cumecs, while the maximum rated flow is 108 cumecs or approximately 50% of the maximum recorded flow. Flows greater than 100 cumecs have occurred approximately 6 times since 1990. 216 gaugings (validating measurements) have been undertaken at the site since 1986, with the highest flows being gauged within the first few years of site establishment. Since 2000, the maximum gauged flow has been approximately 6.5 cumecs.

Consequently, higher recorded flows have higher associated uncertainty. However, the gauging record shows a stable relationship with little scatter, with gaugings covering the majority of observed flows at the site, indicating a reliable stage-discharge curve. The site is therefore rated as suitable for model calibration.

2.6.2 Additional short-term streamflow monitoring sites

Additional streamflow records collected by the ACT government for various short-term studies are included in the model:

- 410650 Upper Stranger Pond (1990-1990) Inflow to the pond at GPT
- 410651 Upper Stranger Pond (2017-2018) Outflow from Upper Stranger Pond
- ES1701 Tuggeranong Channel @ Clive Steele (2017-2018)
- ES1702 Monash Channel @ Charleston (2017-2018)

As validation gaugings are generally unavailable for these short-term monitoring sites, they are used for indicative comparison purposes rather than model calibration.

2.7 Water Sensitive Urban Design assets

Geographic location and pollutant reduction performance data were available for eight existing WSUD assets in the Lake Tuggeranong catchment, built under Stage 1 of the ACT Healthy Waterways program. eWater (eWater Ltd, 2022) modelled the flow and water quality performance of these assets using MUSIC (Table 2). Each of these eight WSUD assets is represented in the current Lake Tuggeranong catchment model as a splitter node that diverts flow to the asset, and a storage node that applies a water quality decay function, representing the percentage reduction in pollutant loads (TP, TN, and TSS) achieved by the asset. Splitter nodes are configured with a maximum flow rate that is diverted into the asset, and any flow above this bypasses the asset, based on the MUSIC modelled high-flow bypass threshold. Storage nodes are configured based on asset design information from their respective preliminary sketch plan (PSP) or design acceptance reports, and their pollutant load decay rate was initially set to match the MUSIC modelled percent reduction rate with a default half-life of 1 day. Field observations indicated that some assets are not currently performing to their full capacity, and the pollutant load decay rates were adjusted to reflect the reduced performance of these assets (Table 2).

Table 2. Adjusted efficiencies (% reduction) of water quality parameters for eight Healthy Waterways Stage 1 WSUD assets, matching the current observed working condition of assets. These values were implemented in the Lake Tuggeranong catchment model. Values in parentheses are the predicted efficiencies from MUSIC models in the technical reports for each asset *(eWater Ltd, 2022)*.

Asset	% Flow bypassed	% TP reduction	% TN reduction	% TSS reduction
TG008	41	27 (54)	25 (51)	41 (82)
TG010	28	54 (78)	51 (74)	66 (95)
TG011N	75	39 (66)	31 (53)	45 (75)
TG011S	75	39 (66)	31 (53)	45 (75)
TG012	29	20 (20)	9 (9)	24 (24)
TG017	52	60 (60)	47 (47)	65 (65)
TG029	49	10 (51)	9 (47)	14 (74)
TG030	66	28 (28)	15 (15)	32 (32)

3. Model build and parameterisation

3.1 Hydrology

3.1.1 Lake Tuggeranong catchment model build

A single catchment model representing the Lake Tuggeranong catchment was developed in Source version 5.3 (https://ewater.org.au/ewater-solutions/tools/source/). The model operated on a daily timestep using long-term, gap-filled climate observations from 01/01/1889 to 30/10/2023. Using a 1 m pit-filled DEM and the ACT Government stormwater network, the catchment was delineated into subcatchments based on flow gauging and water quality monitoring sites as well as WSUD asset locations. A node link network of the catchment model was established. Land use classifications and land surface imperviousness data were combined to define functional units implemented in the model.

The gauge downstream of Lake Tuggeranong (Tuggeranong Creek upstream of Sewer Crossing, gauge 410779) was identified as the node for flow calibration. For hydrologic parameterisation for this gauge, daily timestep streamflow data from 06/02/1986 to 30/10/2023 was input to the catchment model. The internal calibration tool using the objective functions square root daily, exceedance, and bias, was implemented to achieve a suitable fit between modelled and measured data. The daily Nash-Sutcliffe efficiency (NSE) coefficient (Nash & Sutcliffe, 1970) was used as the model performance criterion.

3.1.2 Model calibration

SIMHYD and Sacramento rainfall-runoff models were tested for their suitability for model calibration. The initial flow calibration was conducted for the Lake Tuggeranong catchment before delineation into subcatchments, for the period 01/01/1996 to 30/10/2023, with a warm-up period of 10 years (1986-1995). The permanent impervious fraction of the catchment (pctim) for roads, roofs and hardstand was set to 90% impervious in the Sacramento model as these land uses generate more runoff than permeable surfaces. The objective functions used in the calibration were square root daily, exceedance, and bias. Shuffled Complex Evolution (SCE) followed by Rosenbrock were chosen for optimisation, with 5 iterations and a population number of 500. The Sacramento rainfall-runoff model performed better than the SIMHYD model, providing a better fit with the recorded flow data (Table 3).

Table 3. Model performance statistics for the Sacramento and SIMHYD rainfall-runoff models.

Rainfall-runoff model	Daily Nash-Sutcliffe coefficient	% Volume bias
Sacramento	0.803	-0.85
SIMHYD	0.744	0.001

The initial calibration results confirmed the selection of the Sacramento rainfall-runoff model for the Lake Tuggeranong catchment. The calibrated hydrologic parameters for this model are provided in Table 4.

Table 4. Calibrated hydrologic parameters for the Lake Tuggeranong catchment model using a Sacramento rainfall-runoff model.

Parameter	Suburban	Open space	Commercial	Rural	Bushland	Sports field
Soil moisture store (Lztwm) (mm)	75	75	75	75	75	75
Soil moisture store (Lzfsm) (mm)	15	15	15	15	15	15
Soil moisture store (Lzfpm) (mm)	267.5	267.5	267.5	267.5	267.5	267.5
Rate of lateral outflows (Lzsk)	0.03	0.03	0.03	0.03	0.03	0.03
Rate of lateral outflows (Lzpk)	0.003	0.003	0.003	0.003	0.003	0.003
Rserv	0.346	0.346	0.346	0.346	0.346	0.346
Losses (Side)	0	0	0	0	0	0
Time delay in runoff (UH1)	0.88	0.88	0.88	0.88	0.88	0.88
Time delay in runoff (UH2)	0	0	0	0	0	0
Time delay in runoff (UH3)	0	0	0	0	0	0
Time delay in runoff (UH4)	0.0109	0.0109	0.0109	0.0109	0.0109	0.0109
Time delay in runoff (UH5)	0.03	0.03	0.03	0.03	0.03	0.03
Soil moisture store (Uztwm) (mm)	75.44	75.44	75.44	75.44	75.44	75.44
Soil moisture store (Uzfwm) (mm)	75	75	75	75	75	75
Rate of lateral outflows (Uzk)	0.5	0.5	0.5	0.5	0.5	0.5
Water percolation (Zperc)	153.46	153.46	153.46	153.46	153.46	153.46
Water percolation (Rexp)	3.02	3.02	3.02	3.02	3.02	3.02

Parameter	Suburban	Open space	Commercial	Rural	Bushland	Sports field
Impervious runoff (Pctim)	0.5	0.5	0.5	0.5	0.5	0.5
Losses (Sarva)	0	0	0	0	0	0
Losses (Ssout) (mm)	0	0	0	0	0	0
Impervious runoff (Adimp)	0.30	0.30	0.30	0.30	0.30	0.30
Water percolation (Pfree)	0.19	0.19	0.19	0.19	0.19	0.19

Table 4 continued. See caption previous page.

3.1.3 Model verification

To verify the modelled flow generation of the Lake Tuggeranong catchment, a comparison was made with the Jerrabomberra catchment, which has similar geographic features and location.

A model of the Jerrabomberra catchment was set up in Source using the climate variables daily rainfall and Morton's wet-environment areal evapotranspiration over land (MWet). The rainfall data was obtained from SILO, using station ID 70066 for the NSW portion of the catchment, and station 70249 for the ACT portion. The MWet data was obtained from SILO station ID 70072. The gauged flow data used for calibrating this catchment came from Jerrabomberra at Hindmarsh (gauge 410790), obtained from ALS Pty Ltd. The model was calibrated using a Sacramento rainfall-runoff model, and the objective functions square root daily, exceedance, and bias. SCE followed by Rosenbrock were chosen for optimisation, with 5 iterations and a population number of 500. The calibration was a moderate fit with a daily Nash-Sutcliffe coefficient of 0.59 and volume bias of 0%.

The runoff coefficients of both the Lake Tuggeranong and Jerrabomberra catchments were calculated to compare their performance under predevelopment conditions, represented by 100% bushland land use. The runoff coefficient of the Lake Tuggeranong catchment was approximately 7%, and that of the Jerrabomberra catchment was approximately 8.5%. The two catchments performed similarly under pre-development conditions, verifying the flow generation of the Lake Tuggeranong catchment model.

3.1.4 Model uncertainty estimation

At this stage, model uncertainty estimation has not been undertaken.

3.1.5 Flow routing calibration

Due to the small catchment size and largely urban land use, flow routing was not undertaken in any reach in the Lake Tuggeranong catchment model.

3.1.6 Lake water balance

The lake water balance accounted for all inflows, outflows, rainfall, and evaporation from the lake.

3.2 Water quality

Source catchment models are best suited to estimating long-term mean annual catchment pollutant loads rather than daily concentrations. Ideally, empirical measurements of EMC and DWC from different land uses would be used to parameterise the model. However, as described in section 2.3, water quality data from the Lake Tuggeranong catchment has not been collected concurrently with quantitative flow data, precluding the calculation of EMC. As a result of these data limitations, and noting that long-term inflows and pollutant load into the lake are a key predictive output of the model, a simple approach was adopted to adjust land use -based model water quality parameters using available monitoring data:

1. For each water quality monitoring site, daily median event flow concentrations for each pollutant were calculated for all available dates, as described in section 2.3.
2. A baseline simulation run of the model was performed using EMC and DWC values adapted from the literature (Fletcher, Duncan, Poelsma, & Lloyd, 2004), (Witt, Mainwright, & Weber, 2015), (Melbourne Water, 2024), (Blacktown City Council, 2020), and the modelled daily flows and predicted pollutant concentrations for all monitoring sites were extracted.
3. Baseline modelled pollutant concentrations were date-matched with observed median flows and concentrations to allow for later flow stratification (if appropriate) and to account for sample population representativeness (dry periods or wet periods).
4. Median observed and modelled pollutant concentrations for six major lake inflow sites were then calculated, and used to estimate scaling factors to adjust the literature-derived EMC values for majority land uses (roads, roofs, hardstand, and pervious areas of suburban, commercial, and open space land use categories). Where data allowed, inflow-specific scaling factors were applied.
5. The model was re-run using the scaled EMC values (Appendix D), and modelled median concentrations were once again compared against observed median concentrations.
6. When median modelled and observed values were in agreement, the model parameters were checked against literature values to ensure that the model estimate remained in the anticipated range.

4. Results

4.1 Flow calibration

A hydrograph time series for flows in the Lake Tuggeranong catchment over the model calibration period, 1996-2023, is presented in Figure 4. The hydrograph demonstrates good agreement between the timing and magnitude of modelled and observed flows, which are highly correlated with a daily Nash-Sutcliffe coefficient of 0.88 indicating a very good fit (Moriasi, et al., 2007). There is acceptable peak flow matching with an overall low bias, suggesting the model is reliable in simulating high flow events (Table 5). This strong performance across flow magnitudes confirms the robustness of the model calibration and its suitability for simulating the hydrology of the Lake Tuggeranong catchment.

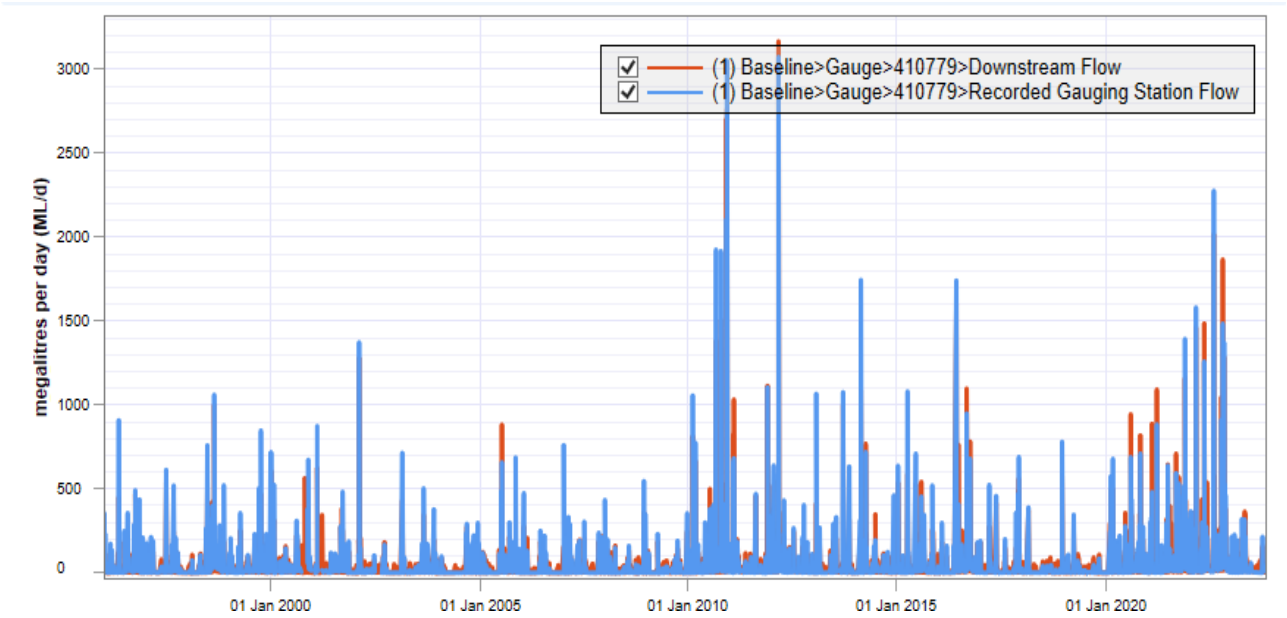

Figure 4. Modelled (red) and observed (blue) flows (daily discharge, ML/d) for Tuggeranong Creek upstream of Sewer Crossing (gauge 410779).

Table 5. Flow calibration model performance statistics for Tuggeranong Creek upstream of Sewer Crossing (gauge 410779).

Performance criterion	
Daily Nash-Sutcliffe Efficiency coefficient	0.88
Monthly Nash-Sutcliffe Efficiency coefficient	0.92
% Volume bias	-0.25

Figure 5 depicts the cumulative flow curve over the calibration period, demonstrating good agreement between modelled and observed flow over the entire period. This agreement indicates that the model accurately captures the total volume of water passing through the catchment, validating its performance in representing the overall hydrological processes.

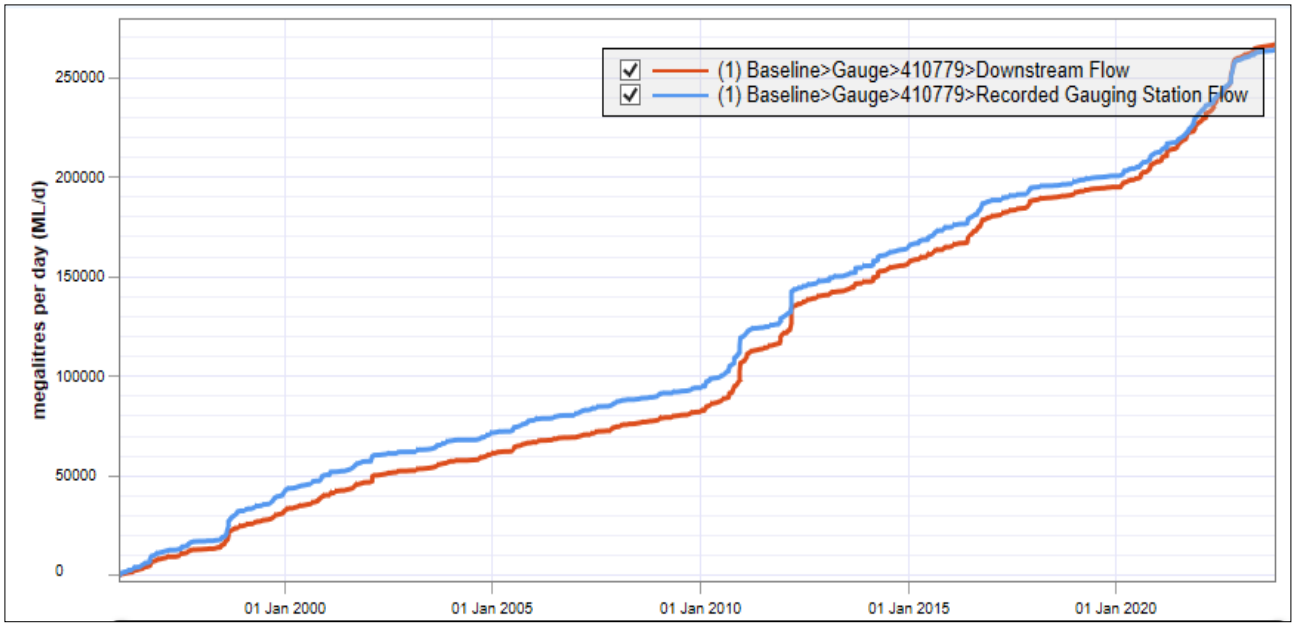

Figure 5. Modelled (red) and observed (blue) cumulative flow for Tuggeranong Creek upstream of Sewer Crossing (gauge 410779), 1996-2023.

Figure 6 illustrates the flow duration curve for flows in the calibration period, showing generally good agreement between modelled and observed flow across most flow conditions. However, discrepancies are noted particularly at low flows. This suggests that while the model performs well overall, there may be areas where the representation of low-flow conditions could be further refined or calibrated.

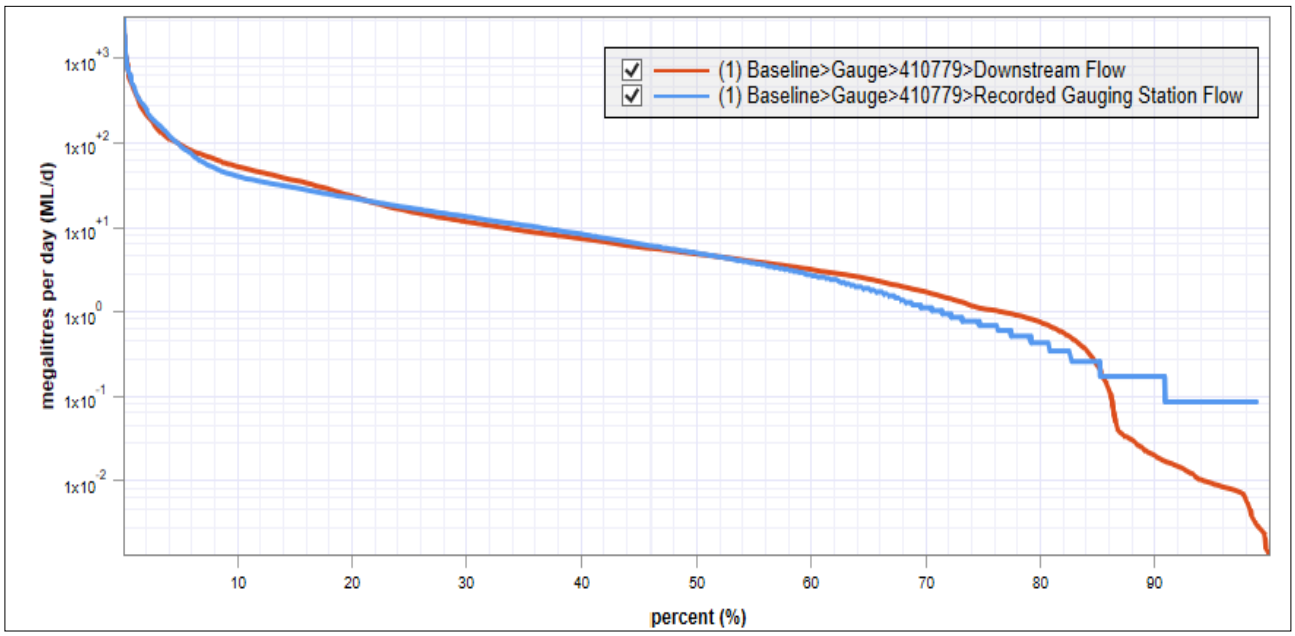

Figure 6. Modelled (red) and observed (blue) flow exceedance curve for Tuggeranong Creek upstream of Sewer Crossing (gauge 410779), 1996-2023.

Figure 7 presents the residual mass curves for observed and modelled flows over the calibration period. The difference between the curves indicates the cumulative difference between observed and modelled flows over time. Ideally, this difference should hover around zero, indicating minimal bias or systematic error in the model.

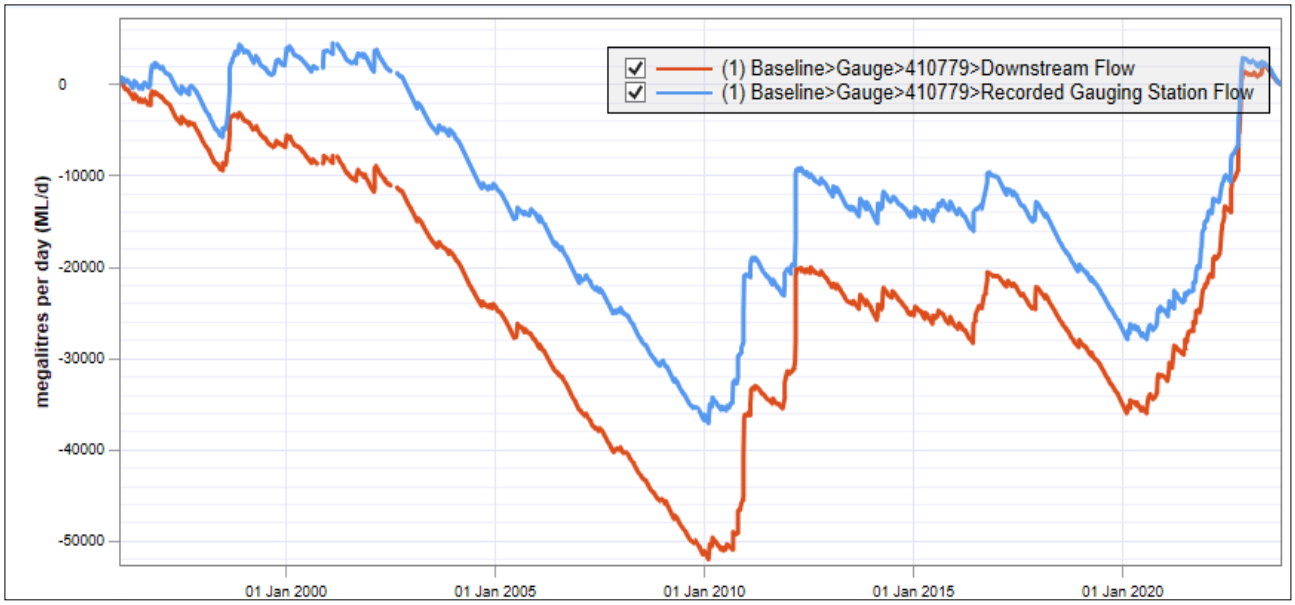

Figure 7. Modelled (red) and observed (blue) residual mass for Tuggeranong Creek upstream of Sewer Crossing (gauge 410779), 1996-2023.

The above plots collectively provide a comprehensive evaluation of the model's performance in simulating hydrological processes in the Lake Tuggeranong catchment, capturing overall flow patterns.

4.2 Water quality calibration

Figure 8 illustrates the comparisons between the median observed and modelled concentrations of TP, TN, and TSS for 34 sites across the Lake Tuggeranong catchment where water quality monitoring was undertaken. These comparisons provide a visual representation of the model's performance in simulating water quality across the catchment. At well-sampled sites, there is generally good agreement between the observed and modelled concentrations. Discrepancies at other sites are primarily due to insufficient sample numbers (Figure 9). Higher median TP concentrations are noted for sites in the Village Creek, Kambah Creek, and Wanniassa subcatchments (site codes beginning with VC, KC, WS respectively) compared to other areas within the Lake Tuggeranong catchment.

As there were multiple sampling locations across the catchment the mean of site medians can provide a robust central tendency measure. The mean of the median modelled concentration for TP is 0.17 mg/L, for TN is 1.33 mg/L, and for TSS is 49.7 mg/L.

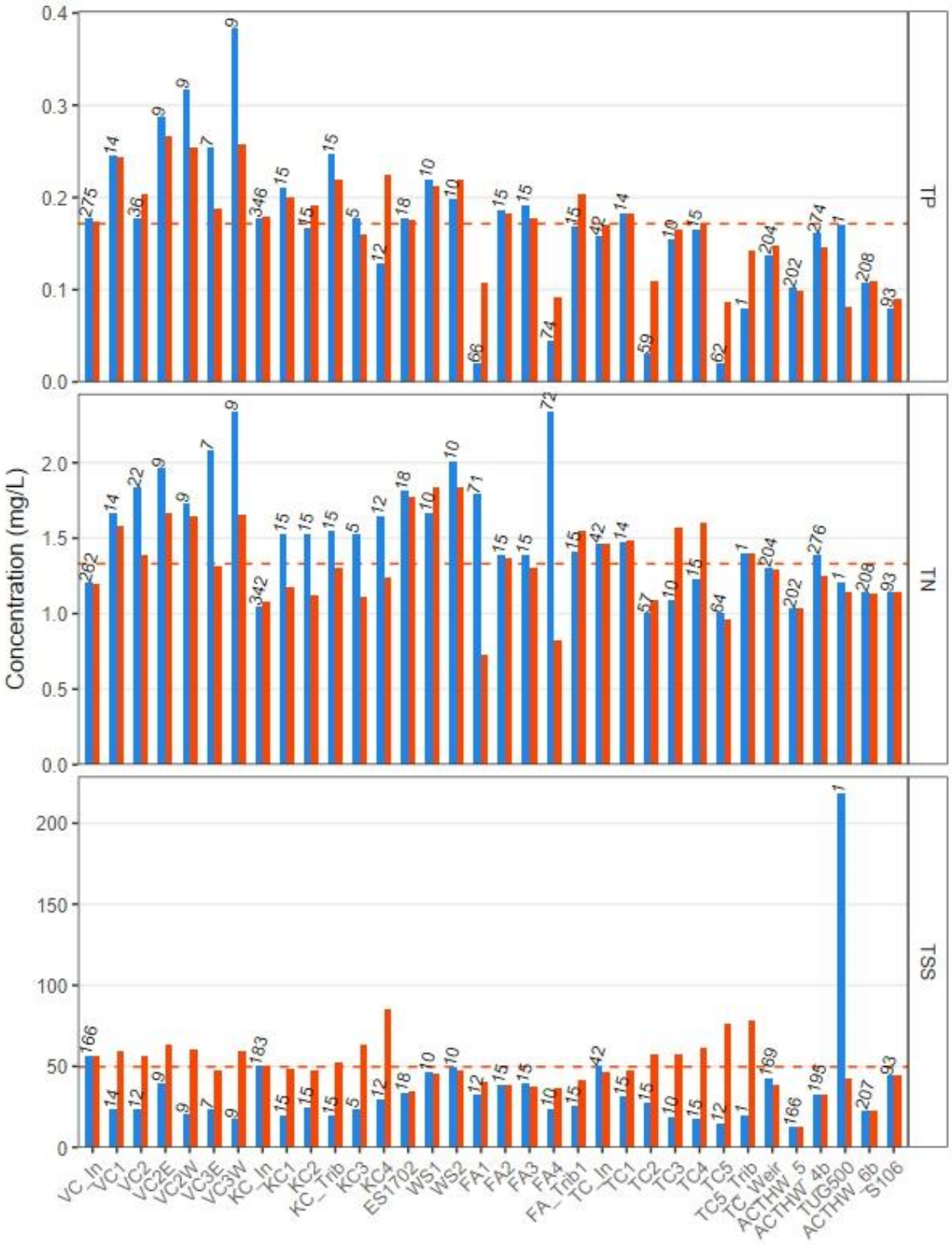

Figure 8. Observed (blue) and modelled (red) median concentrations of total phosphorus (TP; top panel), total nitrogen (TN; middle panel), and total suspended solids (TSS; bottom panel) for each water quality monitoring site in the Lake Tuggeranong catchment. Blue bars are labelled with the number of samples per site analysed for each parameter. The red dashed lines indicate the means of the median modelled concentrations of each pollutant (see text).

Figure 9 illustrates the deviations of modelled from observed site median concentrations for the three water quality parameters, as a function of the number of samples at the monitoring site. A value of zero indicates no bias in the model estimates for that site (i.e. no consistent over- or under-estimation of concentrations, compared to observed values). For all three parameters, deviations decline sharply with increasing sample size. The median deviation for TP is close to zero with a narrow interquartile range, indicating low overall bias. TN deviations are more spread out, with a slight overall positive bias indicated by the median just above zero. TSS deviations have a narrow interquartile range, with a median deviation below zero indicating an overall negative bias, and a notable positive outlier. As for TP and TN, the vast majority of substantial deviations for TSS occur for sites with very low sample sizes.

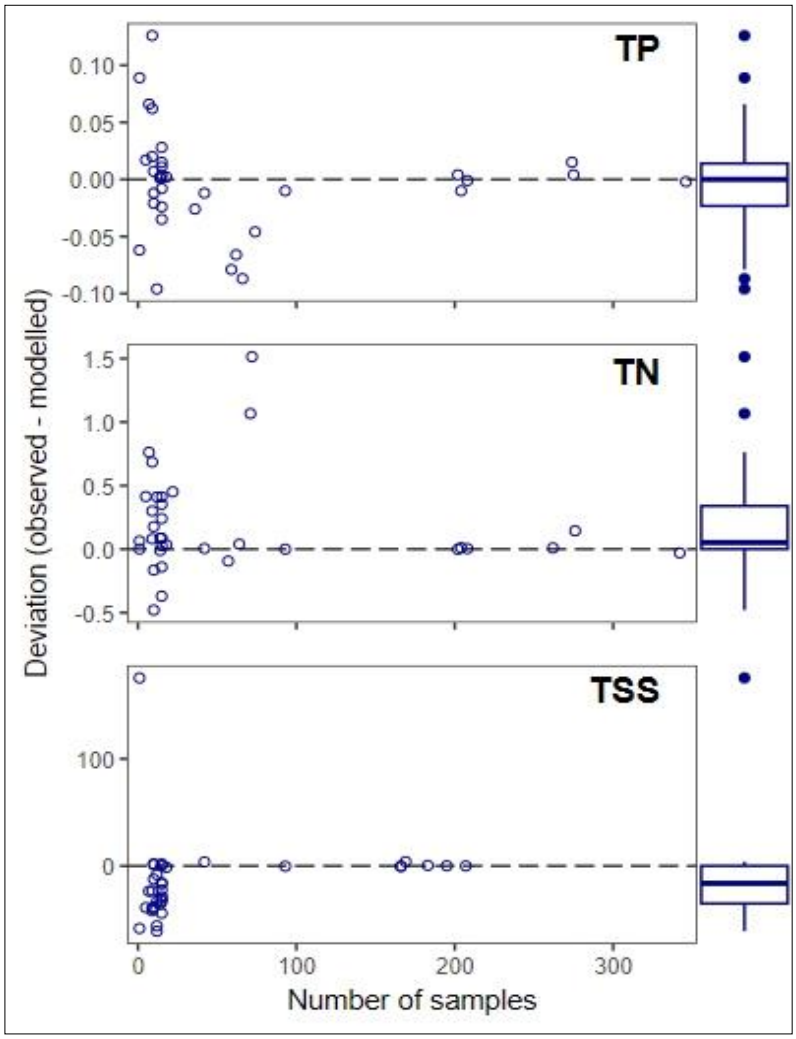

Figure 9. Scatter plots showing the deviation of modelled from observed median concentrations of total phosphorus (TP), total nitrogen (TN), and total suspended solids (TSS) as a function of sample size at 34 water quality monitoring sites in the Lake Tuggeranong catchment. The dashed grey line at zero indicates no bias in the model estimates for a given site. Box-and-whisker plots illustrate the spread of deviations.

4.3 Catchment modelling results

The calibrated catchment model was simulated over the climate period January 1889 – October 2023, and summaries of the total flow and pollutant loads were calculated for each complete year (1889-2022). Under current catchment land use and management conditions, the modelled mean annual inflow to Lake

Tuggeranong was 8.8 GL/year. The modelled mean annual loads of pollutants entering Lake Tuggeranong were 1,442 kg/year total phosphorus, 11,894 kg/year total nitrogen, and 397,064 kg/year total suspended solids.

Figure 10 presents a series of heat maps illustrating the modelled mean annual loads of TP, TN and TSS generated in different subcatchments of the Lake Tuggeranong catchment, with darker shading indicating a higher load. The pollutant load generated depends on the land uses within each subcatchment. The highest mean subcatchment TSS loads fall between 160 – 180 kg/ha/yr. The highest TN loads are between 3.5 – 4 kg/ha/yr, and the highest TP loads are between 0.6 – 0.7 kg/ha/yr. For all three pollutants, higher load generation occurs in more urbanised catchments. This broad visual representation can help in identifying the areas requiring critical attention to improve water quality in the catchment.

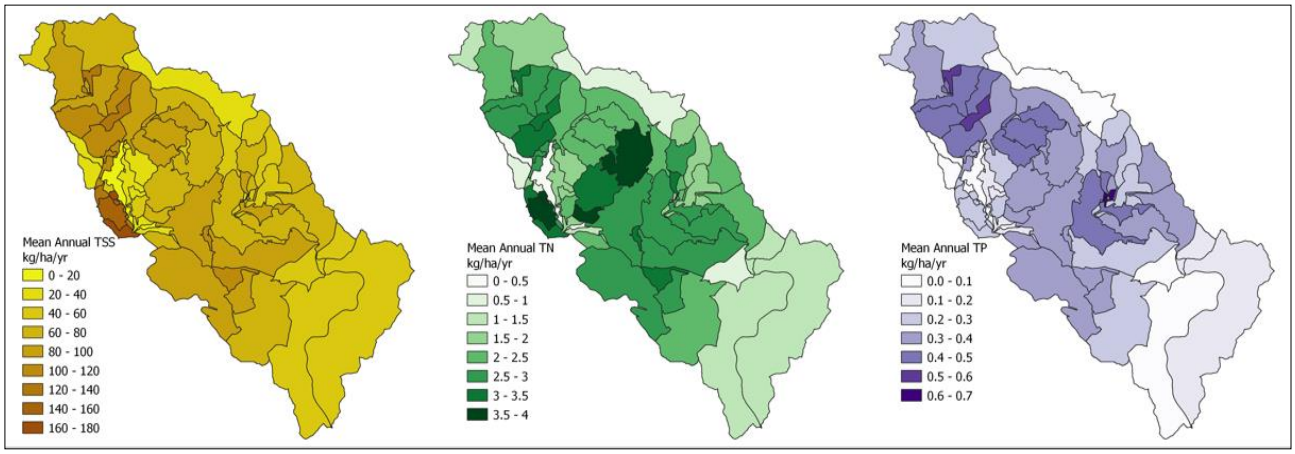

Figure 10. Heat maps of the Lake Tuggeranong catchment for mean annual loads of total suspended solids (TSS, left), total nitrogen (TN, centre) and total phosphorus (TP, right) generated in each subcatchment. Darker shading indicates higher mean annual concentrations.

Figures 11-13 show time-series of modelled daily inflows, pollutant concentrations, and pollutant loads entering Lake Tuggeranong in 2016, a year with a good spread of wet and dry periods. High flow events, likely driven by rainfall, lead to increased runoff, which carries higher concentrations and loads of phosphorus, nitrogen, and suspended solids into the lake. In 2016, the model estimates that the largest flow event saw over 1600 ML enter Lake Tuggeranong in a single day, representing 10% of the total annual inflow that year. This event carried loads of approximately 300 kg TP, 2,500 kg N, and 75,000 kg TSS to the lake, representing 12-13% of the total annual load of each pollutant entering Lake Tuggeranong in 2016. This pattern highlights the impact of storm events on water quality and the importance of managing runoff from the catchment to the lake.

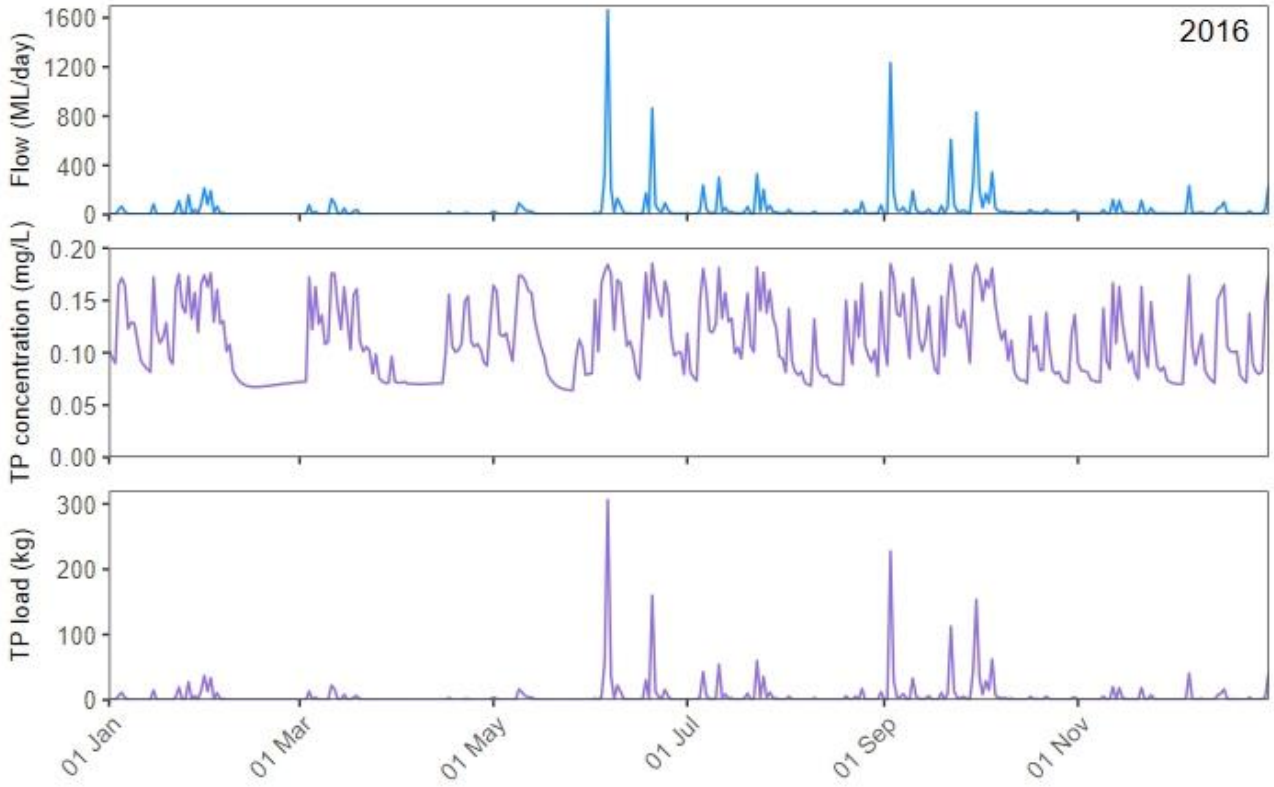

Figure 11. Modelled daily flow and total phosphorus (TP) concentration and load entering Lake Tuggeranong, 2016.

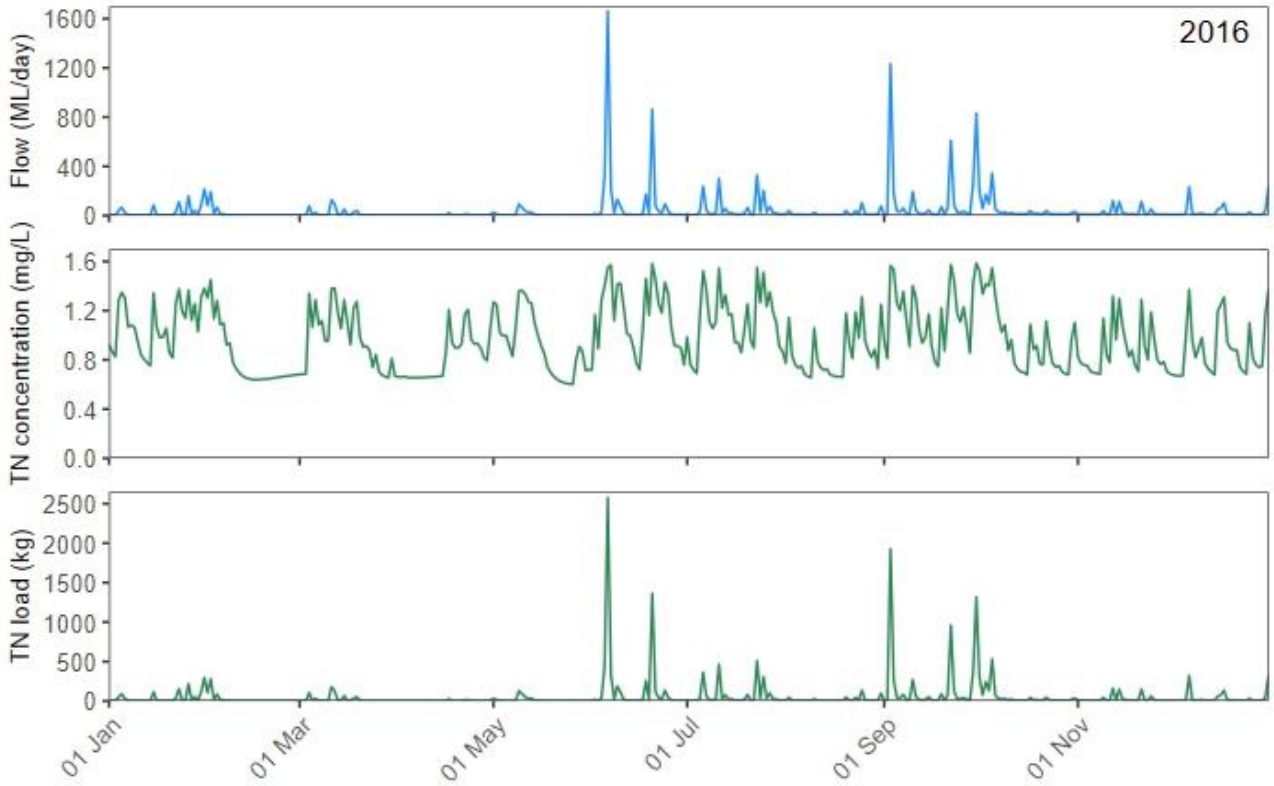

Figure 12. Modelled daily flow and total nitrogen (TN) concentration and load entering Lake Tuggeranong, 2016.

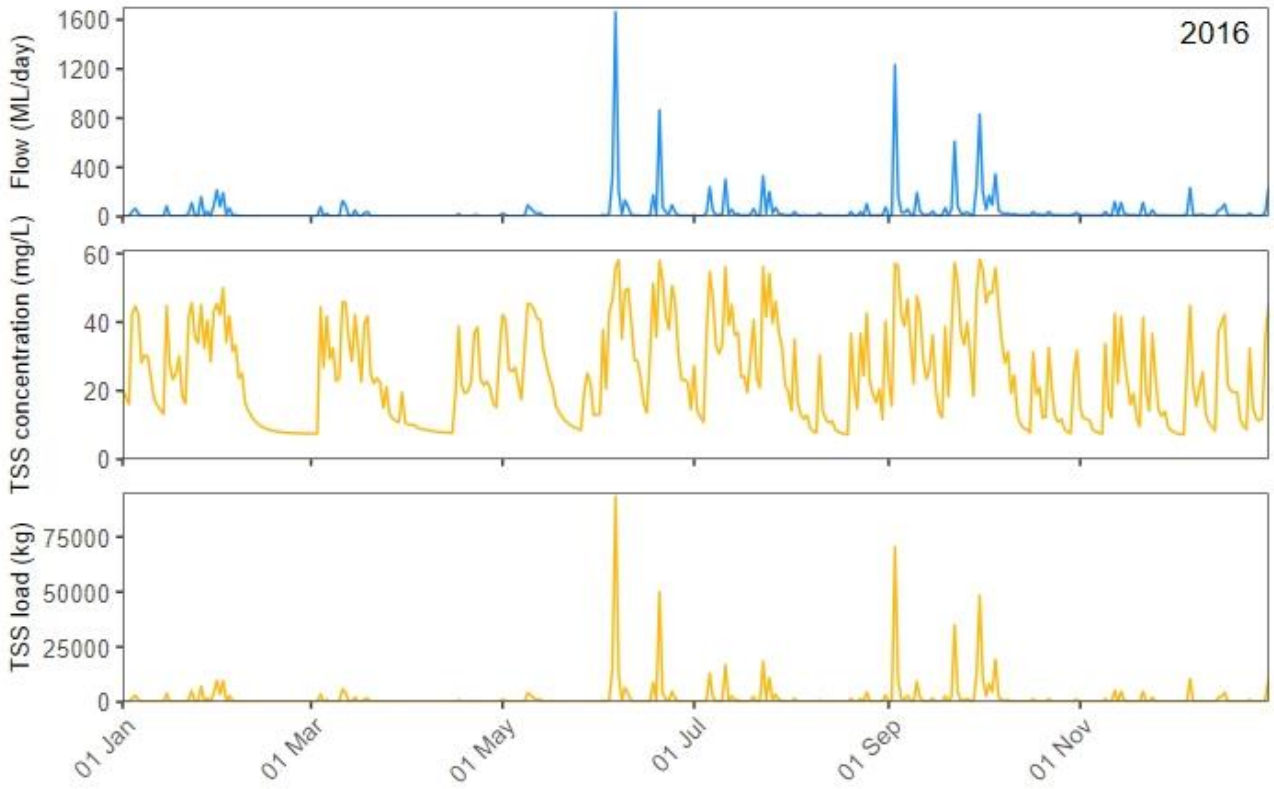

Figure 13. Modelled daily flow and total suspended solids (TSS) concentration and load entering Lake Tuggeranong, 2016.

Figure 14 shows the relationships between daily inflows, concentrations, and loads in 2016 for TP; TN and TSS showed the same patterns in the shape of these relationships.

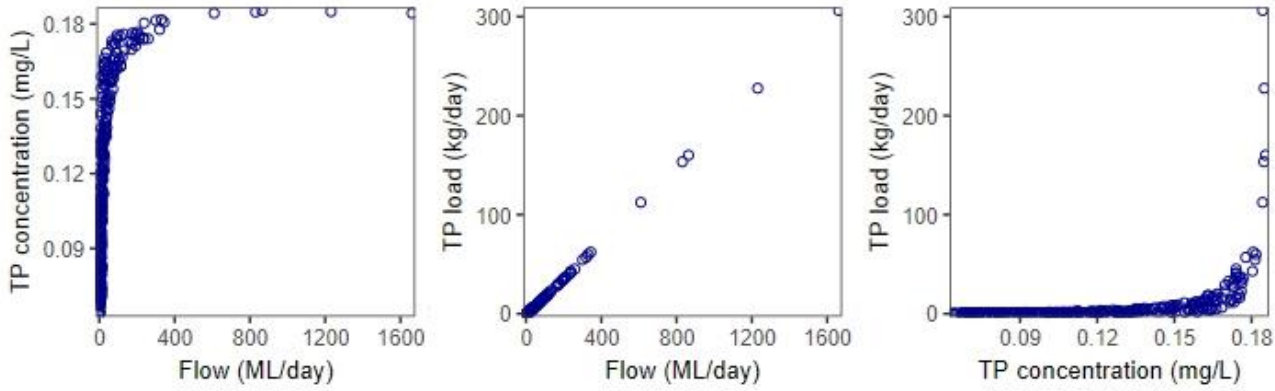

Figure 14. Relationships between the daily inflows and concentrations and loads of total phosphorus (TP) entering Lake Tuggeranong in 2016. The same relationships were seen for total nitrogen and total suspended solids.

4.4 Scenario analysis

4.4.1 Current and predevelopment scenarios

To understand the impact of changes to land use and urban development on the hydrology and water quality of the Lake Tuggeranong catchment, two contrasting land use scenarios were simulated using the

calibrated catchment model. The first, 'current' scenario was the model of current land use and infrastructure conditions described in Section 4.3. Under the current scenario the modelled mean annual inflow to Lake Tuggeranong was approximately 8.8 GL, and the modelled mean annual pollutant loads were 1,442 kg TP, 11,894 kg TN, and 397,064 kg TSS. Figure 15 presents the long-term modelled annual inflow and pollutant loads entering Lake Tuggeranong under the current scenario, for the period 1889-2022.

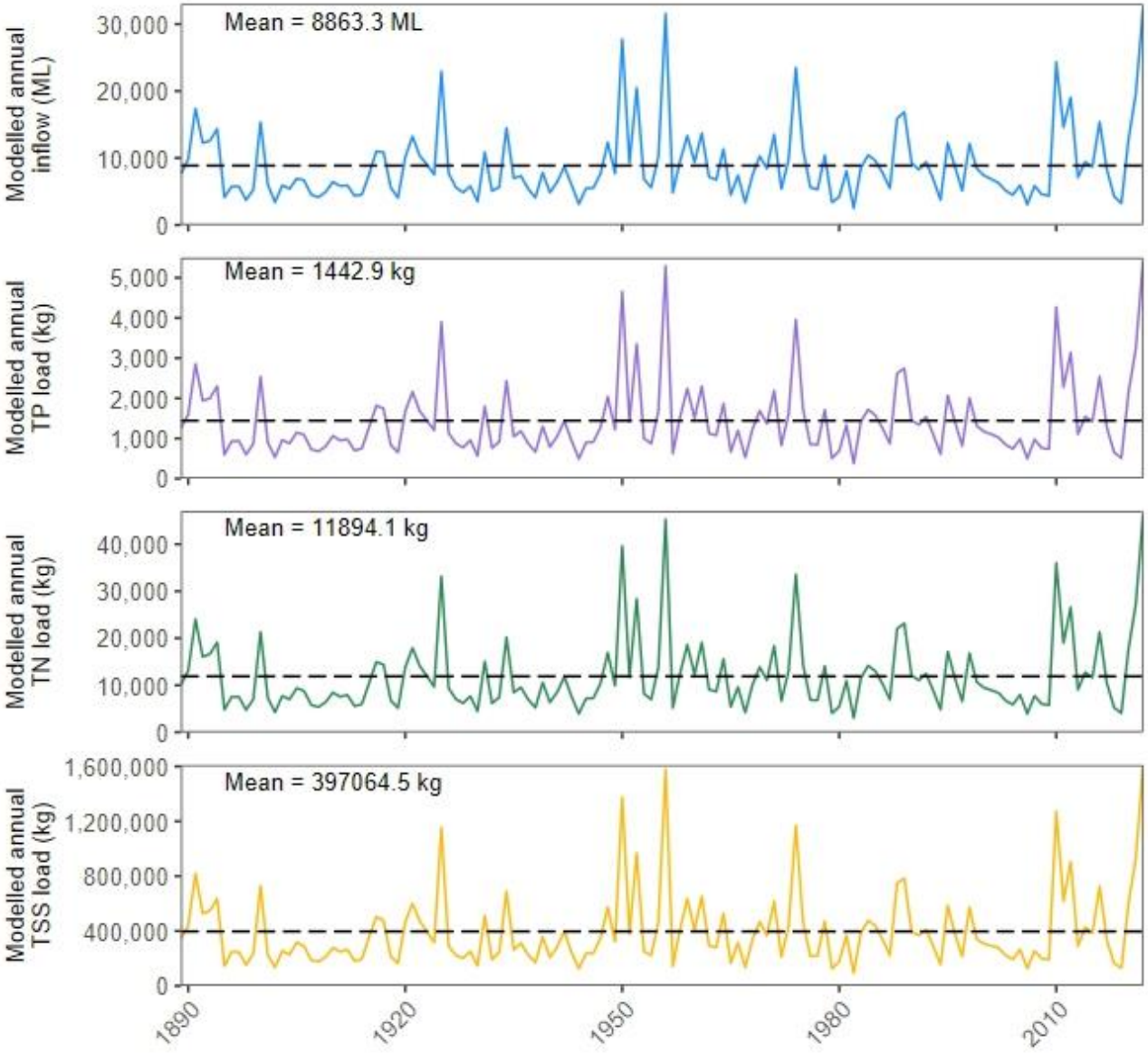

Figure 15. Long-term modelled annual inflows and annual loads of total phosphorus (TP), total nitrogen (TN), and total suspended solids (TSS) entering Lake Tuggeranong under current catchment conditions, for the period 1889 – 2022.

We compared this current scenario to a 'predevelopment' scenario, where all infrastructure (apart from Lake Tuggeranong itself) and developed land uses were removed from the model. Land use for all subcatchments was configured to be entirely bushland, to allow estimation of the runoff and pollutant generation under natural conditions. The results of the predevelopment scenario for the Lake Tuggeranong catchment were validated using the adjacent Jerrabomberra catchment, which has similar geographic conditions, for comparison (see Section 3.1.2). Figure 16 presents the long-term modelled annual inflow and pollutant loads entering Lake Tuggeranong under the predevelopment scenario, for the period 1889-

2022. The mean long-term annual inflow to the lake under predevelopment conditions was approximately 3,268 ML, and the modelled mean annual pollutant loads were 325 kg TP, 2470 kg TN, and 99,673 kg TSS.

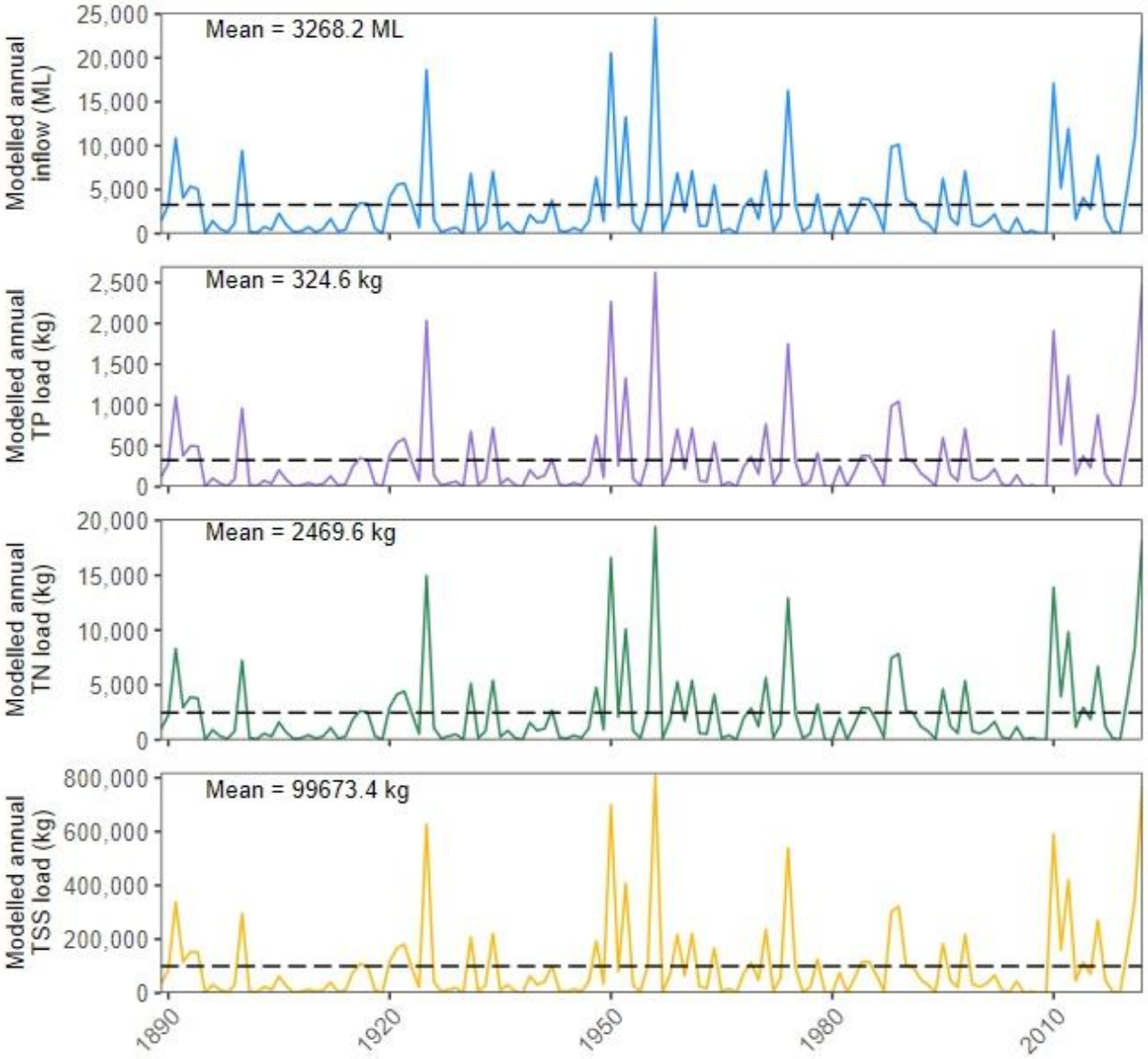

Figure 16. Long-term modelled annual inflows and annual loads of total phosphorus (TP), total nitrogen (TN), and total suspended solids (TSS) entering Lake Tuggeranong under predevelopment catchment conditions, for the period 1889 – 2022.

Table 6 and Figure 17 present comparisons of summary statistics for modelled annual inflows and pollutant loads generated under the current and predevelopment scenarios, for the period 1889-2022. On average, annual inflows to Lake Tuggeranong under predevelopment conditions were 25.5% of annual inflows under current conditions. The reduction in annual inflows, as well as reduced pollution generation modelled from the undeveloped catchment, meant that annual pollutant loads entering Lake Tuggeranong under predevelopment conditions were on average approximately 15% of annual pollutant loads under current conditions.

Table 6. Summary statistics describing modelled annual inflow volumes and loads of total phosphorus (TP), total nitrogen (TN), and total suspended solids (TSS) entering Lake Tuggeranong under the 'current' and 'predevelopment' model scenarios, for the period 1889-2022.

Parameter	Modelled scenario	Minimum	25th percentile	Median	Mean	75th percentile	Maximum
Annual inflow (GL)	Current scenario	2.50	5.39	7.39	8.86	10.37	32.3
Annual inflow (GL)	Predevelopment scenario	0	0.31	1.44	3.27	4.01	24.56
Annual TP load (kg)	Current scenario	377	857	1,176	1,442	1,705	5,412
Annual TP load (kg)	Predevelopment scenario	0	25	133	324	376	2,622
Annual TN load (kg)	Current scenario	3,019	6,893	9,508	11,894	14,100	46,236
Annual TN load (kg)	Predevelopment scenario	0	195	1,041	2,469	2,920	19,420
Annual TSS load (kg)	Current scenario	93,394	221,932	313,352	397,064	471,056	1,607,545
Annual TSS load (kg)	Predevelopment scenario	0	7,558	40,575	99,673	115,094	808,385

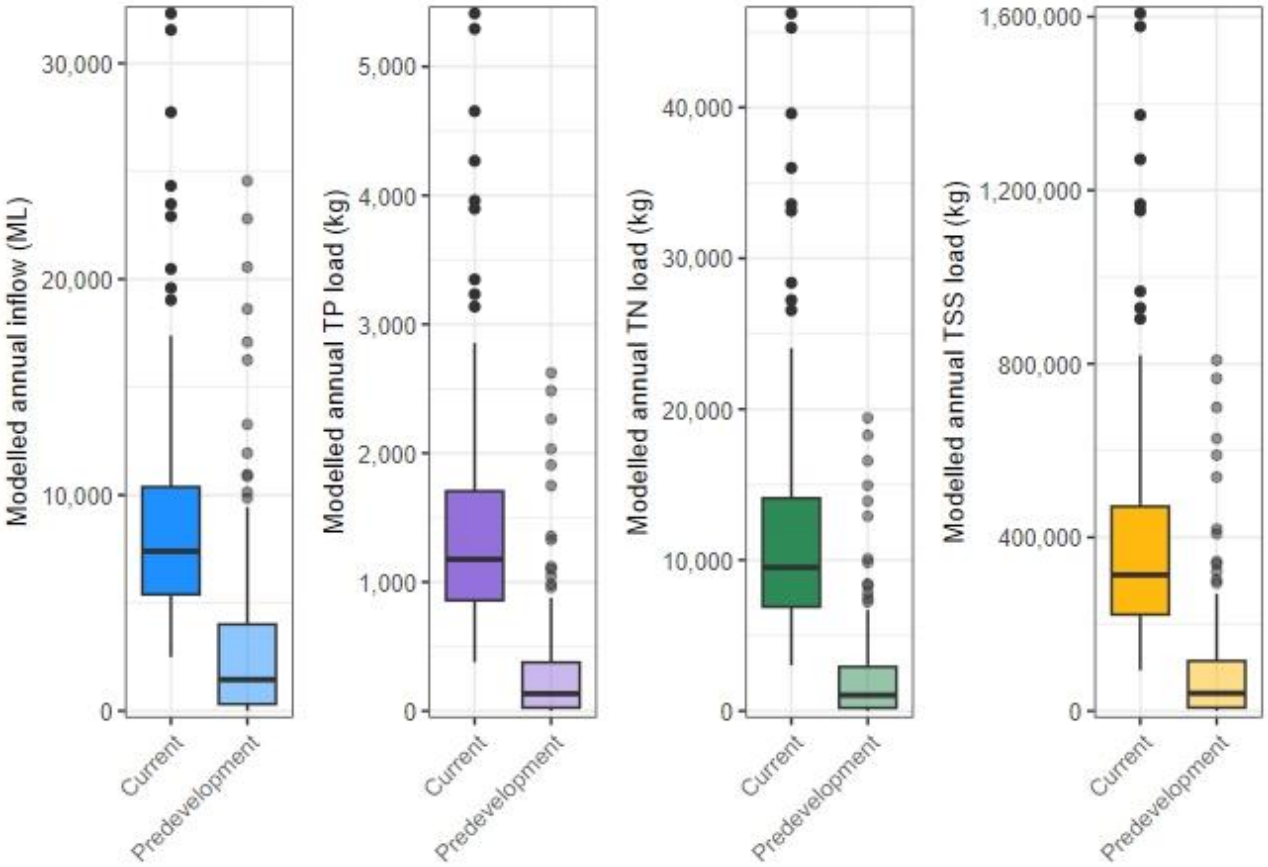

Figure 17. Box-and-whisker plots illustrating the distribution of modelled annual inflows and loads of total phosphorus (TP), total nitrogen (TN), and total suspended solids (TSS) entering Lake Tuggeranong under current and predevelopment catchment conditions, over the period 1889-2022.

Comparing the current and predevelopment scenarios is important for understanding catchment hydrology and pollutant generation before and after development, as well as the impacts of changes in hydrology and pollutant generation on trophic conditions in Lake Tuggeranong. The results from both modelled scenarios were used to parameterise a model of in-lake processes, which estimates the concentrations of phosphorous and chlorophyll a in the lake (Kahn & Dey, 2024). These concentrations were used to predict the distribution of trophic conditions in Lake Tuggeranong under the current and predevelopment scenarios. These analyses help to understand how conditions in the lake are predicted to respond under different inflow and pollutant conditions, and inform management decisions aimed at reducing the occurrence of blue-green algal blooms.

4.4.2 Catchment management option scenarios

The effects of specific management actions aimed at reducing pollutant inputs into the waterways and stormwater network of the Lake Tuggeranong catchment, or filtering or diverting water before it reaches the lake, were investigated in two additional scenarios implemented in the calibrated Source catchment model. Each scenario ('cost-effective' and 'broad benefits') consisted of a combination of different management actions, each with four possible levels of implementation, detailed in the companion to this report, *Lake Tuggeranong Catchment Management Options Assessment* (Booksmythe, Dey, Kahn, Stewart, & Starrs, 2024). The management options included in the two scenarios are detailed in Table 7.

Table 7. Details of the management options included in two scenarios…

Management option	Cost-effective scenario	Broad benefits scenario
Install additional WSUD infrastructure	Investment level 1: install 2 raingardens	Investment level 2: install 5 raingardens
Maintenance of existing WSUD infrastructure	Investment level 3: maintain 4 existing WSUD assets to their designed performance	Investment level 4: maintain 5 existing WSUD assets to their designed performance
Increase frequency of street sweeping	Investment level 4: 48 sweeps per year	Investment level 3: 36 sweeps per year
Manage grass clippings from municipal mowing	Investment level 3: designated street sweeping truck to follow mowers	Investment level 3: designated street sweeping truck to follow mowers
Sports field fertilizer management	Investment level 1: install bioretention swales to intercept 25% of total sports field P	Investment level 3: install bioretention swales to intercept 75% of total sports field P
Household fertilizer management	Investment level 4: very high implementation of community partnership programs aimed at reducing household fertilizer P inputs	Investment level 1: low implementation of community partnership programs aimed at reducing household fertilizer P inputs
Install castellated kerbs	n/a	Investment level 1: install castellated kerb outlets at a rate of 1 per 4 stormwater sumps adjacent to urban open space
Install floating wetlands	n/a	Investment level 4: install 4000 m^2 of floating wetlands
Stormwater recycling for sports field irrigation	Investment level 2: install stormwater recycling infrastructure at 4 sports field sites	Investment level 3: install stormwater recycling infrastructure at 6 sports field sites

Different management actions are implemented in different ways in the catchment model. Some options are explicitly represented by the addition or modification of specified links and nodes in the model:

- **Additional WSUD infrastructure** Proposed raingardens were represented in the catchment model by new storage nodes placed at the locations indicated in the original plans for the raingardens. As for existing assets, each proposed asset was modelled as a splitter node that diverts flow to the asset, and a storage node that applies a water quality decay function, representing the percentage reduction in pollutant loads (TP, TN, and TSS) achieved by the asset. Splitter nodes are configured with a maximum flow rate that is diverted into the asset, and any flow above this bypasses the asset, based on the MUSIC modelled high-flow bypass threshold. The proposed raingarden storage nodes were configured

using the size indicated in the original plans, and the performance details of similar existing WSUD assets.

- **Maintenance of existing WSUD infrastructure** The catchment model includes storage nodes representing each WSUD asset in the Lake Tuggeranong catchment, with the performance of each asset configured to reflect its current phosphorus removal efficiency (Table 2). To represent maintenance of these assets to their designed performance, the performance details were reconfigured to the phosphorus removal rates given in the detailed design reports for each asset.
- **Sports field fertilizer management** For each scenario, we modelled sufficient bioretention swales to intercept the required amount of sports field generated phosphorus (i.e., 25% or 75% of all sports field generated phosphorus, Table 7). We modelled one bioretention swale per subcatchment, starting with the subcatchment containing the largest sports field area, and divided the total swale area across the number of swales included in each scenario, proportionally to the area of sports field in each subcatchment.
    - Each bioretention swale was represented by a storage node configured based on the detailed design of a similar, existing WSUD asset.The percentage removal of TP, TN, and TSS were calculated for each bioretention swale using a MUSIC model consisting of a source, GPT, bioretention, and receiving node.
        - The source node was configured to have the size of the subcatchment's sports field area, and land use set at 100% pervious; remaining parameters used default values.
        - The GPT node was configured with high flow bypass.
        - The bioretention node was configured with size proportional to the subcatchment's sports field area, filter area set to 90% of total swale area, and an extended detention depth of 0.3 m based on recommended MIS08 guidelines; remaining parameters used default values.
        - The MUSIC model for each bioretention swale was run on a 6-minute timestep.
    - As the scale of the catchment model does not delineate sports fields from their subcatchments, a controlled splitter node was added to divert water to the storage node. Because sports fields typically generate higher TP concentrations than the catchment average, but splitters do not allow the adjustment of concentration in the diverted water, we instead increased the load of TP treated by bioretention swales by diverting more water to each sports field storage node. We divided the sports field TP concentration by the subcatchment TP concentration and multiplied this ratio by the proportion of sports field area in the subcatchment, to find the proportion of runoff volume to divert to the storage node.
- **Stormwater recycling infrastructure for sports field irrigation** Each sports field with stormwater recycling infrastructure was represented by a storage node and an irrigator node. A maximum of 1 ML water was diverted to the storage node via a controlled splitter during event flows. The irrigator node was configured as a perennial pasture crop using the crop coefficient from the NSW Environmental Guidelines on the used of effluent by irrigation (NSW Department of Environment and Conservation, 2004), with soil moisture capacity set at 20% and default soil configuration. The subcatchment's sports field area was used to set the size of the irrigated area, determining the water demand for irrigation. Daily rainfall and evapotranspiration (short crop) were obtained from SILO (https://www.longpaddock.qld.gov.au/silo/), covering the climatic period represented in the model (1899 – 2023). During dry periods the irrigation demand specified by the irrigator node was met by the water in the storage node, while in wet periods the demand is first met by rainfall. Excess water was

returned to the stormwater system downstream of the sports field via a link, maintaining water and mass balance.

- **Floating wetlands** To represent floating wetlands in the catchment model, a storage routing link was added just upstream of the Lake Tuggeranong storage node. This was configured using a decay model to reduce the phosphorus concentration in the water passing through the routing link, without affecting water volume. The percentage removal of phosphorus was calculated based on the estimated annual load of TP removed per square metre of floating wetland.

The remaining options cannot be explicitly modelled, and their effects were incorporated in the model by calculating the percentage phosphorus removal attained by each option, compared to the current load of phosphorus available to be intercepted by that option, and adjusting phosphorus concentrations within the catchment model based on these percentage reductions:

- **Household fertilizer management** The percentage reduction in phosphorus concentration due to management of household fertilizer use was applied to all area classified as suburban pervious, and calculated based on the difference in total phosphorus load generated from suburban pervious land across the catchment with and without household fertilizer management.
- **Increase street sweeping frequency | Manage grass clippings from municipal mowing | Install castellated kerbs** The percentage reduction in phosphorus concentration due to these options was applied to all area classified as road. As street sweeping, grass clipping management, and castellated kerbs all act to reduce the load of phosphorus generated from roads, the combined effects of these management options were modelled using a build-up wash-off model (Booksmythe, Dey, Kahn, Stewart, & Starrs, 2024) to predict the total percentage reduction in the phosphorus load from roads for the selected combination of these options in each scenario.

Table 8 presents summary statistics for modelled annual inflows and pollutant loads generated under the cost-effective and broad benefits catchment management scenarios, for the period 1889-2022. The management actions included in these scenarios are not predicted to have a large impact on runoff generation or inflows into Lake Tuggeranong; on average, annual inflows to Lake Tuggeranong under the catchment management scenarios were 97-98% of annual inflows under current conditions. However, the annual TP loads entering Lake Tuggeranong were substantially reduced under the catchment management scenarios. Under the cost-effective scenario annual TP loads were on average approximately 67% of annual TP loads under current conditions, and under the broad benefits scenario annual TP loads were on average approximately 56% of annual TP loads under current conditions.

Table 8. Summary statistics describing modelled annual inflow volumes and loads of total phosphorus (TP) entering Lake Tuggeranong under the 'cost-effective and 'broad benefits' catchment management model scenarios, for the period 1889-2022. Compare to the 'current' scenario, Table 6.

Parameter	Modelled scenario	Minimum	25th percentile	Median	Mean	75th percentile	Maximum
Annual inflow (GL)	Cost-effective scenario	2.36	5.29	7.31	8.76	10.27	32.30
Annual inflow (GL)	Broad benefits scenario	2.31	5.22	7.22	8.64	10.15	31.93
Annual TP load (kg)	Cost-effective scenario	236	551	771	992	1,179	4,076
Annual TP load (kg)	Broad benefits scenario	173	441	639	868	1,041	3,877

5. Summary and future model refinements

5.1 Summary

This report has described the data and methods used to parameterise, configure and calibrate the Lake Tuggeranong catchment model. The model was used to explore four scenarios of different catchment land use and management actions, providing long-term mean annual inflows and pollutant loads to Lake Tuggeranong under each scenario.

The catchment model improves on previous modelling work for the Lake Tuggeranong catchment:

- The model simulates flows and pollutant loads across the Lake Tuggeranong catchment on a daily timestep over 133 years of climate data from 1889-2023.
- The model incorporates updated land use and imperviousness layers to simulate runoff and pollutant generation across six functional land use classes.
- The model is delineated to water quality monitoring locations to facilitate parameterisation with concentrations of three pollutants – total phosphorus (TP), total nitrogen (TN), and total suspended solids (TSS).
- The model is delineated to existing stormwater treatment infrastructure to facilitate estimates of pollutant load reduction after treatment.
- The model hydrology is calibrated to a gauge immediately downstream of Lake Tuggeranong, with a very good fit between observed and modelled flow.
- The model incorporates recently constructed WSUD infrastructure in the Lake Tuggeranong catchment.
- The model incorporates a storage node representing Lake Tuggeranong, simulating flow and pollutant loads entering and leaving the storage.

Key results of the model include:

- Under current catchment land use and management, the model estimates a mean annual inflow to Lake Tuggeranong of approximately 8.8 GL for the period 1889-2022. Under predevelopment conditions, annual flows are on average 75% lower, with an estimated mean annual flow of approximately 3.3 GL.
- Under current catchment land use and management, the model estimates mean annual pollutant loads entering Lake Tuggeranong of 1,442 kg TP, 11,894 kg TN, and 397,064 kg TSS. Under predevelopment conditions, annual pollutant loads to the lake are on average 85% lower.
- By implementing combinations of catchment management options chosen by the ACT Healthy Waterways program, the model estimates that average annual TP loads to Lake Tuggeranong would be reduced to 868-992 kg, a 33-44% decrease compared to current catchment conditions.
- Land use is the major determinant of simulated subcatchment pollutant loads.

5.2 Future model refinements

The reliability and information provided by the Lake Tuggeranong catchment model could be enhanced by improvements to the data used for subcatchment delineation and calibration, and by undertaking assessments of model uncertainty:

- The calibration of water quality (pollutant) estimates in the model was based on observed median concentrations during event flows, which were the only available water quality data. However, observed pollutant loads provide a more robust framework for calibration in Source. Collecting data on pollutant loads requires simultaneous measures of concentration and flow volume and represents a significant change to the water quality and quantity monitoring currently undertaken in the ACT.
- Incorporating observed flow data from additional gauging stations within the Lake Tuggeranong catchment would enhance model reliability by broadening the data available for hydrological calibration.
- Undertaking an uncertainty estimation for the flows and pollutant loads estimated by the catchment model would provide a quantitative assessment of model reliability. Understanding model uncertainty is important when comparing across modelled scenarios, to ensure that differences are explained by modelled management options rather than measurement/estimation error.
- Understanding uncertainty in the model would also allow identification of areas where more hydrological and/or water quality data could improve the reliability of model estimates.

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Appendices

Appendix A: Level-volume-area data for Lake Tuggeranong

To configure the Lake Tuggeranong storage node in the catchment model requires information on the relationship between the water level and volume of the lake. Figure A1 shows the stage-volume rating curve used in configuring the Lake Tuggeranong storage node in the model. The level-volume-area (LVA) relationship for Lake Tuggeranong was derived from bathymetry data collected by Steger and Associates Registered Land Surveyors in 2015, presented in Table A1.

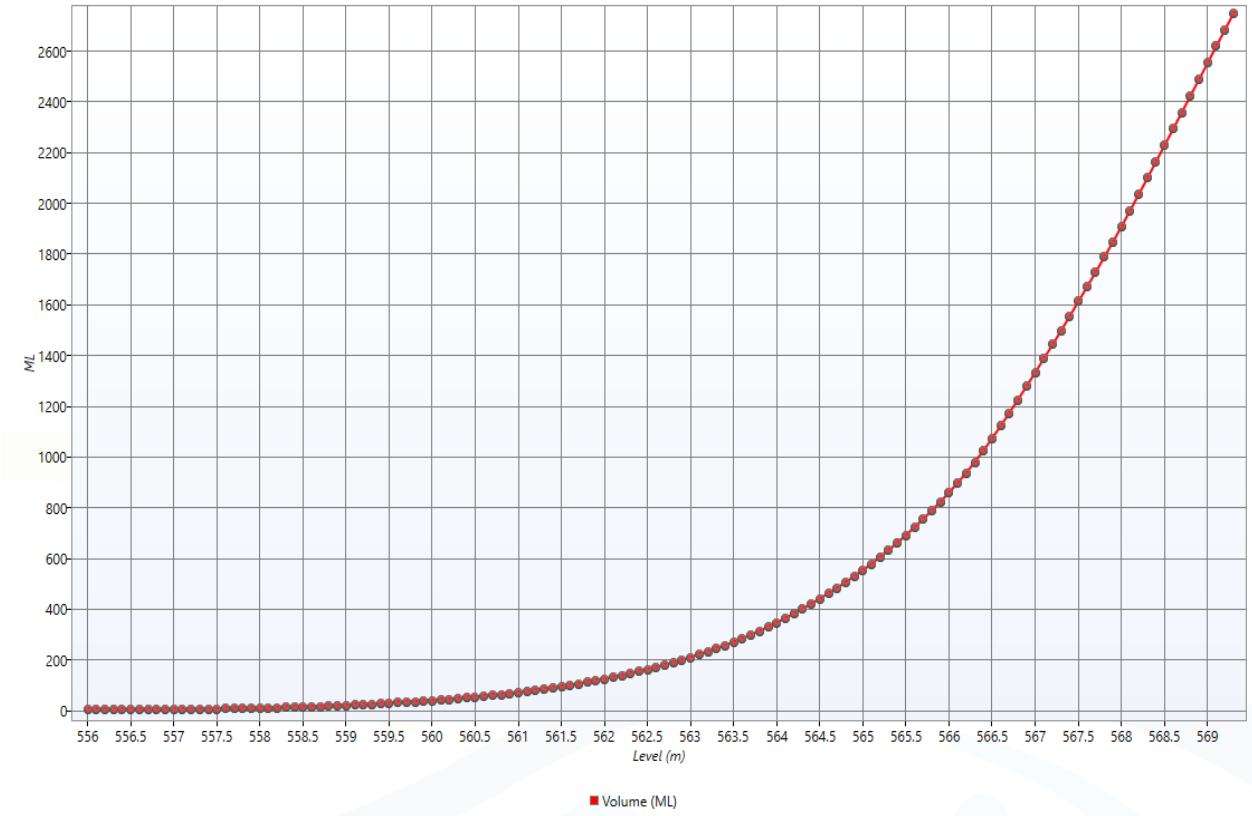

Figure A1. Water level - volume ratings curve for Lake Tuggeranong (gauge 410784) derived from bathymetry data (see Table A1). Source: Steger and Associates Registered Land Surveyors, 2015.

Table A1. Lake Tuggeranong water level, volume, and surface area data. Source: Steger and Associates Registered Land Surveyors, 2015.

Level (m)	Volume (ML)	Surface area (km^2)	Level (m)	Volume (ML)	Surface area (km^2)	Level (m)	Volume (ML)	Surface area (km^2)
556.0	0	0	558.4	10.1361	0.009721	560.8	60.19836	0.035167
556.1	0.014874	0.000119	558.5	11.18874	0.010526	560.9	63.92854	0.037302
556.2	0.036423	0.000215	558.6	12.31101	0.011223	561.0	67.9121	0.039836
556.3	0.072831	0.000364	558.7	13.49978	0.011888	561.1	72.14851	0.042364
556.4	0.122048	0.000492	558.8	14.76326	0.012635	561.2	76.63992	0.044914
556.5	0.222146	0.001001	558.9	16.10082	0.013376	561.3	81.38454	0.047446
556.6	0.374086	0.001519	559.0	17.52169	0.014209	561.4	86.36409	0.049795
556.7	0.570277	0.001962	559.1	19.02266	0.01501	561.5	91.56732	0.052032
556.8	0.808589	0.002383	559.2	20.60679	0.015841	561.6	97.00797	0.054406
556.9	1.104417	0.002958	559.3	22.27321	0.016664	561.7	102.6982	0.056902
557.0	1.442882	0.003385	559.4	24.02014	0.017469	561.8	108.6627	0.059645
557.1	1.824143	0.003813	559.5	25.84861	0.018285	561.9	114.8979	0.062353
557.2	2.241786	0.004176	559.6	27.79639	0.019478	562.0	121.405	0.065071
557.3	2.690724	0.004489	559.7	29.85126	0.020549	562.1	128.2425	0.068375
557.4	3.16953	0.004788	559.8	32.00766	0.021564	562.2	135.4093	0.071668
557.5	3.677818	0.005083	559.9	34.26355	0.022559	562.3	142.8931	0.074838
557.6	4.218615	0.005408	560.0	36.62414	0.023606	562.4	150.7054	0.078123
557.7	4.79095	0.005723	560.1	39.09346	0.024693	562.5	158.8814	0.08176
557.8	5.397505	0.006066	560.2	41.67477	0.025813	562.6	167.4558	0.085744
557.9	6.045165	0.006477	560.3	44.38028	0.027055	562.7	176.4338	0.08978
558.0	6.744306	0.006991	560.4	47.21816	0.028379	562.8	185.8594	0.094256
558.1	7.488318	0.00744	560.5	50.20973	0.029916	562.9	195.7887	0.099293
558.2	8.290076	0.008018	560.6	53.35829	0.031486	563.0	206.241	0.104523
558.3	9.164035	0.00874	560.7	56.6817	0.033234	563.1	217.2403	0.109993

Level (m)	Volume (ML)	Surface area (km^2)
563.2	228.7825	0.115422
563.3	240.9099	0.121274
563.4	253.6379	0.12728
563.5	266.9702	0.133322
563.6	280.9174	0.139472
563.7	295.4839	0.145666
563.8	310.6996	0.152156
563.9	326.6404	0.159409
564.0	343.3933	0.167529
564.1	360.9095	0.175162
564.2	379.1175	0.18208
564.3	398.0267	0.189093
564.4	417.6585	0.196317
564.5	437.9539	0.202954
564.6	458.8675	0.209136
564.7	480.4328	0.215652
564.8	502.7146	0.222818
564.9	525.8767	0.231621
565.0	549.963	0.240863
565.1	575.1935	0.252304
565.2	601.5961	0.264027
565.3	629.1803	0.275842
565.4	657.9845	0.288043
565.5	687.9878	0.300033
565.6	719.1112	0.311234
565.7	751.5013	0.323901
565.8	785.1463	0.336449
565.9	820.0771	0.349308
566.0	856.4557	0.363786
566.1	894.2724	0.378167
566.2	934.0697	0.397974
566.3	976.8441	0.427744
566.4	1022.38	0.455357
566.5	1070.137	0.477574
566.6	1119.482	0.493452
566.7	1170.426	0.509434
566.8	1222.593	0.521672
566.9	1275.738	0.531451
567.0	1329.908	0.541698
567.1	1384.869	0.549609
567.2	1440.435	0.555666
567.3	1496.534	0.56099
567.4	1553.159	0.566248
567.5	1610.312	0.571526
567.6	1668.006	0.576945
567.7	1726.277	0.582703
567.8	1785.19	0.589135
567.9	1844.844	0.596536
568.0	1906.38	0.615362
568.1	1968.905	0.625256
568.2	2032.357	0.634518
568.3	2096.546	0.641889
568.4	2161.172	0.646257
568.5	2226.008	0.648362
568.5	2226.008	0.648362
568.6	2290.955	0.649472
568.7	2355.947	0.649921
568.8	2420.965	0.650178
568.9	2485.993	0.650283
569.0	2551.028	0.650344
569.1	2616.068	0.650402
569.2	2681.113	0.650454
569.3	2746.163	0.650495

Appendix B: Level – discharge data for Lake Tuggeranong outflow

The Lake Tuggeranong outflow was configured as an ungated spillway in the Source model, using the level-discharge relationship from Lake Tuggeranong weir (gauge 410784), presented in Table B1.

Table B1. Lake Tuggeranong weir rating table. *Source: ALS Pty Ltd.*

Level (m)	Discharge (ML/d)	Level (m)	Discharge (ML/d)	Level (m)	Discharge (ML/d)	Level (m)	Discharge (ML/d)
0	0	568.14	740.448	568.43	3957.12	568.72	9072
567.86	0	568.15	809.568	568.44	4121.28	568.73	9244.8
567.87	1.08	568.16	881.28	568.45	4285.44	568.74	9417.6
567.88	6.10848	568.17	959.04	568.46	4458.24	568.75	9676.8
567.89	16.848	568.18	1036.8	568.47	4631.04	568.76	9849.6
567.90	34.56	568.19	1123.2	568.48	4812.48	568.77	10022.4
567.91	41.2992	568.20	1209.6	568.49	4993.92	568.78	10281.6
567.92	48.816	568.21	1296	568.50	5184	568.79	10454.4
567.93	57.1104	568.22	1382.4	568.51	5339.52	568.80	10713.6
567.94	66.096	568.23	1468.8	568.52	5503.68	568.81	10886.4
567.95	76.032	568.24	1563.84	568.53	5667.84	568.82	11059.2
567.96	86.4	568.25	1667.52	568.54	5840.64	568.83	11318.4
567.97	98.496	568.26	1771.2	568.55	6013.44	568.84	11491.2
567.98	110.592	568.27	1874.88	568.56	6186.24	568.85	11664
567.99	124.416	568.28	1978.56	568.57	6359.04	568.86	11923.2
568.00	138.24	568.29	2090.88	568.58	6540.48	568.87	12096
568.01	162.432	568.30	2211.84	568.59	6721.92	568.88	12355.2
568.02	189.216	568.31	2324.16	568.60	6912	568.89	12528
568.03	219.456	568.32	2436.48	568.61	7076.16	568.90	12700.8
568.04	251.424	568.33	2557.44	568.62	7240.32	568.91	12960
568.05	285.984	568.34	2678.4	568.63	7404.48	568.92	13132.8
568.06	323.136	568.35	2808	568.64	7577.28	568.93	13392
568.07	362.88	568.36	2937.6	568.65	7750.08	568.94	13564.8
568.08	406.08	568.37	3067.2	568.66	7922.88	568.95	13824
568.09	451.872	568.38	3205.44	568.67	8095.68	568.96	13996.8
568.10	501.12	568.39	3343.68	568.68	8277.12	568.97	14256
568.11	555.552	568.40	3490.56	568.69	8458.56	568.98	14428.8
568.12	613.44	568.41	3646.08	568.70	8640	568.99	14601.6
568.13	675.648	568.42	3801.6	568.71	8812.8		

Appendix C: Land use and imperviousness classification

Table C1 lists the detailed land use classifications included in each of the six functional land use units defined for the Lake Tuggeranong catchment. Table C2 provides a breakdown of the major and minor subcatchments delineated in the Source catchment model, and Figure C1 shows a map of the major subcatchments. Table C3 provides the subcatchment area breakdown in hectares and area ratio based on land use functional units used in the catchment model.

Table C1. Detailed land use classifications based on ACT Government land zoning grouped into 6 functional units for use in the catchment model.

ACT land zoning	Functional unit
Business zone	commercial
Community Facilities	commercial
Core zone	commercial
Leisure and accommodation	commercial
Local centre	commercial
Services	commercial
Services zone	commercial
Medium density residential	suburban
Suburban	suburban
Suburban core	suburban
Transport	open space
Urban open space	open space
Restricted access recreation zone	open space
Hills ridges and buffer areas	bushland
Designated	bushland
River corridor	bushland
Rural	rural
Sports field (estimated)	sports field

Table C2. Major subcatchments of the Lake Tuggeranong catchment and their component minor subcatchments delineated in the Source catchment model.

Major subcatchment	Minor subcatchments
Village Creek (VC)	VC0, VC1, VC2, VC3, VC4, VC6, VC7, VC8, VC9, VC10, VC11
Kambah Creek (KC)	KC0, KC1, KC2, KC3, KC4, KC5, KC6, KC7
Tuggeranong Creek (TC)	TC0, TC1, TC2, TC3, TC4, TC5, TC6, TC7, TC6_NSW, TC8_NSW
Lake Tuggeranong (Lake T)	
East Lake (EL)	EL1, EL2
West Lake (WL)	WL0, WL1, WL2, WL3, WL4, WL5, WL6, WL7, WL8, WL9, WL10, WL11
Downstream of Lake Tuggeranong (DSL)	DSL1, DSL2
Drakeford Drive South (DDS)	DDS1, DDS2
(DLC)	DLC_N, DLC_S
Stranger Pond (SP)	SP1, SP2
Wanniassa (WS)	WS0, WS1, WS2, WS3, WS4
Fadden stormwater (FA)	FA0, FA1, FA2, FA3, FA5, FA6, FA7, FA8, FA9, FA10, FA11, FA12, FA13, FA14, FA15, FA16, FA17, FA9_NSW

Fig. C1. Map of Lake Tuggeranong catchment showing major subcatchment boundaries. VC, Village Creek; KC, Kambah Creek; WS, Wanniassa; FA, Fadden stormwater; TC, Tuggeranong Creek; DSL, Downstream of Lake Tuggeranong; Lake T, Lake Tuggeranong; DLC, XXX; WL, West Lake; EL, East Lake; DDS, Drakeford Drive South; SP, Stranger Pond.

Table C3. Area of land use functional units within Lake Tuggeranong subcatchments (see Table C2), in hectares (ha) and as a percentage of subcatchment area (%).

Functional unit	VC0 (ha)	VC0 (%)	VC1 (ha)	VC1 (%)	VC2 (ha)	VC2 (%)	VC3 (ha)	VC3 (%)	VC4 (ha)	VC4 (%)	VC6 (ha)	VC6 (%)
Commercial road	1.16654	1.28342	0.55272	1.45670	0.06191	0.06184	0.00053	0.00081	0.00000	0.00000	0.52402	2.40107
Commercial hardstand	2.96745	3.26478	3.54531	9.34381	0.09628	0.09617	0.75895	1.17555	0.72954	0.59131	1.30516	5.98024
Commercial roof	3.62099	3.98381	3.96793	10.45763	0.40466	0.40420	0.96058	1.48785	0.96820	0.78476	1.85026	8.47786
Commercial pervious	3.42116	3.76396	2.91630	7.68602	0.33240	0.33202	2.63463	4.08081	1.87153	1.51694	1.60472	7.35280
Commercial water	0	0	0	0	0	0	0	0	0	0	0	0
Suburban road	3.73592	4.11026	1.45375	3.83141	5.77357	5.76696	3.69303	5.72018	6.43127	5.21276	0.40714	1.86552
Suburban hardstand	5.17332	5.69168	1.37583	3.62604	5.56696	5.56059	2.89318	4.48128	5.92845	4.80520	0.73999	3.39064
Suburban roof	17.15034	18.86877	4.56512	12.03155	22.63823	22.61229	11.73104	18.17036	22.69013	18.39110	2.30035	10.54015
Suburban pervious	29.87385	32.86716	7.64501	20.14873	38.47253	38.42845	20.42040	31.62942	36.44461	29.53956	2.69231	12.33615
Suburban water	0	0	0	0	0.01395	0.01393	2.50E-05	3.87E-05	0.00095	0.00077	0	0
Open space road	4.47567	4.92413	2.24256	5.91036	4.15447	4.14971	2.77265	4.29460	4.04727	3.28044	1.83831	8.42312
Open space hardstand	1.61398	1.77570	0.76704	2.02155	2.45150	2.44869	1.30548	2.02207	3.76469	3.05140	0.72845	3.33773
Open space roof	0.20061	0.22071	0.07460	0.19661	0.48495	0.48439	0.25650	0.39730	0.80075	0.64903	0.14520	0.66532
Open space pervious	14.24994	15.67776	8.83674	23.28958	12.97204	12.95718	16.26664	25.19562	29.51479	23.92272	7.48905	34.31473
Open space water	0.03960	0.04357	0	0	0	0	0	0	0	0	0.19962	0.91466
Bushland road	0	0	0	0	0	0	0	0	0	0	0	0
Bushland hardstand	0.04743	0.05218	0	0	0.24205	0.24177	0	0	0	0	0	0
Bushland roof	0.00363	0.00399	0	0	0.00097	0.00097	0	0	0	0	0	0
Bushland pervious	3.15228	3.46813	0	0	6.44823	6.44084	0	0	0	0	0	0
Bushland water	0	0	0	0	0	0	0	0	0	0	0	0
Rural road	0	0	0	0	0	0	0	0	0	0	0	0
Rural hardstand	0	0	0	0	0	0	0	0	0	0	0	0
Rural roof	0	0	0	0	0	0	0	0	0	0	0	0
Rural pervious	0	0	0	0	0	0	0	0	0	0	0	0
Rural water	0	0	0	0	0	0	0	0	0	0	0	0
Sports field	0	0	0	0	0	0	0.86778	1.34411	10.18341	8.25399	0	0
Total subcatchment area	90.89270	100	37.94290	100	100.11470	100	64.56140	100	123.37560	100	21.82460	100

Table C3 cont. Area of land use functional units within Lake Tuggeranong subcatchments (see Table C2), in hectares (ha) and as a percentage of subcatchment area (%).

Functional unit	VC7 (ha)	VC7 (%)	VC8 (ha)	VC8 (%)	VC9 (ha)	VC9 (%)	VC10 (ha)	VC10 (%)	VC11 (ha)	VC11 (%)	Lake T (ha)	Lake T (%)
Commercial road	0	0	0	0	0.01835	0.00688	0	0	0	0	0	0
Commercial hardstand	0	0	0	0	1.02446	0.38388	1.19452	0.64653	0	0	0	0
Commercial roof	0	0	0	0	0.62828	0.23543	1.79132	0.96955	0	0	0	0
Commercial pervious	0	0	0	0	2.96747	1.11196	4.26940	2.31081	0	0	0	0
Commercial water	0	0	0	0	0	0	0	0	0	0	0	0
Suburban road	0.31054	9.59627	0.00158	0.03398	5.07906	1.90321	10.61841	5.74720	2.75089	3.36567	0	0
Suburban hardstand	0.24232	7.48839	0.00455	0.09815	3.93032	1.47275	6.24872	3.38211	1.53092	1.87306	0	0
Suburban roof	0.71997	22.24891	0.00000	0.00000	17.65425	6.61534	29.89265	16.17935	8.30131	10.15654	0	0
Suburban pervious	1.00224	30.97160	0.09433	2.03477	29.37379	11.00684	51.34650	27.79122	16.30805	19.95268	0	0
Suburban water	0	0	0	0	0	0	0	0	2.50E-05	3.06E-05	0	0
Open space road	0.01912	0.59088	0.73261	15.80361	9.13640	3.42356	3.42844	1.85564	0.08557	0.10470	0.16068	0.22103
Open space hardstand	0.07169	2.21524	0.14298	3.08425	4.31557	1.61712	2.79452	1.51253	0.16162	0.19775	0.31379	0.43165
Open space roof	0.01592	0.49202	0.02103	0.45355	0.45775	0.17152	0.31814	0.17220	0.01235	0.01511	0.30226	0.41579
Open space pervious	0.85420	26.39669	3.63864	78.49169	44.29813	16.59923	34.55149	18.70095	5.38125	6.58389	2.76054	3.79745
Open space water	0	0	0	0	0.17846	0.06687	0	0	0	0	69.15733	95.13407
Bushland road	0	0	0	0	3.77569	1.41481	0.43221	0.23393	1.15907	1.41811	0	0
Bushland hardstand	0	0	0	0	1.75254	0.65671	0.10256	0.05551	0.23837	0.29165	0	0
Bushland roof	0	0	0	0	0.24923	0.09339	0.00665	0.00360	0.11275	0.13795	0	0
Bushland pervious	0	0	0	0	142.00602	53.21198	30.50463	16.51058	45.69143	55.90287	0	0
Bushland water	0	0	0	0	0.02273	0.00852	0	0	0	0	0	0
Rural road	0	0	0	0	0	0	0	0	0	0	0	0
Rural hardstand	0	0	0	0	0	0	0	0	0	0	0	0
Rural roof	0	0	0	0	0	0	0	0	0	0	0	0
Rural pervious	0	0	0	0	0	0	0	0	0	0	0	0
Rural water	0	0	0	0	0	0	0	0	0	0	0	0
Sports field	0	0	0	0	0	0	7.25782	3.92829	0	0	0	0
Total subcatchment area	3.23600	100	4.63570	100	266.86850	100	184.75800	100	81.73360	100	72.69460	100

Table C3 cont. Area of land use functional units within Lake Tuggeranong subcatchments (see Table C2), in hectares (ha) and as a percentage of subcatchment area (%).

Functional unit	KC0 (ha)	KC0 (%)	KC1 (ha)	KC1 (%)	KC2 (ha)	KC2 (%)	KC3 (ha)	KC3 (%)	KC4 (ha)	KC4 (%)	KC5 (ha)	KC5 (%)
Commercial road	0	0	0	0	0	0	0	0	0	0	0.22272	0.32619
Commercial hardstand	0.23590	0.18352	0.10135	0.12613	0.11103	0.12613	0.00800	0.12613	0.00045	0.02089	1.68770	2.47178
Commercial roof	0.46683	0.36317	0.10200	0.12693	0.11174	0.12693	0.00805	0.12693	0.00003	0.00116	1.91152	2.79958
Commercial pervious	0.80327	0.62490	0.02740	0.03410	0.03002	0.03410	0.00216	0.03410	0.01793	0.83192	2.24089	3.28197
Commercial water	0	0	0	0	0	0	0	0	0	0	0	0
Suburban road	7.27826	5.66213	6.20275	7.71915	6.79539	7.71915	0.48981	7.71915	0.00000	0.00000	4.54340	6.65420
Suburban hardstand	7.37201	5.73507	5.85418	7.28537	6.41351	7.28537	0.46229	7.28537	0.02456	1.13940	4.10095	6.00621
Suburban roof	28.02338	21.80082	19.67904	24.49003	21.55926	24.49003	1.55399	24.49003	0.15034	6.97445	14.86127	21.76563
Suburban pervious	45.12123	35.10210	33.59659	41.81005	36.80656	41.81005	2.65302	41.81005	0.19061	8.84250	26.44537	38.73156
Suburban water	0	0	0	0	0	0	0	0	5.00E-05	0.00232	2.50E-05	3.66E-05
Open space road	6.75730	5.25685	2.59264	3.22647	2.84036	3.22647	0.20473	3.22647	0.00375	0.17404	2.08079	3.04750
Open space hardstand	2.98208	2.31991	1.45161	1.80649	1.59030	1.80649	0.11463	1.80649	0.41023	19.03093	1.24580	1.82459
Open space roof	0.23348	0.18164	0.19942	0.24818	0.21848	0.24818	0.01575	0.24818	0.06228	2.88910	0.11700	0.17135
Open space pervious	29.18828	22.70705	10.54832	13.12710	11.55616	13.12710	0.83297	13.12710	1.29149	59.91344	8.08024	11.83421
Open space water	0.01618	0.01258	0	0	0	0	0	0	0	0	0	0
Bushland road	0	0	0	0	0	0	0	0	0	0	0	0
Bushland hardstand	0	0	0	0	0	0	0	0	0	0	0	0
Bushland roof	0	0	0	0	0	0	0	0	0	0	0	0
Bushland pervious	0	0	0	0	0	0	0	0	0	0	0	0
Bushland water	0	0	0	0	0	0	0	0	0	0	0	0
Rural road	0	0	0	0	0	0	0	0	0	0	0	0
Rural hardstand	0	0	0	0	0	0	0	0	0	0	0	0
Rural roof	0	0	0	0	0	0	0	0	0	0	0	0
Rural pervious	0	0	0	0	0	0	0	0	0	0	0	0
Rural water	0	0	0	0	0	0	0	0	0	0	0	0
Sports field	0	0	0	0	0	0	0	0	0.00388	0.17984	0.74094	1.08517
Total subcatchment area	128.54280	100	80.35530	100	88.03280	100	6.34540	100	2.15560	100	68.27860	100

Table C3 cont. Area of land use functional units within Lake Tuggeranong subcatchments (see Table C2), in hectares (ha) and as a percentage of subcatchment area (%).

Functional unit	KC6 (ha)	KC6 (%)	KC7 (ha)	KC7 (%)	SP1 (ha)	SP1 (%)	SP2 (ha)	SP2 (%)	EL1 (ha)	EL1 (%)	EL2 (ha)	EL2 (%)
Commercial road	0	0	0	0	0.34455	0.09473	0.25623	0.65596	0	0	0.1566	0.8058
Commercial hardstand	0.06448	0.04990	0	0	2.55082	0.70133	0.34418	0.88112	0	0	0.7782	4.0044
Commercial roof	0.08659	0.06701	0	0	2.85592	0.78521	1.33480	3.41714	0	0	1.1017	5.6688
Commercial pervious	0.00426	0.00329	0	0	8.95477	2.46205	1.59170	4.07482	0	0	1.6979	8.7366
Commercial water	0	0	0	0	0	0	0	0	0	0	0	0
Suburban road	6.73670	5.21343	0	0	16.71164	4.59474	0.75529	1.93357	1.96217	3.10053	0	0
Suburban hardstand	6.08694	4.71059	0	0	21.71844	5.97132	2.18503	5.59379	5.25066	8.29684	0	0
Suburban roof	23.68161	18.32684	0	0	73.29687	20.15242	5.26468	13.47782	7.70244	12.17103	0.00198	0.01016
Suburban pervious	41.86302	32.39716	0	0	102.74356	28.24856	5.68414	14.55165	10.69712	16.90309	0.03886	0.19994
Suburban water	0	0	0	0	0.00210	0.00058	0	0	0	0	0	0
Open space road	5.30084	4.10224	2.16018	0.69905	12.17165	3.34650	1.47995	3.78873	1.76602	2.79058	1.38581	7.13058
Open space hardstand	2.65729	2.05644	2.24234	0.72564	5.34020	1.46825	1.23752	3.16811	2.27993	3.60263	0.97812	5.03284
Open space roof	0.16133	0.12485	0.10101	0.03269	0.58110	0.15977	0.09868	0.25262	0.39105	0.61793	0.08547	0.43977
Open space pervious	38.37112	29.69483	13.61355	4.40542	58.24083	16.01287	12.63747	32.35250	32.93501	52.04237	12.78198	65.76885
Open space water	0	0	0	0	0	0	4.32094	11.06181	0.30060	0.47500	0.06847	0.35228
Bushland road	0	0	6.17691	1.99888	0.86652	0.23824	0	0	0	0	0	0
Bushland hardstand	0.00225	0.00174	2.42975	0.78628	0.74172	0.20393	0	0	0	0	0	0
Bushland roof	0.00093	0.00072	1.47904	0.47863	0.70985	0.19517	0	0	0	0	0	0
Bushland pervious	4.20082	3.25095	280.72872	90.84543	52.08091	14.31925	0	0	0	0	0	0
Bushland water	0	0	0.08650	0.02799	0	0	0	0	0	0	0	0
Rural road	0	0	0	0	0	0	0	0	0	0	0	0
Rural hardstand	0	0	0	0	0	0	0	0	0	0	0	0
Rural roof	0	0	0	0	0	0	0	0	0	0	0	0
Rural pervious	0	0	0	0	0	0	0	0	0	0	0	0
Rural water	0	0	0	0	0	0	0	0	0	0	0	0
Sports field	0	0	0	0	3.80112	1.04509	1.87120	4.79037	0	0	0.35953	1.84994
Total subcatchment area	129.21820	100	309.01800	100	363.71260	100	39.06180	100	63.28500	100	19.43470	100

Table C3 cont. Area of land use functional units within Lake Tuggeranong subcatchments (see Table C2), in hectares (ha) and as a percentage of subcatchment area (%).

Functional unit	WL0 (ha)	WL0 (%)	WL1 (ha)	WL1 (%)	WL2 (ha)	WL2 (%)	WL3 (ha)	WL3 (%)	WL4 (ha)	WL4 (%)	WL5 (ha)	WL5 (%)
Commercial road	4.3703	7.9703	0.8347	3.1681	1.0011	6.7299	0	0	0.62984	11.02963	0	0
Commercial hardstand	11.5970	21.1500	6.8472	25.9884	1.2159	8.1740	0.00085	0.01072	2.13908	37.45934	0	0
Commercial roof	25.6801	46.8340	5.6090	21.2888	4.2901	28.8403	0.00085	0.01072	1.99816	34.99153	0	0
Commercial pervious	4.4233	8.0669	3.4839	13.2230	2.1629	14.5404	0.00355	0.04478	0.60119	10.52793	0.13435	2.80000
Commercial water	0	0	0	0	0	0	0	0	0	0	0	0
Suburban road	0	0	0.01252	0.04754	0	0	0	0	0	0	0	0
Suburban hardstand	0	0	0.10727	0.40713	0	0	0	0	0	0	0	0
Suburban roof	0	0	0.09979	0.37877	0	0	0	0	0	0	0	0
Suburban pervious	0	0	0.23981	0.91019	0	0	0	0	0	0	0	0
Suburban water	0	0	0	0	0	0	0	0	0	0	0	0
Open space road	3.84955	7.02060	3.52733	13.38791	2.07414	13.94361	0.01007	0.12708	0.00397	0.06961	0.76260	15.89337
Open space hardstand	2.01038	3.66643	0.97456	3.69894	1.33538	8.97721	0.81178	10.24202	0.06327	1.10804	0.59875	12.47873
Open space roof	0.65246	1.18991	0.17189	0.65240	0.72916	4.90187	0.14906	1.88065	0.04205	0.73636	0.43773	9.12289
Open space pervious	2.24307	4.09078	4.41994	16.77583	2.06527	13.88395	6.94281	87.59543	0.22977	4.02371	2.82017	58.77550
Open space water	0.00605	0.01103	0.01925	0.07306	0	0	0.00702	0.08861	0.00307	0.05385	0.00874	0.18216
Bushland road	0	0	0	0	0	0	0	0	0	0	0	0
Bushland hardstand	0	0	0	0	0	0	0	0	0	0	0	0
Bushland roof	0	0	0	0	0	0	0	0	0	0	0	0
Bushland pervious	0	0	0	0	0.00130	0.00874	0	0	0	0	0.03586	0.74736
Bushland water	0	0	0	0	0	0	0	0	0	0	0	0
Rural road	0	0	0	0	0	0	0	0	0	0	0	0
Rural hardstand	0	0	0	0	0	0	0	0	0	0	0	0
Rural roof	0	0	0	0	0	0	0	0	0	0	0	0
Rural pervious	0	0	0	0	0	0	0	0	0	0	0	0
Rural water	0	0	0	0	0	0	0	0	0	0	0	0
Sports field	0	0	0	0	0	0	0	0	0	0	0	0
Total subcatchment area	54.83220	100	26.34710	100	14.87520	100	7.92600	100	5.71040	100	4.79820	100

Table C3 cont. Area of land use functional units within Lake Tuggeranong subcatchments (see Table C2), in hectares (ha) and as a percentage of subcatchment area (%).

Functional unit	WL6 (ha)	WL6 (%)	WL7 (ha)	WL7 (%)	WL8 (ha)	WL8 (%)	WL9 (ha)	WL9 (%)	WL10 (ha)	WL10 (%)	WL11 (ha)	WL11 (%)
Commercial road	0.22090	9.12689	0.48320	9.59071	0.10770	9.94735	0	0	0.00152	0.00688	0.00052	0.00688
Commercial hardstand	0.75873	31.34842	0.70091	13.91191	0.09505	8.77898	0.09312	8.05055	0.08472	0.38388	0.02891	0.38388
Commercial roof	1.34172	55.43604	1.17561	23.33390	0.22848	21.10234	0.28581	24.70893	0.05195	0.23543	0.01773	0.23543
Commercial pervious	0.07700	3.18144	0.66586	13.21619	0.21683	20.02632	0.09627	8.32271	0.24539	1.11196	0.08373	1.11196
Commercial water	0.00003	0.00103	0.01950	0.38706	0	0	0	0	0	0	0	0
Suburban road	0	0	0	0	0	0	0	0	0.42001	1.90321	0.14331	1.90321
Suburban hardstand	0	0	0	0	0	0	0	0	0.32501	1.47275	0.11090	1.47275
Suburban roof	0	0	0	0	0	0	0	0	1.45989	6.61534	0.49813	6.61534
Suburban pervious	0	0	0	0	0	0	0	0	2.42902	11.00684	0.82882	11.00684
Suburban water	0	0	0	0	0	0	0	0	0	0	0	0
Open space road	0	0	0.00018	0.00347	0.09565	8.83440	0	0	0.75552	3.42356	0.25779	3.42356
Open space hardstand	0.01015	0.41951	0.59345	11.77910	0.07803	7.20652	0.22165	19.16190	0.35687	1.61712	0.12177	1.61712
Open space roof	0.00730	0.30172	0.15618	3.09997	0.03780	3.49127	0.12877	11.13295	0.03785	0.17152	0.01292	0.17152
Open space pervious	0.00448	0.18496	1.22931	24.39981	0.19978	18.45156	0.30532	26.39594	3.66317	16.59923	1.24992	16.59923
Open space water	0	0	0.01400	0.27789	0.02340	2.16126	0.02576	2.22702	0.01476	0.06687	0.00504	0.06687
Bushland road	0	0	0	0	0	0	0	0	0.31222	1.41481	0.10654	1.41481
Bushland hardstand	0	0	0	0	0	0	0	0	0.14492	0.65671	0.04945	0.65671
Bushland roof	0	0	0	0	0	0	0	0	0.02061	0.09339	0.00703	0.09339
Bushland pervious	0	0	0	0	0	0	0	0	11.74298	53.21198	4.00686	53.21198
Bushland water	0	0	0	0	0	0	0	0	0.00188	0.00852	0.00064	0.00852
Rural road	0	0	0	0	0	0	0	0	0	0	0	0
Rural hardstand	0	0	0	0	0	0	0	0	0	0	0	0
Rural roof	0	0	0	0	0	0	0	0	0	0	0	0
Rural pervious	0	0	0	0	0	0	0	0	0	0	0	0
Rural water	0	0	0	0	0	0	0	0	0	0	0	0
Sports field	0	0	0	0	0	0	0	0	0	0	0	0
Total subcatchment area	2.42030	100	5.03820	100	1.08270	100	1.15670	100	22.06830	100	7.53000	100

Table C3 cont. Area of land use functional units within Lake Tuggeranong subcatchments (see Table C2), in hectares (ha) and as a percentage of subcatchment area (%).

Functional unit	DDS1 (ha)	DDS1 (%)	DDS2 (ha)	DDS2 (%)	DSL1 (ha)	DSL1 (%)	DSL2 (ha)	DSL2 (%)	DLC N (ha)	DLC N (%)	DLC S (ha)	DLC S (%)
Commercial road	0	0	0	0	0	0	0	0	0	0	0	0
Commercial hardstand	0	0	0	0	0.00817	0.01807	0	0	0	0	0.08175	0.12357
Commercial roof	0	0	0	0	0.00840	0.01857	0	0	0	0	0.14145	0.21382
Commercial pervious	0	0	0	0	6.11195	13.52072	0	0	0	0	0.03060	0.04626
Commercial water	0	0	0	0	0	0	0	0	0	0	0	0
Suburban road	0.89352	7.67025	1.04632	3.69542	0	0	0	0	0.25714	8.61201	3.97777	6.01283
Suburban hardstand	0.63470	5.44849	2.06447	7.29133	0	0	0	0	0.35156	11.77441	5.04227	7.62195
Suburban roof	1.85668	15.93838	4.99336	17.63565	0	0	0	0	1.31517	44.04747	15.13896	22.88422
Suburban pervious	3.18648	27.35385	5.69499	20.11369	0	0	0	0	0.74893	25.08312	22.82264	34.49895
Suburban water	0	0	0	0	0	0	0	0	0	0	0	0
Open space road	0.74070	6.35840	3.08179	10.88433	0	0	0	0	0	0	3.06436	4.63212
Open space hardstand	0.10360	0.88930	1.21974	4.30791	0.00737	0.01631	0.00040	0.00118	0.02711	0.90785	1.28473	1.94201
Open space roof	0.02935	0.25194	0.11342	0.40059	0.00070	0.00155	0	0	0.00355	0.11892	0.17930	0.27103
Open space pervious	4.20409	36.08938	10.09991	35.67110	0.25166	0.55672	0.09442	0.27857	0.28234	9.45621	14.39076	21.75323
Open space water	0	0	0	0	0	0	0	0	0	0	0	0
Bushland road	0	0	0	0	0	0	0	0	0	0	0	0
Bushland hardstand	0	0	0	0	0.65479	1.44850	0.28300	0.83498	0	0	0	0
Bushland roof	0	0	0	0	0.05969	0.13205	0.00107	0.00317	0	0	0	0
Bushland pervious	0	0	0	0	37.96401	83.98318	33.51431	98.88211	0	0	0	0
Bushland water	0	0	0	0	0.13757	0.30434	0	0	0	0	0	0
Rural road	0	0	0	0	0	0	0	0	0	0	0	0
Rural hardstand	0	0	0	0	0	0	0	0	0	0	0	0
Rural roof	0	0	0	0	0	0	0	0	0	0	0	0
Rural pervious	0	0	0	0	0	0	0	0	0	0	0	0
Rural water	0	0	0	0	0	0	0	0	0	0	0	0
Sports field	0	0	0	0	0	0	0	0	0	0	0	0
Total subcatchment area	11.64910	100	28.31400	100	45.20430	100	33.89320	100	2.98580	100	66.15460	100

Table C3 cont. Area of land use functional units within Lake Tuggeranong subcatchments (see Table C2), in hectares (ha) and as a percentage of subcatchment area (%).

Functional unit	TC0 (ha)	TC0 (%)	TC1 (ha)	TC1 (%)	TC2 (ha)	TC2 (%)	TC3 (ha)	TC3 (%)	TC4 (ha)	TC4 (%)	TC5 (ha)	TC5 (%)
Commercial road	0.58272	0.22654	0	0	0.32153	0.12952	0.06495	0.12948	0.06495	0.12948	0.33632	0.09282
Commercial hardstand	6.51431	2.53251	0	0	1.28484	0.51756	0.77034	1.53569	0.77034	1.53569	3.38792	0.93498
Commercial roof	7.38043	2.86922	0	0	1.32700	0.53454	0.64949	1.29477	0.64949	1.29477	3.90561	1.07785
Commercial pervious	17.78314	6.91338	0	0	32.92973	13.26479	2.22145	4.42849	2.22145	4.42849	9.11530	2.51558
Commercial water	0	0	0	0	0.05460	0.02199	0	0	0	0	0	0
Suburban road	10.77831	4.19018	0.73186	6.26525	12.30299	4.95590	2.64384	5.27054	2.64384	5.27054	12.01325	3.31534
Suburban hardstand	13.56212	5.27241	1.15220	9.86371	14.49177	5.83759	3.18411	6.34758	3.18411	6.34758	12.88176	3.55503
Suburban roof	49.75319	19.34207	3.12461	26.74904	46.70982	18.81570	11.68760	23.29944	11.68760	23.29944	47.17029	13.01776
Suburban pervious	55.40174	21.53800	3.50165	29.97680	72.67577	29.27533	14.37982	28.66642	14.37982	28.66642	77.11695	21.28225
Suburban water	7.51E-05	2.92E-05	0	0	2.51E-05	1.01E-05	0	0	0	0	0.00033	8.97E-05
Open space road	10.01014	3.89155	0	0	5.67404	2.28562	2.44259	4.86935	2.44259	4.86935	6.28860	1.73549
Open space hardstand	6.52754	2.53765	0.53100	4.54575	4.94635	1.99249	1.51306	3.01630	1.51306	3.01630	5.23212	1.44393
Open space roof	0.72237	0.28083	0.00733	0.06271	0.39423	0.15880	0.12290	0.24500	0.12290	0.24500	0.85361	0.23557
Open space pervious	46.04883	17.90196	2.63256	22.53675	49.70804	20.02344	10.34895	20.63080	10.34895	20.63080	50.24425	13.86609
Open space water	0.52547	0.20428	0	0	0	0	0	0	0	0	0	0
Bushland road	0	0	0	0	0	0	0	0	0	0	3.29003	0.90796
Bushland hardstand	0	0	0	0	0	0	0	0	0	0	0.86734	0.23936
Bushland roof	0	0	0	0	0	0	0	0	0	0	0.11853	0.03271
Bushland pervious	0	0	0	0	4	2	0	0	0	0	116.54473	32.16329
Bushland water	0	0	0	0	0	0	0	0	0	0	0	0
Rural road	0	0	0	0	0	0	0	0	0	0	0	0
Rural hardstand	0	0	0	0	0	0	0	0	0	0	0	0
Rural roof	0	0	0	0	0	0	0	0	0	0	0	0
Rural pervious	30.00000	11.66281	0	0	0	0	0	0	0	0	0	0
Rural water	0	0	0	0	0	0	0	0	0	0	0	0
Sports field	1.63753	0.63661	0	0	1.16687	0.47004	0.13350	0.26613	0.13350	0.26613	12.98638	3.58390
Total subcatchment area	257.22790	100	11.68120	100	248.24920	100	50.16260	100	50.16260	100	362.35330	100

Table C3 cont. Area of land use functional units within Lake Tuggeranong subcatchments (see Table C2), in hectares (ha) and as a percentage of subcatchment area (%).

Functional unit	TC6 (ha)	TC6 (%)	TC7 (ha)	TC7 (%)	TC6 NSW (ha)	TC6 NSW (%)	TC8 NSW (ha)	TC8 NSW (%)
Commercial road	0	0	0	0	0	0	0	0
Commercial hardstand	0	0	0	0	0	0	0	0
Commercial roof	0	0	0	0	0	0	0	0
Commercial pervious	0	0	0	0	0	0	0	0
Commercial water	0	0	0	0	0	0	0	0
Suburban road	0	0	0	0	0	0	0	0
Suburban hardstand	0.00375	0.00369	0	0	0	0	0	0
Suburban roof	0.00153	0.00150	0	0	0	0	0	0
Suburban pervious	0.00685	0.00674	0	0	0	0	0	0
Suburban water	0	0	0	0	0	0	0	0
Open space road	0.20877	0.20533	0.04334	0.00706	0	0	0	0
Open space hardstand	0.07513	0.07389	0.03677	0.00599	0	0	0	0
Open space roof	0.01225	0.01205	0.00597	0.00097	0	0	0	0
Open space pervious	4.06725	4.00025	0.25709	0.04191	0.00258	0.02625	2.64149	0.31220
Open space water	0	0	0	0	0	0	0	0
Bushland road	6.02788	5.92859	6.56298	1.06977	0	0	0	0
Bushland hardstand	0.71094	0.69923	1.62155	0.26431	0	0	0	0
Bushland roof	0.27050	0.26604	0.35840	0.05842	0	0	0	0
Bushland pervious	90.27019	88.78316	298.69189	48.68689	0.00055	0.00561	0.00130	0.00015
Bushland water	0.01985	0.01952	0.10036	0.01636	0	0	0	0
Rural road	0	0	0.24039	0.03918	0	0	0	0
Rural hardstand	0	0	0.53294	0.08687	0	0	5.00E-05	5.91E-06
Rural roof	0	0	0.64118	0.10451	0	0	7.50E-05	8.87E-06
Rural pervious	0	0	304.00698	49.55325	9.82337	99.96815	843.45908	99.68764
Rural water	0	0	0.39566	0.06449	0	0	0	0
Sports field	0	0	0	0	0	0	0	0
Total subcatchment area	101.67490	100	613.49550	100	9.82650	100	846.10200	100

Table C3 cont. Area of land use functional units within Lake Tuggeranong subcatchments (see Table C2), in hectares (ha) and as a percentage of subcatchment area (%).

Functional unit	WS0 (ha)	WS0 (%)	WS1 (ha)	WS1 (%)	WS2 (ha)	WS2 (%)	WS3 (ha)	WS3 (%)	WS4 (ha)	WS4 (%)
Commercial road	0	0	0	0	1.54112	0.82442	0	0	0	0
Commercial hardstand	0.22877	0.74891	1.55212	1.03660	6.70734	3.58810	0	0	0.01836	0.02462
Commercial roof	0.36464	1.19371	2.44706	1.63431	8.64741	4.62595	0	0	0.00633	0.00849
Commercial pervious	1.71141	5.60254	3.03841	2.02924	8.14436	4.35684	0	0	0.07058	0.09467
Commercial water	0	0	0	0	0	0	0	0	0	0
Suburban road	1.18540	3.88057	9.03820	6.03629	7.84594	4.19720	0.67185	6.88093	1.71359	2.29845
Suburban hardstand	2.50062	8.18613	9.28827	6.20331	8.99315	4.81090	0.51682	5.29313	2.21056	2.96504
Suburban roof	8.63839	28.27903	32.95523	22.00964	32.99276	17.64954	2.46192	25.21422	8.27366	11.09754
Suburban pervious	8.11016	26.54977	49.31735	32.93733	54.74475	29.28581	4.14976	42.50066	12.91723	17.32601
Suburban water	0	0	2.50E-05	1.67E-05	0.00105	0.00056	0	0	0.00045	0.00060
Open space road	1.26220	4.13198	4.93795	3.29788	9.44718	5.05379	0.16886	1.72939	5.19069	6.96232
Open space hardstand	0.97098	3.17863	3.53733	2.36246	5.75370	3.07795	0.07289	0.74654	1.88015	2.52187
Open space roof	0.11025	0.36091	0.46175	0.30838	1.12409	0.60134	0.00465	0.04762	0.24454	0.32801
Open space pervious	5.43135	17.78029	31.69643	21.16893	35.70274	19.09925	1.71724	17.58751	15.71887	21.08387
Open space water	0.03285	0.10754	0.00560	0.00374	0	0	0	0	0	0
Bushland road	0	0	0	0	0	0	0	0	0.51420	0.68970
Bushland hardstand	0	0	0	0	0.00187	0.00100	0	0	0.06840	0.09175
Bushland roof	0	0	0	0	0	0	0	0	0.02153	0.02888
Bushland pervious	0	0	0	0	0.32207	0.17229	0	0	25.70486	34.47818
Bushland water	0	0	0	0	0	0	0	0	0	0
Rural road	0	0	0	0	0	0	0	0	0	0
Rural hardstand	0	0	0	0	0	0	0	0	0	0
Rural roof	0	0	0	0	0	0	0	0	0	0
Rural pervious	0	0	0	0	0	0	0	0	0	0
Rural water	0	0	0	0	0	0	0	0	0	0
Sports field	0	0	1.45519	0.97187	4.96317	2.65506	0	0	0	0
Total subcatchment area	30.547	100	149.7309	100	186.9327	100	9.764	100	74.554	100

Table C3 cont. Area of land use functional units within Lake Tuggeranong subcatchments (see Table C2), in hectares (ha) and as a percentage of subcatchment area (%).

Functional unit	FA0 (ha)	FA0 (%)	FA1 (ha)	FA1 (%)	FA2 (ha)	FA2 (%)	FA3 (ha)	FA3 (%)	FA5 (ha)	FA5 (%)	FA6 (ha)	FA6 (%)
Commercial road	0.00155	0.00077	0.00178	0.00390	0	0	0	0	0	0	0	0
Commercial hardstand	0.68547	0.33986	1.27610	2.80488	0	0	0.56164	0.42239	0	0	0	0
Commercial roof	1.04842	0.51982	1.47323	3.23817	0	0	0.68604	0.51595	0	0	0	0
Commercial pervious	3.23227	1.60258	6.71763	14.76535	0	0	4.86537	3.65908	0	0	0	0
Commercial water	0	0	0	0	0	0	0	0	0	0	0	0
Suburban road	12.21125	6.05443	3.05012	6.70417	0.26349	3.19399	8.76270	6.59013	0	0	1.31484	1.83693
Suburban hardstand	12.72037	6.30686	2.42518	5.33055	0.25484	3.08907	9.77361	7.35040	0.00222	0.03223	1.43267	2.00154
Suburban roof	48.91619	24.25304	7.39270	16.24915	1.04438	12.65981	33.22342	24.98620	0.05123	0.74231	5.36633	7.49712
Suburban pervious	74.69462	37.03419	11.53219	25.34776	1.75898	21.32205	50.77288	38.18454	0.10458	1.51540	8.99825	12.57116
Suburban water	0.00150	0.00074	0	0	0	0	0.00090	0.00068	0	0	0	0
Open space road	8.37676	4.15327	2.07507	4.56101	0.00935	0.11339	2.20094	1.65525	0.33517	4.85688	1.70013	2.37520
Open space hardstand	4.42618	2.19454	1.77967	3.91171	0.03974	0.48167	1.71507	1.28985	0.20396	2.95548	2.54351	3.55345
Open space roof	0.47688	0.23644	0.10978	0.24129	0.00427	0.05176	0.20312	0.15276	0.04800	0.69560	1.01666	1.42034
Open space pervious	34.29041	17.00146	6.51373	14.31717	0.42130	5.10688	18.91811	14.22766	2.77117	40.15607	40.27044	56.26052
Open space water	0	0	0	0	0.04402	0.53359	0	0	0	0	5.00E-05	6.99E-05
Bushland road	0	0	0	0	0.15460	1.87402	0	0	0	0	0.00000	0.00000
Bushland hardstand	0	0	0	0	0.01489	0.18053	0	0	0	0	0.00713	0.00995
Bushland roof	0	0	0	0	0.01464	0.17746	0	0	0	0	0.01075	0.01502
Bushland pervious	0	0	0	0	4.22510	51.21578	0	0	0	0	8.91775	12.45869
Bushland water	0	0	0	0	0	0	0	0	0	0	0	0
Rural road	0	0	0	0	0	0	0	0	0	0	0	0
Rural hardstand	0	0	0	0	0	0	0	0	0	0	0	0
Rural roof	0	0	0	0	0	0	0	0	0	0	0	0
Rural pervious	0	0	0	0	0	0	0	0	0	0	0	0
Rural water	0	0	0	0	0	0	0	0	0	0	0	0
Sports field	0.60912	0.30201	1.14873	2.52490	0	0	1.28330	0.96513	3.38467	49.04604	0	0
Total subcatchment area	201.69100	100	45.49590	100	8.24960	100	132.96710	100	6.90100	100	71.57845	100

Table C3 cont. Area of land use functional units within Lake Tuggeranong subcatchments (see Table C2), in hectares (ha) and as a percentage of subcatchment area (%).

Functional unit	FA7 (ha)	FA7 (%)	FA8 (ha)	FA8 (%)	FA9 (ha)	FA9 (%)	FA10 (ha)	FA10 (%)	FA11 (ha)	FA11 (%)	FA12 (ha)	FA12 (%)
Commercial road	0	0	0	0	0.96626	0.58898	0	0	0.15920	0.21730	0	0
Commercial hardstand	0	0	0.09825	0.09336	2.87939	1.75511	0.01547	0.62058	0.81899	1.11787	0.84147	7.30903
Commercial roof	0	0	0.28170	0.26767	2.81759	1.71744	0.01910	0.76595	0.99322	1.35568	1.03335	8.97575
Commercial pervious	0	0	1.17809	1.11941	3.34845	2.04102	0.12335	4.94762	2.15616	2.94302	2.27579	19.76764
Commercial water	0	0	0	0	0	0	0	0	0	0	0	0
Suburban road	0.24393	1.83693	3.40824	3.23849	7.53109	4.59051	0	0	2.25456	3.07734	0.05280	0.45865
Suburban hardstand	0.26579	2.00154	4.42791	4.20736	8.06460	4.91570	0	0	2.19261	2.99278	0.08285	0.71968
Suburban roof	0.99555	7.49712	18.40574	17.48898	28.53998	17.39629	0	0	9.76619	13.33023	0.71281	6.19152
Suburban pervious	1.66934	12.57116	29.18282	27.72928	45.86605	27.95723	0	0	14.57372	19.89220	1.08328	9.40943
Suburban water	0	0	0	0	2.49E-05	1.52E-05	0	0	2.50E-05	3.41E-05	0	0
Open space road	0.31540	2.37520	4.65181	4.42011	3.14482	1.91690	0.41795	16.76375	1.63615	2.23324	0.58038	5.04121
Open space hardstand	0.47187	3.55345	2.44401	2.32228	1.98188	1.20804	0.17292	6.93569	1.13037	1.54288	0.57485	4.99321
Open space roof	0.18861	1.42034	0.20423	0.19406	0.18810	0.11466	0.00655	0.26267	0.17858	0.24375	0.09548	0.82934
Open space pervious	7.47089	56.26052	15.52775	14.75434	17.56257	10.70510	1.50429	60.33586	10.68431	14.58340	4.16896	36.21182
Open space water	9.28E-06	6.99E-05	0.01460	0.01387	0	0	0	0	0	0	0.01068	0.09273
Bushland road	0.00000	0.00000	0.14620	0.13892	2.44566	1.49073	0	0	0.18495	0.25245	0	0
Bushland hardstand	0.00132	0.00995	0.74621	0.70904	0.57236	0.34888	0	0	0.12498	0.17059	0	0
Bushland roof	0.00199	0.01502	0.21660	0.20581	0.06938	0.04229	0	0	0.00813	0.01109	0	0
Bushland pervious	1.65440	12.45869	24.30774	23.09701	34.67503	21.13585	0	0	25.02885	34.16279	0	0
Bushland water	0	0	0	0	0.01220	0.00744	0	0	0	0	0	0
Rural road	0	0	0	0	0	0	0	0	0	0	0	0
Rural hardstand	0	0	0	0	0	0	0	0	0	0	0	0
Rural roof	0	0	0	0	0	0	0	0	0	0	0	0
Rural pervious	0	0	0	0	0	0	0	0	0	0	0	0
Rural water	0	0	0	0	0	0	0	0	0	0	0	0
Sports field	0	0	0	0	3.39245	2.06784	0.23356	9.36789	1.37250	1.87337	0	0
Total subcatchment area	13.27909	100	105.24190	100	164.05787	100	2.49320	100	73.26347	100	11.51270	100

Table C3 cont. Area of land use functional units within Lake Tuggeranong subcatchments (see Table C2), in hectares (ha) and as a percentage of subcatchment area (%).

Functional unit	FA13 (ha)	FA13 (%)	FA14 (ha)	FA14 (%)	FA15 (ha)	FA15 (%)	FA16 (ha)	FA16 (%)	FA17 (ha)	FA17 (%)	FA9 NSW (ha)	FA9 NSW (%)
Commercial road	0	0	0	0	0	0	0	0	0	0	0	0
Commercial hardstand	0	0	0	0	0	0	0.00048	0.00069	0	0	0	0
Commercial roof	0	0	0	0	0	0	0.01188	0.01718	0	0	0	0
Commercial pervious	0.02585	1.29481	0	0	0	0	0.04275	0.06184	0	0	0	0
Commercial water	0	0	0	0	0	0	0	0	0	0	0	0
Suburban road	0	0	0	0	0.99534	6.47445	4.91072	7.10386	2.05614	3.19399	0	0
Suburban hardstand	0	0	0	0	0.98473	6.40548	4.14411	5.99488	1.98860	3.08907	0	0
Suburban roof	0	0	0	0	4.20349	27.34277	16.32055	23.60934	8.14979	12.65981	0	0
Suburban pervious	0	0	0	0	5.84599	38.02693	24.30567	35.16064	13.72613	21.32205	0	0
Suburban water	0	0	0	0	0	0	0	0	0	0	0	0
Open space road	0.02215	1.10948	0	0	0.84631	5.50505	1.22231	1.76820	0.07299	0.11339	0	0
Open space hardstand	0.01945	0.97424	0.01723	4.25808	0.46344	3.01456	1.04693	1.51450	0.31008	0.48167	0	0
Open space roof	0.02070	1.03685	0.00050	0.12360	0.07351	0.47819	0.07243	0.10477	0.03332	0.05176	0	0
Open space pervious	0.62372	31.24084	0.38697	95.61832	1.84850	12.02407	7.92437	11.46341	3.28757	5.10688	0.02229	0.03109
Open space water	0	0	0	0	0	0	0.00198	0.00286	0.34350	0.53359	0	0
Bushland road	0	0	0	0	0	0	0.04578	0.06622	1.20641	1.87402	0	0
Bushland hardstand	0	0	0	0	0	0	0.00348	0.00503	0.11622	0.18053	0	0
Bushland roof	0	0	0	0	0	0	0.00023	0.00033	0.11424	0.17746	2.50E-05	3.49E-05
Bushland pervious	0	0	0	0	0	0	9.02073	13.04941	32.97031	51.21578	0.00283	0.00394
Bushland water	0	0	0	0	0	0	0	0	0	0	0	0
Rural road	0	0	0	0	0	0	0	0	0	0	0	0
Rural hardstand	0	0	0	0	0	0	0	0	0	0	0	0
Rural roof	0	0	0	0	0	0	0	0	0	0	0	0
Rural pervious	0	0	0	0	0	0	0	0	0	0	71.66356	99.96493
Rural water	0	0	0	0	0	0	0	0	0	0	0	0
Sports field	1.28462	64.34376	0	0	0.11200	0.72851	0.05313	0.07685	0	0	0	0
Total subcatchment area	1.99650	100	0.40470	100	15.37330	100	69.12750	100	64.37530	100	71.68867	100

Appendix D: Literature-derived EMC and DWC values

Baseline values of the event mean concentrations (EMC) and dry weather concentrations (DWC) of total phosphorus (TP), total nitrogen (TN) and total suspended solids (TSS) generated by functional land use units were derived from the literature for initial parameterisation of the model. The EMC values were then scaled based on date-matched observations. Tables D1-D3 present the baseline EMC and DWC values for each functional unit.

Table D1: Baseline total phosphorus (TP) EMC and DWC values (mg/L) derived from the literature for each combination of functional land use and surface imperviousness.

Land surface imperviousness	Suburban	Commercial	Open space	Rural	Bushland	Sports field
Road	EMC: 0.501 DWC: 0.015	EMC: 0.501 DWC: 0.015	EMC: 0.501 DWC: 0.015	EMC: 0.251 DWC: 0.015	EMC: 0.251 DWC: 0.015	
Hardstand	EMC: 0.251 DWC: 0.015	EMC: 0.251 DWC: 0.015	EMC: 0.251 DWC: 0.015	EMC: 0.251 DWC: 0.015	EMC: 0.251 DWC: 0.015	
Roof	EMC: 0.128 DWC: 0.015	EMC: 0.128 DWC: 0.015	EMC: 0.128 DWC: 0.015	EMC: 0.251 DWC: 0.015	EMC: 0.251 DWC: 0.015	
Pervious	EMC: 0.251 DWC: 0.04	EMC: 0.251 DWC: 0.04	EMC: 0.251 DWC: 0.04	EMC: 0.218 DWC: 0.04	EMC: 0.079 DWC: 0.04	EMC: 0.251 DWC: 0.015
Water	EMC: 0 DWC: 0	EMC: 0 DWC: 0	EMC: 0 DWC: 0	EMC: 0 DWC: 0	EMC: 0 DWC: 0	

Table D2: Baseline total nitrogen (TN) EMC and DWC values (mg/L) derived from the literature for each combination of functional land use and surface imperviousness.

Land surface imperviousness	Suburban	Commercial	Open space	Rural	Bushland	Sports field
Road	EMC: 2.187 DWC: 1.0	EMC: 2.187 DWC: 1.0	EMC: 2.187 DWC: 1.0	EMC: 2.187 DWC: 1.0	EMC: 2.187 DWC: 1.0	
Hardstand	EMC: 2.187 DWC: 1.0	EMC: 2.187 DWC: 1.0	EMC: 2.187 DWC: 1.0	EMC: 2.187 DWC: 1.0	EMC: 2.187 DWC: 1.0	
Roof	EMC: 1.995 DWC: 1.0	EMC: 1.995 DWC: 1.0	EMC: 1.995 DWC: 1.0	EMC: 1.995 DWC: 1.0	EMC: 1.995 DWC: 1.0	
Pervious	EMC: 1.995 DWC: 0.4	EMC: 1.995 DWC: 0.4	EMC: 1.995 DWC: 0.4	EMC: 1.995 DWC: 0.4	EMC: 1.995 DWC: 0.4	EMC: 1.995 DWC: 1.0
Water	EMC: 0 DWC: 0	EMC: 0 DWC: 0	EMC: 0 DWC: 0	EMC: 0 DWC: 0	EMC: 0 DWC: 0	

Table D3: Baseline total suspended solids (TSS) EMC and DWC values (mg/L) derived from the literature for each combination of functional land use and surface imperviousness.

Land surface imperviousness	Suburban	Commercial	Open space	Rural	Bushland	Sports field
Road	EMC: 269.15 DWC: 15.849	EMC: 269.15 DWC: 15.849	EMC: 269.15 DWC: 15.849	EMC: 269.15 DWC: 15.849	EMC: 269.15 DWC: 15.849	
Hardstand	EMC: 269.15 DWC: 15.849	EMC: 269.15 DWC: 15.849	EMC: 269.15 DWC: 15.849	EMC: 269.15 DWC: 15.849	EMC: 269.15 DWC: 15.849	
Roof	EMC: 19.95 DWC: 15.849	EMC: 19.95 DWC: 15.849	EMC: 19.95 DWC: 15.849	EMC: 19.95 DWC: 15.849	EMC: 19.95 DWC: 15.849	
Pervious	EMC: 141.25 DWC: 15.849	EMC: 141.25 DWC: 15.849	EMC: 141.25 DWC: 15.849	EMC: 89.12 DWC: 15.849	EMC: 39.81 DWC: 15.849	EMC: 141.25 DWC: 15.849
Water	EMC: 0 DWC: 0	EMC: 0 DWC: 0	EMC: 0 DWC: 0	EMC: 0 DWC: 0	EMC: 0 DWC: 0	

Appendix E: Modelled annual load of total phosphorous

The table below provides total phosphorous generated for each combination of functional land use and surface imperviousness annually.

Table E1: Modelled annual total phosphorus (TP) load (kg/yr) generated for each combination of functional land use and surface imperviousness.

Land surface imperviousness	Road TP (kg/yr)	Hardstand TP (kg/yr)	Roof TP (kg/yr)	Pervious TP (kg/yr)	Water TP (kg/yr)
Suburban	322	169	314	140	0
Commercial	17	45	30	16	0
Open space	243	76	5	88	0
Rural	0	0	1	132	0
Sports field	0	0	0	58	0
Total annual load (kg/yr)	582	290	350	434	0

Attachment H

ACT Government

Predicting phosphorus concentration and trophic state of Lake Tuggeranong

Technical report supplement to the Lake Tuggeranong Catchment Model

Water Information Services, ACT Office of Water

December 2024

Environment, Planning and Sustainable Development Directorate

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1. Introduction

Vollenweider's (1975, 1976) mass-balance equations, overall, model how the total phosphorous (TP) concentration of a lake ($\mathrm{TP_{lake}}$) is related to the TP concentration of inflows ($\mathrm{TP_{in}}$) and the hydraulic residence/retention time (τ_w). This residence time can be thought of as the average time an incoming water molecule can expect to remain in the lake before leaving the lake through outflow and is calculated by simply dividing the volume of the lake by the outflow rate.

Vollenweider (1976 – Equation 2.13) described this relationship mathematically with the equation below (as re-stated in Brett & Benjamin 2008 – Equation 6):

$$\mathrm{TP_{lake}} = \frac{\mathrm{TP_{in}}}{1+\sigma\tau_w} \qquad (1)$$

Where σ is the first-order rate coefficient of TP loss within the lake due to sedimentation. As this rate is not easily quantified, several different approaches have been proposed to approximate it. Brett & Benjamin (2008) summarised and compared the relative performance of these different approaches using known values from 305 lakes from Europe and North America. They found that all approaches provided a useful fit with real-world values, but that the best-fitting approach was to assume that σ is a function of ${k\tau_w}^x$, where k and x are constants, fitted statistically. This approach was previously used by Larsen & Mercier (1976), who reported a value of x near -0.5.

With this approximation, equation 1 becomes:

$$\mathrm{TP_{lake}} = \frac{\mathrm{TP_{in}}}{1+(k{\tau_w}^x)\tau_w} \qquad (2)$$

Brett & Benjamin (2008) found that values of around k=1.12 and x=-0.53 yielded a correlation between predicted and observed TP_{lake} values with r^2>0.8 for the dataset investigated, yielding the following relationship:

$$\mathrm{TP_{lake}} = \frac{\mathrm{TP_{in}}}{1+\left(1.12\times\tau_w^{-0.53}\right)*\tau_w} \qquad (3)$$

If we then approximate k=1 and x=-0.5, equation 3 simplifies to:

$$\mathrm{TP_{lake}} = \frac{\mathrm{TP_{in}}}{1+\sqrt{\tau_w}} \qquad (4)$$

Vollenweider (1976) previously suggested this approximation of the general equation fits with empirical studies, and this relationship was used by Beer *et al.* 1982 in their early work on Lake Tuggeranong.

2. In-Lake Model

2.1 Parameterisation of the modified Vollenweider model

The adjusted Vollenweider model (equation 2) was parameterised using estimates of inflow TP concentrations and inflow and outflow volumes from the Lake Tuggeranong catchment model (Dey et al. 2024), and observed Lake Tuggeranong TP concentrations from the ALS Lakes and Rivers Water Quality Monitoring Program, but with the following caveats:

- The model assumes a steady state of inflows and influent concentrations, which is a limitation to real-world applications, so it is unclear how reliable we should expect its predictions over shorter time periods to be. That being said, past modelling of TP loads has suggested that 3 hydraulic residence times is sufficient for 95% convergence with steady-state predictions (Sonzogni *et al.* 1976), which is <1 year for most years in Lake Tuggeranong. For this reason, our modelling approach will work with annual time steps, with all model inputs and outputs to be interpreted as annual averages.
- In past applications of this model-fitting approach, data across many different lakes were used, with each lake representing a separated datapoint (e.g. Brett & Benjamin 2008, Larsen & Mercier 1976). Here, the datapoints are all from Lake Tuggeranong, just from different years, and are thus pseudo-replicated. However, to provide a Lake Tuggeranong -specific model that will not be applied elsewhere this approach is probably reasonable. It would be informative to repeat this modelling approach in other ACT lakes and compare fitted values later, to investigate the appropriateness of an overall ACT-wide model using data from all different lakes.
- In other applications of Vollenweider model the same value for water inflow and outflow are used (i.e. assumption of no other source of water loss). Since the catchment model have taken into account of the lake water balance.

To parametrise the modified Vollenweider model, we can use annual total TP loads and water inflows and outflows from the Tuggeranong Source Catchment Model. Specifically:

- l_{in}: the annual TP load flowing into Lake Tuggeranong (converted to mg),
- v_{in}: the annual inflow volume of water into Lake Tuggeranong (converted to L)
- v_{out}: the annual outflow volume of water from Lake Tuggeranong (converted to L)

We can then combine these parameters, along with the approximate total volume of Lake Tuggeranong (V= 1,780,000,000L), to calculate the TP concentration of inflows (TP_{in}, measured in mg/L) and the hydraulic residence time (τ_w, measured in years) as follows:

$$\text{TP}_{\text{in}} = \frac{l_{\text{in}}}{v_{\text{in}}} \quad (5)$$

$$\tau_w = \frac{V}{v_{\text{out}}} \quad (6)$$

The predicted annual average TP_{in} and τ_w values from 1990-2022 are summarised in Table 1 and shown in Figure 1.

Table 1. Summary of Lake Tuggeranong annual values of inflow total phosphorus concentration TP_{in} and hydraulic residence time τ_w from 1990-2022.

	$\mathbf{TP_{in}}$ **(mg/L)**	$\boldsymbol{\tau_w}$ **(y)**
Minimum	0.152	0.055
Median	0.163	0.251
Maximum	0.174	0.727

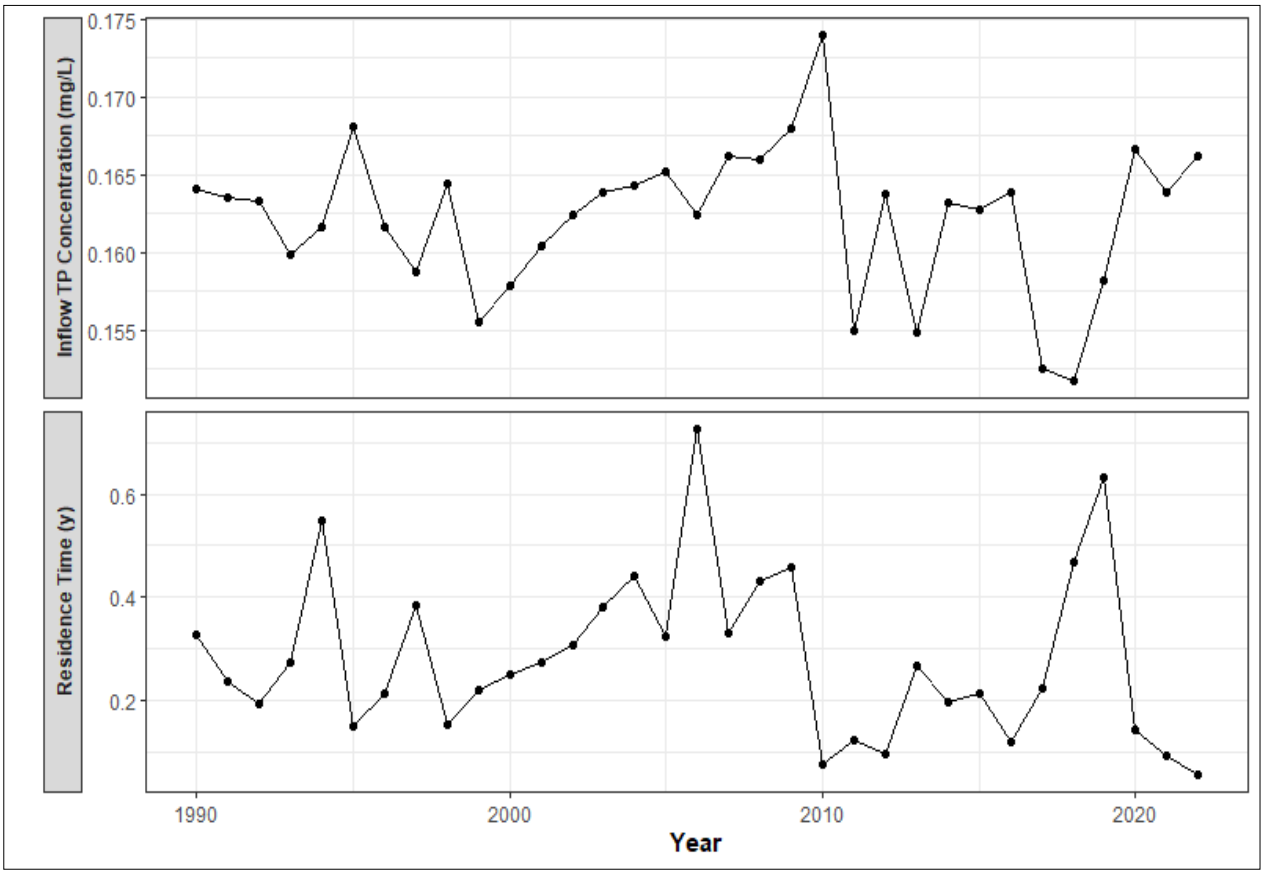

Figure 1. Annual changes in inflow concentrations of total phosphorus (TP_{in}, top panel) and residence time (τ_w, bottom panel) in Lake Tuggeranong, 1990-2022.

2.2 Estimation of total phosphorus and chlorophyll a concentration

Using the modified Vollenweider model (equation 2) $\mathrm{TP_{lake}}$ concentration can be predicted using $\mathrm{TP_{in}}$ and τ_w values. Before estimating the TP_{lake}, fitting of the constants k and x is required such that modelled $\mathrm{TP_{lake}}$ values provide as close-as-possible match to observed $\mathrm{TP_{lake}}$ values. Here, our source of observed $\mathrm{TP_{lake}}$ values come from the ALS Lakes and Rivers Water Quality Monitoring Program from 2005-2022. This period was chosen because it represents the longest run of annual sampling of LT TP concentrations with

relatively constant annual sampling effort (most years had 8 samples from each of two locations within Lake Tuggeranong: LTG248 and LTG249). Other sources of data (e.g. University of Canberra research) did not provide a similar temporal scope, meaning their inclusion would have led to large variability in the underlying sampling effort behind annual averages, which was undesirable here. Waterwatch data was also not used here due to questions about data reliability specifically related to TP measures relative to lab techniques (Harrison *et al.* 2013).

To fit optimal values of k and x to our modified Vollenweider model, an approach similar to Brett & Benjamin (2008) was adopted. Specifically, a function was created in R that would, for given values of k and x, predict lake TP concentrations ($\mathrm{TP}_{\mathrm{predicted}}$) and compare them to average annual observed lake TP concentrations $\mathrm{TP}_{\mathrm{observed}}$ values to calculate the weighted error sum of squares (WESS) as follows:

$$\mathrm{WESS} = \sum \mathrm{weight} \times \left(\mathrm{TP}_{\mathrm{observed}} - \mathrm{TP}_{\mathrm{predicted}}\right)^2 \qquad (7)$$

The number of samples that each annual average was based on as weights was used, such that years that had annual averages based on relatively few datapoints (e.g. 2020 due to lockdowns) contributed relatively less to the WESS. This WESS provides a measure of how closely matched predicted and observed TP values are, with low WESS values indicating a better fitting model.

This function was then used alongside a solver function in R to find a combination of k and x values that minimised the WESS and thus represented the best fit to the observed data. This solver yielded values of $k = 1.093$ and $x = -0.791$. These values are similar to those reported elsewhere (e.g. Brett & Benjamin 2008) and not particularly inconsistent with the unmodified Vollenweider model used by Beer *et al.* 1982 in their early work on LT. Sensitivity analysis of this optimisation was performed by re-calculating the

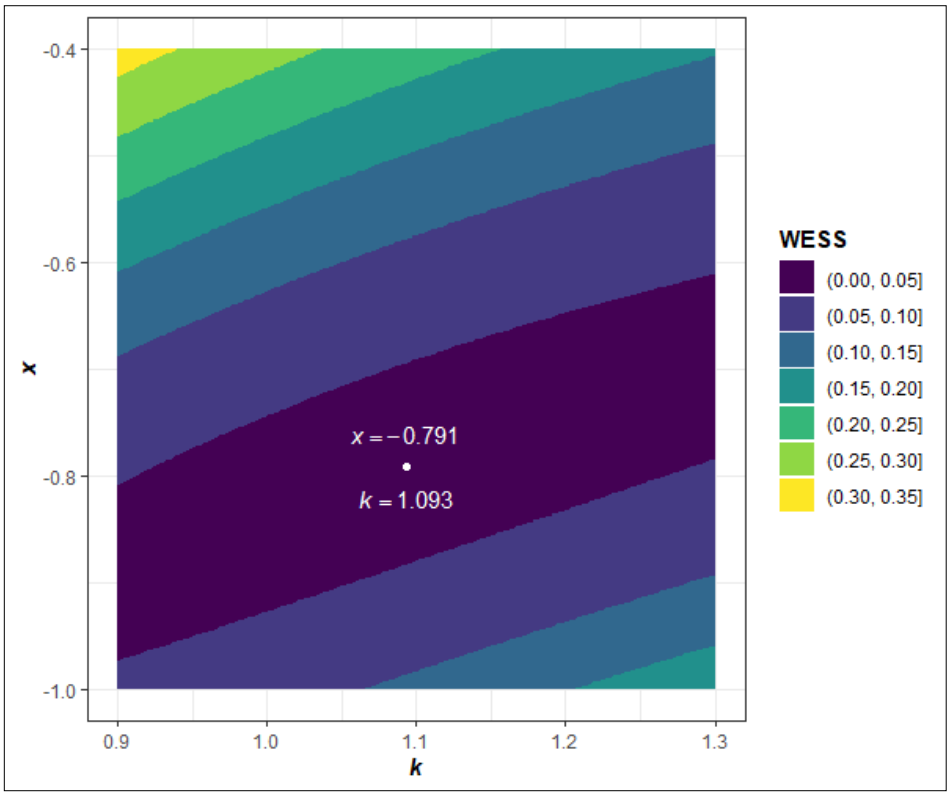

Figure 2. Sensitivity of the Lake Tuggeranong modified Vollenweider model to changes in *k* and *x* in terms of the resultant weighted error sum of squares (WESS). The white point indicates the optimal values.

resultant WESS with a range of k and x values. This analysis indicated that a relatively wide band of k and x values yielded similarly good fits (indicated by relatively low WESS values: Figure 2), which again was consistent with the findings of Brett & Benjamin 2008.

Using the fitted values of k and x, the modified Vollenweider model is represented in equation 8:

$$\mathrm{TP}_{\mathrm{lake}} = \frac{\mathrm{TP}_{\mathrm{in}}}{1+\left(1.093\times\tau_w^{-0.791}\right)*\tau_w} \qquad (8)$$

This yielded predicted $\mathrm{TP}_{\mathrm{lake}}$ values similar to observed values (Table 2, Figure 3).

Table 2. Comparison of observed annual average and predicted total phosphorus concentrations in Lake Tuggeranong (TP_{lake}) from 2005-2022.

	Observed $\mathrm{TP}_{\mathrm{lake}}$ (mg/L)	**Predicted $\mathrm{TP}_{\mathrm{lake}}$ (mg/L)**
Minimum	0.064	0.079
Median	0.086	0.090
Maximum	0.114	0.107

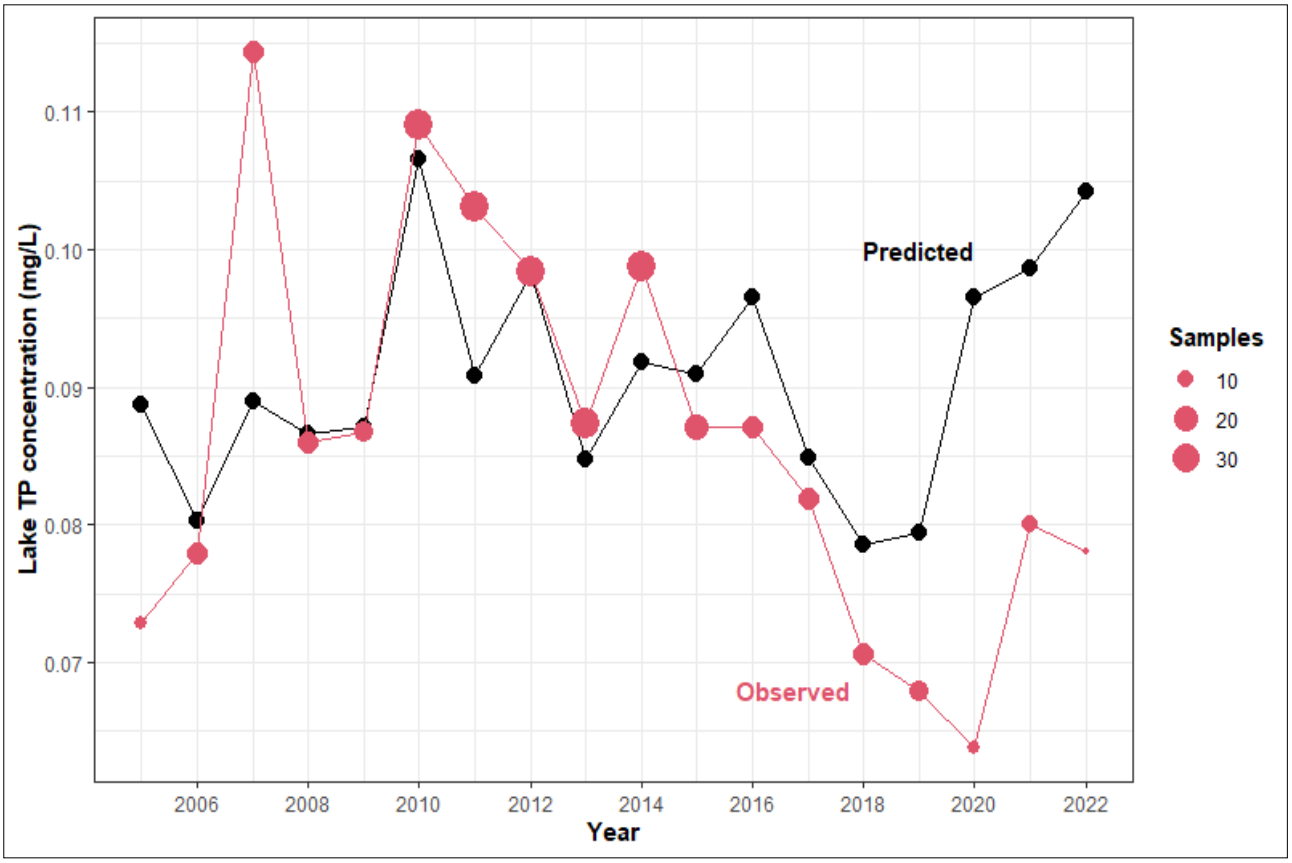

Figure 3. Comparison of observed (red) and predicted (black) annual total phosphorus (TP) concentrations in Lake Tuggeranong from 2005-2022 shows the modified Vollenweider model captures the centre and spread of observed values well with some mirroring of year-to-year trends. Observed values are averages of samples for each year, and data point size represents the number of underlying samples.

The predicted TP concentrations in Lake Tuggeranong had a very similar average and variability to observed TP concentrations, and for many years the two time-series followed similar up/down-wards trajectories (Figure 3). Overall, predicted and observed TP concentrations in Lake Tuggeranong were positively correlated. This was confirmed by a linear regression model relating the two (weighted based on annual sample number), which yielded a significant association between the two variables (ANOVA F-test of slope coefficient: F=8.5889, p=0.0098), and an adjusted r^2 value of 0.3086.

This model can be used to predict the chlorophyll a level using the power relationship described by Lawrence (1980) and applied in Beer *et al.* (1982) in their early work on Lake Tuggeranong:

$$\text{Chlorophyll a} = 0.367 * TP_{Lake}^{0.91} \qquad (9)$$

This relationship was derived from a comparison of several Canberra lakes.

3. Estimation of Lake Trophic State

Using 133 years of annually aggregated Source model output of TP load and inflow water volumes, the above-mentioned models were combined under a range of influent TP reduction scenarios ranging from current/business as usual (BAU: no reduction in TP load), and 100kg to 900kg reduction in annual TP load coming into the lake (with no change to inflow water volumes). Additionally, a predevelopment flow and TP load scenario was considered, which assumed a wholly undeveloped catchment. The Vollenweider model was used to predict annual TP concentrations in the lake for each year under each scenario. This was then converted to predicted chlorophyll a concentration using equation 9. Finally, these predicted concentrations were compared to published cut-offs (e.g. Neil 2012) of chlorophyll a concentration under different trophic states: Oligotrophic <5 µg/L, Mesotrophic <15 µg/L, Eutrophic >15 µg/L.

The predictions for the predevelopment scenario show that, in the absence of development within the catchment, Lake Tuggeranong would likely have experienced a wide range of trophic conditions. In some years the lake would not have received any inflow at all and would likely have reached an oligotrophic state. But in high rainfall years the lake's size and the inflow of TP would have pushed it towards a eutrophic state. This provides a good baseline for considering realistic futures for the lake.

Under the 'current' scenario (BAU), Lake Tuggeranong is predicted to (at the annual, average timescale) remain in a eutrophic state (Figure 4). To avoid a constant eutrophic state, the results of the TP reduction scenarios show that TP load reductions of 600kg or more into Lake Tuggeranong are predicted to result in conditions that are eutrophic less often than not (Figure 4). However, even under high TP load reduction scenarios there will be years of high TP inflow (wet years) where we probably cannot avoid eutrophic conditions developing (as with the pre-development scenario) simply because of the large total TP load entering the lake via stormwater (such that even a >600kg reduction in TP is proportionally fairly insignificant). Conversely, though, dry years with low TP inflows could yield oligotrophic conditions in scenarios with greater than 500kg TP reduction (Figure 4).

Overall, these modelling results suggest that an annual 700kg reduction in TP entering Lake Tuggeranong is an appropriate target for future lake management plans. This level of TP reduction is predicted to lead to

favourable conditions for human recreation in the lake in ~75% of years (~25% oligotrophic, ~50% mesotrophic; Figure 4).

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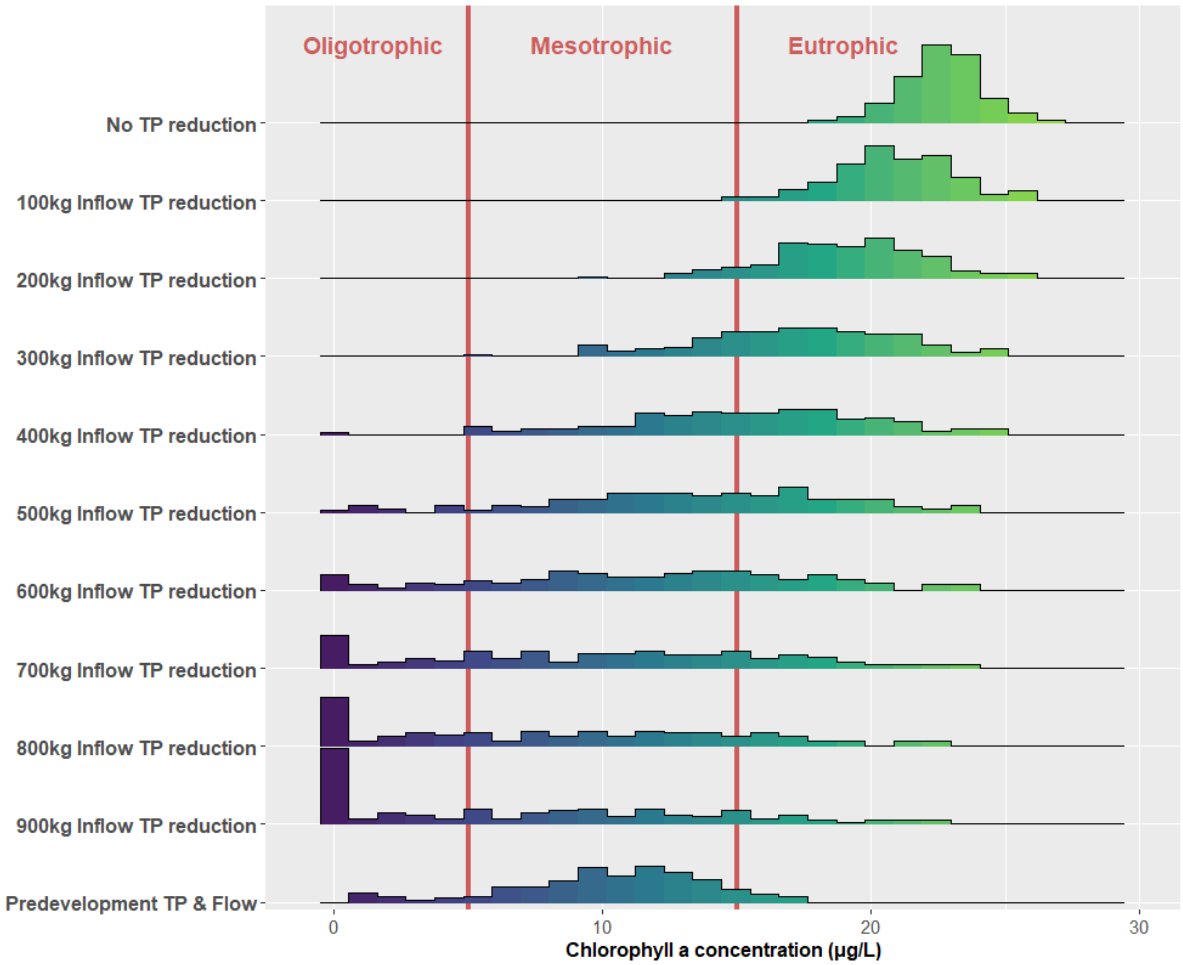

Figure 4. Distribution of annual predicted chlorophyll a concentration (i.e. trophic state) in Lake Tuggeranong under different scenarios of reductions in inflow total phosphorus (TP).

4. Conclusion

Vollenweider's mass-balance model is a simple, but useful, tool for predicting nutrient concentrations in lakes based on influent volumes and concentrations. Whilst they are typically used for comparisons between lakes, in this study the Vollenweider model was modified to derive Lake Tuggeranong specific total phosphorous concentrations. The model produced a reasonable fit with observed values over a 17-year period and could be used in conjunction with catchment model inputs to predict general trends in phosphorous levels in Lake Tuggeranong into the future. The model output was then used to provide an estimate chlorophyll a which is a measure of the trophic state. The estimated chlorophyll a concentration was used to determine the trophic state of the lake under different scenarios. The findings provide an approximate estimate of the target inflow TP load for Lake Tuggeranong to improve the lake trophic conditions, with a target annual reduction of ~700kg of TP yielding favourable predictions.

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Attachment I

ACT Government

Lake Tuggeranong Catchment Management Options Assessment

Technical report supporting the Healthy Waterways Plan for Lake Tuggeranong

Water Information Services, ACT Office of Water

December 2024

Environment, Planning and Sustainable Development Directorate

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Executive Summary

Lake Tuggeranong is a small (57 ha) urban lake in southern Canberra. Lake Tuggeranong was constructed in the late 1980s on Tuggeranong Creek, a 66 km^2 catchment that is predominantly (62%) urbanised. In recent decades, Lake Tuggeranong has been plagued by poor water quality. Since 2017, there has been a concerted effort to improve water quality in the lake through the construction of Water Sensitive Urban Design (WSUD) infrastructure throughout the catchment, and a major research program to understand the causes of poor water quality, and sources of pollutants entering the lake. This work has been undertaken as part of the ACT Healthy Waterways program.

The ACT Government has commited to developing Healthy Waterways Plans for priority catchments in the ACT. The Lake Tuggeranong draft plan provides a suite of potential management options to Government to further improve water quality in Lake Tuggeranong. To acheive this, modelling and analyses have been undertaken to examine a broad range of management scenarios and identify cost-effective options to improve water quality in Lake Tuggeranong, with a focus on reducing the annual load of phosphorus entering the lake.

This report documents the approach taken to assess the predicted performance and cost of 10 proposed catchment management options for reducing the load of phosphorus entering Lake Tuggeranong. For each management option identified, details of the data and information used to calculate the estimates of performance and cost are presented, and summarised in an assessment of cost-effectiveness. To provide a comparison of cost-effectiveness both across and within management options, the cost-effectiveness of four different levels of investment was calculated for each option, ranging from relatively low to relatively high investment. An evaluation of the quality of evidence supporting these estimates and its impact on our confidence in specific values is provided for each management option.

These assessments found that increasing the frequency of municipal street sweeping and the construction of additional WSUD infrastructure were the management options predicted to remove the greatest loads of phosphorus, with street sweeping the most cost-effective option at all levels of investment.

The assessments of management option cost-effectiveness were provided to the ACT Healthy Waterways team who chose options to combine into two proposed management scenarios, with the aim of reducing the phosphorus load entering Lake Tuggeranong (currently ~ 1440 kg/year) by approximately 700 kg/year. A reduction of this amount is predicted to maintain Lake Tuggeranong in a predominantly mesotrophic state, substantially reducing the frequency, extent and duration of blue-green algal blooms (Kahn & Dey, 2024). The proposed management scenarios were then implemented in the catchment model for the Lake Tuggeranong catchment (Dey, Stewart, Kahn, Booksmythe, & Starrs, 2024), to estimate their average annual phosphorus load reductions, accounting for interactive effects of the different options included in a scenario.

Modelling the proposed management scenarios revised down the estimated annual load of phosphorus they were predicted to remove,from 700-750 kg/year to 450-575 kg/year. This is mainly due to the large impact of street sweeping on reducing the concentration of phosphorus in stormwater, which alters the rate of phosphorus removal estimated for management options involving WSUD infrastructure.

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1. Introduction

Lake Tuggeranong is a small (57 ha) urban lake in southern Canberra. The lake was constructed in the late 1980s on Tuggeranong Creek, a 66 km^2 catchment that is predominantly (62%) urbanised. In recent decades, Lake Tuggeranong has been plagued by poor water quality, with high loads of nutrients (phosphorus and nitrogen) and sediments entering the lake, leading to frequent, extensive blue-green algal blooms that result in lake closures. Since 2017, there has been a concerted effort to improve water quality in the lake through the construction of Water Sensitive Urban Design (WSUD) infrastructure such as wetlands, bioretention swales and raingardens throughout the catchment, and a major research program to understand the causes of poor water quality, and sources of pollutants. This work has been undertaken as part of the ACT Healthy Waterways program.

The ACT Government has commited to developing Healthy Waterways Plans for priority catchments in the ACT. The Lake Tuggeranong draft plan aims to provide a suite of potential management options to Government to further improve water quality in Lake Tuggeranong (ACT Government, 2025). To achieve this, modelling and analyses have been undertaken to examine a broad range of management scenarios and identify cost-effective options to improve water quality in Lake Tuggeranong, with a focus on reducing the annual load of phosphorus entering the lake. The availability of phosphorus is the main controllable factor limiting blue-green algal growth (Ubrihien, et al., 2020). While large amounts of phosphorus are bound to sediments on the lake bottom, reducing the phosphorus inputs to the lake is necessary before this in-lake source of phosphorus can be effectively addressed.

This report documents the approach taken to assess the predicted performance and cost of proposed catchment management options for reducing the load of phosphorus entering Lake Tuggeranong. For each management option identified, details of the data and information used to calculate the estimates of performance and cost are presented, and summarised in an assessment of cost-effectiveness. An evaluation of the quality of evidence supporting these estimates and its impact on our confidence in specific values is provided for each management option.

Government experts identified a range of potential management options for mitigating phosphorus pollution. They then narrowed their consideration of options based on the availability of data to support cost-effectiveness analyses. In some instances, cost-effectiveness data were based on local trials of mitigation options.

Ten management options are assessed in this report:

- Construction of additional WSUD infrastructure
- Improved maintenance of existing WSUD assets
- Increased frequency of street sweeping
- Improved management of grass clippings from municipal mowing
- Management of public sports field fertilizer use practices
- Management of household fertilizer use practices
- Installation (retrofitting) of castellated kerbs
- Installation of in-lake floating wetlands

- Installation of stormwater recycling infrastructure for sports field irrigation
- Installation of household rainwater tanks

The assessments used to generate estimates of the cost-effectiveness of each of these management options is detailed in section 2 of this report. Sections 3.1 and 3.2 describe the process of comparing management options and combining them into proposed management scenarios with the aim of reducing the phosphorus load entering Lake Tuggeranong by approximately 700 kg/year. A reduction of this amount is predicted to maintain Lake Tuggeranong in a predominantly mesotrophic state, substantially reducing the frequency, extent and duration of blue-green algal blooms (Kahn & Dey, 2024). Section 3.3 outlines the results of implementing the proposed management scenarios in the catchment model for the Lake Tuggeranong catchment (Dey, Stewart, Kahn, Booksmythe, & Starrs, 2024).

1.1 Management option performance

The performance of each management option is assessed in terms of the amount of total phosphorus (TP) it is predicted to prevent from entering Lake Tuggeranong in a year. To facilitate comparison between different types of management option, we assume a 30-year lifecycle for each option. Total lifecycle performance is estimated by multiplying the annual TP removal by 30.

Phosphorus reduction has been chosen as the primary quantitative metric for management option performance due to its key role in promoting blue-green algal blooms in Lake Tuggeranong. Further assessment could consider other aspects of water quality improvement (e.g. the reduction of total nitrogen, TN, and total suspended solids, TSS), along with non-water quality benefits, as part of performance.

1.2 Management option costs

Costs are estimated in Australian Dollars (AUD) as at 2024. Costs are broken down into three components:

- Capital costs (in 2024 currency; assumed to be incurred in the first year of implementation)
- Annual operating costs (in 2024 currency)
- Total 30-year lifecycle costs (capital costs + annual operating costs over 30 years, using an annual discount rate of 7% after the first year (Infrastructure Australia, 2021))

We assume that management options have no residual value at the end of lifecycle, facilitating a like-for-like comparison between management options with vastly different cost profiles (e.g. infrastructure vs. non-infrastructure options).

1.3 Management option cost-effectiveness

By calculating an estimate of cost-effectiveness we aim to provide a metric allowing direct comparison of different management options. The cost-effectiveness of each management option is calculated by dividing the total lifecycle cost by the total lifecycle performance (TP removal). This produces a standardised metric for comparison between disparate management options in a consistent unit ($/kg). To provide a comparison of cost-effectiveness both across and within management options, the cost-effectiveness of

four different levels of investment was calculated for each option, ranging from relatively low to relatively high investment.

1.4 Quality of supporting evidence

With any process of estimation comes uncertainty. In assessing the cost-effectiveness of phosphorus-reducing management options in the Lake Tuggeranong catchment, uncertainty may arise through three main channels:

- Uncertainty about estimates of the cost of implementing a management option
- Uncertainty about estimates of the efficacy of the management option in removing phosphorus (e.g., uncertainty about the amount of leaf litter prevented from entering the stormwater system by street sweeping)
- Uncertainty about estimates of the amount of phosphorus available for removal by a particular management option (e.g., uncertainty about the pollutant load generated from leaf litter on roads)

We use both quantitative and qualitative approaches to address these sources of uncertainty in our assessment of management options.

1.4.2 Quantitative assessment of estimate uncertainty

A wide range of data and information were collated to estimate the phosphorus-removal performance and cost of each assessed option. In some cases, when incorporating multiple sources of information about the same aspects of performance or cost, a range of estimates was obtained. We assessed this range of estimates statistically, to understand whether it was likely to represent a realistic range of possible variability in outcomes, or to over- or under-estimate the expected variability.

1.4.2 Qualitative assessment of estimate uncertainty

We developed a rubric to systematically assess the quality of evidence sources contributing to the cost-effectiveness estimates of each management option (Appendix A). The data informing the calculations of predicted cost and performance were scored on nine criteria and the scores summed to give an overall uncertainty rating for the cost-effectiveness estimate.

Box 1. Key definitions and abbreviations used in this report

- Annual operating cost – the estimated annual cost of day-to-day operation of a management option, including routine maintenance and staff costs unless otherwise specified.
- Capital cost – the cost of capital works (i.e. construction planning, materials and delivery) of a management option, excluding operation and maintenance costs. Some management options do not have a capital cost (e.g. community partnership programs).
- Discount rate – the interest rate at which future dollar values are adjusted to represent their value in today's dollars. This adjustment is made to account for the fact that money today is more valuable than money in the future.
- EPSDD – Environment, Planning and Sustainable Development directorate, ACT Government
- Gross pollutant trap (GPT) – infrastructure installed upstream of stormwater management infrastructure to capture large debris and prevent it from causing blockage of the infrastructure.
- Model for Urban Stormwater Improvement Conceptualisation (MUSIC) – software that simulates rainfall, stormwater runoff, flows, and pollution. Used to simulate flow reduction and pollution removal through stormwater management infrastructure such as wetlands, bioretention, and sediment ponds.
- O&M – Operation and maintenance
- TCCS – Transport Canberra and City Services directorate, ACT Government
- Total lifecycle cost – the estimated cost of implementing and operating a management option over 30 years, with annual (O&M) costs discounted by 7% per annum after the first year.
- Total phosphorus (TP) – the sum of all forms of phosphorus present in a sample. In this report the term phosphorus refers to total phosphorus (TP) unless otherwise specified, and these terms may be used interchangeably.
- Water-sensitive Urban Design (WSUD) assets – infrastructure such as constructed wetlands, bioretention, and sediment ponds, for the management of stormwater and its pollutants using natural biological and physical processes including sediment settlement, filtration, and uptake by plants.

2. Management option assessments

2.1 Construction of additional WSUD infrastructure

2.1.1 Background

Stages 1 and 2 of the ACT Healthy Waterways program saw the construction of several different types of water-sensitive urban design (WSUD) infrastructure across urban Canberra waterways, including 8 assets in the Lake Tuggeranong catchment. WSUD infrastructure, including constructed wetlands, raingardens, and bioretention swales, can be situated directly on a branch of the stormwater network (online) or receive inflows diverted from the stormwater network (offline), or be positioned to intercept runoff before it enters the stormwater network (at-source). While water is within the infrastructure, a proportion of the nutrient and sediment pollutants in the water are removed through processes including natural settling, filtration, and uptake by plants. Outflows from the infrastructure are returned to the stormwater network. This section assesses the cost-effectiveness of installing additional WSUD infrastructure in the catchment.

The amount of total phosphorus (TP) available for removal by additional WSUD infrastructure is that which is intercepted by the infrastructure as it travels through the catchment. The catchment model for the Lake Tuggeranong catchment estimates the load of TP generated and entering the stormwater network in each subcatchment, allowing calculation of the accumulated load that would be received by a new WSUD asset depending on its location in the catchment (Dey, Stewart, Kahn, Booksmythe, & Starrs, 2024).

2.1.2 Phosphorus removal performance

We estimate the TP removal performance of additional WSUD infrastructure based on the performance of similar existing infrastructure. MUSIC models were developed for each of the WSUD assets constructed as part of Stage 1 of the ACT Healthy Waterways program. These models are configured to reflect the final design of each asset and model the predicted TP removal for each asset over a known climatic period, adopting MUSIC's default TP concentrations for stormwater runoff generated from different land uses in the catchment. The models for the 8 WSUD assets installed in the Lake Tuggeranong catchment were reviewed and updated by eWater (eWater Ltd, 2022), which estimated annual mean percentage reductions in TP of between 15-80% for these assets. These percentage reductions were applied in the Lake Tuggeranong catchment model (Dey, Stewart, Kahn, Booksmythe, & Starrs, 2024) to estimate the TP load removed by each asset. The total annual load of TP removed depends on the type, size, and location of assets. The two constructed wetlands in the Lake Tuggeranong catchment remove an estimated 0.003-0.01 kg TP per square metre of wetland per year. However, we excluded wetlands from the infrastructure used to estimate the performance of additional WSUD infrastructure, as there is very little scope to build further wetlands in the Lake Tuggeranong catchment, and modelling smaller assets is more realistic. For the 6 non-wetland assets (bioretention swales, raingardens, and channel restorations) in the catchment, the annual load of TP removed ranges between 0.0048-0.014 kg TP per square metre of asset area (Table 1).

The installation of additional WSUD infrastructure, and the size of infrastructure that can be built, is limited by the availability of suitable locations in the catchment. This means that specific asset designs, of known type, size, and location, are needed when estimating the impact of additional WSUD infrastructure on reducing the TP load entering Lake Tuggeranong. Here, the size and possible locations of additional WSUD infrastructure were determined from design reports for 10 proposed raingardens in the Lake Tuggeranong

catchment (Alluvium, 2015), undertaken as part of the ACT Healthy Waterways program Stage 1, that were not selected as priorities for construction during that project (Table 2). As there may be planning and feasibility constraints that determined why these particular raingardens were not built at the time, the estimates in this section should be read as an example of the kind of infrastructure that could be installed in the Lake Tuggeranong catchment, not a specific proposal.

Table 1. Summary statistics for the performance of 6 existing non-wetland WSUD assets in the Lake Tuggeranong catchment.

Parameter	Total annual TP removed (kg/m^2)
Minimum	0.0048
Median	0.0074
Mean	0.0081
Maximum	0.0142

We assigned each of these hypothetical assets an annual TP removal rate, assuming that raingarden performance efficacy improves with increasing treatment area. To implement this relationship, we ranked the raingardens by size, and applied the maximum TP removal rate from Table 1 to the largest two assets, the mean TP removal rate to the next three largest assets, the median TP removal rate to the next three largest assets, and the minimum TP removal rate to the two smallest assets (Table 2).

Table 2. Size, assigned rate of TP removal, and estimated total annual TP removed for 10 proposed raingardens in the Lake Tuggeranong catchment.

Asset	Asset size (m^2)[1]	Annual TP removed (kg/m^2)	Total annual TP removed (kg)
TG018	4,800	0.0142	68.16
TG014	2,700	0.0142	38.34
TG004	2,600	0.0081	21.06
TG013	2,600	0.0081	21.06
TG015	2,600	0.0081	21.06
TG016	2,600	0.0074	19.24
TG031	2,600	0.0074	19.24
TG005	2,459	0.0074	18.20
TG007B	1,500	0.0048	7.20
TG009	1,440	0.0048	6.91

1 Assets with no projected treatment area were assigned an area of 2,600 m^2, the average area for a raingarden in the catchment.

2.1.3 Costing

G2W Pty Ltd were engaged to review the capital and ongoing operation and maintenance costs associated with existing WSUD infrastructure in the Lake Tuggeranong catchment (G2W Pty Ltd, 2024). Bioretention assets (raingardens and swales) in the Lake Tuggeranong catchment ranged between 765 - 5,270m^2 in size, and between $774 - 2,532/m^2 in capital construction cost, with a strongly negative relationship between

size and cost such that on average, larger assets had a lower capital cost per square metre. We used this size - capital cost relationship to estimate the capital cost of constructing the 10 proposed raingardens based on the sizes presented in Table 2. We used the capital cost of the cheapest existing raingarden as a lower limit for the cost estimates of the proposed raingardens. Similarly, the annual operation and maintenance (O&M) cost of existing bioretention assets ranged between \$62 – 170/m^2, with larger assets having a lower O&M cost per square metre. We used the asset size - O&M cost relationship to estimate the annual maintenance cost of the 10 proposed raingardens, again using the lowest existing O&M cost as a lower limit for our estimates. We used the capital and O&M cost estimates to calculate the 30-year lifecycle cost of the 10 proposed raingardens, assuming an annual discount rate of 7% each year on the O&M costs.

2.1.4 Cost-effectiveness

We calculated the individual cost-effectiveness of each of 10 proposed raingardens based on the assigned rate of TP removal for each asset (Table 3).

Table 3. Capital costs, annual operation and maintenance costs, 30-year lifecycle costs, and individual cost-effectiveness of 10 proposed raingardens in the Lake Tuggeranong catchment.

Asset	Capital cost	Annual operation and maintenance cost	Total 30-year lifecycle cost[1]	Cost per unit TP removed ($/kg)
TG018	\$4,882,560	\$338,496	\$13,025,856	\$6,388
TG014	\$4,226,310	\$261,846	\$8,878,356	\$7,740
TG004	\$4,137,640	\$255,424	\$8,620,664	\$13,585
TG013	\$4,137,640	\$255,424	\$8,620,664	\$13,585
TG015	\$4,137,640	\$255,424	\$8,620,664	\$13,585
TG016	\$4,137,640	\$255,424	\$8,620,664	\$14,969
TG031	\$4,137,640	\$255,424	\$8,620,664	\$14,969
TG005	\$4,003,746	\$245,941	\$8,248,021	\$15,143
TG007B	\$2,817,750	\$168,150	\$5,424,900	\$24,882
TG009	\$2,727,590	\$162,513	\$5,231,543	\$24,995

1 Total lifecycle cost is calculated over 30 years using a discount rate of 7% per annum on O&M costs.

To provide four levels of investment in the additional WSUD infrastructure management option, we grouped the 10 proposed raingardens by their size and cost-effectiveness and created four tiers of installation: to either build the two, five, 8 or 10 most cost-effective of these assets. We re-calculated the overall 30-year lifecycle cost and cost-effectiveness for the group of assets included in each investment level (Table 4), incorporating additional cost scaling factors to account for total construction size, number of assets to be constructed and the number of gross pollutant traps required (we assumed that each asset would need one gross pollutant trap).

Table 4. Costing summary for four levels of investment in additional WSUD infrastructure in the Lake Tuggeranong catchment.

Investment level	Number of assets built	Total annual TP removed (kg/year)	Total 30-year lifecycle cost[1]	Cost per unit TP removed ($/kg)
1	Build 2 assets	106.21	$22,507,500	$7,064
2	Build 5 assets	169.67	$48,369,492	$9,502
3	Build 8 assets	226.22	$73,862,467	$10,884
4	Build 10 assets	240.46	$84,519,403	$11,716

1 Total lifecycle cost is calculated over 30 years using a discount rate of 7% per annum on O&M costs.

2.1.5 Quality of supporting evidence

Using the evaluation rubric (Appendix A), the above estimates of cost-effectiveness of installing additional WSUD infrastructure scored 13/14 for confidence in cost estimates, and 9/16 for confidence in performance estimates.

2.2 Maintenance of existing WSUD infrastructure

2.2.1 Background

WSUD infrastructure requires ongoing maintenance to function at its designed phosphorus removal efficiency. Transport Canberra and City Services (TCCS) undertake this maintenance for the 8 existing WSUD assets in the Lake Tuggeranong catchment.

2.2.2 Phosphorus removal performance

Six of the 8 WSUD assets in the Lake Tuggeranong catchment were visually assessed for their current level of maintenance and treatment efficacy in February 2024. Five of these assets were assessed as performing at between 20% and 70% of their designed efficiency due to maintenance shortfalls. The estimated reduction in performance of each asset was incorporated into the baseline run of the catchment model, used to calculate the current (business-as-usual) annual load of TP entering Lake Tuggeranong (Dey, Stewart, Kahn, Booksmythe, & Starrs, 2024). To estimate the amount of TP that could be removed if all existing assets were maintained to 100% of their designed efficiency, the catchment model was then run without applying the asset performance reductions. The total difference in TP load between the business-as-usual and optimal asset maintenance model runs was 88 kg/year (Table 5).

Table 5. Current asset total phosphorus (TP) removal performance efficiency as a percentage of designed performance, and the additional annual TP load that could be removed if assets were maintained to designed performance.

Asset	Current TP removal performance	Marginal increase in TP removed with optimal maintenance (kg/year)
TG011N – wetland	60%	23.28
TG029 – raingarden	20%	12.56
TG010 – raingarden	70%	25.94
TG011S – wetland	60%	18.15
TG008 – raingarden	50%	8.09

2.2.3 Costing

The costs provided for asset operation and maintenance are based on annualised operational cost estimates from TCCS budget requests, and incorporate costs of major renewal activities such as cleaning GPTs, mucking out sediment forebays and replacing raingarden filter media at regular intervals. We used the costs provided without modification, to calculate the 30-year lifecycle cost of each asset assuming an annual discount rate of 7% after the first year.

2.2.4 Cost-effectiveness

Our estimates of cost-effectiveness assume that there is currently no funding provided for WSUD asset maintenance, and that if the estimated O&M costs (Table 6) *were* to be spent on these assets, the marginal gains in TP removal (Table 5) would be achieved.

Table 6. Annual operation and maintenance costs, 30-year lifecycle costs, and cost-effectiveness of maintaining 5 existing WSUD assets to their designed performance.

Asset	Annual operation and maintenance cost	Total 30-year lifecycle cost[1]	Cost per unit TP removed ($/kg)
TG011N – wetland	$485,352	$6,508,917	$9,320
TG029 – raingarden	$221,091	$3,668,211	$9,735
TG010 – raingarden	$340,432	$8,909,451	$11,449
TG011S – wetland	$541,800	$7,265,925	$13,344
TG008 – raingarden	$235,739	$3,999,929	$16,481

1 Total lifecycle cost is calculated over 30 years using a discount rate of 7% per annum on O&M costs.

To provide four levels of investment in the WSUD maintenance management option, we grouped the five assets by the cost-effectiveness of their maintenance and created four tiers of implementation: to maintain either the two, three, four or five most cost-effective of these assets. We re-calculated the overall 30-year lifecycle cost and cost-effectiveness for the group of assets included in each investment level (Table 7).

Table 7. Costing summary for four levels of investment in maintenance of existing WSUD infrastructure in the Lake Tuggeranong catchment.

Investment level	Number of assets maintained	Total annual TP removed (kg/year)	Total 30-year lifecycle cost[1]	Cost per unit TP removed ($/kg)
1	Maintain 2 assets	35.84	$10,177,128	$9,465
2	Maintain 3 assets	61.78	$19,086,579	$10,298
3	Maintain 4 assets	79.93	$26,352,433	$10,990
4	Maintain 5 assets	88.02	$30,352,433	$11,495

1 Total lifecycle cost is calculated over 30 years using a discount rate of 7% per annum on O&M costs.

2.2.5 Quality of supporting evidence

Using the evaluation rubric (Appendix A), the above estimates of cost-effectiveness of maintaining existing WSUD infrastructure scored 4/14 for confidence in cost estimates, and 8/16 for confidence in performance estimates.

2.3 Increased frequency of street sweeping

2.3.1 Background

In the Lake Tuggeranong catchment, research by the University of Canberra (Ubrihien, et al., 2020) indicates that a large amount of nutrients enter the waterways from diffuse, rather than point, sources – i.e. from widespread land uses across the catchment such as residential blocks and roads. One potential contributing factor found across these land uses is leaf litter (here defined as fallen leaves and other plant and soil matter) on impervious surfaces like roads, footpaths and driveways. Water passing over this leaf litter can take up nutrients in both dissolved and particulate forms, and enter the stormwater system via street gutter sumps. Dissolved nutrients may be leached out of leaf litter by the passing water, while particulate nutrients are chemically bound to particles such as soil and leaf fragments. In addition, with sufficient flows intact leaf litter may be washed into the stormwater system and transported to the lakes and waterways where they will break down and release nutrients into the water.

The primary function of the municipal street sweeping program is to prevent blockage of the stormwater system and ensure its effectiveness in flood mitigation. While increasing the frequency of street sweeping is often raised as a possible action to reduce leaf litter as a source of nutrient pollution, the impact of street sweeping on reducing nutrient inputs into the urban waterways of the ACT has not previously been quantified.

Phosphorus generated from leaf litter on roads

The amount of TP available for removal by street sweeping is that which originates as leaf litter on roads. The Lake Tuggeranong catchment model estimates the total annual TP load that runs off roads in the Lake Tuggeranong catchment as 582 kg TP/year (Dey, Stewart, Kahn, Booksmythe, & Starrs, 2024), and we use this as an estimate of the maximum available load of TP generated by leaf litter on roads.

There is strong seasonal variation in leaf fall in *Eucalyptus* species, which are predominant among the street tree and other public tree assets in the Lake Tuggeranong catchment (Ubrihien, et al., 2024), with most leaves falling in the warmer months (Crockford & Richardson, 1998). This variation, as well as seasonal variation in rainfall, will affect the accumulated load of leaf litter on the roads at any given time, and means that not just the frequency but also the timing of street sweeping can impact the amount of TP removed by this management option.

2.3.2 Phosphorus removal performance

We created a simple build-up wash-off model ('leaf load calculator') to incorporate these sources of seasonal variation in TP load, and the influence of sweeping frequency and timing, into our estimate of the TP removal performance of street sweeping. The calculator is based on 24 years of daily rainfall data from the Tuggeranong (Isabella Plains) climatological station (Bureau of Meteorology station ID 070339). It allows manual adjustment of variability in leaf fall, and specification of the frequency and timing of street sweeping. Using these inputs it calculates the cumulative load of leaf litter each day:

Load today = load yesterday + new fall today – load swept today – load washed away by rain today.

We used data from University of Canberra research into the leaf fall and TP content of four *Eucalypt* species in urban Canberra (Ubrihien, et al., 2024) to generate an approximate seasonal leaf fall pattern for the Lake Tuggeranong catchment. We input this seasonal pattern into the leaf load calculator, scaling the daily maximum leaf fall rate to be consistent with the average annual load of 582 kg TP on roads in the catchment estimated by the catchment model (Dey, Stewart, Kahn, Booksmythe, & Starrs, 2024). We then compared different annual street sweeping schedules, from two sweeps per year (business-as-usual) to 48 sweeps per year. We explored schedules of sweeping evenly spaced throughout the year, as well as seasonally focused schedules with increased frequency during high leaf fall periods and reduced or no sweeping during low leaf fall periods. For all schedules we assumed a minimum of one week between sweeps.

To compare each sweeping schedule explored using the leaf load calculator, we calculated their monthly and annual statistics on the leaf litter load on roads, the load collected by street sweeping trucks (and the approximate number of truckloads), and the load washed away into the stormwater network, over the 24 years of rainfall data.

2.3.3 Costing

To find the cost of a single sweep event for the Lake Tuggeranong catchment, we multiplied the current daily cost of one street sweeping truck by the number of truck-days needed to sweep the entire catchment once. We then added the cost of transporting and disposing of the swept material in landfill. We assume an expansion of the current operational model based on leasing trucks, so no capital cost (e.g. outright purchase of trucks) is included in our costings for this management option.

Days needed for one catchment sweeping event A pilot experiment investigating the impact of frequent street sweeping on nutrient concentrations in stormwater included a 12-week period of fortnightly street sweeping in two subcatchments of the Lake Tuggeranong catchment, comprising 10% of the total catchment road area. From records of the number of shifts needed to complete sweeping of this area each

fortnight during the experiment, we calculate that on average 24.17 truck-days would be needed to sweep the entire Lake Tuggeranong catchment.

Daily truck cost An estimate of daily cost per truck, based on the current running costs of a truck in the ACT street sweeping fleet, was provided by the TCCS Street Sweeping team. The fleet runs 5 days per week, with up to two staff shifts per truck per day, allowing each truck to operate for up to 10 hours per day. At the maximum (2 shift/day) rate of operation, the cost of one truck, including leasing, staff, running and maintenance costs, is $1,200-$1,500/day. Here we conservatively use the higher cost estimate. Over 24.17 truck-days, the estimated truck cost to sweep the entire Lake Tuggeranong catchment is $36,255.

Disposal costs The total cost of disposing of material to landfill in 2024 currency is $181/tonne. Of this, tip fees comprise $171/tonne and the cost of transporting collected material to landfill sites is $10/tonne (both excluding GST).

From data provided by TCCS, the estimated tonnage of material removed in one year (260 weekdays) by the fleet of 6 trucks is 2,364 tonnes, or an average of 9.1 tonnes/day. Assuming that each truck spends about 10% of its time non-operational (due to breakdowns, time out for servicing, etc.), this equates to an estimated average of 1.7 tonnes of material removed per truck per day (9.1 / (6 * 0.9)). Given 24.17 truck-days per catchment sweeping event, the disposal cost per sweeping event is $7,437. The total combined truck and disposal cost to sweep the Lake Tuggeranong catchment is $43,692 per street sweeping event. These estimates assume a constant load of material collected at each sweeping event (i.e., no seasonality or decrease due to sweeping frequency is included in disposal cost estimates, due to a lack of data on these possible effects).

2.3.4 Cost-effectiveness

To provide four levels of investment in the street sweeping management option, we considered four sweeping schedules ranging between 12 - 48 sweeping events in a year (1 - 4 per month). The three lower-frequency schedules account for the seasonality of leaf fall to obtain the best performance for each level of investment. The 48-sweep schedule is essentially equivalent to sweeping every week, so no seasonal adjustment is made. We calculated the 30-year lifecycle cost of each schedule using an annual discount rate of 7% on annual program costs after the first year.

Table 8. Costing summary for four levels of investment in increased frequencies of street sweeping in the Lake Tuggeranong catchment.

Investment level	Sweeping schedule	Total annual TP removed (kg/year)	Annual program cost	Total 30-year lifecycle cost[1]	Cost per unit TP removed ($/kg)
1	12 sweeps – seasonal focus	203.7	$524,304	$7,030,414	$1,150
2	24 sweeps – seasonal focus	320.1	$1,048,608	$14,060,827	$1,464
3	36 sweeps – seasonal focus	372.5	$1,572,912	$21,091,242	$1,887
4	48 sweeps – weekly	395.8	$2,097,216	$28,121,656	$2,369

1 Total lifecycle cost is calculated over 30 years using a discount rate of 7% per annum on annual costs after the first year.

2.3.5 Quality of supporting evidence

Using the evaluation rubric (Appendix A), the above estimates of cost-effectiveness of increasing the frequency of street sweeping scored 10/14 for confidence in cost estimates, and 9/16 for confidence in performance estimates.

2.4 Management of grass clippings from municipal mowing

2.4.1 Background

Grass clippings resulting from mowing of public open space can be blown onto adjacent roads, from where they can enter the stormwater system. Public perception is that large amounts of clippings end up on the roads, and if so these clippings may be a sizeable contributor to nutrient pollution of the waterways. Preventing or reducing the input of phosphorus from this source could be achieved by installing catchers on lawnmowers, using blowers to return clippings to the verge, or running designated street sweeping trucks along mown roadsides.

Phosphorus export from municipal mowing activity

The total area of pervious, ground-level (i.e., likely grassed and subject to TCCS mowing) public open space in the Lake Tuggeranong catchment is 928.5 ha. We assume that clippings from areas within 2m of a road are likely to end up on the road - this is probably an overestimate, and gives an area of 98.1 ha of mown area from which grass clippings will reach the road.

The estimated amount of clippings generated from this area in a year is between 327,000 - 523,000 kg dry mass. This is based on a 2016 report for the South Australian Government investigating the effect of watering regime on turf grass yields (Barton, 2016). University of Canberra research (Ubrihien, et al., 2024) estimates the phosphorus content of grass clippings at 0.1% of the dry weight of clippings, which gives between 327 - 523 kg TP for the estimated annual load of clippings on roads in the Lake Tuggeranong catchment.

When considered in light of information from the street sweeping pilot experiment (see section 2.3), this estimate appears unrealistically high. At this rate, the TP load from 12 weeks' worth of grass clippings on the road in the subcatchments monitored in the experiment would comprise around 50% of the total TP load estimated from the experiment. Furthermore, the mass of these clippings would be around 100 times greater than the total mass of material collected during the experiment. Rough visual estimates suggest that only between 0-10% (by volume) of the swept material was grass clippings. To reconcile these different estimates, we assume that current mowing management practices are 90% effective in keeping clippings off the road, so clippings contribute 32.7 - 52.3 kg TP/year (at this rate, TP loads from clippings would comprise around 5% of the total TP load measured in the street sweeping experiment).

2.4.2 Phosphorus removal performance

Only two of the three suggested management methods for municipal grass clippings are assessed here. Through consultation with the Transport Canberra and City Services mowing team, the use of catchers has

been discounted – most of the current fleet of mowers cannot accommodate a catcher, and the team does not have the capacity (time or resources) to dispose of collected clippings.

Management method 1 is to adopt the use of electric blowers towed behind mowers to move clippings away from road edges. This option is assumed to improve current practices to be 95% effective at keeping clippings off the roads, reducing TP inputs by 50% (removing between 16.4 - 26.1 kg TP/year).

Management method 2 is to use street sweeping trucks to immediately remove all remaining grass clippings on roads. A suggestion to do this by coordinating with the current street sweeping program has previously been trialled and found to be logistically infeasible. This option would instead require the lease of a designated street sweeping truck(s) to run immediately after mowing and is assumed to remove the entire TP load from clippings (removing 32.7 - 52.3 kg TP/year).

2.4.3 Costing

Management method 1 To achieve the full reduction in phosphorus inputs estimated for this method would require enough blowers to provide operational coverage to current municipal mowing activities in the Lake Tuggeranong catchment. Based on consultation with the TCCS mowing team, the purchase of two blowers and their ongoing operation and maintenance are costed:

- Capital purchase (2 blowers) = $160,000
- Annual cost (2 staff at $65,000/year + maintenance at $5,000/year) = $140,000/year

Management method 2 Here we assume that operational coverage for current municipal mowing activities in the Lake Tuggeranong catchment would require the lease of one dedicated street sweeping truck running full time (2 shifts per day, 5 days per week). Costing is based on leasing and operational cost information provided by the TCCS street sweeping team:

- No capital cost
- Annual operational cost (truck lease, staff, fuel, and maintenance) = $108,996/year
- Additional annual cost (landfill charges at $171/tonne ex. GST, for 32,700-52,300 kg material) = $5,592-$8,943/year

2.4.4 Cost-effectiveness

These two methods for the management of grass clippings from municipal mowing are predicted to remove between 16 - 52 kg TP per year at a cost of between $998 - $4,103 per kg P removed, over 30 years. We use the high and low estimates of TP removal performance for each method to provide four levels of investment in this management option (Table 9).

2.4.5 Quality of supporting evidence

Using the evaluation rubric (Appendix A), the estimates of cost-effectiveness of managing grass clippings from municipal mowing scored 9/14 for confidence in cost estimates, and 7/16 for confidence in performance estimates.

Table 9. Estimated annual load of total phosphorus (TP) prevented from entering Lake Tuggeranong, total 30-year lifecycle cost, and cost-effectiveness of options for management of grass clippings from municipal mowing.

Investment level	Management method and level of TP removal	Total annual TP removed (kg/year)	Total 30-year lifecycle cost[1]	Cost per unit TP removed ($/kg)
1	Method 1 (blowers) – low TP removal estimate	16.4	$2,018,874	$4,103
2	Method 1 (blowers) – high TP removal estimate	26.1	$2,018,874	$2,578
3	Method 2 (sweeping) – low TP removal estimate	32.7	$1,521,462	$1,551
4	Method 2 (sweeping) – high TP removal estimate	52.3	$1,565,956	$998

1 Total lifecycle cost is calculated over 30 years using a discount rate of 7% per annum on annual costs after the first year.

2.5 Management of sports field fertilizer use practices

2.5.1 Background

The use of fertilizers containing phosphorus on sports grounds and other 'managed' green space is undertaken by both government and private managers. The Lake Tuggeranong catchment includes ~60 ha of actively managed (irrigated and fertilized) sports grounds, and a few additional privately managed assets: Vikings Club football ground, and three school sports grounds (Trinity Christian School, St Mary Mackillop College, Erindale College) with an estimated combined total of 7.5 ha.

Interviews with Canberra sports field and turf managers (Edmondson, 2022) suggest that in general, sports field managers are motivated to use fertilizer efficiently within the constraints of their management priorities. There is likely little to be gained in trying to further reduce fertilizer application rates. An additional option to address fertilizer export from sports fields is to install bioretention swales to intercept runoff from sports fields, and this is the management option we assess here.

Phosphorus application and export rates from sports field fertilizer use

TCCS provided information on the fertilizer application of the public sports grounds in the catchment. Estimates of fertilizer application regimes of privately managed sports grounds are based on information from interviews with Canberra sports turf managers (Edmondson, 2022). Export rates of phosphorus from different fertilizer products (Table 10) were estimated based on a review of experimental studies of TP export rates (Booksmythe, 2023).

Table 10. The amount of phosphorus (P) applied in fertilizers, and literature-derived rates of P export for the fertilizers applied, for three categories of sports field management in the Lake Tuggeranong catchment. Lower, medium, and upper estimates of P export rates are provided, based on the range of values reported for each fertilizer type in the literature.

Sports field type	TP applied (kg/year)	Lower TP export rate (kg/ha/year)	Medium TP export rate (kg/ha/year)	Upper TP export rate (kg/ha/year)
Public sports field	10	0.2	1.2	2.5
'Elite' public sports field	36	0.72	4.32	9
Private sports field	3	0.06	0.36	0.75

We multiplied the annual amount of P applied by the export rates given in Table 10 to calculate a range of estimates of the total P load exported from sports fields in the Lake Tuggeranong catchment (Table 11).

Table 11. The total area of three categories of sports field management in the Lake Tuggeranong catchment, and the estimated total annual load of total phosphorus (TP) exported from each category.

Sports field type	Total area (ha)	Lower total TP exported (kg/year)	Medium total TP exported (kg/year)	Upper total TP exported (kg/year)
Public sports field	58.7	11.74	70.44	146.75
'Elite' public sports field	2.3	1.66	9.94	20.7
Private sports field	7.5	0.45	2.7	5.63
Total	68.5	13.85	83.08	173.08

The median and upper estimates of the total TP exported from sports fields (based on the upper bound of estimates of TP export rate from the literature) are larger than the total TP load of 57.9 kg/year from sports field land use estimated by the Lake Tuggeranong catchment model (Dey, Stewart, Kahn, Booksmythe, & Starrs, 2024).

2.5.2 Phosphorus removal performance

We assess the TP removal performance of installing bioretention swales below public managed sports fields in the Lake Tuggeranong catchment based on the performance of similar existing WSUD infrastructure in the catchment (see Section 2.1.2). We calculated the swale area required to remove the total TP load from sports fields, 57.9 kg P/year, across the range of performance rates in Table 1. In the absence of explicit scoping work investigating possible locations and designs for swales, we made a simplified assumption of the range of TP removal performance: of the total infrastructure required to remove 57.9 kg TP/year, 25% would perform at the highest rate, 25% would perform at the lowest rate, and 50% would perform at the average rate (Table 12). Based on this assumed performance range, the total swale area required to remove the total TP load from sports fields is 7,882 m^2.

Table 12. Phosphorus removal performance bands assumed for bioretention swales installed below sports fields in the Lake Tuggeranong catchment

Performance band	Annual TP removal (kg/m^2/year)	TP load addressed (kg)	Swale area required (m^2)
High performance (25% of assets)	0.0142	14.93	1,016
Average performance (50% of assets)	0.0077	29.86	3,878
Low performance (25% of assets)	0.0048	14.93	2,988

2.5.3 Costing

G2W Pty Ltd were engaged to review the capital and ongoing operation and maintenance costs associated with existing WSUD infrastructure in the Lake Tuggeranong catchment (see section 2.1.3) (G2W Pty Ltd, 2024). Bioretention assets (raingardens and swales) in the Lake Tuggeranong catchment ranged between 765–5,270m^2 in size, and between \$774 - 2,532/m^2 in capital cost, with a strongly negative relationship between size and cost such that on average, larger assets had a lower capital cost per square metre. Similarly, the annual operation and maintenance (O&M) cost of existing bioretention assets ranged between \$62 – 170/m^2, with larger assets having a lower annual O&M cost per square metre. We used these asset size - cost relationships to estimate the capital and O&M costs of constructing between 4 and 24 swales with a total combined area of between 1,016 - 7,882 m^2, and used these capital and O&M cost estimates to calculate the 30-year lifecycle cost, assuming an annual discount rate of 7% each year for O&M costs.

2.5.4 Cost-effectiveness

To provide four levels of investment for this management option, we used the performance bands described in Section 2.5.2 to define four tiers of implementation: to build the best-performing 25%, 50%, 75% or 100% of the swales required to remove the TP load from sports fields (Table 13). Investment option 1 is to build all assets in the 'high performance' band, addressing 25% of the sports field TP load. Investment option 2 builds the assets from option 1, and additionally half the assets in the 'average performance' band, in total addressing 50% of the sports field TP load. Investment option 3 builds all the assets in the 'high' and 'average performance' band, addressing 75% of the sports field TP load, and investment option 4 builds all the assets in all performance bands, addressing 100% of the sports field TP load.

Table 13. Costing summary for four levels of investment in constructing bioretention swales below managed sports fields in the Lake Tuggeranong catchment.

Investment option	Costing level	Total annual TP removed (kg/year)	Total 30-year lifecycle cost[1]	Cost per unit TP removed ($/kg)
1	Build best 25%	14.93	$4,204,451	$9,387
2	Build best 50%	29.85	$11,817,327	$13,196
3	Build best 75%	44.78	$19,430,204	$14,463
4	Build all	59.70	$31,445,222	$17,557

1 Total lifecycle cost is calculated over 30 years using a discount rate of 7% per annum on O&M costs.

2.5.5 Quality of supporting evidence

Using the evaluation rubric (Appendix A), the above estimates of cost-effectiveness of installing bioretention swales below managed sports fields scored 13/14 for confidence in cost estimates, and 9/16 for confidence in performance estimates.

2.6 Management of household fertilizer use practices

2.6.1 Background

Household use of fertilizer products was investigated as a source of TP in the catchment that may be exported from residential blocks. The loss of fertilizer TP from residential blocks could be reduced by community partnership programs designed to alter how people use fertilizer on their block, and/or by legislating to reduce the TP content of fertilizer products, e.g. (Environmental Protection (Packaged Fertiliser) Regulations, 2010).

Concepts of Change were contracted to survey Canberra households on their fertilizer use (including purchased compost, manures, and 'chemical' fertilizer products). Based on the detailed information the survey obtained about the usage rates of different types of fertilizer products, Concepts of Change estimated the amount of phosphorus applied to residential properties (Concepts of Change, 2023). Export rates of phosphorus from different fertilizer products were estimated based on a review of experimental studies of TP export rates (Booksmythe, 2023).

Phosphorus application and export rates from household fertilizer use

Survey respondents lived on residential blocks with garden space - i.e. RZ1 or RZ2 -zoned blocks. The total per-household rate of TP application in fertilizer products estimated from the survey was 0.59 kg TP/year (Table 14).

Table 14. Average annual amounts of total phosphorus (TP) applied to residential blocks in the ACT from chemical fertilizers, commercial composts and raw manures, and literature-derived rates of TP export for these products. Lower, medium, and upper estimates of TP export rates are provided, based on the range of values reported for each fertilizer type in the literature.

Product type	TP applied (kg/household/year)	Lower TP export rate (% of applied)	Medium TP export rate (% of applied)	Upper TP export rate (% of applied)
Fertilizers	0.15	2%	12%	25%
Composts	0.36	0.2%	1%	2.5%
Raw manures	0.07	1%	9%	17%

There are ~21,000 RZ1 and RZ2 -zoned blocks (low to medium density residential, detached and semi-detached dwellings with garden) in the Lake Tuggeranong catchment comprising ~1030 hectares of permeable area (out of 1950 ha total area of RZ1 and RZ2 blocks). Chemical fertilizers account for about 25% of the TP applied to household gardens, but their higher export rates compared to composts and manures mean they are estimated to account for about 65% of the exported TP (Table 15).

Table 15. Annual amounts of total phosphorus (TP) from fertilizer products applied to and exported from residential blocks (RZ1 and RZ2) in the Lake Tuggeranong catchment.

Product type	Total TP applied in catchment (kg/year)	TP applied (kg/ha/year)	Lower total TP exported (kg/year)	Medium total TP exported (kg/year)	Upper total TP exported (kg/year)
Fertilizers	3192	3.10	0.06	0.37	0.78
Composts	7644	7.42	0.02	0.07	0.19
Raw manures	1533	1.49	0.02	0.13	0.25
Total	12369	12.01	0.09	0.58	1.21

The Lake Tuggeranong catchment model (Dey, Stewart, Kahn, Booksmythe, & Starrs, 2024) estimates the total TP load from suburban pervious land in the Lake Tuggeranong catchment to be ~0.12 - 0.16 kg/ha/year, or in the vicinity of the lower estimate from the survey data. The catchment model estimate includes all TP inputs from suburban pervious land (e.g. any TP from leaves & grass clippings, pet waste, etc.) so it suggests that our estimates from the survey data might be too high (even the lower value). Caveats to our current understanding of the TP inputs contributed by household fertilizer use include:

- Although the survey was very detailed and thorough, and estimates of fertilizer use included correction factors based on on-the-ground verification of reported product use, these estimates may still over-estimate the amount of fertilizer applied to residential blocks. Information on Bunnings' annual ACT fertilizer sales suggest rates of 'chemical' fertilizer use are between 12 - 20 times lower than survey estimates.
- Estimates of export rates obtained from the literature varied widely between studies and depend on a large number of factors (e.g. soil type, 'rainfall' intensity and duration, vegetation type and presence). The highest export rate reported in the literature for a given type of fertilizer product was used as the upper estimate in these calculations. This is similar to assuming a 1-in-10 year rain event occurring immediately after fertilizer is applied. The lower estimates may be more realistic, and are more

consistent with the catchment model estimates of the TP load generated by suburban pervious land use in the Lake Tuggeranong catchment.

- The reported rates of phosphorus application suggest that we should see far more phosphorus exported from residential blocks than current water quality data indicates. If the survey-derived estimates of phosphorus application are broadly correct, several further avenues of investigation are required to understand what is happening to this phosphorus, e.g.:
  - how long has phosphorus been applied at this rate?
  - how much phosphorus can be stored in the soil?
  - is excess phosphorus taken up by trees?

2.6.2 Phosphorus removal performance

The management option assessed here is to use specialised community partnership approaches to encourage households to reduce the amount of phosphorus fertilizer products they apply to residential blocks.

To estimate the potential TP reduction resulting from this approach, we assume a community partnership program that gets the top 20% of P-inputting households to reduce their inputs by 20% (this outcome is chosen based on advice from Concepts of Change). Using the fertilizer survey data and TP export rates from the literature, the amount of TP applied and exported by the top 20% of users can be calculated. Reducing these inputs by 20% and adding the unaltered inputs from the remaining 80% of users, gives a reduction of 17% of the current total household P exports.

To calculate the estimated TP load reduction of this option, we assume that household fertilizer TP exports occur in event flows, and any reduction will not affect the baseflow TP loads coming from suburban pervious areas in the Source catchment model. This baseflow TP load is estimated to be 0.018 kg/ha/year. This is subtracted from the total modelled TP load from suburban pervious areas (~0.12 - 0.16 kg/ha/year) to give the estimated event flow TP load, of between 0.103 - 0.142 kg/ha/year.

We also assume that the catchment model estimates represent the upper limit of current household fertilizer TP exports. This means that the median and upper TP export estimates (Table 13) based on the survey data and export rates from the literature are too large to be consistent with the model. In providing an estimated range of the TP load reduction from banning phosphorus in fertilizers, we use the lower TP export estimate from the survey and literature review as the lower bound, and the catchment model estimate of suburban pervious event flow load as the upper bound (Table 16).

To calculate the percent reduction in the suburban pervious TP load resulting from this community partnership program, we add the baseflow loads to the new event flow loads from fertilizer and divide this by the current total suburban pervious load. This gives an estimated maximum TP reduction of between 14 - 41% of the current load contributed by suburban pervious areas, or the removal of between 20 - 58 kg of the current 140.3 kg TP/year.

Table 16. Estimating the reduction in TP load from suburban pervious land use resulting from a 17% reduction in current TP inputs from household fertilizer use. The range of values in each cell reflects the range of estimated TP export rates from the fertilizer applied to residential blocks.

Total TP load from suburban pervious land use (kg/ha/year)[1]	Current event-flow TP load from fertilizer (kg/ha/year)[2]	Reduced event-flow TP load from fertilizer (kg/ha/year)	Reduced event-flow TP load from fertilizer, plus baseflow load (kg/ha/year)	Percent reduction in total TP load from suburban pervious land use (kg/ha/year)
Lower estimate: 0.121	0.092 – 0.103	0.076 – 0.085	0.094 – 0.103	14.5 – 22.2%
Upper estimate: 0.160	0.092 – 0.142	0.076 – 0.118	0.094 – 0.136	15.1 – 41.2%

1 Estimated from the catchment model for the Lake Tuggeranong catchment (Dey, Stewart, Kahn, Booksmythe, & Starrs, 2024).

2 Estimates for the event-flow TP load from household fertilizer use are capped at the model-estimated total event-flow TP load from all suburban pervious land use, 0.103 or 0.142 kg TP/ha/year.

2.6.3 Costing

The lower cost estimate is based on the cost of a 6-month Concepts of Change community partnership program implemented in 2024, scaled up to run over 5 years and reach all households in the Lake Tuggeranong catchment. The higher cost estimate is based on expert opinion provided by Concepts of Change for the cost of a 5-year intensive campaign to achieve the reductions described in this section across all of Canberra. 30-year costings use a discount rate of 7% per annum after the first year, and assume that the intensive 5-year campaign runs twice (years 0-4 and 15-19), and that for all intervening years, maintenance costs of $350,000/year are required for both costing levels.

2.6.4 Cost-effectiveness

Based on the above, management of household fertilizer use by way of a community partnership program aimed at reducing the TP inputs of the top 20% of users by 20% is predicted to remove between 20 - 58 kg TP per year at a cost of between $3,700 - $24,000 per kg TP removed, over 30 years (Table 17).

Table 17. Estimated annual program and maintenance costs, total 30-year lifecycle cost, and cost-effectiveness of options for management of household fertilizer use.

Costing level	Annual program cost (2 x 5-year programs in 30-year lifecycle)	Annual maintenance cost (non-program years)	Total 30-year lifecycle cost[1]	Cost per unit TP removed ($/kg) – low performance	Cost per unit TP removed ($/kg) – high performance
Lower cost estimate	$637,000	$350,000	$6,362,682	$10,604	$3,657
Higher cost estimate	$2,000,000	$350,000	$14,509,794	$24,183	$8,399

1 Total lifecycle cost is calculated over 30 years using a discount rate of 7% per annum on O&M costs.

However, how cost estimates relate to the efficacy of this option is uncertain. We have no information on whether cost-effectiveness would increase or decrease with the scale of investment in a community partnership program to manage household fertilizer use.

In providing four levels of investment for this management option, we therefore assumed a uniform cost-effectiveness of $10,000/kg TP removed at all four levels of investment. This value was chosen as it falls within the cost-effectiveness estimates generated from both cost estimates above, and results in a realistic range of total program costs (between $6 and $17 million) when applied to the lower and upper estimates of the reduction in TP achieved by such a program. We used the lower and upper estimates of TP removal as the amount that would be removed by the lowest and highest levels of investment in this management option, respectively, and interpolated two evenly-spaced levels of TP removal between these extremes (Table 18).

Table 18. Costing summary for four levels of investment in community partnership programs aimed at managing household fertilizer use to reduce TP inputs in the Lake Tuggeranong catchment.

Investment level	Assumed program implementation	Annual TP removed (kg)	Total 30-year lifecycle cost[1]	Cost per unit TP removed ($/kg)
1	Low implementation	20	$6,000,000	$10,000
2	Medium implementation	32.67	$9,800,000	$10,000
3	High implementation	45.33	$13,600,000	$10,000
4	Very high implementation	58	$17,400,000	$10,000

1 Total lifecycle cost is calculated over 30 years using a discount rate of 7% per annum on annual costs after the first year.

2.6.5 Quality of supporting evidence

Using the evaluation rubric (Appendix A), the above estimates of cost-effectiveness of community partnership programs aimed at managing household fertilizer use scored 9/14 for confidence in cost estimates, and 7/16 for confidence in performance estimates.

2.7 Installation of castellated kerbs

2.7.1 Background

The stormwater network of the Lake Tuggeranong catchment was designed and built to be extremely efficient at directing stormwater into the piped network. The prevailing paradigm at the time was to minimise flood risk by getting stormwater out of residential areas as efficiently as possible. Consequently, the Lake Tuggeranong catchment stormwater network is dominated by concrete drains and a significant underground stormwater pipe network.

Almost all stormwater that ends up on sealed roads is diverted directly into the underground stormwater pipe network via the sumps along the kerbs. A small number of sealed roads in the Lake Tuggeranong catchment divert stormwater directly to public open space.

Castellated kerbs are concrete kerbs that include engineered breaks or channels diverting water to adjacent pervious land. Retrofitting castellated kerbs on roads adjacent to public open space in the Lake Tuggeranong catchment has two potential benefits for improving water quality in the lake. Firstly,

stormwater diverted to public open space is able to infiltrate the soil, allowing the capture of nutrients and sediment from the water. Secondly, the flow of the portion of stormwater diverted to public open space is slowed, and the volume of water remaining in the stormwater network is reduced. These effects reduce the hydrological flashiness in downstream areas of the catchment, with benefits for the function of other WSUD infrastructure. Estimating these secondary effects on downstream hydrology is extremely complex and beyond the capability of this assessment. Here, phosphorus removal performance estimates are estimates of the amount of stormwater and pollution diverted from sealed roads.

The Lake Tuggeranong catchment model estimates that 582 kg TP/year is generated from the 388 ha of impervious road surface area in the catchment (Dey, Stewart, Kahn, Booksmythe, & Starrs, 2024). Using ACT Government GIS layers for land zoning and roads, the surface area of road that is adjacent to public open space is 166.15 ha, or 43% of the total road area. Assuming that pollutant generation is uniform, the amount of TP generated on roads adjacent to public open space is calculated as 249 kg/year (43% of the total road TP load). However, in some instances, the road will slope away from the adjacent open space – here we assume that on average, half of the road area adjacent to public open space has a slope suitable to allow drainage towards the open space, and so half of the TP generated on this road area – 124.5 kg TP/year – is currently received by the 1813 stormwater sumps located along kerbs bordering public open space.

2.7.2 Phosphorus removal performance

Not all of the TP currently received by stormwater sumps bordering open space would be diverted to castellated kerb outlets, as these outlets are not able to receive as much road runoff as stormwater sumps, and will be bypassed when the pervious land is saturated. Here we conservatively assume that a castellated kerb outlet can receive half as much runoff as a stormwater sump.

Under these assumptions, if a castellated kerb outlet was installed immediately ‘upstream’ of each of the 1813 stormwater sumps located on kerbs bordering public open space, intercepting half of the road runoff received by each sump, 62 kg TP/year would be diverted from the stormwater network. This represents an upper limit to the amount of TP removed, as it is likely an unrealistically high rate of installation, and does not take into account logistical considerations for construction or issues such as changes to the road flooding risk. Lower rates of installation result in proportionally lower rates of TP removal: installing a castellated kerb outlet for every second, third, or fourth sump would remove 31, 20.75, or 15.5 kg TP/year, respectively.

2.7.3 Costing

The cost to retrofit castellated kerb outlets was reported as $6,872 per outlet in the preliminary sketch plan (PSP) report by Construction Control Australia for a project to construct 36 outlets in the Lake Tuggeranong catchment as part of Stage 2 of the ACT Healthy Waterways project (Construction Control Australia Pty Ltd, 2022). We used this figure as our lower estimate of the cost of this management option. An alternative costing estimate of $10,000 per outlet is is derived from the estimated cost in 2024 for the construction of 51 outlets of $18,802 per outlet (GW2, 2024), and assumes an economy of scale to achieve a reduced per unit cost.

2.7.4 Cost-effectiveness

We assume a lifecycle of 30 years for castellated kerbs, consistent with other management options. However, no reliable estimate of the maintenance costs of castellated kerb outlets was obtained, and our estimates of cost-effectiveness of this management option are based solely on the capital cost of installation.

In calculating the cost-effectiveness of castellated kerbs as a management option, we incorporated a range of installation frequencies (an outlet for every sump – an outlet for every 4 sumps) and costs (between the lower and higher cost estimates obtained, above). We assumed an economy of scale such that installing outlets at the lower rate of one for every four sumps incurs the highest per-outlet cost of $10,000, but there is a marginal decrease in per-outlet costs as more outlets are installed (Table 19).

2.7.5 Quality of supporting evidence

Using the evaluation rubric (Appendix A), the estimates of cost-effectiveness of installing castellated kerb outlets scored 11/14 for confidence in cost estimates, and 7/16 for confidence in performance estimates.

Table 19. Estimated annual load of total phosphorus (TP) prevented from entering Lake Tuggeranong, cost per castellated kerb outlet installed, total 30-year lifecycle cost, and cost-effectiveness of for four levels of investment into retrofitting castellated kerb outlets to divert road runoff from the stormwater network.

Investment level	Number of outlets installed	TP removed (kg/year)	Cost per outlet	Cumulative total lifecycle cost[1]	Cost per unit TP removed ($/kg)
1	453 (1 per 4 sumps)	15.56	$10,000	$4,532,500	$9,708
2	604 (1 per 3 sumps)	20.75	$9,652	$5,990,823	$9,624
3	906 (1 per 2 sumps)	31.13	$8,957	$8,539,901	$9,146
4	1813 (1 per sump)	62.25	$6,872	$14,349291	$7,684

1 Cumulative total lifecycle cost is calculated based on the assumed marginal improvement in per-unit cost between installation tiers. For example, the total cost of installing 453 outlets (the lowest installation rate) is equal to 453 times the unit cost of $10,000. The total cost of installing 604 outlets (the second-lowest installation rate) is equal to the cost of installing 453 outlets at $10,000, plus 153 outlets at the unit cost of $9,652.

2.8 Installation of floating wetlands

2.8.1 Background

Once nutrients are transported into a waterbody, they may become available for uptake by plants, algae, and bacteria, including blue-green algae. Fringing and in-lake vegetation can help to limit blue-green algae blooms by competing with them for these nutrients, particularly phosphorus. One approach to increasing in-lake vegetation is to install floating wetlands.

Floating wetlands are floating structures supporting beds of emergent wetland vegetation, deployed in lakes and ponds to remove nutrients from the water. The plants take up the nutrients they need as they grow, and regular harvesting of the plants prevents the recycling of those nutrients back into the water. The ACT Healthy Waterways program contracted Atlan Stormwater to trial floating wetlands in Lake Tuggeranong in 2023 (Atlan Stormwater, 2023). Three floating platforms totalling 500m^2 were installed, with three species of wetland plants compared for their nutrient uptake rates. The data from this trial inform the estimates of TP removal performance and cost of this management option.

2.8.2 Phosphorus removal performance

In the trial, the floating wetland plants were harvested once, after a year of deployment, and the increase in their TP content was recorded as a measure of the amount of TP they removed from the lake. From this we can calculate the amount of TP removed from the lake per square metre of floating wetland area for each plant species separately. The worst-performing species removed 0.001kg TP/m^2/year, and the best-performing species removed 0.005kg TP/m^2/year. The average amount of TP removed by all three species was 0.003kg TP/m^2/year, and we used this as our estimate of floating wetland TP removal performance.

2.8.3 Costing

G2W Pty Ltd were engaged to review the costs associated with existing WSUD infrastructure in the Lake Tuggeranong catchment (G2W Pty Ltd, 2024). The average capital cost of the trialled floating wetlands was \$1,049/m^2, and the annual maintenance cost was \$13.24/m^2.

2.8.4 Cost-effectiveness

We calculated the cost-effectiveness of floating wetlands based on the above TP removal performance and costs over a 30-year lifecycle, as \$13,622.2/kg TP removed. We assume that both cost and performance scale linearly with floating wetland area, so cost-effectiveness remains the same for any size of wetland. To provide four levels of investment in this management option, we used four sizes of floating wetland area (Table 20).

Table 20. Wetland area, estimated TP removal performance, estimated capital cost and annual operation and maintenance costs, 30-year lifecycle costs and cost-effectiveness for four levels of investment in installation of floating wetlands in Lake Tuggeranong.

Investment level	Wetland area (m^2)	Total annual TP removed (kg)	Capital cost	Annual operation and maintenance costs	Total 30-year lifecycle cost[1]	Cost per unit TP removed ($/kg)
1	1000	3	$1,049,000	$13,240	$1,226,000	$13,622.2
2	2000	6	$2,098,000	$26,480	$2,452,000	$13,622.2
3	3000	9	$3,147,000	$39,720	$3,678,000	$13,622.2
4	4000	12	$4,196,000	$52,960	$4,904,000	$13,622.2

1 Total lifecycle cost is calculated over 30 years using a discount rate of 7% per annum on O&M costs.

2.8.5 Quality of supporting evidence

Using the evaluation rubric (Appendix A), the above estimates of cost-effectiveness of installing floating wetlands in Lake Tuggeranong scored 10/14 for confidence in cost estimates, and 9/16 for confidence in performance estimates.

2.9 Installation of stormwater recycling infrastructure

2.9.1 Background

Urban stormwater contains high concentrations of nutrients because the large area covered by impervious surfaces in the urban environment prevents water from soaking into the ground and being naturally filtered through the soil. Diverting some stormwater for use in the irrigation of public sports fields removes nutrients from the stormwater system. It also slightly reduces the volume of stormwater that continues through the system, reducing hydrological flashiness to the benefit of downstream WSUD infrastructure.

In the Lake Tuggeranong catchment, a stormwater recycling system for sports field irrigation has been installed at one publicly managed sports field (TCCS ID: Kambah 3). A further ten publicly managed sports fields at 8 sites in the Lake Tuggeranong catchment are currently irrigated using potable water, with a combined irrigation water demand of 194 ML/year, at an average cost of $5,478/ML. Here we assess the TP removal performance and cost of installing stormwater recycling infrastructure for sports field irrigation across these sites.

2.9.2 Phosphorus removal performance

As we assume that 100% of the P in stormwater is removed when water is used for irrigation, the amount of TP removed depends on the amount of stormwater used for irrigation. TCCS provided data on the average annual water demand for 10 irrigated sports fields at 8 sites in the Lake Tuggeranong catchment (Table 18). In wet years, irrigation water demand is low and stormwater is abundant, conditions that make it likely that 100% of demand can be met using recycled stormwater. In dry years, however, water demand is high and stormwater is relatively scarce. This, combined with the flashy nature of stormwater hydrographs, make it unlikely that all the irrigation demands will be met by stormwater. We therefore assume that overall, 75% of average annual potable water demands would be met using stormwater (Table

20). We assume a TP concentration of 0.15mg/L to calculate the potential load of TP removed by harvesting stormwater to irrigate these sports fields (Table 21). This value is the average median observed TP in the University of Canberra research data used to calibrate the catchment model (Ubrihien, et al., 2020).

Table 21. Annual irrigation demand, estimated demand met by recycled stormwater, and estimated annual TP load in recycled stormwater, for 8 sports field sites[1] in the Lake Tuggeranong catchment.

Sports field ID	Total annual irrigation water demand (ML)	Demand met by stormwater = 75% of total (ML)	TP load in stormwater used for irrigation (kg)
Calwell 1, 2, 3[1]	47.15	35.36	5.30
Kambah 1	31.18	23.38	3.51
Wanniassa 2	28.40	21.30	3.19
Greenway 1	27.70	20.77	3.12
Gowrie 1	18.68	14.01	2.10
Kambah 2	17.49	13.12	1.97
Chisholm 1	15.21	11.41	1.71
Isabella 1	7.76	5.82	0.87
Total	193.57	145.17	21.78

1 TCCS provided a combined irrigation demand for three Calwell sports fields, which are treated as a single site.

2.9.3 Costing

The estimated costs of installing stormwater recycling infrastructure are based on the realised cost of the infrastructure installed at Kambah 3 (GW2, 2024) and assume that each system will include the same components, namely:

- Stormwater treatment train (gross pollutant trap, sediment forebay, and wetland/pond/raingarden)
- Pumps and pipe infrastructure
- Water treatment plant (sand filter and UV filter)
- Water holding tanks (1 ML capacity)
- Operation and maintenance

These costs will be offset by the savings accrued as a result of the 75% reduction in the use of potable water and its associated cost of $5,478/ML.

The infrastructure installed at sports field Kambah 3, which has an average annual water demand of 26.6 ML, had capital costs of approximately $1,500,000, and annual operation and maintenance costs of $65,000. This site had existing water tanks for irrigation, which is not the case for all of the sites costed here. We therefore take these as the lower bound of cost estimates, and assign this minimum cost to sports fields with an average annual water demand equal to or less than that of Kambah 3. We assume that more infrastructure will be required to divert, filter, store, and irrigate more water, and that operation and maintenance of larger facilities will increase similarly. Both the capital costs and O&M costs for stormwater

recycling infrastructure installed at sports fields with larger water demands than Kambah 3 are scaled up in proportion to their demand (Table 22).

2.9.4 Cost-effectiveness

While sports fields with the highest annual irrigation demands have the highest capital and O&M costs, they also experience the largest savings from reduced potable water expenses and remove the largest TP loads, representing the most cost-effective options (Table 22).

Table 22. Capital cost, annual operation and maintenance cost, savings from reduced potable water use, 30-year lifecycle cost, and cost-effectiveness for the installation of stormwater recycling infrastructure for irrigation at 8 sports field sites in the Lake Tuggeranong catchment.

Sports field ID	Capital cost	Annual operation and maintenance cost	Savings from potable water expenses	Total 30-year lifecycle cost[1]	Cost per unit TP removed ($/kg)
Calwell 1, 2, 3	$2,661,034	$115,311	-$193,726	$1,609,575	$10,115
Kambah 1	$1,759,537	$76,247	-$128,096	$1,064,288	$10,115
Wanniassa 2	$1,602,639	$69,452	-$116,681	$969,446	$10,115
Greenway 1	$1,563,316	$67,744	-$113,811	$945,600	$10,115
Gowrie 1	$1,500,000	$65,000	- $76,748	$1,342,472	$21,295
Kambah 2	$1,500,000	$65,000	- $71,868	$1,407,903	$23,850
Chisholm 1	$1,500,000	$65,000	- $62,496	$1,533,578	$29,875
Isabella 1	$1,500,000	$65,000	- $31,887	$1,994,008	$74,221

1 Total lifecycle cost is calculated over 30 years using a discount rate of 7% per annum on both annual O&M costs and savings from reduced potable water expenses.

To provide four levels of investment in this management option, we grouped the 8 sports field sites by size and cost-effectiveness and created four tiers of installation: either build the best two, best four, best six, or all 8 stormwater recycling systems (Table 23).

Table 23. Costing summary for four levels of investment in installing stormwater recycling infrastructure for sports field irrigation in the Lake Tuggeranong catchment.

Investment option	Costing level	Total annual TP removed (kg/year)	Total 30-year lifecycle cost[1]	Cost per unit TP removed ($/kg)
1	Build best 2	8.81	$2,673,863	$10,115
2	Build best 4	15.12	$4,588,909	$10,115
3	Build best 6	19.19	$7,339,284	$12,748
4	Build all 8	21.78	$10,816,870	$16,558

1 Total lifecycle cost is calculated over 30 years using a discount rate of 7% per annum on O&M costs.

2.9.5 Quality of supporting evidence

Using the evaluation rubric (Appendix A), the above estimates of cost-effectiveness of installing stormwater recycling infrastructure for sports field irrigation scored 10/14 for confidence in cost estimates, and 10/16 for confidence in performance estimates.

2.10 Installation of household rainwater tanks

2.10.1 Background

Residential properties make up a large proportion of the Lake Tuggeranong catchment area, and consist of large areas of impervious surface in the form of rooftops. Residential properties are therefore expected to be a significant contributor to the generation of nutrient pollutants and runoff in the catchment.

Encouraging the installation of plumbed household rainwater tanks on residential properties, by covering some or all of the associated costs to property owners, is a potential approach to reducing this source of runoff. Installation of plumbed rainwater tanks at residential properties diverts runoff, and the phosphorus it carries, from the stormwater system, instead directing it to non-potable household uses and on to the wastewater (sewage treatment) system, or to garden uses from where it completes the water cycle either via evapotranspiration or by entering the groundwater. When properly plumbed in and used, household rainwater tanks help to reduce the intensity of rises in water level and flow during rainfall events (i.e. flatten the hydrograph), which should be beneficial for the TP removal performance of downstream WSUD infrastructure. Rainwater tanks provide some opportunity to directly capture phosphorus when particulate forms are deposited within the tanks, although this effect is likely to be small.

2.10.2 Phosphorus removal performance

To calculate the amount of TP diverted from the stormwater system by rainwater tanks we used estimates of the annual amount of water captured and used by plumbed rainwater tanks, from a study that modelled the savings in potable water offered by residential rainwater tanks in Canberra (Imteaz, Yilmaz, Santos, & Ahsan, 2023). Their estimates account for seasonal variability in rainfall, the typical non-potable water demands of a household, and the spillover of water to the stormwater system when tanks are over capacity, and are broadly summarised for a range of roof and tank sizes in Table 24.

Table 24. Potable water savings from plumbed household rainwater tanks, estimated by Imteaz et al. 2023.

Roof size (m^2)	Tank size (L)	Water saved – dry year (L/year)	Water saved – average year (L/year)	Water saved – wet year (L/year)
100	2,500	35,000	50,000	55,000
200	5,000	40,000	55,000	60,000
100	2,500	50,000	60,000	65,000
200	5,000	60,000	75,000	80,000

These estimated water savings represent the amount of residential runoff diverted from the stormwater system by plumbed rainwater tanks. By multiplying these by the estimated concentration of TP in runoff from suburban roof area in the Lake Tuggeranong catchment (from the calibrated catchment model) we can calculate the approximate load of TP removed per household (Table 25).

Table 25. Estimated loads of TP diverted from the stormwater system by plumbed household rainwater tanks.

Roof size (m^2)	Tank size (L)	TP removed – dry year (L/year)	TP removed – average year (L/year)	TP removed – wet year (L/year)
100	2,500	3.82	5.45	5.99
200	5,000	4.36	5.99	6.54
100	2,500	5.45	6.54	7.09
200	5,000	6.54	8.18	8.72

While the annual load of TP removed from the stormwater system per household is small, ranging between approximately 4-8 g/year, multiplying by the number of residential properties in the Lake Tuggeranong catchment (~21,000 RZ1- and RZ2-zoned blocks) gives an upper estimate of annual TP removal of between 84-168 kg/year.

However, this assumes 100% uptake in rainwater tank installation, which is unlikely for several reasons. An estimated 36% of households in the ACT already have rainwater tanks installed, and therefore do not contribute to this source of TP (Schirmer & Dale, 2023). Some households may not be willing or able to install rainwater tanks, and others may not make full use of the water captured by their tanks, which increases spillover and reduces the amount of water diverted from the stormwater system. In costing this option we assume that the highest rate of uptake of new household rainwater tanks would be 10,000 households, or around 50% of residential properties in the Lake Tuggeranong catchment.

2.10.3 Costing

For this management option we estimate costs for a government grant scheme that covers the capital cost of rainwater tank installation for residential properties in the Lake Tuggeranong catchment. Rainwater tanks installed on suburban residential properties are typically of 1,000 - 3,000 L capacity, and cost between $1,000 - $2,000. Adding the costs of installation and plumbing, here we assume a total cost per household of $5,000 that would be provided by government funding. Rainwater tanks are fairly low maintenance, and we assume any operation and maintenance costs would be left to property owners in costing this management option.

2.10.4 Cost-effectiveness

We assume an average rainwater tank TP removal performance of 6 g/year, at a cost of $5,000 per tank installed. Over a 30-year lifecycle, this gives a cost-effectiveness estimate of $27,778 per kg TP removed. To provide four levels of investment in this management option, we costed rates of uptake of rainwater tank installation of between 2,500 and 10,000 households (Table 26).

Table 26. Costing summary for four levels of investment in installing household rainwater tanks on residential properties in the Lake Tuggeranong catchment.

Investment level	Number of households	Total TP removed (kg)	Total 30-year lifecycle cost[1]	Cost per unit TP removed ($/kg)
1	2,500	15	$12,500,000	$27,778
2	5,000	30	$25,000,000	$27,778
3	7,500	45	$37,500,000	$27,778
4	10,000	60	$50,000,000	$27,778

1 30-year lifecycle cost is the capital cost of tank installation, as we assume no operation and maintenance costs for this option.

2.10.5 Quality of supporting evidence

Using the evaluation rubric (Appendix A), the above estimates of cost-effectiveness of a government grant scheme that covers the capital cost of rainwater tank installation for residential properties in the Lake Tuggeranong catchment scored 6/14 for confidence in cost estimates, and 9/16 for confidence in performance estimates.

3. Designing management scenarios

3.1 Comparing the cost-effectiveness of management options

Table 27 presents the annual load of TP removed, the 30-year cost, and the cost-effectiveness of the four levels of investment for the management options assessed in Section 2. We plotted the range of TP removal performance and cost of each management option across the levels of investment to provide a visual comparison of the management options and the range of cost-effectiveness for each option (Fig. 1). Increasing street sweeping frequency and constructing additional WSUD infrastructure were estimated to remove the largest amounts of phosphorus annually, in the range of 100-400 kg/year. Street sweeping was the more cost-effective of these two approaches, estimated at $1,000-2,500 per kg TP removed, while constructing WSUD infrastructure had costs of between $7,000-12,000 per kg P. The remaining options all had lower total annual TP removal performances and ranged in cost-effectiveness up to $28,000 per kg TP.

Table 27. Summary of phosphorus removal performance, total cost, and cost-effectiveness for four levels of investment for each of 10 management options assessed in this report. See Section 2 for details of the investment levels for each management option.

Management option and level	TP removed (kg/year)	30-year cost ($)[1]	Cost-effectiveness ($/kg TP)
Install additional WSUD 1	106.21	$22,507,500	$7,064
Install additional WSUD 2	169.67	$48,369,492	$9,502
Install additional WSUD 3	226.22	$73,862,467	$10,884
Install additional WSUD 4	240.46	$84,519,403	$11,716
Maintenance of existing WSUD 1	35.84	$10,177,128	$9,465
Maintenance of existing WSUD 2	61.78	$19,086,579	$10,298
Maintenance of existing WSUD 3	79.93	$26,352,433	$10,990
Maintenance of existing WSUD 4	88.02	$30,352,433	$11,495
Increase street sweeping 1	203.7	$7,030,414	$1,150
Increase street sweeping 2	320.1	$14,060,827	$1,464
Increase street sweeping 3	372.5	$21,091,242	$1,887
Increase street sweeping 4	395.8	$28,121,656	$2,369
Manage grass clippings 1	16.4	$2,018,874	$4,103
Manage grass clippings 2	26.1	$2,018,874	$2,578
Manage grass clippings 3	32.7	$1,521,462	$1,551
Manage grass clippings 4	52.3	$1,565,956	$998
Sports field fertilizer management 1	14.93	$4,204,451	$9,387
Sports field fertilizer management 2	29.85	$11,817,327	$13,196
Sports field fertilizer management 3	44.78	$19,430,204	$14,463

Management option and level	TP removed (kg/year)	30-year cost ($)[1]	Cost-effectiveness ($/kg TP)
Sports field fertilizer management 4	59.70	$31,445,222	$17,557
Household fertilizer management 1	20	$6,000,000	$10,000
Household fertilizer management 2	32.67	$9,800,000	$10,000
Household fertilizer management 3	45.33	$13,600,000	$10,000
Household fertilizer management 4	58	$17,400,000	$10,000
Install castellated kerbs 1	15.56	$4,532,500	$9,708
Install castellated kerbs 2	20.75	$5,990,823	$9,624
Install castellated kerbs 3	31.13	$8,539,901	$9,146
Install castellated kerbs 4	62.25	$14,349,291	$7,684
Install floating wetlands 1	3	$1,226,000	$13,622.2
Install floating wetlands 2	6	$2,452,000	$13,622.2
Install floating wetlands 3	9	$3,678,000	$13,622.2
Install floating wetlands 4	12	$4,904,000	$13,622.2
Stormwater recycling for irrigation 1	8.81	$2,673,863	$10,115
Stormwater recycling for irrigation 2	15.12	$4,588,909	$10,115
Stormwater recycling for irrigation 3	19.19	$7,339,284	$12,748
Stormwater recycling for irrigation 4	21.78	$10,816,870	$16,558
Household rainwater tanks 1	15	$12,500,000	$27,778
Household rainwater tanks 2	30	$25,000,000	$27,778
Household rainwater tanks 3	45	$37,500,000	$27,778
Household rainwater tanks 4	60	$50,000,000	$27,778

1 Total lifecycle cost is calculated over 30 years using a discount rate of 7% per annum on annual (O&M) costs after the first year.

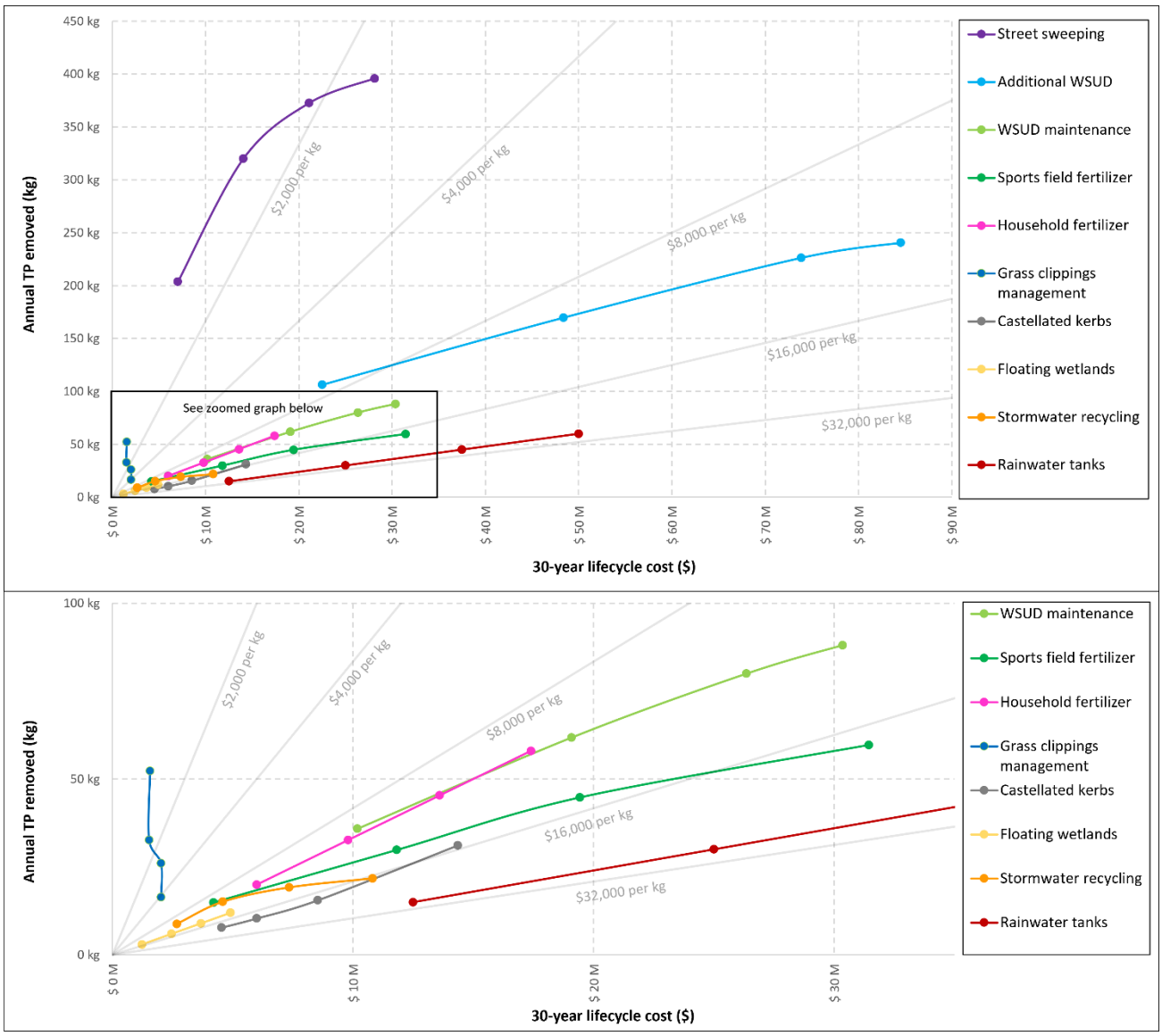

Figure 1. Annual total phosphorus load removed, and 30-year lifecycle cost, of each investment level for the 10 management options assessed in Section 2. Coloured lines connect the four estimates for each management option. Grey lines are a guide indicating the cost-effectiveness (cost per kg TP removed) of the estimates. The top panel shows all estimates; the bottom panel shows a zoomed in view of the estimates within the inset box.

The results of the management option assessments show that there is no single option capable of achieving the estimated ~700 kg reduction in annual phosphorus load required to maintain Lake Tuggeranong in a predominantly mesotrophic state (Kahn & Dey, 2024). To approach this target reduction, a combination of several management options aimed at reducing and intercepting catchment sources of phosphorus will be necessary.

3.2 Combining options to build management scenarios

The Healthy Waterways planning team used the information in Section 2, Table 27 and Figure 1 to create two scenarios, consisting of different combinations of management options, that achieved a reduction in the total annual phosphorus load entering Lake Tuggeranong of around 700 kg (Table 28).

Table 28. Comparison of the investment levels of management options selected for inclusion in the Cost-effective and Broad benefits scenarios designed to achieve a 700 kg reduction in the annual phosphorus load entering Lake Tuggeranong.

Management option	Cost-effective scenario	Broad benefits scenario
Install additional WSUD infrastructure	Investment level 1	Investment level 2
Maintenance of existing WSUD infrastructure	Investment level 3	Investment level 4
Increase frequency of street sweeping	Investment level 4	Investment level 3
Manage grass clippings from municipal mowing	Investment level 3	Investment level 3
Sports field fertilizer management	Investment level 1	Investment level 3
Household fertilizer management	Investment level 4	Investment level 1
Install castellated kerbs	n/a	Investment level 1
Install floating wetlands	n/a	Investment level 4
Stormwater recycling for sports field irrigation	Investment level 2	Investment level 3
Sum of annual TP removed	702.65 kg	766.62 kg
Total 30-year cost	$104,696,482	$143,540,616

The **Cost-effective scenario** systematically ranked the investment levels of each management option by cost-effectiveness, and selected the most cost-effective investment level of the most cost-effective options until the total annual phosphorus load removed met the 700 kg target. This scenario prioritized management options that prevent pollutants from entering the stormwater system, such as street sweeping and fertilizer management, as these have high cost-effectiveness. Options involving WSUD infrastructure were given lower priority under this approach, as they tend to have high costs for more limited phosphorus removal capacity. Some options, including rainwater tanks, floating wetlands, and castellated kerbs, were not considered to be sufficiently cost-effective for inclusion in this scenario.

The **Broad benefits scenario** considered additional information, as well as cost-effectiveness, when selecting management options to meet the 700 kg phosphorus removal target. This approach took into account the quality of evidence underlying each management option assessment, avoiding large investments into options with less certainty around their cost or performance estimates. Broader community and government values, including wellbeing, climate resilience, and public amenity, were also considered when selecting options to include in this scenario. This led to a wider variety of options being

selected for the broad benefits scenario compared to the cost-effective scenario, including more options involving WSUD infrastructure (Table 28).

The TP removal and cost-effectiveness estimates obtained for each management option do not consider the way that options may interact and affect each other's performance. For example, decreasing the load of phosphorus entering stormwater by frequent street sweeping in the catchment should result in lower phosphorus concentrations in the stormwater intercepted by a raingarden further downstream, reducing the phosphorus available for the raingarden to remove. Some of these interacting effects can be estimated by implementing combinations of management options in the catchment model, and calculating the total reduction in the phosphorus load entering Lake Tuggeranong under different combinations.

3.3 Modelling management scenarios

The two scenarios summarised in Table 28 were implemented in the catchment model, to generate estimates of the total annual load of phosphorus entering Lake Tuggeranong under each scenario, while accounting for interactive effects of different management options (Dey, Stewart, Kahn, Booksmythe, & Starrs, 2024).

Different management options are implemented in different ways in the catchment model. Some options are explicitly represented by the addition or modification of specified links and nodes in the model:

- **Additional WSUD infrastructure** Proposed raingardens were represented in the catchment model by new storage nodes placed at the locations indicated in the original plans for the raingardens. The raingarden nodes were configured using the size indicated in the original plans, and the performance details of similar existing WSUD assets.
- **Maintenance of existing WSUD infrastructure** The catchment model includes storage nodes representing each WSUD asset in the Lake Tuggeranong catchment, with the performance of each asset configured to reflect its current phosphorus removal efficiency. To represent maintenance of these assets to their designed performance, the performance details were reconfigured to the phosphorus removal rates given in the detailed design reports for each asset.
- **Sports field fertilizer management** For each scenario we modelled sufficient bioretention swales to intercept the required amount of sports field-generated phosphorus (i.e., 25% or 75% of all sports field generated phosphorus). We modelled one swale per subcatchment, with swale size proportional to the area of sports field in each subcatchment. Bioretention swale performance was configured using the performance details of similar existing WSUD assets. As the scale of the catchment model does not delineate sports fields from their subcatchments, a controlled splitter was used to divert water to the node representing each swale, in proportion to the swale : subcatchment area ratio.
- **Stormwater recycling infrastructure for sports field irrigation** Each sports field with stormwater recycling infrastructure was represented by a storage node and an irrigator node. A maximum of 1 ML water was diverted to the storage node via a controlled splitter during event flows. The water in the storage node was used to meet the irrigation demand specified by the irrigator node. Excess water was returned to the stormwater system downstream of the sports field.
- **Floating wetlands** To represent floating wetlands in the catchment model, a storage routing link was added just upstream of the Lake Tuggeranong storage node. This was configured using a decay model to reduce the phosphorus concentration in the water passing through the routing link.

The remaining options were implemented in the model by calculating the percentage phosphorus removal attained by each option, compared to the current load of phosphorus available to be intercepted by that option, and adjusting phosphorus concentrations within the catchment model based on these percentage reductions:

- **Increase street sweeping frequency** The percentage reduction in phosphorus concentration due to increased street sweeping was applied to all area classified as road, and calculated based on the difference in total phosphorus load generated from roads across the catchment with and without an increase in street sweeping frequency.
- **Manage grass clippings from municipal mowing** The percentage reduction in phosphorus concentration due to management of grass clippings from municipal mowing was applied to all area classified as road, and calculated based on the difference in total phosphorus load generated from roads across the catchment with and without management of grass clippings.
- **Install castellated kerbs** The percentage reduction in phosphorus concentration due to the installation of castellated kerbs was applied to all area classified as road, and calculated based on the difference in total phosphorus load generated from roads across the catchment with and without the installation of castellated kerbs.

  As street sweeping, grass clipping management, and castellated kerbs all act to reduce the load of phosphorus generated from roads, the combined effects of these management options were modelled using a build-up wash-off model as described in 2.3.2 and used to predict the total percentage reduction in the phosphorus load from roads due to the selected combination of these options in each scenario.
- **Household fertilizer management** The percentage reduction in phosphorus concentration due to management of household fertilizer use was applied to all area classified as suburban and permeable, and calculated based on the difference in total phosphorus load generated from suburban pervious land across the catchment with and without household fertilizer management.

The catchment model for the Lake Tuggeranong catchment estimates the current load of phosphorus entering Lake Tuggeranong at 1,442 kg/year (Dey, Stewart, Kahn, Booksmythe, & Starrs, 2024). Under the cost-effective scenario, the model estimates that this load would be reduced to 992 kg TP/year (a reduction of 450 kg/year) and under the broad benefits scenario, the model estimates that the load would be reduced to 868 kg TP/year (a reduction of 574 kg/year; Figs. 2, 3).

The estimated reductions in TP load for each proposed management scenario generated by the catchment model are substantially lower than the reductions calculated by adding the individual estimated reductions for each management option (~ 450-575 kg/year vs. ~ 700-750 kg/year, respectively). The major interactive effects explaining this difference are those between management options that prevent TP from entering the stormwater system, such as street sweeping and household fertilizer management, and options that intercept and remove TP from stormwater, such as WSUD infrastructure. Options that prevent TP from entering stormwater have the effect of reducing TP concentrations in the stormwater that will be intercepted by WSUD-type options, which lowers the rate at which these can remove P. Considering management options that act to reduce runoff generation and flatten the peaks of storm flows, might help to improve the performance of WSUD management options in these scenarios.

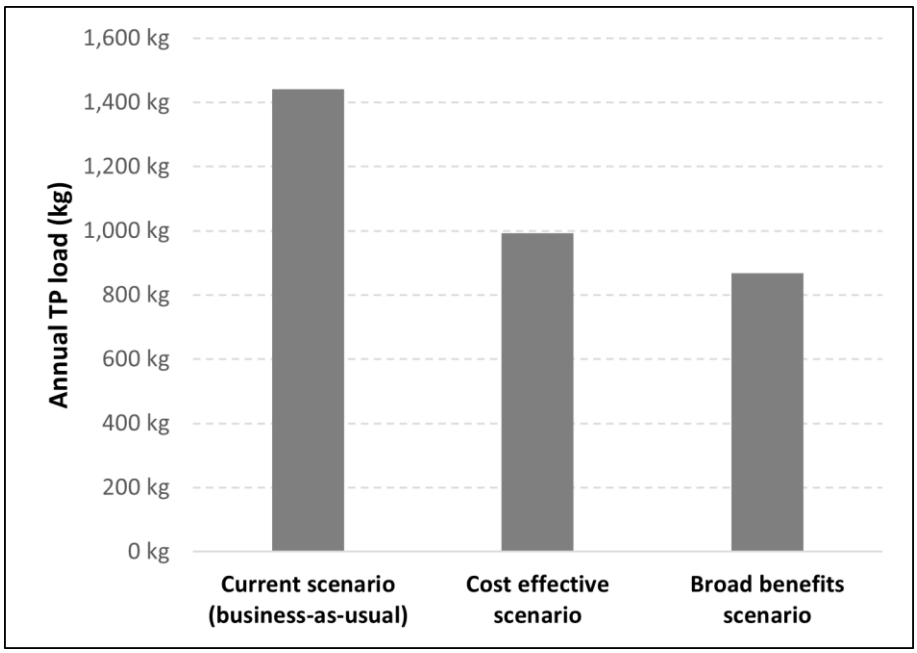

Figure 2. Modelled average annual load of total phosphorus (TP) generated in the Lake Tuggeranong catchment under three management scenarios.

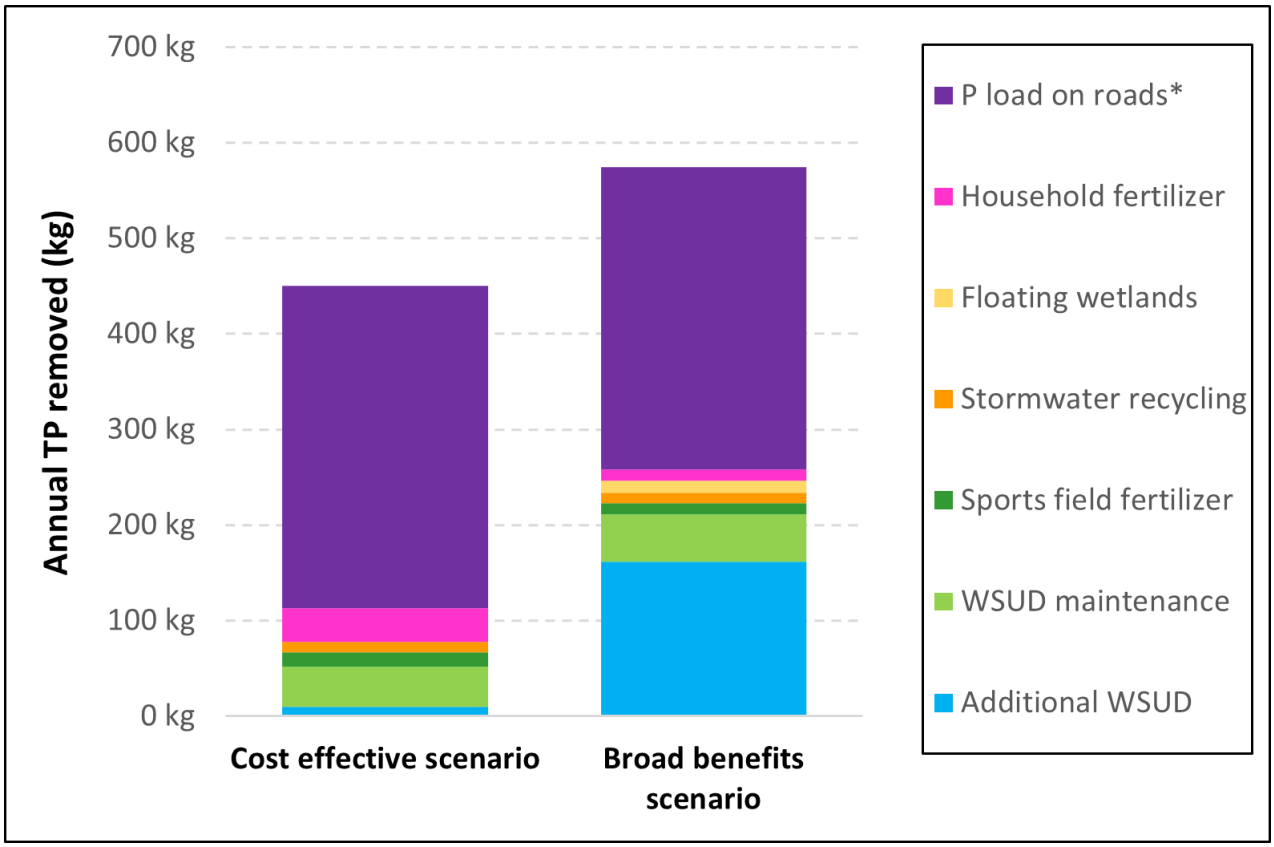

Figure 3. Modelled average annual reduction in the load of total phosphorus (TP) generated in the Lake Tuggeranong catchment, under the cost effective and broad benefits management scenarios. Colours indicate the reduction due to different management options in each scenario. * P load on roads includes the reductions in TP load due to street sweeping, grass clippings management and installation of castellated kerbs.

3.4 Summary

This report has described the approaches used to estimate the phosphorus removal performance and implementation cost of proposed management options for the Lake Tuggeranong catchment. These estimates were used to compare the cost-effectiveness of different management options, and create combinations of options aimed at achieving a ~700 kg reduction in the annual phosphorus load entering Lake Tuggeranong. The Lake Tuggeranong catchment model was used to simulate the effects of these combinations of management options and estimate long-term mean annual inflows and phosphorus loads to Lake Tuggeranong under each scenario.

The management option assessments aimed to provide evidence-based estimates of cost-effectiveness:

- Estimates of the phosphorus removal performance and implementation costs of management options were based on multiple sources, including local implementation of similar management options wherever possible.
- Estimates of the cost of implementation were calculated over a 30-year lifespan for all management options, to allow for the comparison of options with disparate cost distributions.
- A range of estimates was produced for both performance and cost wherever possible, to understand and incorporate uncertainty in the predicted cost-effectiveness of each management option.
- Cost-effectiveness was calculated for each option at four levels of investment to allow its assessment within as well as between management options.
- Confidence in the estimates provided by these assessments was evaluated systematically using a rubric to score the quality of supporting evidence for both the performance and cost estimates for each management option.

Key results of the management options assessment exercise include:

- Increasing the frequency of street sweeping and installing additional WSUD infrastructure are the management options with the largest predicted impacts on reducing phosphorus loads entering Lake Tuggeranong each year.
- Increasing the frequency of street sweeping is estimated to be the most cost-effective management option of those assessed.
- Management scenarios created by combining management options with the aim of achieving a 700 kg reduction in the annual load of phosphorus entering Lake Tuggeranong are estimated to have a total 30-year cost of between $100-145 million.
- Simulating these management scenarios in the Lake Tuggeranong catchment model allows estimation of the predicted reduction in phosphorus entering the lake while accounting for interactions between the different management options included. The model estimates that the average annual phosphorus load to Lake Tuggeranong would be reduced to between 868-992 kg, a 33-44% decrease compared to current catchment conditions.

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5. Appendices

5.1 Appendix A: Quality of evidence assessment rubric

To evaluate the sources of evidence used to inform our assessments of the cost-effectiveness of catchment management options, we designed a rubric to score each option against 9 criteria addressing the information on option cost (4 criteria) and option efficacy (5 criteria) (Table A1).

Table A1. Rubric used to score the quality of evidence informing the assessments of cost-effectiveness of the 10 catchment management options included in this report.

Criterion	Maximum score	1 (weak)	2 (fair)	3 (good)	4 (very good)
Estimates of cost	14				
C1: How recent are cost estimates?	4	Based on implementation 5-10 years ago; **not** 2024 currency	Based on implementation 5-10 years ago; 2024 currency	Based on implementation within the last 5 years; **not** 2024 currency	Based on implementation within the last 5 years; 2024 currency
C2: Source of cost estimates?	4	Not based on previous implementation	Based on implementation overseas	Based on implementation in Australia	Based on implementation in the ACT
C3: Number of independent sources of cost estimates?	3	Costs inferred, from a single source	Based on implementation, from a single source	Based on implementation, from multiple independent sources	
C4: How is variability in cost estimates considered?	3	Based on a single point estimate (+/- 50% or more)	Based on a limited range of estimates (+/- 20-50%)	Based on a substantial range of estimates (+/- 20% or less)	
Estimates of performance	16				
P1: Source of pollutant estimates?	4	Poorly understood	Indirectly inferred from Australian/ overseas data	Indirectly inferred from local empirical data	Directly quantified from local empirical data
P2: Source of performance estimates?	3	Not based on empirical data	Indirectly inferred from local data, or quantified elsewhere	Directly quantified from local empirical data	

Criterion	Maximum score	1 (weak)	2 (fair)	3 (good)	4 (very good)
P3: Is the option explicitly modelled?	3	Represented indirectly in the catchment model, conceptually inconsistent	Represented indirectly in the catchment model, conceptually consistent	Represented explicitly in the catchment model	
P4: Confidence in scaleability of performance?	3	Not understood or not explicitly represented	Inferred from conceptual understanding, explicitly represented	Based on empirical data, explicitly represented	
P5: How is variability in performance estimates considered?	3	Based on a single point estimate (+/- 50% or more)	Based on a range of estimates (+/- 20-50%)	Based on statistical analysis of empirical/ modelled data (+/- 20% or less)	

ACT Government

CABINET SUBMISSION

Cabinet number	**25/222**
Title	**Healthy Waterways Plan for Lake Tuggeranong**
Meeting Type	Cabinet
Minister	Suzanne Orr MLA Minister for Climate Change, Environment, Energy & Water
Co-Sponsoring Minister/s	N/A
ERC date	Tuesday, 26 August 2025
Cabinet date	Wednesday, 10 September 2025

Status	FINAL
Relationship to previous decisions	2023/24 ERC EPSDD CO2 Expanding Healthy Waterways – Consolidating Gains

Submission type	Agree to public consultation
Purpose	To approve release of 'Options for Restoring Lake Tuggeranong' (draft Plan) for public consultation
Category	Category 2 - Government business

Financial Impact	No	
Treasury Agreement	Yes	28/04/2025
	Date of Treasury agreement:	13/05/2025
Technology Impact	No	
Digital, Data & Technology Solutions Consultation	No	Click or tap to enter a date.
Service delivery impact	No	
Access Canberra Consultation	No	Click or tap to enter a date.

Legislative change	No - change to legislation not required	
PCO/JACS Human Rights	N/A	Click here to enter a date.
	N/A	Click here to enter a date.
Regulatory impact	No	Click here to enter text
Wellbeing Impact Assessment	Yes	
Primary Wellbeing Domain	Environment and climate	
Closing the Gap - Priority Reforms	Not in Scope for Closing the Gap Priority Reform	

Minister's signature_____ Date 12/08/2025

RECOMMENDATIONS

1) I recommend Cabinet agree:

   a. To release the report 'Options for Restoring Lake Tuggeranong' (the draft Plan) (Attachment F) and the 'At a glance snapshot' (Attachment E) for public consultation using the Communications Strategy outlined in Attachment D, and

   b. that the Minister for Climate Change, Environment, Energy and Water finalise any minor amendments to the draft Plan prior to releasing for public consultation.

   c. Supporting communications materials will be approved by the Minister for Climate Change, Environment, Energy and Water.

2) I recommend Cabinet note:

   a. The final 'Healthy Waterways Plan for Lake Tuggeranong' (the final Plan) will be brought to Cabinet following the public consultation, likely early 2026.

   b. The final Plan will deliver on a 2024 election commitment to *'develop and deliver a 10-year plan for a healthier Lake Tuggeranong'*.

   c. The draft Plan is underpinned by three comprehensive technical reports detailing modelling and other analyses. These will be made publicly available on the EPSDD website at the time of the draft Plan's public release (Attachments G, H, I).

   d. The proposed release of the following Cabinet Decision and Wellbeing Impact Summaries as required under Section 23 of the *Freedom of Information Act 2016*:

      i. Cabinet agreed to the release of the draft Healthy Waterways Plan for Lake Tuggeranong for public consultation. The draft Plan describes current knowledge about what's causing blue-green algal blooms in Lake Tuggeranong, and, using modelling of catchment hydrology and mitigation costs, presents management options for addressing them.

      ii. Lake Tuggeranong's frequent blue-green algal blooms have negative visual and smell impacts, present health risks, and prevent people from recreating in and around the lake. Using current scientific understanding of what's causing Lake Tuggeranong's algal blooms, the draft Plan presents a ten-year vision to improve water quality in the catchment to reduce the frequency and severity of blooms. This will have positive wellbeing benefits for the Tuggeranong community through reducing health risks, providing access to blue-green space, and enhancing cultural and biodiversity values.

   e. The Minister for Climate Change, Environment, Energy and Water has brought forward a proposal relating to the implementation of the draft Plan for consideration in the 2025-26 budget (*Healthy Waterways – Improving Lake Tuggeranong – election commitment).*

SUPPORTING ARGUMENT

BACKGROUND

1) For at least the past decade Lake Tuggeranong has experienced poor water quality and regular blue-green algae blooms in summer, reducing the amenity and recreational values provided by the lake. This has been a consistent, high-profile issue for the Tuggeranong community and a complex problem to address.

2) The ACT Healthy Waterways program (Healthy Waterways) was established in 2014 to address water quality problems in Canberra —including in Lake Tuggeranong—through planning and on-ground actions. There have been two stages to the program:

   a. Stage 1 (2014-2021), a $94 million joint initiative of the Australian and ACT Governments

   b. Stage 2 (2021-June 2025) 'Expanding Healthy Waterways', to fulfil the Parliamentary and Governing Agreement for the 10th Legislative Assembly commitment to *Expand Healthy Waterways: $30 million over 4 years*. This commitment is to investigate water quality and plan and deliver pollution mitigation works for Lakes Tuggeranong, Burley Griffin and Ginninderra, Yerrabi Pond and the Nass/Gudgenby rural catchment. The outputs will be finalised through 2027.

3) Across the two stages approximately $44 million has been invested to better understand Lake Tuggeranong water quality issues and how to solve them, as well as on-ground works to begin to improve water quality in Lake Tuggeranong. These include:

   a. Building nine water quality assets

   b. Education programs

   c. Research and monitoring

   d. Catchment hydrological and water quality modelling and data analyses.

ISSUES AND OPTIONS

Plan scope - a water quality plan focusing on blue-green algae

4) The draft Plan presents, for the first time, a comprehensive suite of management options to reduce the nutrients coming off the catchment contributing to the formation of algal blooms, drawing on lessons learned from the past ten years of investment.

5) The draft Plan focuses on one aspect of water quality - nutrient pollution, and specifically the nutrient phosphorus, because of its key role driving algal blooms which most heavily impact the amenity of the Lake.

6) A ten-year timeframe is proposed to implement the Plan, with interim goals set for 2030. This timeframe is needed to implement management interventions and to evaluate their effectiveness.

Public Consultation Plan

7) The public consultation process described in this submission is an important way to confirm community support (or otherwise) for the proposed mitigation options. Feedback from this process will inform the final Plan along with technical and budget considerations.

8) The Communications and engagement strategy (Attachment D) has been developed to provide community with the opportunity to have their say and allows for an eight-week consultation period.

9) An 'At a glance snapshot' document (Attachment E) will form part of the communications materials, giving community a snapshot of what the consultation is about and how they can participate. The snapshot is designed to complement the data rich and technically detailed draft Plan (Attachment F).

10) Communication consultants will be engaged to help facilitate engagement with the community, and with First Nations.

The options presented to reduce phosphorus to prevent algal blooms

11) Modelling suggests that the level of phosphorus reduction required to reduce the incidence of algal blooms in Lake Tuggeranong is 700 kg phosphorus/year (phosphorus reduction target). This target was derived using an in-lake model (Attachment G).

12) Modelling indicates that achieving the phosphorus reduction target would shift the lake away from a state of being primed for an algal bloom most summers to a state where algal blooms form in just one out of every four years on average.

13) Detailed analyses were undertaken of the cost and benefit (kg phosphorus removed/year) of ten management options for reducing phosphorus pollution, including:

a. Increasing street sweeping to remove leaf litter from roads

b. Using behaviour change strategies to encourage high-fertiliser-using households to use less fertiliser

c. Implementing extra measures to prevent grass clippings from open space mowing operations ending up in waterways

d. Subsidising the installation of household rainwater tanks

e. Building stormwater recycling on sportsfields

f. Retrofitting outlets into road kerbs (castellated kerbs) to divert stormwater to open green space

g. Building bioretention swales on sportsfields (using vegetation to filter surface flow of nutrients)

h. Building more large water quality assets low in the catchment (e.g. raingardens – a type of constructed wetland)

i. Improving maintenance of existing water quality assets, built via the Healthy Waterways program, to optimise their phosphorus removal performance

j. Building more floating wetlands.

14) The costs and phosphorus reduction benefits of each option are summarised in the draft Plan and detailed further in a supporting technical report (Attachment I).

15) Key conclusions are:

a. The most effective way to reduce phosphorus is through increased street sweeping.

b. There is no 'silver bullet' for solving the problem. Multiple management options will need to be implemented to reach the phosphorus reduction target and so reduce the incidence of algal blooms.

c. Building additional large wetlands low in the catchment—the focus of Healthy Waterways investment to date—is necessary but not the answer on its own.

16) Two packages of mitigation options were developed to demonstrate how combinations of options might reach the target, and the cost of doing this: a 'cost-effective' package and a 'broad benefits' package. These were developed for indicative purposes only, with the intention that they would be informed by feedback from the community on the different options.

Alignment with other Territory planning priorities

17) The draft Plan aligns with community feedback heard during the development of the Tuggeranong District Strategy, in which the Tuggeranong community expressed that they value the lake for a range of recreational activities throughout the year, including walking, cycling, swimming, fishing and windsurfing (ACT Government, 2023).

18) Building and maintaining large water quality assets like wetlands and raingardens can also help achieve Territory Planning objectives to improve Biodiversity Sensitive Urban Design, enhance the Blue-Green network, and promote urban cooling.

a. Large water quality assets have an urban cooling effect, contributing to the implementation of Canberra's Living Infrastructure Plan: Cooling the City.

i. A recent study on ACT living infrastructure found two sites (Crace stormwater basin, and Bonner wetland) were 2-2.5^{0}C cooler than the overall average of sites measured (CSIRO. 2024. *Measuring the Cooling benefits of Living Infrastructure– report for EPSDD*).

b. Constructed wetlands and raingardens help to restore aquatic habitat to degraded urban channels, supporting the implementation of the ACT Nature Conservation Strategy and Connecting Nature Connecting People initiative.

FINANCIAL IMPACT

19) There are no financial impacts from this paper, there will be financial impacts arising from implementing actions under the Healthy Waterways Plan which will be subject to future budget processes. Cost modelling indicates that fully implementing the plan to achieve target phosphorus reductions would cost between $105-$144 million over ten years (Attachment I).

20) The Minister for Climate Change, Energy, Environment and Water has brought forward a business case for consideration in the 2025-26 budget for one year of investment to undertake trials into in-lake treatment in Isabella Ponds and plan for capital works.

TECHNOLOGY IMPACT

21) There is no technology impact from this proposal.

SERVICE DELIVERY IMPACT

22) One management option presented in the draft plan is to increase the frequency of street sweeping. This would impact on service delivery by Roads ACT. Funding for increased service delivery would be sought through the budget process.

WELLBEING IMPACT SUMMARY

23) Lake Tuggeranong's frequent blue-green algal blooms have negative visual and smell impacts, present health risks, and prevent people from recreating in and around the lake. Using current scientific

understanding of what's causing Lake Tuggeranong's algal blooms, the draft Plan presents a ten-year vision to improve water quality in the catchment to reduce the frequency and severity of blooms. This will have positive wellbeing benefits for the Tuggeranong community through reducing health risks, providing access to blue-green space, and enhancing cultural and biodiversity values.

CLOSING THE GAP - PRIORITY REFORMS

24) Not in scope for Closing the Gap – Priority Reforms.

CONSULTATION

External stakeholders

25) The draft Plan has been reviewed by two external experts, Prof Fiona Dyer (University of Canberra) and Prof Tim Fletcher (University of Melbourne).

26) The Healthy Waterways team have delivered presentations on the research findings and proposed direction of the draft Plan to the Tuggeranong Community Council, ACT and Region Catchment Management Coordination Group, and Upper Murrumbidgee Catchment Network.

27) Initial Ngunnawal Traditional Custodian input on the draft Plan was gained through an Aboriginal Water Assessment undertaken in 2022, facilitated by the Office of Water's Ngunnawal Water Policy Officer. To gain further perspectives of Ngunnawal Traditional Custodians and other Aboriginal and Torres Strait Islander people with connections to the lands and waters of the ACT, Aboriginal consultant Paul Knight will lead facilitated conversations in the first half of August on options for Lake Tuggeranong as part of an Office of Water project to strengthen engagement with First Nations on water issues.

ACT Government Agencies

28) The Healthy Waterways team worked closely with TCCS on asset designs, street sweeping, sports field fertiliser management and grass clipping management on road verges in preparing the draft Plan.

29) The ACT Chief Health Officer provided advice on current understanding of the links between cyanobacteria (from blue-green algae) and motor neurone disease.

MEDIA AND COMMUNICATIONS

30) The Communications and Engagement Strategy is at Attachment D. A draft 'At a Glance' snapshot is at Attachment E.

IMPLEMENTATION

31) The final Plan will be presented to Cabinet in early February 2026, with more refined options based on community feedback from the draft, and in consultation with ACT Government agencies including the EPA. Further implementation will depend on ERC's consideration of future business cases.

Table 2: **Implementation milestones and timeframes to publishing of final Plan**

Milestones	Date complete
1. Public consultation on draft Plan (including with First Nations)	24 September 2025
2. Listening/consultation report published	24 October 2025
3. Consultation with other ACT government agencies to develop implementation approach in final plan	November 2025
4. Final Plan brought to Cabinet	Early February 2026

5. Plan published	March 2026
Final completion date:	March 2026

HUMAN RIGHTS IMPACT

32) The right to a healthy environment is enshrined in the *Human Rights Act 2004*, with the right applying to all relevant policies and legislation. The Healthy Waterways Program aims to improve water quality for the Territory, contributing to healthy environments.

ATTACHMENTS

A	Table of comments
B	Open Access Assessment: Cabinet Decision and Wellbeing Impact Assessment summary
C	Wellbeing Impact Assessment
D	Communications and Engagement Strategy
E	'At a Glance' snapshot
F	*Options for Restoring Lake Tuggeranong* (draft Plan)
G	Technical report #1 – Dey et al (2024) Lake Tuggeranong Catchment Model Calibration Report
H	Technical report #2 – Kahn and Dey (2024) Report supplement – Lake Tuggeranong In-Lake model
I	Technical report #3– Booksmythe et al (2024) Lake Tuggeranong Catchment Management Options Assessment Report

ACT Government

MINISTER'S CABINET BRIEF

Cabinet Number	**25/222**
Title	Draft Healthy Waterways Plan for Lake Tuggeranong - Public Consultation
Minister	Suzanne Orr MLA
Portfolio	Minister for Climate Change, Environment, Energy & Water
Cabinet date	Wednesday, 10 September 2025
Recommended position	SUPPORT

Submission recommendations

This is your submission – CED recommends you support all recommendations.

Issues/comment

The Minister for City and Government Services may raise concerns around the presentation of city operations costs (street sweeping) in the *Options* report and backing technical reports; whether the costs have been developed in consultation with City Operations; and the risk that public consultation on the *Options* report will raise expectations in the community of services and works that City Operations (or the ACT Government) does not have fiscal capacity to provide.

The Office of Water has worked closely with City Operations in the development of the options and costings, informed in part by street sweeping trials over the last two summers.

As most people will read the At-a-glance brochure and take the YourSay survey (which seeks views on impacts on community members and ability for people to change behaviour), if Cabinet is seeking options to mitigate expectation-raising risks, CED can review these key documents to emphasise options that residents can apply (preventing pollution at the source) and targeting the interventions (street sweeping, maintenance) the Government is already undertaking, rather than more expensive options like infrastructure investment. You could seek agreement that any requested changes be settled between relevant Ministers.

Wellbeing Impact Assessment

Implementation of the Healthy Waterways Plan will have a positive impact on the wellbeing of residents in Tuggeranong and visitors to Tuggeranong within the domains of, primarily, Environment and Climate and secondarily, Health, Social connection, Economy and Governance and institutions.

Context and consultation

The *Options* report is not a statement of government commitment nor a proposal for investment. The method for costing enhanced street sweeping is based on figures provided by the former TCCS, was conservatively interpreted, and was appropriate as an indicative estimate for comparison with other options.

Cleared:	David Clapham, EBM Office of Water
Prepared by:	Ralph Ogden, Healthy Waterways program manager

The *Options* report is consistent with the expectations raised by the election commitment to *Develop and deliver a plan to restore the health of Lake Tuggeranong*. A future Lake Tuggeranong Plan would be supported by a business case for funding, co-developed with City Operations and EPA. Costings for all options will be refined at this time, supported by an external analysis.

Restoring Lake Tuggeranong is not a 'set and forget' initiative. The *Options* report makes it clear that the Government will monitor and evaluate the cost and benefits of different management options and continuously refine and improve the suite of options applied to ensure the greatest benefit for the least cost.

ACT Government

TABLE OF COMMENTS

Attachment A

EXPOSURE DRAFT COMMENTS – 25/222

Exposure circulation undertaken: Full exposure circulation

Dates circulated: 19-26 May 2025

Directorate	Comment	Response
CMTEDD	Support with comment The Environment Protection Authority (EPA) suggests that the cabinet submission, draft plan and attachments be amended to: • provide formal acknowledgment of the role of government agencies including the EPA in the protection of lake Tuggeranong to date and into the future. • formally acknowledge and include the EPA and other government agencies in the development of the consultation process • highlight and address resourcing implications for additional regulatory work that will result from the proposed activities	Text has been added to the draft plan (Attachment F - p16) noting the role of the EPA administering the *Environment Protection Act 1997,* and *Lakes Act 1976.* A summary of agency responsibilities regarding management of Lake Tuggeranong has been added to the draft plan (Attachment F - p17). The Cabinet Submission has been amended to note proposed consultation with other agencies in the development of the final plan (Para 31 – Implementation). Text has been added to the 'Cross-portfolio collaboration and partnerships' section of the Wellbeing Impact Assessment to note collaboration with the EPA (Attachment C p4). No changes to Cabinet Submission regarding resourcing implications for additional regulatory work since additional regulatory work has

		not yet been identified. This will be discussed with EPA at the stage of budget bid development and implementation planning and.
JACS	Supported.	
HD	Supported.	
CHS	Supported.	
EDU	Supported.	
TCCS	Supported.	
CSD	Supported.	
EPSDD	Supported.	
MPC	Supported.	
Statutory Office Holder	Supported.	

FINAL COMMENTS – 25/222

Final circulation undertaken: Yes

Dates circulated: 13/08/2025 to 18/08/2025

Directorate	Comment	Response
CMTEDD	Supported.	
HCSD	Supported.	
CHS	Supported.	
EDU	Supported.	
DCBR	Supported.	

CSD	Supported.	
CED	Lead Directorate.	
MPC	Supported.	
Statutory Office Holder	Supported.	

Wellbeing Impact Assessment (WIA)

Resources and support

The Wellbeing Toolkit provides a range of resources to support you to complete a WIA, including the WIA Drafting Guide and details of the Wellbeing Domains. The Drafting Guide includes definitions, prompting questions, examples and other advice related to each section of the WIA.

Support is available from Wellbeing Champions in each directorate. The Wellbeing Team can review and provide advice on draft WIAs where capacity allows – contact the team at WellbeingFeedback@act.gov.au.

Healthy Waterways Plan for Lake Tuggeranong

CED

Purpose of proposal

This proposal seeks Cabinet approval to release the 'Options for Restoring Lake Tuggeranong (draft Healthy Waterways Plan for Lake Tuggeranong) for public comment. The Plan's purpose is to address the problem of blue-green algal blooms in Lake Tuggeranong to improve amenity for Tuggeranong residents and the lake's ecological health.
The Plan summarises current knowledge and scientific understanding about why blooms occur in Lake Tuggeranong and describes alternative ways to reduce nutrients in the catchment, a key contributor to algal blooms.

Wellbeing domains and impact description

Access and connectivity	Economy	Education and life-long learning	Environment and climate	Governance and institutions	Health
Housing and home	Identity and belonging	Living standards	Safety	Social connection	Time

Primary domain	Impact description
Environment and climate	By reducing the frequency and intensity of algal blooms, this proposal will improve the lake's ecological health as severe blue-green algal blooms can impact fish populations and other aquatic biota. There will also be improved urban ecosystem function locally throughout the catchment where non-polluting practices are adopted, and water quality assets are built.
Other domains	
Health	There are health risks to humans and pets associated with contact and/or ingestion of water from lakes affected by toxic blue-green algal blooms. This is why the Government closes lakes when algal populations rise above a threshold level. There are also potential health risks (neurological disorders) associated with aerosolised exposure to the cyanotoxins present in blue-green algae. This proposal aims to reduce the frequency of algal blooms, reducing the potential health risks. This proposal will also significantly improve Lake Tuggeranong's recreational and amenity value and the associated wellbeing of residents and visitors by reducing the frequency of algal blooms and providing access to blue-green spaces.
Social connection	Improved blue-green network (by improving the health of the lake and its catchment's waterways, including building new wetlands) will create more opportunities for increased social connection as people walk, run, cycle, and picnic near the waterways.
Economy	Businesses operating on and near the lake will benefit from reduced algal blooms - a recent literature review found there was a drop in property values of 2-22% for residences nearby waterways that experienced toxic algal blooms (NC Economics 2021).
Governance and institutions	The proposal will improve trust in Government because the Tuggeranong community will see the Government acting on an issue of longstanding concern.

Evidence base and data

Provide evidence that your proposal will have the wellbeing impacts described above. Note that it is not enough to only provide evidence that the issue exists.

Evidence	Source	Type of evidence

• Ecological impacts of blue-green algal blooms	• Potter et al (1983) Blue-green algae and fish population changes in a eutrophic estuary. *Marine Pollution Bulletin* V14 I6: 228-233.	National data or research
• Ecological impacts of blue-green algal blooms	• Sharma et al (2011) Freshwater cyanobacterial (blue-green algae) blooms: causes, consequences, and control. Impact Monitoring and Management	International data or research
• Reduced urban heat and risks of heat stress where water quality assets are built	• Tapsuwan, S, Ingleton, G & Capon, T (2024). Measuring the cooling benefits of living infrastructure in urban Canberra: a report of findings. Canberra.	ACT government data or research
• The importance of blue-green spaces for wellbeing	• Dushkova et al (2021). Human Dimensions of Urban Blue and Green Infrastructure during a pandemic. Case study of Moscow (Russia) and Perth (Australia). *Sustainability* 13: 414-4172	National data or research
• The importance of blue-green spaces for wellbeing	• UK Environment Agency (2020) The social benefits of blue space: a systematic review	International data or research
• Residents want an improved blue-green network and improved water quality in Lake Tuggeranong	• Tuggeranong District Strategy Planning System Review and Reform Project (Listening Report)	ACT government data or research
• Residents want an improved blue-green network and improved water quality in Lake Tuggeranong	• Tuggeranong Community Council 2024 survey of residents	ACT government data or research
• Residents want an improved blue-green network and improved water quality in Lake Tuggeranong	• Schirmer and Mylek (2016) Water Quality and the community: understanding the views, values and actions of residents of the ACT and surrounding region.	ACT government data or research
• Residents are willing to pay up to $280/pp/year to *greatly improve* the amenity of Lake Tuggeranong	• Natural Capital Economics 2023. Economic values of ACT Urban Lakes.	ACT government data or research
• Potential human health risks associated with exposure to blue-green algae	• Cox et al 2003 Biomagnification of cyanobacterial neurotoxins and neurodegenerative disease among the Chamorro people of Guam.	International data or research
• Potential human health risks associated with aerosolised exposure to blue-green algae	• Plaas, H & Paerl, H (2021). Toxic cyanobacteria: a growing threat to water and air quality. Environmental Science and Technology 55:44–64.	International data or research
• Economic impacts (property values reduced by 2-22% for residences nearby waterways that experience toxic algal blooms)	• Natural Capital Economics 2021 Economic impacts of blue-green algae for urban lakes: a literature review.	ACT government data or research

What don't we know?

- We don't have specific data on the links between Tuggeranong's natural spaces—green corridors between suburbs, ponds and lakes—and Tuggeranong residents' wellbeing.
- The causal links between toxins in blue-green algae and neurological disease have not been definitively established, and the scientific community does not agree on the level of risk posed through aerosolised exposure.

Measuring wellbeing outcomes

How will the Government know this proposal has achieved the anticipated wellbeing impacts?

Your thinking on this does not need to be finalised – this is an opportunity to set out ideas about what may need to be measured in order to understand whether this proposal has had the anticipated impact.

What is the measurable outcome?	How will you measure it?
• Decreasing phosphorus concentrations in stormwater	• Water quality monitoring (sampling)
• Decreasing lake closures due to blue-green algal blooms	• EPA monitoring data on lake closures

- Reduced frequency, intensity and or duration of blue-green algal blooms
- Improved ecological outcomes
- Contribution to urban cooling
- Residents' and visitors' wellbeing due to access to 'blue' spaces in the Tuggeranong catchment.
- Water quality monitoring
- CHIP reports
- WSUD assets to be included in ongoing studies as part of Living Infrastructure Plan
- Survey of residents, potentially through Omnibus survey.

Evaluation

- The impacts of this proposal will be evaluated as part of evaluating the implementation of the (draft) Healthy Waterways Plan for Lake Tuggeranong.

Who is impacted?

The population of Tuggeranong was approximately 87, 680 in 2021.People who use the lake for recreation (walking, running, picnicking, cycling, swimming, boating, fishing), as well as businesses and clubs nearby to the lake, will be most impacted.

Table 1.1 – Lake Tuggeranong lake user characteristics, from survey of 316 people who said they visit the lake once or more a year. Source: NC Economics, 2023.

Gender	
Male	48.7%
Female	50.6%
Non-binary/use other term	0.6%
Area of residence in Canberra	
Tuggeranong	35.7%
Other parts of Canberra	64.3%
Age	
18-34	34.1%
35-54	27.4%
55-74	33.1%
75 and over	5.4%
Aboriginal and Torres Strait Islander	2.5%

Will the proposal have a different or disproportionate impact (positive or negative) on any groups?

- The proposal will not have a disproportionate impact on any specific groups, using Tuggeranong District population data and the results of the lake user survey data shown in Table 1 above.

Gendered impacts

- To understand whether there are gendered impacts of this proposal, we would need data on to what extent cisgender, transgender, gender diverse and non-binary people use lake Tuggeranong. This data does not currently exist and would need to be collected through a survey of lake users.

Impacts on Aboriginal and Torres Strait Islander people

- The proposal will not explicitly support commitments under the National Agreement on Closing the Gap or the ACT Aboriginal and Torres Strait Islander Agreement 2019-2028. It is not predicted to have a disproportionate impact on Aboriginal and Torres Strait Islander people.
- The Healthy Waterways program has attempted to gain Ngunnawal perspectives in planning for the Tuggeranong catchment through undertaking a Healthy Waterways-funded Aboriginal Waterway Assessment, facilitated by the EPSDD Ngunnawal Water Policy Officer. This is undertaken by the Ngunnawal community on country, and as part of the assessment, Ngunnawal community members went on country in the Tuggeranong catchment to assess it for culturally significant values. The outcomes of the Aboriginal Waterway Assessment have not yet been shared with the Healthy Waterways team.
- Broader consultation with other Traditional Custodians and groups on cultural values and aspirations for the Tuggeranong catchment is planned to occur through an Office of Water First Nations engagement procurement in Q1 2025.

Impacts on future generations

- The proposal will positively impact future generations by securing their ability to enjoy a healthy Lake Tuggeranong and blue-green network.

Will the proposal have an impact on or be impacted by climate change?

Emissions reduction

- The proposed activities are unlikely to have a significant positive or negative impact on carbon emissions.

Adaptation and risk management

- Susceptibility to algal blooms will be impacted by projected changes to rainfall, storm intensity, and temperature because these influence nutrient dynamics in the catchment and lake. These effects have not yet been quantified in the Tuggeranong context, but it is expected that the net impact will be to increase the lake's susceptibility to algal blooms.
- The proposal will help support a more climate resilient waterbody, by reducing its susceptibility to algal blooms.
- The proposal helps support an adaptation response by contributing to urban cooling and providing people with access to blue spaces as temperatures increase.

Cross-portfolio collaboration and partnerships

- The Healthy Waterways Team has been collaborating with Transport Canberra and City Services (City Services) on how increasing street sweeping can help to address the problem of algal blooms, and with ACT No Waste on how we can support the community to more effectively pick up leaf litter from their properties (a source of nutrients causing algal blooms), and exploring options for recycling green waste collected from street sweeping.
- The Healthy Waterways Team will collaborate with the EPA to maximise any opportunities to use the regulatory framework to improve the health of waterways.

Open Access Wellbeing Impact Summary (Cabinet Submission WIAs only)

Lake Tuggeranong's frequent blue-green algal blooms have negative visual and smell impacts, present health risks, and prevent people from recreating in and around the lake. Using current scientific understanding of what's causing Lake Tuggeranong's algal blooms, the draft Plan presents a ten-year vision to improve water quality in the catchment to reduce the frequency and severity of blooms. This will have positive wellbeing benefits for the Tuggeranong community through reducing health risks, providing access to blue-green space, and enhancing cultural and biodiversity values.

Communications Plan

Project: Community consultation – Options for Restoring Lake Tuggeranong
Directorate: Environment, Planning and Sustainable Development Directorate
Release date: October 2025 **Attachment D**

What is government's involvement/interest?	The ACT Government is seeking feedback from Tuggeranong residents and Canberrans who use, or take an interest in, Lake Tuggeranong on proposed options to restore the Lake.
Why are we communicating on this issue?	• **To inform and educate** the Tuggeranong community about the importance of improving water quality in Lake Tuggeranong and how they can help. • **To engage** with a range of stakeholders who may be substantially impacted by the water quality of Lake Tuggeranong and/or the proposed methods to improve the lake. • **To drive participation** throughout the engagement process to make sure the Healthy Waterways Plan for Lake Tuggeranong has incorporated feedback from the community, experts and First Nation's people. The condition of Lake Tuggeranong has been a contentious issue for many years. We need to engage with the community as early as possible, acknowledge the community and stakeholder feedback that has been received to date, and ensure that they feel their voice is being heard. It will be important to demonstrate that long-term action has been undertaken but there needs to be more work done. The new plan seeks to take more preventative action at the source. The community will also have an important role to play in implementing the plan to improve the water quality of Lake Tuggeranong.
Background/research/insights	• **The Planning Act (2023)** prioritises management objectives for all public land (including waterways) as (1) prevent and control floods, (2) prevent and control pollution, (3) provide for public recreation and (4) habitat for flora and fauna. Since there is little urban infrastructure downstream of Lake Tuggeranong to protect from floods, the highest priority management objective for Lake Tuggeranong under the Planning Act is to prevent and control pollution. • **The ACT Water Strategy 2024–2044 Striking the Balance** sets a 20-year vision for ACT water management as: 'A community working together, managing water wisely to support a vibrant, sustainable and thriving region'. Outcome 1 of the Strategy—Healthy Catchments and Waterbodies—aims to achieve 'Well managed, functioning catchments that provide sufficient clean water for the environment and human consumption, support healthy waterbodies, and contribute to liveability of the ACT community'. • **The ACT and Region Catchment Strategy 2016-2046**. This Strategy establishes a 30-year vision to guide priority actions for a healthy Upper Murrumbidgee River region (upstream of Burrinjuck Dam to Tantangara Dam in NSW).

	• **A 2002 Legislative Assembly commitment** to manage downstream water quality through an agreed motion that the water leaving the ACT via the Murrumbidgee River should be of no less quality than the water flowing into the ACT (ACT Legislative Assembly motion 5 June 2002 9.1(b)). • **The Canberra Urban Lakes and Ponds Land Management Plan's** vision is to 'enrich local communities through the aesthetic, recreational, sporting, tourism, cultural and ecological values of lakes and ponds, and to provide opportunities for people to be involved in their use, care, and management'. Under this Plan, 'recreation' and 'visual landscape' are listed as Lake Tuggeranong's highest values (Figure 3, ACT Government, 2022b). • **The ACT's Water Resource Plan,** developed under the Murray-Darling Basin Plan, contains a Water Quality Management Plan that sets locally relevant water quality targets. • **A 2016 survey of** over 7000 people on Canberra's urban lake use found that the lake use activity most often rated as 'highly important' was walking with other people, followed by picnics/barbeques, cycling, and using playground areas (Schirmer & Mylek, 2016). • In community engagements as part of developing the **Tuggeranong District Strategy**, the Tuggeranong community expressed that they value the lake for a range of recreational activities throughout the year, including walking, cycling, swimming, fishing and windsurfing (ACT Government, 2023). • In the findings of an **ACT 'Better Suburbs' community survey** from 2018, the citizen forum's first recommendation (out of 14) was to increase funding for lakes, ponds, wetlands, stormwater and water quality. This was ranked as more important for community members than issues such as street trees, roads, footpaths and public libraries (ACT Government, 2018). • A **report commissioned by the ACT Government in 2023** explored ACT residents' willingness to pay for environmental amenity and recreational use of Canberra's lakes (NCEconomics, 2023). ACT residents surveyed indicated that they were prepared to pay up to $70/pp/quarter (or $280/pp/year, to greatly improve the environmental—visual and smell—amenity of Lake Tuggeranong (NCEconomics, 2023). • In a 2024 **Tuggeranong Community Council annual community survey,** 'improved water quality in Lake Tuggeranong', was one of the top four priorities for the general community, and the number one priority for young people		
Does it cross over other Directorates/ agencies?	Transport Canberra and City Services Environment Protection Authority ACT Health	**Spokesperson**	Ms Suzanne Orr, Minister for Climate, Change, Environment, Energy and Water Fiona Wright, Executive General Manager, Climate Change, Energy & Water Kieran Lawton, Executive Branch Manager, Office of Water

			Dr Ralph Odgen, Director, Healthy Waterways Program
Communications tier	Tier 2		

Engagement areas of influence	The research shows that the water quality can be improved in Lake Tuggeranong and the instances of lake closures due to algae blooms can be significantly reduced by employing a range of nutrient pollution mitigating actions.
	
	• The focus areas of these actions are:
	  ○ Stop pollution at the source
	  ○ Treat stormwater before it reaches the lake
	  ○ Treat the lake itself
	
	• The strongest focus and area of influence for this consultation falls within the 'Stop pollution at the source' area.
	
	• This focus area is the most effective at preventing algae blooms but also has the most impact on community members as it will require residents to take action to reduce pollution entering the lake.
	
	• A lesser focus will be on 'Treat stormwater before it reaches the lake', and even less feedback needed for 'Treat the lake itself'. The former will be a focus of engagement during implementation of the plan. The latter will be a focus of awareness raising—that we need to curb pollution from the catchment before considering lake treatments.
	
	• The engagement will also seek to educate community on what actions can be taken to improve the health of the lake and how they prioritise and value the water quality of the lake.		

EPSDD Strategic Indicators	**Deliver a compact, efficient and sustainable city to be enjoyed now and into the future** (*Access and connectivity, Economy, Environment and climate, Health, Housing and home, Identity and belonging, Governance and institutions, Time)* **Enhance Canberrans wellbeing by conserving and experiencing nature and culture** (*Environment and climate, Social Connection, Health, Education and life-long learning, Identity and belonging, Governance and institutions, Safety)* **Create our climate-ready city** (*Economy, Environment and climate, Social Connection, Health, Education and life-long learning, Housing and home, Governance and institutions, Safety*) **Respect our Ngunnawal Traditional Custodians' history, knowledge and aspirations and work in partnership with Ngunnawal people to build a strong and shared future that respects and values Ngunnawal Country. Acknowledge and celebrate the diverse First Nations peoples and their unique cultures through shared opportunities, respecting and valuing their knowledge and contributions to the work we do** (*Economy, Environment and climate, Education and life-long learning, Housing and home, Identity and belonging, Governance and institutions, Safety*)		

Target audiences

A detailed stakeholder engagement matrix is included at the end of this document.

Primary	• Residents that live near the lake • Tuggeranong District residents • Lakeside residents, businesses, and other organisations. • Lake users including Tuggeranong Sea Scouts, Rowing Club
Key influencers/stakeholders	• **Tuggeranong Community Council** • **Lake users:** Tuggeranong Sea Scouts, Rowing Club, Park Run, Seniors Centre, Leisure Centre, Arts Centre • **Entities that operate near the lake:** Lake Tuggeranong College, Seniors Centre, Leisure Centre, Arts Centre, businesses, Playgroups and childcare centres on lake edge • **Aboriginal and Torres Strait Islander community:** Representative Aboriginal Organisations (RAOs), United Ngunnawal Elders Council, Aboriginal and Torres Strait Islander Elected Body. • **Water catchment groups:** Southern ACT Catchment Group (primary), Ginninderra Catchment Group, Molonglo Conservation Group, Upper Murrumbidgee Catchment Group • **Environmental groups:** Conservation Council ACT Region, Landcare ACT, ACT Australian Conservation Foundation Community, SEE Change. • **ACT Government advisory bodies and reference groups:** ACTNRM Advisory Group, ACT and Region Catchment Coordination Group, Environment and Planning Forum, Office of the Commissioner for Sustainability and the Environment, ACT Climate Change Council • **Tuggeranong residents** that live near the lake and further afield. • **Wider Canberra community** who may use the lake or take an interest in the health of Lake Tuggeranong**.** • **Academics and universities** who research water quality and take an active interest in water quality strategies and plans.
ACTPS (if relevant)	• Transport Canberra and City Services • Treasury • Traditional Custodian Engagement (EPSDD) • ACT Health

Key Messages

General about the consultation

- ACT Government is inviting the community to have their say to help develop the ACT's first 10-year dedicated plan to improve water quality in Lake Tuggeranong. This is a key priority for Government.
- ACT Government will be consulting with the Tuggeranong community, residents and stakeholders who live, work and use Lake Tuggeranong to seek their feedback on options that ACT Government is proposing to improve the water quality and restore the health of Lake Tuggeranong.
- This consultation is open from [XX to XX] for an 8-week period.
- The Tuggeranong District Strategy envisions Tuggeranong Town Centre as a thriving hub for jobs, shopping, and services, supported by a clean and healthy lake that enhances the area's appeal, attracts visitors, boosts local businesses, and strengthens the ACT economy.
- Lake Tuggeranong is at the heart of the region, and the ACT Government has been working to improve the lake's water quality and is committed to ongoing investment to creating a long-term plan to restore Lake Tuggeranong.
- The proposed options build on previous ACT Government work including the construction of nine wetlands and other water quality assets, funded research and community engagement and education that has already seen a reduction in nutrient pollution entering the lake.
- Our vision is that by 2035, Lake Tuggeranong is more consistently free of blue-green algal blooms and, when they do occur, they are short-lived so the Tuggeranong community can enjoy the lake most of the year.
- But there is more for us to do. We know that there continues to be several sustained periods of poor water quality caused by blue-green algae blooms. This means that the lake is unable to be used and enjoyed by the Tuggeranong community, as well as impacting the environmental sustainability which helps protect local ecosystems.
- We know that the community has provided significant feedback to Government already on initiatives and challenges over a number of years.
- Our goal is to gauge the community's support for restoring Lake Tuggeranong and to explore any concerns they may have regarding the process.
- This consultation focuses on the new proposed options to restore Lake Tuggeranong, as well as seeking feedback on how we maintain existing wetland infrastructure.

What are we consulting on

- An excess of plant nutrients (fallen leaves, grass clippings and fertilisers) makes its way down drains via our stormwater systems and pollute our lakes, stimulating algal blooms.
- The consultation will provide 10 options along the journey of stormwater where nutrient reduction can occur:
  - **At its source** - by preventing nutrient pollution from occurring in the first place
  - **Within the stormwater system** - by slowing the flow and filtering pollution from the stormwater
  - **In the lake** - we can build wetlands or use substances that compete with algae, or use chemicals that kill algae

- We now understand that the most effective option for preventing algal blooms is to stop nutrient pollution from entering the stormwater system in the first place followed by the construction of more wetlands.
- The ACT Government have taken steps to improve the water quality of Lake Tuggeranong, with projects delivered through nine constructed wetlands. This has greatly improved the health of the lake, but more must be done.
- The proposed new options focus on what we can do to prevent nutrient pollution occurring in the first place, such as increasing the frequency of street sweeping, new street kerb designs, and changing how we manage leaf and grass litter and fertiliser use.
- Research and modelling indicate that Lake Tuggeranong can be improved over the next 10 years and experience fewer lake closures if the ACT Government can work with the local community to reduce these nutrients entering the lake.

Why we are consulting

For Tuggeranong residents

- Every option presented may impact the local community. It could mean temporarily moving cars for more frequent street sweeping, adjusting gardening habits, or the construction of local wetlands.
- As a Tuggeranong resident, you are likely to benefit from a clean and healthy lake that can provide enhanced recreational space, decreased health risks, help to boost local economy and community pride.
- You will also continue to have in important role to play in keeping the lake clean by keeping leaves and fertilisers out of the stormwater system.

For lake users

- Every option presented may impact you, the consultation is your opportunity to provide your input to shape the Plan.
- As a lake user, you'll benefit from a cleaner, fresher environment with little to no unpleasant odours and fewer health risks.
- With time the lake will be available for recreational activities most of the time throughout the year and if we do have lake closures, they will be short lived.

For lakefront residents and businesses and other entities operating on the lakefront

- Every option presented may impact you, the consultation is your opportunity to provide input to shape the Plan.
- As someone who is close to the lake, you are likely to benefit from the implementation of the plan.
- A clean lake has the potential to attract more visitors, boost local businesses and make the Tuggeranong town centre a prime location for jobs, shopping, and services.

Public consultation action plan

Date	Communications tactic and collateral	Distribution	Responsibility
Pre-launch of consultation			
June/July	**Engage Ngunnawal Water Policy Officer and First Nations consultant**, and co-design engagement approach to ensure the voice of First Nations people is included.		Office of Water CED Comms
Early September	**Set up YourSay page** - Survey - Quick comments - Cost allocation sliders - Written submissions (using consultation/survey questions).		CED Comms
Week prior to launch	**Key Stakeholder pre-briefing** 4-5 key stakeholders pre-briefing to get an outline of what the consultation process will look like and key areas of influence. This would include the Tuggeranong Community Council. Briefings of other ACT MLAs and local MPs will occur as requested. - Powerpoint presentation - Media release - Talking points - At a glance		Option for Office of Water CED Comms
Day prior to launch	**Media pre-briefing** A pre-briefing is recommended to ensure media are able to understand the subject matter within the consultation. - Powerpoint presentation - Media release - Talking points - At a glance - Q&A		Office of Water CED Comms
Day of Consultation launch			
September (Date TBC)	**Media release** with supporting talking points and Q&As		CED Comms
September (Date TBC)	**YourSay project page** published YourSay conversations		CED Comms
September (Date TBC)	**Social media post** on ACT Government social media channels		CED Comms

September	**Direct emails** to stakeholder list and EPF to formally notify of the consultation being launched. This will include a partnership pack which will allow them to share promotional material through their owned channels.		Office of Water
During the Consultation period – 8 weeks			
September – November	**Community Events** - 1 x in-person information session for Tuggeranong Community Council (provide option for a second session) - 2 x Stakeholder information workshops - 1 x online (and recorded) information session for Tuggeranong residents and general public - 2-4 pop-ups at different areas around the lake and broader Tuggeranong district. **Targeted stakeholder events** - Workshop/s with Tuggeranong Community Council, Southern ACT Catchment Group, Landcare, ACT NRM, ACTCMCG **First Nations** - Facilitated engagement with Ngunnawal and other Family Groups with connections to the ACT and Region		Office of Water CED Comms
September – November	**Communications** - Development and distribution of a range of print collateral: ○ Poster for community noticeboards and lakeside businesses ○ Postcards at businesses ○ Temporary Corflutes installed around lake		CED Comms

	- Article in the October edition - OurCanberra print, online and digital newsletter - Social media posts, including geotargeted dark posts for Tuggeranong district - Physical display at Tuggeranong Library - Stakeholder emails - Letterbox drop for homes near the lake - Easy English translation		
Following consultation			
November	**Media Release** wrapping-up the consultation (if appropriate)		CED Comms
November	**Direct emails** to the stakeholder list and EPF including the Listening Report.		Office of Water
December	**Listening Report** – upload the to the YourSay project page		CED Comms

Stakeholder Engagement Matrix

Community or Stakeholder Group	Level of impact on policy direction (low, moderate, high)	Level of interest (low, moderate, high)	Engagement needs or expectations	Level of engagement (inform, involve, collaborate)	How we will engage	Responsibility (line area/comms team)
Tuggeranong Community Council	High	High	Participate in workshops, be presented a detailed draft plan and be provided an opportunity to provide feedback on proposed options.	Collaborate	Will write to council and invite the opportunity to present the Plan at council meeting and seek feedback from council members.	Office of Water
Southern ACT Catchment Group	High	High	Participate in workshops, be presented a detailed draft plan be provided an opportunity to provide feedback to the Healthy Waterways team.	Collaborate	Contact the SACG and host a workshop with members of the group to run through details of the Plan and consultation.	Office of Water
Lake users e.g. Tuggeranong Sea Scouts, Rowing Club	Low	High	Opportunity to participate in YourSay or take part in a “Pop up” event to talk about the consultation. They like to be kept informed about health risks, likelihood of future blooms under Plan and how the plan might impact lake usage.	Involve (YourSay)	Email targeting these groups with information about the consultation, link to YourSay provide snap-shot doc and provide information about upcoming pop-up events.	EPSDD Comms
Around the lake users	Low	High	To provide input by YourSay, to be kept informed about	Involve (YourSay)	Email targeting these groups with	EPSDD Comms

ACT Government

e.g. Park Run, Seniors Centre, Leisure Centre, Arts Centre,			health risks. May want to participate in a pop-up event.		information about the consultation, link to YourSay provide snap-shot doc and provide information about upcoming pop-up events.	
Lake Tuggeranong College	Low	High	To provide input via YourSay, to be kept informed about health risks and any future blooms under plan. May take part in a pop-up event to understand the consultation better.	Involve (YourSay)	Email targeting the college with information about the consultation, link to YourSay provide snap-shot doc and provide information about upcoming pop-up events as well as links to learning resources.	EPSDD Comms
Playgroups and childcare centres on lake edge	Low	High	To provide input by YourSay, to be kept informed about health risks, they would like to know about algae blooms in future. They would like information and resources about how to care for Lakes and Waterways to aid teaching.	Involve (YourSay)	Email targeting this group with information about the consultation, link to YourSay provide snap-shot doc and provide information about upcoming pop-up events as well as links to learning resources.	EPSDD Comms
Lakeside businesses	Low	High	To provide input by YourSay, and to be kept informed about health risks, and future blooms under the Plan. Could provide information on how their businesses have	Involve (YourSay)	Email targeting local business. Provide information about the consultation, link to YourSay provide snap-shot doc and provide	EPSDD Comms Office of Water to hold workshops.

			been impacted by blooms over years. May want to participate in a pop-up event.		information about upcoming pop-up events.	
Ngunnawal people	High	Moderate	This group will want to participate in design of assets to enhance cultural values.	Collaborate (targeted workshops, Aboriginal Waterway Assessments)	Engage with a consulting firm who specialises in first nation consultations.	Office of Water to manage First Nations engagement
Residents that live near the lake [need to define boundary]	Moderate	High	To provide input into YourSay, to be kept informed about health risks, to understand how they can participate in waterway friendly gardening	Involve	Letterbox drop postcards that contain a snapshot of the consultation and QR code linking to YourSay.	EPSDD Comms
Tuggeranong Residents and Canberra residents further afield	Moderate	Moderate	To provide input by YourSay, information about how they can participate and be interested in waterway friendly gardening	Involve	Dark posts on social media geo-targeting Tuggeranong residents with links to YourSay.	EPSDD Comms
Other Catchment groups	Low	Moderate	Will be keen to understand approach in Tuggeranong and how it may be rolled out in other catchments in future	Collaborate	Email targeting Catchments groups to participate in pop-up events or in a dedicated workshop.	Office of Water
Landcare ACT	Moderate	Moderate	Membership is Ngunnawal community, rural landholders, catchment groups. May be helpful to coordinate input from these interests.	Collaborate	Email with information about the Plan and consultation. Provide information to take part in You-Say or attend a workshop.	Office of Water

ACT Government

ACTNRM Advisory Group	Moderate	Moderate	Membership includes various experts, landholders, urban parks volunteering. May be helpful to coordinate input from these interests.	Collaborate	Email with information about the Plan and consultation. Provide information to take part in You-Say or attend a workshop.	Office of Water
ACT and Region Catchment Coordination Group	Moderate	Moderate	Membership includes ACT, NSW Government, water experts. Dr Maxine Cooper is Chair.	Collaborate	Email targeting Catchments groups to participate in pop-up events or in a workshop	Office of Water
University of Canberra ANU, CSIRO and other academics in the sector	High	High	Participate in workshops, be presented a detailed draft plan be provided an opportunity to provide feedback to the Healthy Waterways team.	Collaborate	Contact academics and host a workshop to run through details of the Plan and consultation.	Office of Water

CABINET

ACT Government

ACT Healthy Waterways

A 10-year plan to restore Lake Tuggeranong

The ACT Government invites the community to be an active partner in reducing nutrients entering Lake Tuggeranong, to improve the water quality in the Lake for everyone.

CABINET

AT A GLANCE:

A 10-year plan to restore Lake Tuggeranong

The Vision

By 2035, Lake Tuggeranong is more consistently free of blue-green algal blooms and, when they do occur, they are short-lived so the Tuggeranong community can enjoy the lake most of the year.

The Government has some infrastructure options and other potential methods to improve water quality such as increased street sweeping. But none of these can be truly successful without the community also taking action in their own homes to help reduce nutrients from fallen leaves and grass clippings and fertiliser from entering the storm water system.

The ACT Government is developing a 10-year plan to improve the water quality in Lake Tuggeranong. This will include options for community action in homes and gardens, as well as additional ACT Government work that we want you to have your say on.

The challenge

Lake Tuggeranong is closed when blue-green algal blooms occur and the lake becomes unsafe, particularly for swimming and boating.

Most years, the lake is closed for recreation for several months due to blue-green algae blooms.

The same nutrients that help our gardens and plants grow help algal blooms grow too. Those nutrients are in residential fertiliser products, fallen leaves, and grass clippings. Stormwater carries them from kerbs, paved areas and our gardens down drains and eventually into our lakes, polluting the water.

The changing climate contributes to the challenge as the warmer temperatures expected will lead to warmer lake temperatures, which help the algae grow.

Explainer:
Algal blooms and nutrients

What are nutrients?

Nutrients refer to things like nitrogen and phosphorus that help plants (and people) grow. In our urban waterways, these nutrients come from sources such as leaf and grass litter, fertilisers (including composts and manure), sewage leaks and agricultural runoff. In big amounts they become pollutants.

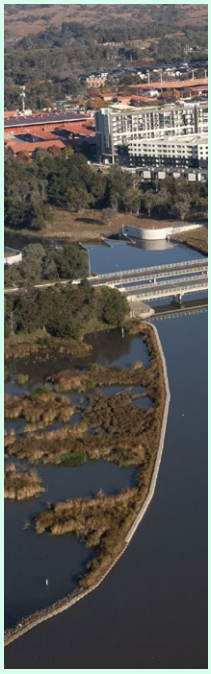
What causes algal blooms?

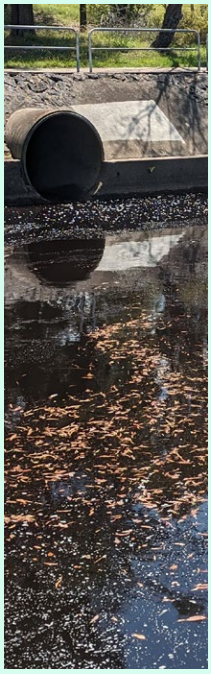
Algal blooms can grow rapidly when there are high levels of nutrients, warm water, slow-moving water bodies and plenty of sunlight.

Algal blooms can make the water smell and look green and can sometimes be harmful because they produce toxins that can hurt animals and people. The blooms can also impact the lake's ecosystem.

What's been done so far?

To improve the water quality of Lake Tuggeranong, the ACT Government has delivered wetlands, raingardens, ponds and other water quality improvement features. This has improved the health of the lake and has provided improved amenity in Tuggeranong, but more must be done.





2017/18

Wetlands built flanking the north and south sides of Isabella Pond

A raingarden built at Isabella Plains

2019

Three raingardens built at Gowrie Playing Fields, Fadden Pines, Wanniassa

A concrete drain naturalised in Monash

A pond built below Kambah Shops

2021

A set of floating wetland platforms deployed in the north arm of Lake Tuggeranong

'Leaf Collective' community education program launched in Tuggeranong

2022

Four bioretention swales installed in drains around Playing Fields in Kambah

2023

ACT Healthy Waterways public information campaign on managing leaves commences

45 Roadside kerb outlets to water green space created in Kambah

2024

'Love the Lakes' community education program targeting Tuggeranong

A major concrete drain naturalised in Calwell

A filtration unit added to Kambah Playing Fields to recycle stormwater to irrigate the fields

What else can we do?

During the 'journey of the stormwater', it's possible to remove nutrients from the system, or to treat algae directly, at three stages:

At the source by preventing nutrient pollution from occurring in the first place.

Within the stormwater system by slowing the flow and filtering nutrient pollution from the stormwater.

In the lake by promoting natural competitors of blue-green algae or using chemicals to kill the algae.

The research shows there is not one single solution. A range of options will be needed to stop the blooms in addition to community efforts.

The most effective way to reduce nutrients in the lake is to prevent nutrient pollution at its source. Households can greatly contribute to this by joining the majority of Canberrans who use little or no fertiliser and ensuring grass clippings and leaves end up in green bins, not in the gutters.

What are the options?

Here are the options we are consulting on:

At the source

Prevent excess nutrients entering urban stormwater

More street sweeping	Increase the amount of street sweeping in the Lake Tuggeranong catchment to remove more organic material, including leaves and grass clippings, from the roads.
Better leaf/grass litter management	Provide householders with education and support to better manage leaf and grass litter. This would complement the Street Sweeping program.
Less fertiliser	Identify and target the relatively small number of households who use excessive amounts of fertilisers and manures to help them apply less.
Better open-space mowing practises	Reduce the amount of grass clippings from municipal mowing that end up on the road.
Rainwater tanks	Capture stormwater from roofs for reuse on residential blocks.
Stormwater recycling	Divert and filter stormwater to storage tanks at sports fields for use in irrigating the fields.
Castellated kerbs	Replace standard road kerbs with specially designed kerbs that divert some of the stormwater to open green space and allow it to filter into the ground.
New water quality infrastructure at sports fields	Build swales around sports fields to capture any excess nutrients from fertiliser.

Within the stormwater system

Intercept and filter nutrients that have entered the stormwater system

New water quality infrastructure	Construct more wetlands at suitable locations in the Lake Tuggeranong catchment.
Maintain existing water quality infrastructure	Ensure maintenance of existing infrastructure, such as wetlands, in the catchment.

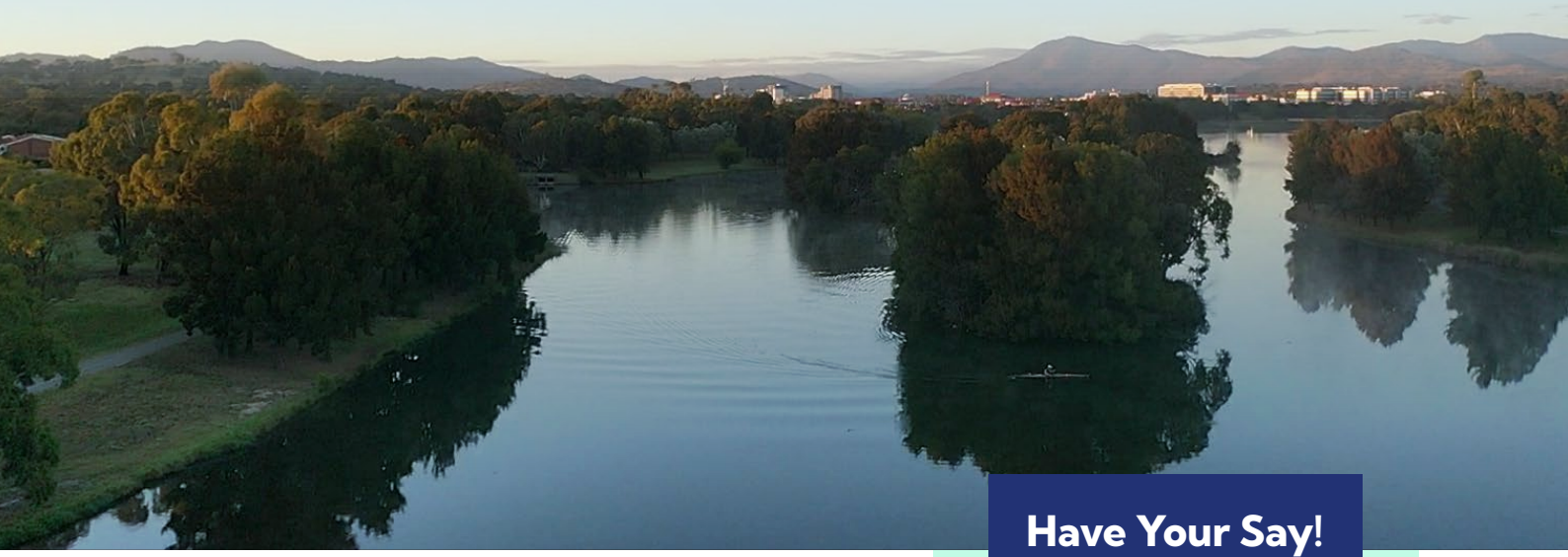
In the lake

Manage the pollutants and blue-green algae in-lake

Floating wetlands	Install more floating wetlands on Lake Tuggeranong to draw nutrients out of the lake water and shade algae.
Anti-algal agents	Promote natural competitors of blue-green algae or use safe chemicals to kill algae.

The consultation

The ACT Government is developing a 10-year plan to improve the water quality in Lake Tuggeranong. The Government has additional options which will support these important efforts by the community.



Have Your Say!

SHARE: Your feedback online or in person

ENGAGE: Help us understand how the options will impact you and your community

VISIT: A pop up and chat to our project team or join us for an information session and share your feedback

yoursayconversations.act.gov.au

QR code placeholder

Your feedback will help the ACT Government to understand the level of support for the additional options to improve the lake. For example:

- **what you think are the benefits or drawbacks of each option**
- **how the options would affect you**

The consultation will be open from 22 September to 17 November for 8 weeks. There will be several ways you can have your say both in-person and online.

The ACT Government wants your feedback on the additional options that will form part of the 10-year plan to restore Lake Tuggeranong.

Each option may impact the local community. It could mean temporarily moving cars for more frequent street sweeping or constructing local wetlands.

CABINET

Options for restoring Lake Tuggeranong

August 2025

ACT Government

ACT Healthy Waterways

CABINET

Acknowledgement of Country

Yuma

Dhawura nguna ngurumbangu gunanggu Ngunnawal. Nginggada dindi dhawura Ngunnawalbun yindjumaralidjinyin.

Mura bidji mulanggaridjindjula.

Naraganawaliyiri yarabindjula.

Hello,

This country is Ngunnawal (ancestral/spiritual) homeland. We all always respect elders, male and female, as well as Ngunnawal country itself.

They always keep the pathways of their ancestors alive.

They walk together as one.

We acknowledge the Ngunnawal people as traditional custodians of the ACT and recognise any other people or families with connection to the lands of the ACT and region. We acknowledge and respect their continuing culture and the contribution they make to the life of this city and this region.

Privacy

Any personal information provided during your submission will be used solely for the purpose of this community engagement process. Submissions may be partially or fully published on an ACT Government website or incorporated into a subsequent consultation report. As the ACT operates under a pro-release policy, citizens and others have the right to access information obtained through this engagement process under the Freedom of Information Act 2016. While the names of organisations may be disclosed, individuals' identities will be de-identified unless explicit prior consent has been obtained.

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Executive summary

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Executive summary

There is a rich history of Aboriginal use of the Tuggeranong valley and its waterways, with evidence of the Ngunnawal people occupying the valley for more than 20,000 years. The name 'Tuggeranong' comes from a Ngunnawal word for 'cold place' or 'cold plains'.

The valley has changed dramatically in the past 200 years, shifting the traditional life patterns that Traditional Custodians have understood and worked with for thousands of years. Sheep and cattle stations were established in the early 1800s. Since suburban development started in the 1970s, around 50% of the water catchment has been urbanised. Lake Tuggeranong was built in 1987 as a focal point for the growing town centre and to protect the downstream Murrumbidgee River from the water quality effects of development. Around the same time, a stormwater system was built to manage flood risk by converting natural creek lines such as Tuggeranong Creek into concrete channels.

Lake Tuggeranong has experienced elevated nutrient levels for more than ten years, which has led to frequent blue-green algal blooms. The algal blooms smell unpleasant, are unsightly and require the government to close the lake to activities such as swimming and water sports due to health risks. They also may pose health risks to residents of suburbs surrounding the lake who are exposed to aerosolised lake water on windy days.

These nutrient levels and algal blooms can be reduced to a manageable level using current knowledge.

Several key conclusions can be drawn from the analyses in this report:

- There is sufficient knowledge to have confidence that better water management can lead to a substantial reduction in the frequency of blue-green algal blooms in Lake Tuggeranong.
- A suite of pollution mitigation options to prevent nutrients entering the lake will be needed for success.
- There will be a limit to what can be done to prevent algal blooms; the best that can be achieved is to prevent algal blooms in three out of four years on average.
- Water managers may need to develop options to treat algal blooms when they do arise.

This report presents the best ways to apply our current knowledge in terms of impact and cost-effectiveness. This report builds on previous Healthy Waterways work in the Lake Tuggeranong catchment that saw the construction of nine important wetlands and funded research and community engagement to reduce the sources of nutrient pollutants.

Following consideration of community feedback on the report, the Government will present its preferred options for achieving a healthier Lake Tuggeranong as a *Healthy Waterways Plan for Lake Tuggeranong* (the Plan).

The vision

This report and the Plan that will follow, address an ACT Government commitment for the 11th Assembly to *develop and deliver a 10-year plan for a healthier Lake Tuggeranong*.

THE 10-YEAR VISION IS:

By 2035, Lake Tuggeranong is more consistently free of blue-green algal blooms and, when they do occur, they are short-lived so the Tuggeranong community can enjoy the lake most of the year.

AQUATIC ECOSYSTEMS in the ACT are highly valued by Traditional Custodians and the broader community as living systems that embody the interconnectedness of all life. Achieving this 10-year vision will support Traditional Custodian responsibilities to care for Country for future generations, as practiced for tens of thousands of years. This reflects Traditional Custodian understanding of water as an interconnected part of Country.

View of lake Tuggeranong from the North

The underpinning research and analyses

Research and modelling funded through the ACT Healthy Waterways program over the past decade has greatly improved understanding of blue-green algal blooms in Lake Tuggeranong. It is now well established that the inflow of phosphorus and other nutrients from the catchment is the main factor driving the blooms. They effectively feed the blooms.

There is currently far more phosphorus entering the lake from its catchment than is released to the water column from lake-bottom sediments. Phosphorus is generated from many diffuse sources across the urban catchment such as leaves, grass clippings, fertiliser products (including composts and manures), soil and sewage. Roughly half of it is in a dissolved form that is readily taken up by algae.

The stormwater flowing off the catchment carries an average annual generation of 1,656 kg phosphorus/year. The seven constructed wetlands built in Stage 1 of Healthy Waterways have reduced this by about 214 kg a year (to 1,442 kg). However, under current flow and levels of phosphorus supply, Lake Tuggeranong will remain in a eutrophic state—which means it is primed for algal growth.

Research shows that blue-green algal blooms can be significantly reduced if the supply of phosphorus to the lake is curbed or 'mitigated' by about 50%, or around 700 kg a year. Once this happens, any further algal blooms can be prevented through in-lake actions.

If the average annual amount of phosphorus entering the lake can be reduced by another 700 kg, the water quality models predict a eutrophic state can be avoided for an average of three out of four years. The 700 kg target is based on annual averages. In very wet years the reductions in phosphorus will need to be higher, while in dry years they can be lower. Some blue-green algae will be present in all years, but if the 700 kg target can be achieved, the likelihood of problem blooms would be lower than at present and the lake should usually be available for contact-based activities.

CABINET

Options for removing phosphorus

It is possible to remove phosphorus from the system, or to treat algae directly, at three stages during the 'journey of the stormwater':

1. At the sources of pollution, by preventing pollution from occurring in the first place.
2. Within the stormwater system, by slowing the flow and filtering pollution from the stormwater.
3. In the lake, by using agents that compete with algae for nutrients, or by using algicides.

Potential options are presented for reducing or mitigating phosphorus levels (pollution mitigation options) or directly treating algal blooms. A subset of ten options are examined in detail. These were chosen for discussion because their costs and effectiveness could be well characterised based on local trials or the scientific literature.

The analyses clearly show that the most effective options for reducing phosphorus pollution are an increased frequency of street sweeping and building extra water quality assets, such as wetlands, which cleanse stormwater of pollutants. Street sweeping is by far the most cost-effective mitigation measure, decreasing phosphorous by 200–400 kg per year, depending on the frequency of sweeps. Constructing more water quality assets would decrease phosphorous by 100–200 kg per year, depending on the scale of the wetlands and other water quality assets already in the system.

However, the analyses highlight that no single option is a 'silver bullet' that has the potential to reach the phosphorus mitigation target on its own. Multiple options will be needed. Notably, options to prevent stormwater from getting polluted in the first place will be needed to substantially reduce the frequency of blue-green algal blooms.

CABINET

Management scenarios

After outlining the options, this report investigates solutions by defining two management scenarios that are comprised of multiple pollution mitigation options:

1. A 'cost-effective' scenario that represents the most cost-effective set of options to reach the 700 kg target.
2. A 'broad benefits' scenario that recognises that some options that rank lower for cost-effectiveness, such as constructed wetlands, should nevertheless still be included in the solution because they provide additional values to the community beyond water quality improvement, such as wellbeing.

The management scenarios reflect reality; water managers implement pollution mitigation options concurrently (at the same time). However, the water quality models estimate that concurrent implementation would result in a lower amount of phosphorus being removed than when the options are implemented in isolation from one another. For example, the combination of street sweeping, additional wetlands and eight other options (the 'broad benefits' scenario) was modelled as decreasing phosphorus by just under 600 kg per year compared with 746 kg per year when the options were considered in isolation from one another. This makes sense. For example, campaigns to get residents to remove leaves from roadside gutters will reduce the volume of leaves collected by increased street sweeping, but the sweeping will still be needed.

Despite the result of just under 600 kg per year being slightly lower than the 700 kg per year target, there are reasons to suggest the ACT Government could successfully curb algal blooms in the lake if it implements a program to reduce phosphorous pollution.

- First, reducing phosphorus pollution by just 500–600 kg/year would represent a substantial improvement and would significantly lower the frequency of blue-green algal blooms in Lake Tuggeranong.
- Second, the options to mitigate pollution have only been represented in models in a simple way and their refinement, both during implementation planning and in models, should both decrease their cost and increase their effectiveness.
- Last, there are several promising options that have yet to be tested that may help meet the phosphorus mitigation target of 700 kg/year, such as in-lake phosphorus adsorption materials.

The main cautionary note is about how quickly algae in Lake Tuggeranong will respond to reduced supplies of phosphorus from the catchment. If the phosphorus already in the lake sediments is able to sustain the blooms, it may take longer than the goal of a decade to fix the problem. However, there are options that the government can explore through research and trials for directly dealing with both phosphorus in lake sediments and algal blooms. This increases the likelihood of good progress over the next decade.

The costs

The analyses suggest the cost of mitigating phosphorus pollution in stormwater by 500–600 kg/year (or by the target 700 kg per year with refinement of the mitigation options) is $105 million over 30 years, or $146 million over 30 years for the broad benefits management scenario. However, refinement of the pollution mitigation options should not only increase the effectiveness of the management solutions but may reduce their costs.

Future research and monitoring

An active research and monitoring program has played a central role in the work to date. Ongoing research and monitoring will be critical to refining pollution mitigation options to maximise their effectiveness and minimise their costs. New evidence and knowledge can be incorporated into future versions of the Plan, and its implementation plans.

The highest research priorities are trials of promising options and investigations to better understand the fate of fertilisers applied to residents' blocks and to determine whether sewage (either through cross-connections or by other mechanisms) is a significant source of phosphorus in stormwater. It will be critical to continue to monitor the effectiveness of wetlands and other water quality assets, as well as other interventions.

Additional research will continue to refine knowledge and understanding of how to reduce phosphorus in the catchment. However, there is enough evidence already to identify priorities for restoration. Substantial improvements should occur in the lake within several years of the commencement of a material pollution mitigation program.

Next steps

Version 1 of the Healthy Waterways Plan for Lake Tuggeranong will be created based on this report and incorporating further inputs from First Nations people and feedback from the community and experts on the proposed approach. An implementation plan will then be developed to set out how the vision will be achieved over the next 10 years, including how it will be monitored and evaluated.

Floating wetland in Lake Tuggeranong

Aerial view of Lake Tuggeranong. Source: MetroMap

CABINET

Part 1
Context

- The ACT Healthy Waterways Program
- Objective and scope of the report
- Vision
- Lake values
- Legislative and policy context for managing water quality in Lake Tuggeranong
- Lake Tuggeranong and its catchment

CABINET

Part 1: Context

The ACT Healthy Waterways Program

Addressing water quality in our urban lakes, and specifically the issue of blue-green algae, is a major challenge. The ACT Healthy Waterways Program (Healthy Waterways) was created to address the issue of declining water quality in ACT's rivers and urban lakes.

Stage 1 Healthy Waterways (2014–21) was a joint Australian Government and ACT Government investment, while the ACT Government is fully funding Stage 2 (2021–25).

Over the last decade, Healthy Waterways has delivered a comprehensive suite of activities to help improve water quality and improve our understanding of the problem. It has built water quality assets (such as wetlands and raingardens); invested in research, monitoring and data analyses; built water modelling capability; and initiated community partnership programs to uplift catchment management practices.

Through this work, we have greatly improved our understanding about how ACT's urban catchments operate, the different sources of nutrient pollution that enter waterbodies and lead to algal blooms, the in-lake processes that promote algal blooms, and how the community wishes to participate in caring for waterways.

Of the urban lakes, Lake Tuggeranong has suffered the most chronically from water quality issues in recent years and has been the primary focus of investigative efforts to date. This report will underpin a *Healthy Waterways Plan for Lake Tuggeranong (the Plan; Figure 1), which is the first of four Healthy Waterways plans for urban waterways*.

Objective and scope of the report

The objectives of this report are to:

1. determine whether it is feasible to achieve a substantial reduction in the incidence of algal blooms in Lake Tuggeranong
2. evaluate various options for mitigating stormwater pollution that drives algal blooms.

The Government will finalise the report as a *Healthy Waterways Plan for Lake Tuggeranong* once the community has provided feedback on the options (Figure 1). Subsequently, funding will be investigated for the Plan to be implemented. Funded restoration activities will be monitored and evaluated, and further research and stakeholder engagement will be conducted. The Government will periodically update the Plan as new knowledge comes to hand to ensure the plan achieves maximum value for the community at least cost.

This report and the Plan prioritise focussing on algal blooms over other water quality issues because the ACT Government believes they are the highest priority for the Tuggeranong community (for example, TCC, 2024, Draft). Reducing the incidence of blue-green algal blooms in Lake Tuggeranong should improve its amenity and recreational values for residents and reduce health risks.

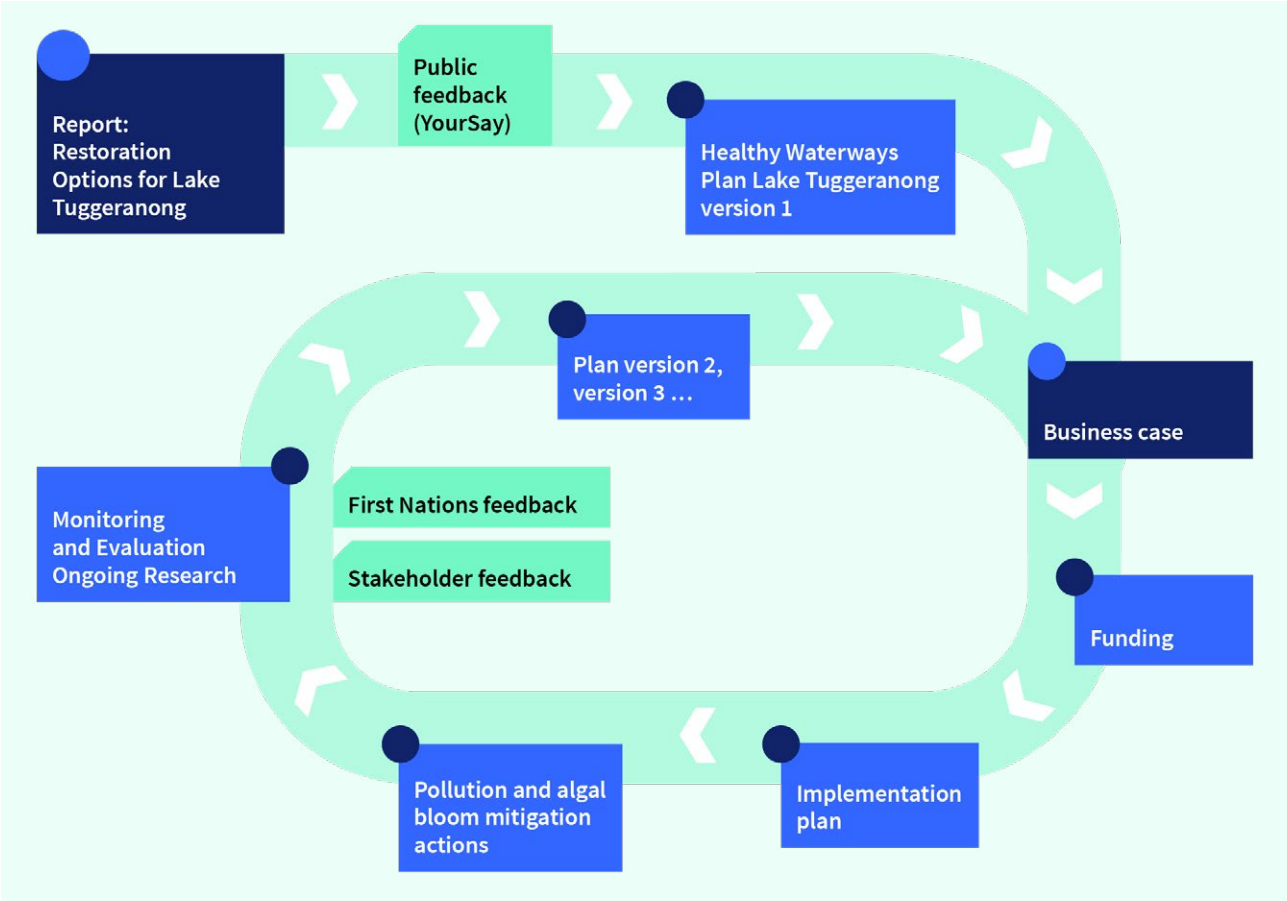


Figure 1. Role of Restoration Options for Lake Tuggeranong in the adaptive management cycle for mitigating algal blooms in the lake.

Vision

This report and the subsequent Plan address an ACT Government commitment for the 11th Assembly to develop and deliver a 10-year plan for a healthier Lake Tuggeranong.

The 10-year vision is:

By 2035, Lake Tuggeranong is more consistently free of blue-green algal blooms and, when they do occur, they are short-lived so the Tuggeranong community can enjoy the lake for most of the year.

We need a 10-year time frame because new infrastructure assets will take time to build and become fully functional, and to allow enough time to assess the effectiveness of interventions while considering the background influence of year-to-year climate variability. Nevertheless, fulsome implementation of the Plan should lead to substantial improvements in water quality within several years.

Lake values

Lake Tuggeranong provides multiple social, economic and environmental values for the ACT and region community. However, the lake does not provide all these values consistently. The 2022 State of the Lakes and Waterways highlights that there are tensions between the competing values of urban lakes and waterways—for example the amenity of Lake Tuggeranong versus its role as a pollution trap—and widely differing expectations of urban water management (OCSE, 2022).

Mitigating downstream pollution

Canberra's lakes reduce downstream pollution by acting as sediment and pollution filters. NCEconomics (2023) estimated the market value of this function, known as 'avoided abatement cost', which describes how much it would cost to provide the equivalent pollution abatement if the lakes were not serving that function.

They estimated value of Canberra's urban lakes as pollution filters using a hypothetical comparison of water quality outcomes 'with' and 'without' the lake, where water quality upstream of the lake was used as a proxy for water quality 'without' the lake (NCEconomics, 2023). Total nitrogen was used as the water quality indicator. This was used because pollution abatement assets can reduce multiple pollutants at the same time, so only the highest-cost pollutant for each lake was used, to avoid the risk of double counting. The abatement costs were based on the cost of creating equivalent abatement capacity by building water quality assets. The cost of water quality assets was derived from construction costs in the ACT in the six years from 2017 to 2023. The study estimated the net present value associated with Lake Tuggeranong's pollution abatement value is $133–144 million (over 30 years). As discussed in Part 7, water quality assets are not the most cost-effective option for mitigating phosphorus pollution, so this is likely an overestimate of Lake Tuggeranong's pollution abatement value.

However, Lake Tuggeranong is not always effective as a pollution filter. The 2023 State of the Environment Report concludes, 'Lake Tuggeranong does not appear to be consistently mitigating the effects of urbanisation for the downstream waters with periods of higher phosphorus and nitrogen concentrations within and downstream of the lake compared to upstream of the lake'.

Providing opportunities for recreation and amenity

Canberra's urban lakes and their catchments provide important social values for Canberra residents. Access to blue spaces also contributes to improving people's physical, mental and spiritual wellbeing (UK Environment Agency, 2020; Dushkova et al., 2021; Lal and Akhikari, 2024). It follows that when algal blooms require the government to close the lake for long periods, there may be negative consequences for people's health and wellbeing.

The high value that Canberra residents place in their waterways is reflected in several surveys and community engagements undertaken from 2016 to 2023:

- A 2016 survey of more than 7000 people on Canberra's urban lake use found that the activity most often rated as 'highly important' was walking with other people, followed by picnics/barbeques, cycling and using playground areas (Schirmer & Mylek, 2016).
- In community engagements as part of developing the Tuggeranong District Strategy, the Tuggeranong community said they value the lake for a range of recreational activities throughout the year, including walking, cycling, swimming, fishing and windsurfing (ACT Government, 2023b).
- In the findings of a 2018 ACT 'Better Suburbs' community survey, the citizen forum's first recommendation (out of 14) was to increase funding for lakes, ponds, wetlands, stormwater and water quality. This was ranked as more important for community members than issues such as street trees, roads, footpaths and public libraries (ACT Government, 2018).
- A report commissioned by the ACT Government in 2023 explored residents' willingness to pay for environmental amenity and recreational use of Canberra's lakes (NCEconomics, 2023). The report found that the total annual non-market economic value of the lakes based on pollution control and amenity was approximately $159 million a year for Lake Tuggeranong, with the economic value from benefits to the community significantly outweighing the benefits attributable to water quality management (pollution abatement) provided by the lakes (Figure 2). (The much lower value of Lake Tuggeranong for pollution abatement in Figure 2 compared with its net present value is because Figure 2 reports annualised data whereas net present value is assessed for a 30-year period.)

- A 2023 survey of ACT residents indicated they were prepared to pay up to $70/per person/quarter (or $280/per person/year) to greatly improve the environmental (visual and smell) amenity of Lake Tuggeranong (NCEconomics, 2023). Across all lakes, the survey found that most lake users are infrequent, casual users who draw more value from lake amenity and lakeside facilities than from primary and secondary contact activities like swimming and boating. This finding is also consistent with findings from the earlier survey of Schirmer & Mylek (2016).

Environmental values

There is limited information on the ecological values of the lake. The Waterwatch Catchment Health Indicator Program (CHIP) 2023 report notes the lake has poor riparian condition with little native vegetation, but Eastern Long-necked Turtles, water dragons and occasionally Rakali (Australian native water rats) are present in the wetlands at the southern end of the lake (Upper Murrumbidgee Waterwatch, 2023).

The 2023 State of the Lakes Report found that the aquatic health of the lake supported ecological values to a 'fair' degree, noting limited information to determine a trend. This conclusion was based on the CHIP assessments and because water quality and ecosystem health of the lake are sufficient for the survival of stocked native fish (OCSE, 2022). Murray Cod and Golden Perch are stocked, primarily to support recreational fishing, it also to improve biodiversity and help balance the fish composition by adding native predators to the system. There are a lot of carp in the lake; surveys in 2015 and 2018 showed carp comprised around 90% of all biomass caught. This decreased to 60% in 2024 due to increased stocking of native fish (ACT Government, unpublished data, 2025).

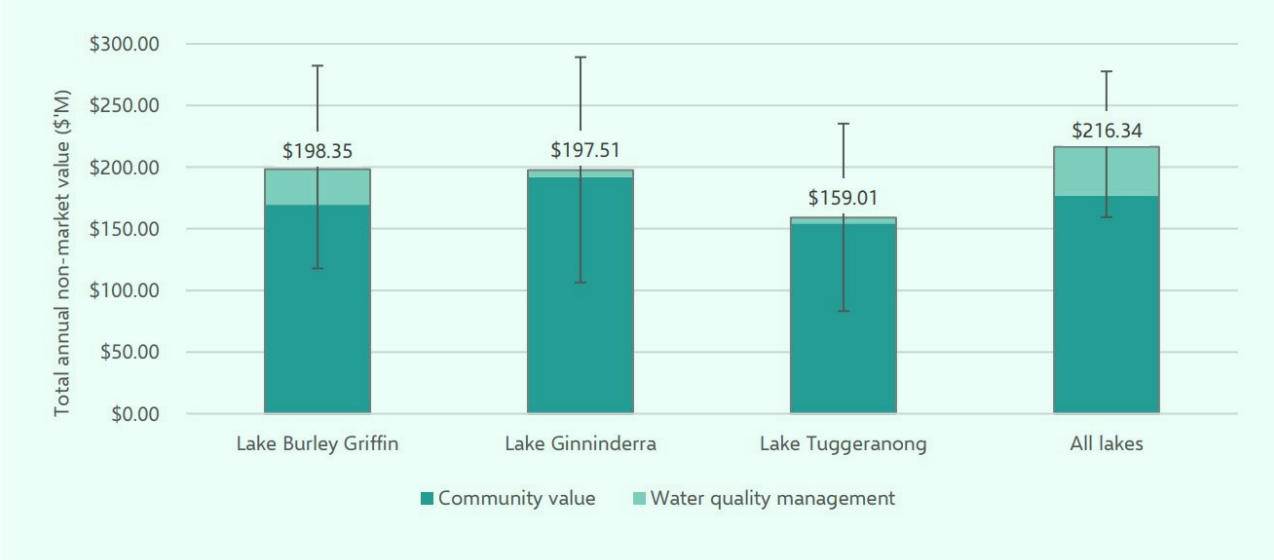


Figure 2. Total annual non-market value from ACT urban lakes. The community value is based on surveyed residents' willingness to pay for good water quality within the lakes through increases in rates. The water quality management value is based on the avoided cost of building water quality assets that provide the same level of treatment as the lake. Source: NCEconomics (2023).

Cultural values

Cultural values mapping can help to identify what First Nations cultural values and uses are associated with the lake, its tributaries and catchment. This should be undertaken with Traditional Custodians as part of implementation planning to guide an integrated design approach that supports and enhances place-based management actions.

This would build upon a Ngunnawal Aboriginal Waterway Assessment (AWA), which assessed the health of Country and the waterways in the Tuggeranong catchment from a cultural perspective. The Assessment stressed the importance of:

- recognising Ngunnawal people as a part of the solution to restoring the health of Lake Tuggeranong
- reintroducing and respecting cultural practice in catchment management such as cultural burning and cultivation of pointer and keeping trees
- establishing Ngunnawal rangers
- continuing to conduct AWAs
- introducing more native plants to the creek and surrounding riparian and dry landscapes, including natives of cultural significance such as reeds for weaving
- restoring key features such as naturalising concrete drains
- creating a fully connected cultural way from the headwaters of Tuggeranong Creek to its confluence with the Murrumbidgee River
- concerns about pollution, including blue-green algae, entering the Tuggeranong Creek
- considering river health and Country health as intertwined
- exploring opportunities for an entitlement to water for cultural purposes.

Smoking ceremony at an opening of a wetland

Legislative and policy context for managing water quality in Lake Tuggeranong

Lake Tuggeranong's management is prescribed by the *Planning Act 2023 (ACT)*, which prioritises management objectives for all public land (including waterways) in the following order:

- Prevent and control floods by providing a reservoir to receive flows.
- Prevent and control pollution of waterways.
- Provide for public use for recreation.
- Provide habitat for fauna and flora (Schedule 3 [Part 3.2]).

Since there is little urban infrastructure downstream of Lake Tuggeranong to protect from floods, the primary management objective for Lake Tuggeranong under the Planning Act is to prevent and control pollution.

The Plan aligns with and supports the implementation of other ACT legislative and policy commitments on water quality, specifically the following:

- The *Lakes Act 1976*, administered by the Environment Protection Authority (EPA), which provides for the administration, control and use of urban lakes in Canberra (other than Lake Burley Griffin).
- The ACT Water Strategy 2024–2044 Striking the Balance sets a 20-year vision for ACT water management as: *'A community working together, managing water wisely to support a vibrant, sustainable and thriving region.'* Outcome 1 of the Strategy—Healthy Catchments and Waterbodies—aims to achieve 'Well managed, functioning catchments that provide sufficient clean water for the environment and human consumption, support healthy waterbodies, and contribute to liveability of the ACT community'.
- Focus on improved water quality standards to support identified environmental values and permitted uses for Lake Tuggeranong. Environmental values and permitted uses are defined through the Water Use and Catchment General Code (the Code), a subordinate instrument of the *Water Resources Act 2007* (ACT). Under the Code, Lake Tuggeranong and its catchment is defined as drainage and open space with the following environmental values and permitted uses of:
  - discharge of stormwater
  - irrigation water supply
  - waterscape view
  - aquatic habitat (lowland streams, urban lakes and ponds, urban wetland)
  - water-based recreation (boating).
- Water quality standards are set through the Environment Protection Regulation 2005 (ACT) Schedule 4, a subordinate instrument under the *Environment Protection Act 1997* (ACT), and support the policies, management objectives and values of the Code. Access Canberra (EPA) ensures compliance with the Environment Protection Regulation, including s44 that 'a person must not place, or permit to be placed, a pollutant in a waterway if the pollutant is likely to cause environmental harm.'
- The ACT and Region Catchment Strategy 2016–2046 establishes a 30-year vision to guide priority actions for a healthy Upper Murrumbidgee River region (upstream of Burrinjuck Dam to Tantangara Dam in NSW). Developed in partnership with the Australian Government, ACT Government, NSW Government, local councils, Icon Water and the community, it is currently undergoing a 5-yearly review.
- The 2002 Legislative Assembly committed to manage downstream water quality through an agreed motion that the water leaving the ACT via the Murrumbidgee River should be of no less quality than the water flowing into the ACT (ACT Legislative Assembly motion 5 June 2002 9.1[b]).

- The Canberra Urban Lakes and Ponds Land Management Plan's vision is to: enrich local communities through the aesthetic, recreational, sporting, tourism, cultural and ecological values of lakes and ponds, and to provide opportunities for people to be involved in their use, care and management. Under this plan, 'recreation' and 'visual landscape' are listed as Lake Tuggeranong's highest values.
- The ACT's Water Resource Plan, developed under the Murray–Darling Basin Plan, contains a Water Quality Management Plan that sets locally relevant water quality targets.

None of these legislative and policy commitments consider whether and how to reduce the problem of blue-green algal blooms in Lake Tuggeranong, but they do underpin this report, which fills that gap.

Management of the ACT's lakes and ponds represents a collaborative effort across government, the private sector and the community (residents). ACT Government agencies and other organisations with responsibilities include:

- City and Environment Directorate
  - delivers the Healthy Waterways Program, undertakes water science, monitoring and modelling, implements the ACT Aquatic and Riparian Strategy,
  - implements Murray-Darling Basin commitments,
  - undertakes planning to include water sensitive urban design,
  - owns, manages, maintains the stormwater system and water sensitive urban design assets,
  - manages urban open spaces, water quality services (dredging, street sweeping, GPT cleaning) recreation services on lakes and ponds, and dam safety.
  - includes the Environment Protection Authority – the statutory decision maker under the *Water Resources Act 2007 and Environment Protection Act 1997*, administers Environment Protection Regulations on environment, water quality and waterway health.
- Health and Community Services Directorate – monitors water quality of recreational water sites.
- ACT Emergency Services Agency – undertakes strategic and emergency flood risk management.
- Icon Water – owns, operates, maintains drinking water supply and wastewater system, undertakes long-term water resource planning.
- National Capital Authority – manages Lake Burley Griffin's water quality and waterway health.

Lake Tuggeranong and its catchment

Three major tributaries deliver inflows to Lake Tuggeranong—Kambah and Village creeks in the north (draining a fully urban area) and Tuggeranong Creek in the south (draining urban and rural areas)—as do several minor drains (Figure 3). Tuggeranong Creek runs through a series of settling ponds to improve water quality—Isabella Pond then Lake Tuggeranong wetlands—before discharging into Lake Tuggeranong (Figure 4). Key lake statistics are shown in Table 1 and Figure 4.

Geographical setting and early history

Before it was developed, the Tuggeranong Creek catchment featured hills and valleys with a large, shallow gravel aquifer with 1.5 times the current lake's volume. Tuggeranong Creek would have had a hydrology consistent with a 'chain-of-ponds' system (Lawrence, 2012). Chain-of-ponds systems usually occur in shallow, alluvial valleys where a river doesn't carry flow under baseflow conditions; instead of a continuous channel the river forms a series of irregularly spaced ponds (Mould and Fryirs, 2016). The other tributaries may originally also have been damp valleys, chains of ponds or small creeks.

There is evidence to suggest Ngunnawal people have occupied the Tuggeranong Valley for more than 20,000 years. The name 'Tuggeranong' comes from a Ngunnawal word for 'cold place' or 'cold plains'. Tuggeranong Creek would have provided an important source of water. Important cultural sites in the valley include scarred trees found at Lanyon (canoe tree) and the Wanniassa–Kambah area (ACT Heritage Council, 2024). Axe-grinding grooves have been found in a sandstone outcrop in what is now the suburb of Theodore (Flood, 1996). Tuggeranong Creek remains a culturally and spiritually important part of country for Ngunnawal people today, and undertaking cultural values mapping would help provide us with a better understanding of this.

Europeans began grazing the valley with sheep and cattle in the late 1820s and homesteads were established close to watercourses, including Tuggeranong Creek. Lanyon Station was established in 1835 and the Tuggeranong and Lanyon Homesteads, which remain today, are reminders of this period.

Lake Tuggeranong looking north towards Mount Taylor (photo: Jennifer Smits)

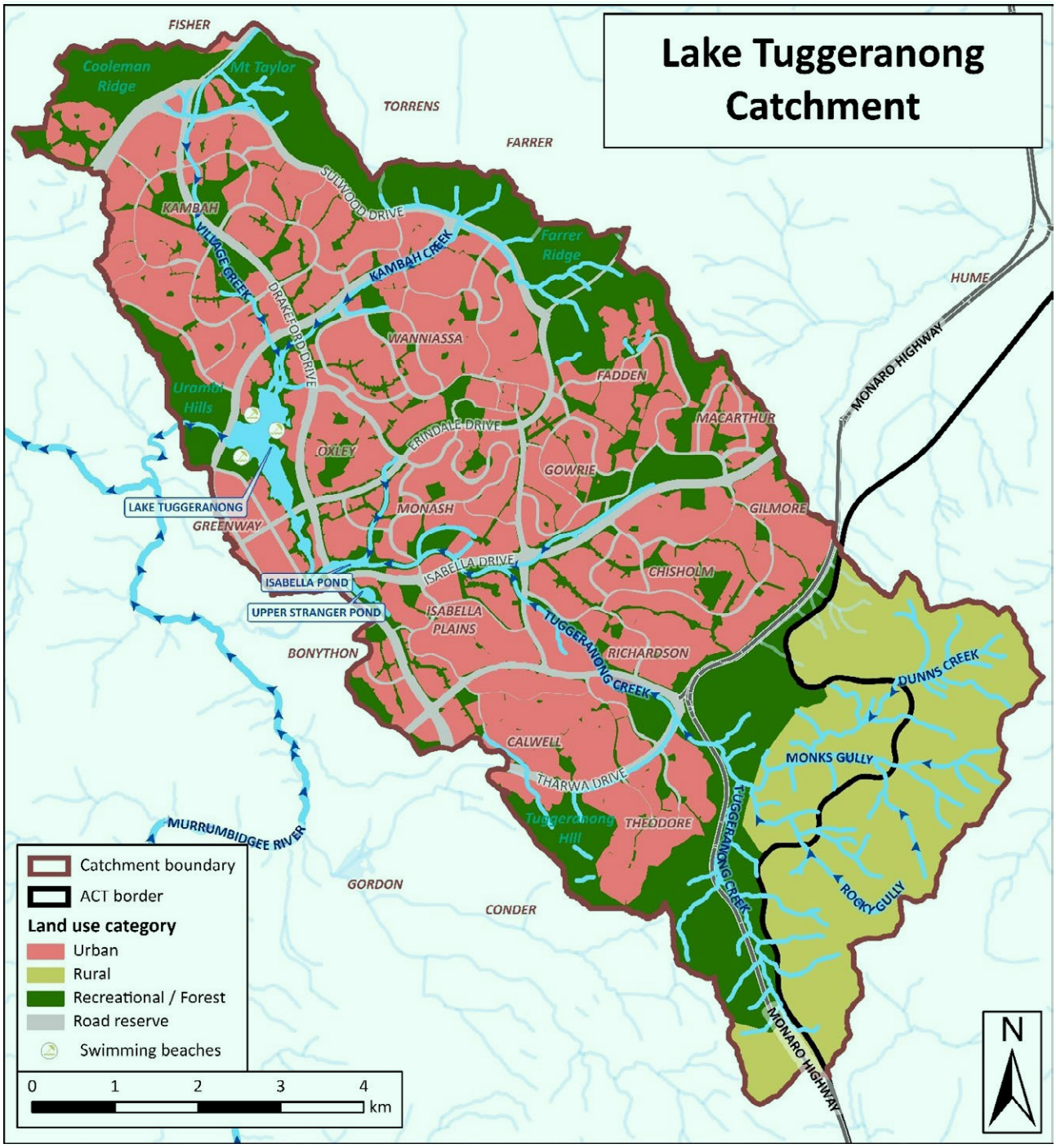


Figure 3. Lake Tuggeranong catchment showing its tributaries. The lake discharges into a short section of Tuggeranong Creek via an outflow channel and weir at the west corner of the lake. This creek then flows into the Murrumbidgee River.

Table 1. Lake characteristics and Tuggeranong climate. Source: (GHD, 2024) and www.bom.gov.au

Lake characteristic	
Size	57 hectares
Volume	1,790 megalitres (at normal operation)
Average depth	2.9 metres
Maximum depth	12.2 metres
Average residence time of water	58 days
Average annual inflows	9,000 megalitres
Minimum inflows (dry year)	3,000 megalitres
Maximum inflows (wet year)	18,000 megalitres
Tuggeranong climate	
Summer mean maximum temperature	28.1° Celcius
Summer mean minimum temperature	13.6° Celcius
Winter mean maximum temperature	14.4° Celcius
Winter mean minimum temperature	0.7° Celcius

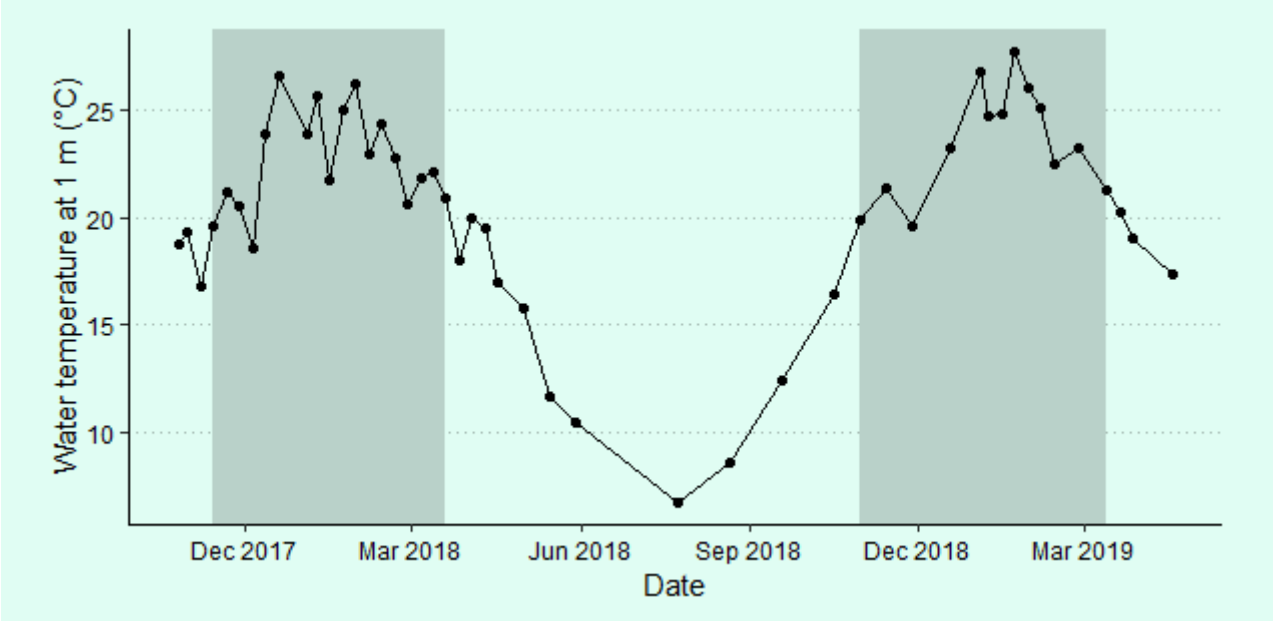


Figure 4. Surface water temperature in Lake Tuggeranong: Mean water temperature at a depth of 1 metre in the central basin of the lake. The grey rectangles that overlay the plot indicate the period from the first detected stratification to the final breakdown of stratification in the lake for the year. (Source: Figure 4-2 in Ubrihien et al., 2019, p.77).

An urbanised catchment—a new lake to filter sediment and concrete drains to channel flows

Tuggeranong was earmarked to be the third town centre of Canberra and was rapidly developed into suburbs throughout the 1970s and 1980s. Much of the shallow aquifer was drained using agricultural drains, stormwater pipes and concreting of the channel bed inset into the aquifer (Lawrence, 2012). To manage the flood impacts of urban runoff, most of the catchment's tributaries have been modified to become a constructed stormwater system of concreted open channels and underground pipes. Lake Tuggeranong was built in 1987 by damming the Tuggeranong Creek at Athllon Drive. While some rural land still exists within the Tuggeranong catchment, it now has a built-up area of more than 50% (Table 2).

Urbanisation changes flow regimes by increasing the impervious surface area (Walsh et al., 2012). Dey et al. (2024) estimated that runoff is four times higher in the Lake Tuggeranong catchment now than when it was a natural catchment. This is because roads, buildings and concrete are water-resistant materials that prevent water from being absorbed into the landscape. This leads to high surface water runoff that makes its way to the stormwater system (Ladson et al., 2006), carrying pollutants with it.

Table 2. Land use in the Tuggeranong catchment

Built-up area		Green space area	
Urban	41.2%	Rural land	28.3%
Roads/transport	8.9%	Urban open space	10.2%
Commercial land use	1.8%	Natural bushland	9.5%
Approx total	52%	Approx total	48%

Concreting of the Tuggeranong Creek channel bed

CABINET

Part 2
Water quality problems in Lake Tuggeranong

- Blue-green algae
- Faecal indicator bacteria

CABINET

Part 2: Water quality problems in Lake Tuggeranong

Lake Tuggeranong currently experiences frequent blue-green algal blooms and periods of elevated bacteria levels. Other water quality issues in the lake or its tributaries include high turbidity and industrial pollution events; for example, from paint (Upper Murrumbidgee Waterwatch, 2022).

This report and the subsequent Healthy Waterways Plan focus primarily on addressing algal blooms over other water quality issues. This is because of the higher potential health risk associated with blue-green algal blooms, the fact they contribute to a large proportion of lake closures, and the significant visual and odour impact on the community during severe blooms, such as reported in TCC (in draft).

Blue-green algae

Blue-green algae (Cyanobacteria) are a group of bacteria present in virtually all aquatic environments worldwide. Blue-green algae are not plants but are photosynthetic bacteria, reproducing rapidly when given sunlight and warm, nutrient-rich conditions (Joehnk et al., 2008). They are buoyant, forming surface scums known as a blue-green algal bloom. When this happens, they block the light that would otherwise be available for favourable plant growth, discolour the water and may release a range of toxins. Such blooms are a growing problem in Lake Tuggeranong, especially in summer. Algal blooms reduce visual amenity, release foul odours, pose a health hazard to residents and visitors and require the ACT Government to close the lake to recreational use.

Blue-green algae and human health

Some types of blue-green algae produce toxins (cyanotoxins) that can be harmful for humans, domestic animals and livestock that drink or make contact with the water, and for fish and other organisms living in the water.

There is increasing research and community interest in Australia and overseas into potential associations between cyanobacteria and neuro-degenerative diseases in humans (as noted, for example, by NSW Health, 2023). For example, studies have found an increased incidence of motor neurone disease in people living near waterbodies with blue-green algal blooms (Cox et al., 2003; Caller et al., 2009; Andrew et al., 2017; ABC Online, 2023; Torbick et al., 2018), although most of these studies could not confirm whether direct exposure to cyanobacteria had occurred.

The link between exposure to blue-green algae through primary or secondary contact and neuro-degenerative diseases has not been proven, except where foods have been grown in the presence of blue-green algae (Cox et al. 2003). Clusters of residents with motor neurone disease might be caused by a myriad of factors unrelated to blue-green algae blooms. However, researchers have yet to fully evaluate all plausible cause–effect mechanisms related to blue-green algae blooms and there is an argument for adopting the precautionary principle to mitigate potential risks to human health (Dunlop et al., 2021; Cox, 2021). This is particularly important while investigating airborne exposure pathways such as chronic exposure to aerosolised cyanotoxins downwind of affected waterbodies (Sutherland et al., 2021; Schaefer et al., 2020; Plaas & Paerl, 2021).

Lake Tuggeranong experienced a significant blue-green algae bloom over the summer of 2019/20 (photo: Alica Tschierschke)

Blue-green algae monitoring and lake closures

The Environment Protection Authority (EPA) monitors five sites in Lake Tuggeranong during the recreational season, which runs from October to April. The lake is closed to recreational use if either blue-green algae or faecal bacteria concentrations exceed the levels specified in the ACT Guidelines for Recreational Water Quality. Data analysed from 2015 to 2024 shows frequent closures throughout the recreational season with at least one swimming beach closed for more than 50% of the time for seven of those nine years (Figure 6).

In the 2022–23 season, EPA monitoring showed that all three swimming beaches were closed for almost the entire recreational season. In addition, blue-green algal blooms kept the lake closed to primary contact recreation from mid-January 2023 through to the beginning of June 2023, well beyond the recreational season.

Information about how water quality in Lake Tuggeranong is monitored, and current alerts and closures, is published on the ACT City Services website www.cityservices.act.gov.au.

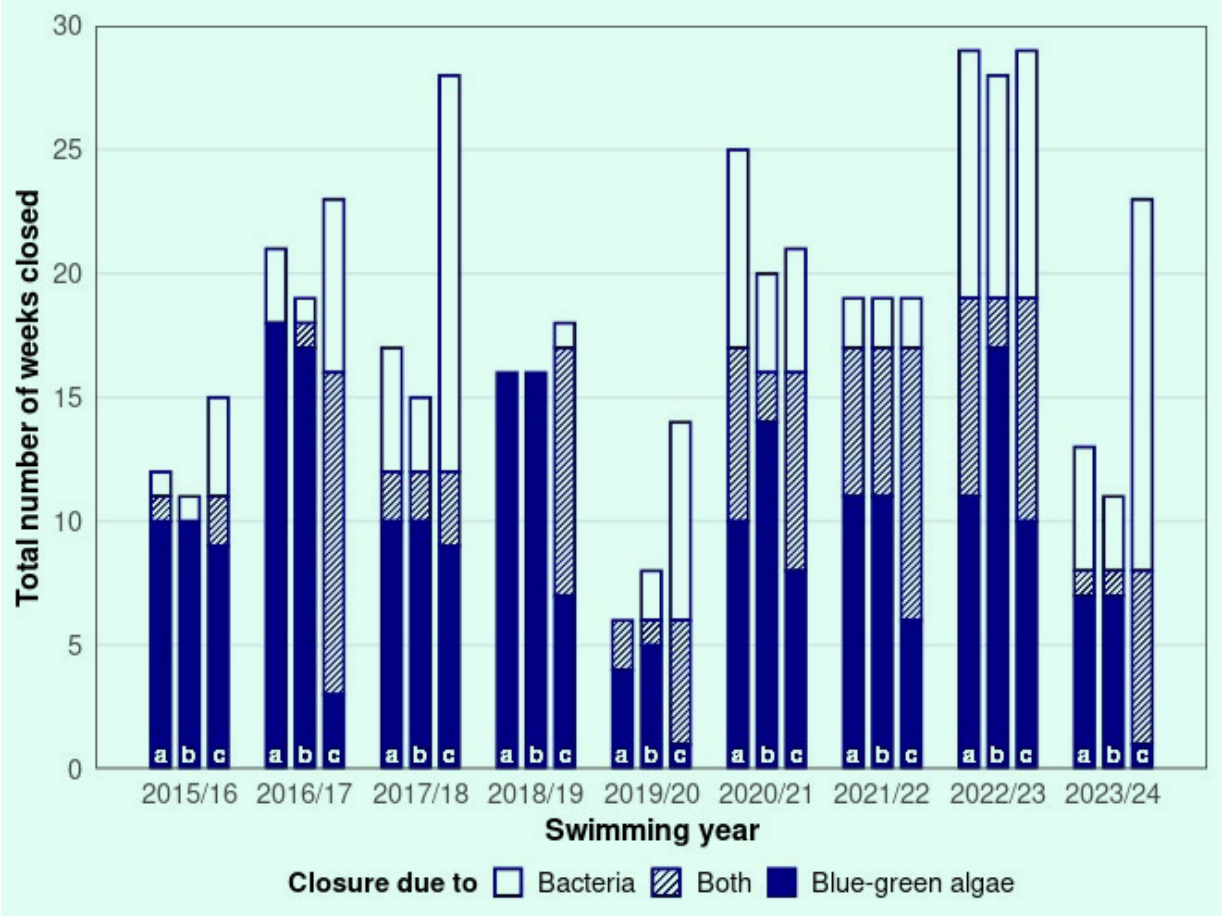


Figure 5. Number of weeks of the swimming season (30 weeks from Oct–April) that Lake Tuggeranong was closed to swimming at one or more beaches due to blue-green algae or bacteria between 2015 and 2024. Column a: Ngadyung Beach, Column b: Nguru Beach, Column c: Tuggeranong Town Beach

Faecal indicator bacteria

As Figure 6 shows, lake closures can also be due to the presence of faecal indicator bacteria, with Tuggeranong Town Beach showing a higher incidence of closures due to this cause.

ACT Health routinely tests ACT lakes for faecal contamination using the faecal indicator bacteria enterococci. These are a group of bacteria found in the intestines of humans and animals; their presence in water may indicate domestic sewage leaks or contamination from diffuse sources of human and animal waste. Water managers use enterococci as the standard faecal indicator bacteria to test water quality in recreational waters in Australia because they are well understood, easy to detect and their presence reliably predicts health risks associated with exposure to waterborne bacterial pathogens.

Monitoring work using Microbial Source Tracking is currently underway to understand the extent the faecal matter is coming from human or animal sources. Findings from this work will inform future iterations of the Plan. In the meantime, many of the interventions proposed to reduce algal blooms will also remove bacteria and other pollutants, such as excess carbon, nitrogen and total dissolved solids, that are potentially causing issues in the catchment.

CABINET

Part 3
The cause of algal blooms

- Drivers of algal blooms
- Supply of phosphorus: catchment versus lake sediments
- Catchment sources of phosphorus

CABINET

Part 3: The cause of algal blooms

Drivers of algal blooms

The prevalence of blue-green algae is linked to the trophic state of a water body. Trophic state is a description of the biological productivity of a water body and depends on factors such as the concentration of nutrients used by plants (and blue-green algae) such as phosphorus and nitrogen (South Dakota State University Extension, 2022).

Water bodies in an oligotrophic state have very low nutrient concentrations and tend to have very clear water with little plant or algal growth and high oxygen concentrations that depress the release of algal nutrients stored in lake-bottom sediments. Hence, oligotrophic lakes are not prone to algal blooms. Water bodies in a mesotrophic state have a moderate amount of nutrients, moderately clear water, some algal blooms in late summer and oxygen depletion at bottom of lake as biomass decomposes. Most of the time, the water quality is within an acceptable limit to provide recreation, amenity and ecological benefits. Finally, water bodies in a eutrophic state are nutrient rich, with highly productive plant growth and high turbidity. They are seasonally deficient in oxygen, which may lead to fish kills. Eutrophic lakes may experience regular algal blooms.

When a waterway is in a eutrophic state, nutrient concentrations are so high that blue-green algae blooms are likely to occur whenever the conditions are stable (low flow), the water is warm enough and there is enough light penetrating through the water column (Paerl, 1988). These have been the conditions in Lake Tuggeranong for more than a decade, with blooms occurring every summer.

Nutrient overload in Lake Tuggeranong

It is widely accepted that phosphorus is the main nutrient that drives algal blooms in freshwater systems; without it, algal growth is severely limited (Carvalho et al., 2013). While nitrogen is also essential for algal growth, its absence in lake water does not limit algal growth in the same way as phosphorus because blue-green algae can source nitrogen from the atmosphere (a process called nitrogen fixing) as well as from the water. Therefore, to reduce the incidence and severity of algal blooms, we need to reduce the availability of phosphorus in the system. However, most management options to reduce phosphorus in stormwater will also reduce nitrogen.

In 2019, Healthy Waterways funded research into the conditions leading to algal blooms in Lake Tuggeranong (Ubrihien et al., 2019). This research found high concentrations of both dissolved phosphorus and nitrogen in the lake and determined that a large proportion of these nutrients were being delivered to the lake through the stormwater system. The research, conducted during a significant algal bloom, also demonstrated the importance of controlling phosphorus for limiting the severity of algal growth in Lake Tuggeranong.

Supply of phosphorus: catchment versus lake sediments

To reduce the phosphorus available to blue-green algae in the lake, and therefore the risk of severe algal blooms, we need to know where the phosphorus is coming from; whether it's mainly coming from the Tuggeranong catchment and reaching the lake via stormwater inflows, or if it is mainly coming from phosphorus already trapped within the lake bottom sediments (Lawrence et al. 2000; e.g. Nikolai and Dzialowski, 2014).

Phosphorus is transported to the lake in stormwater, either in a dissolved or particulate form. Particulate forms are small pieces of plant matter containing phosphorus or phosphorus bound to sediments. Sediment-bound phosphorus is often a result of erosion in the catchment or is blown into drains as dust and dirt. In its dissolved forms, phosphorus, especially phosphate, is more readily available for use by blue-green algae (bioavailable; Lawrence et al. 2000), making it more immediately problematic in causing algal blooms.

Much of the particulate phosphorus that is washed by storms into Lake Tuggeranong settles on the bottom of the lake and creates a nutrient-rich sediment layer. This creates an internal supply of phosphorus in the lake that can be released in a dissolved form later to become bioavailable through in-lake processes (Box 1).

Research by the University of Canberra (Ubrihien et al., 2019) found that the concentration of phosphorus observed in the surface water of Lake Tuggeranong was more than three times that required to support an algal bloom, with further significant amounts detected in sediments at the bottom of the lake. The internal supply of phosphorus—released from lake-bottom sediments—was enough to drive an algal bloom. However, the research found that the external supply of phosphorus to the lake from its catchment was five times the internal supply of phosphorus from lake sediments.

These findings suggest that internal supply of phosphorus is not driving most algal blooms in Lake Tuggeranong. Therefore, to mitigate blooms, water managers need to address catchment sources of phosphorus pollution before dealing with sources within Lake Tuggeranong.

Catchment sources of phosphorus

There are many potential sources of nutrients and other pollutants from urban catchments (as shown, for example, by Muller et al. 2020). Recent research and water quality monitoring in the Tuggeranong catchment has found that:

- phosphorus is mainly coming from urban, not rural, areas (Ubrihien et al., 2020; Upper Murrumbidgee Waterwatch, 2023)
- phosphorus is coming from many small sources across the whole catchment (diffuse sources), rather than from one or two large, concentrated locations (point-source) (Ubrihien et al. 2019)
- around 50% of the catchment-based phosphorus is in dissolved, bioavailable forms (Ubrihien et al., 2019), meaning it is available for uptake by blue-green algae
- leaves, grass clippings, fertiliser products (including composts and manures), soil and sewage are all likely contributing to catchment-based phosphorus (Ubrihien et al., 2019; Concepts of Change, 2023).

Soil

Soil can contain phosphorus both in its crystalline structure and adsorbed to soil particles. Sediments can release the adsorbed portion of phosphorus to water, after which algae can take it up. Because this is a slow process, most of the adsorbed phosphorus is not immediately bioavailable. However, sediments may release phosphorus over time once they are deposited in a lake.

Phosphorus adsorbed to clays suspended in the water column can take hours to weeks or longer to be released into water and available for uptake by algae.

Development sites

Tuggeranong District's population is predicted to be stable between 2022 and 2060, but there is still a potential future housing demand of 1,100 dwellings by 2050 in the district forecast (ACT Government, 2022c, 2023b). While there are no greenfield suburbs planned, there are plans to redevelop existing areas through infill, and smaller-scale construction projects like knock-down rebuilds or major home renovations will also occur.

Development sites might contribute phosphorus to the stormwater system as phosphorus bound to the sediments in drainage or from roads that construction vehicles track mud onto. The University of Canberra examined the overall effect of urban development sites on the stormwater system in Lake Tuggeranong catchments in 2024 (Ubrihien et al., 2024b). They found that during storms, stormwater concentrations of total suspended solids were significantly higher downstream of development sites compared to upstream. However, levels of total and dissolved phosphorus did not vary significantly between stormwater sampled above and below development sites. The sediments from development sites are likely to be subsurface soils and thus low in phosphorus.

Leaf litter and grass

Phosphorus from plant materials can make up a substantial portion of the total phosphorus inputs in an urban catchment (Duan et al., 2014; Janke et al. 2017; Selbig, 2016; Muller et al. 2020). Plant materials have different amounts of phosphorus depending on the plant species and part of the plant (blossoms, fruits or leaves; Hill, et al., 2022).

Leaf litter (leaves, sticks, nuts, flowers) and grass clippings release nutrients as they decompose or are wet. This can happen quickly; research in the Tuggeranong catchment by the University of Canberra suggests that leaves will leach out most of their phosphorus within two days of either continuous or periodic inundation (Ubrihien et al., 2024a). In an urban environment with lots of impervious surfaces, leached, dissolved phosphorus cannot soak into the soil where soil particles could absorb it, or vegetation take it up. Instead, it enters the stormwater system where concrete channels and pipes convey it rapidly to lakes and waterways.

While much of Canberra is known for its deciduous street trees, nearly 80% of street trees in the Tuggeranong catchment are eucalypts (ACT Government, 2022a). From December 2022 to November 2023 the University of Canberra investigated the potential contribution of street trees' leaves to nutrients in the Tuggeranong catchment (Ubrihien et al. 2024a). They measured the deposition rate of leaves for the four most common eucalypt species onto impervious surfaces to determine their potential nutrient leaching rates, and then extrapolated this across the catchment by using estimates of tree canopy hanging over impervious surfaces. They found:

- the amount of leaf fall from these species was greatest in summer
- the phosphorus leached from leaves differed greatly between eucalypt species, with *Eucalyptus sideroxylon* leaching the most phosphorus
- the annual supply to Lake Tuggeranong of dissolved nitrogen, phosphorus and organic carbon contributed by leaves across the catchment as 25, 43 and 6,748 kg per year, respectively. They note these are probably underestimates because they only capture litter that falls directly from the overhanging canopy, not any that is blown or washed onto roads.

Box 1. Why did dry weather in 2019–2020 limit algal blooms?

The Tuggeranong catchment experienced a dry period from September 2019 to January 2020, with only 6 mm of rain falling in the catchment. In Lake Tuggeranong, no blooms occurred and there were no lake closures due to blue-green algae during that time.

Dry conditions impact the lake's susceptibility to algal blooms by impacting in-lake processes. During the warmer months, Lake Tuggeranong experiences thermal stratification. This is where a marked, stable zone of cooler water forms at depth in the lake where daylight does not penetrate and a warmer, light-filled, less-dense layer of water sits on top. In this top layer the light allows for photosynthesis to occur and bacteria, algae and other micro-organisms consume the available nutrients, most of which are washed in from the catchment. During dry periods, these top-layer nutrients are not replenished as they are consumed, which prevents blue-green algae from blooming.

Catchment phosphorus can also end up in the cool lower layer, with much of it bound to sediment on the lake floor where it's not bioavailable. Carbon also gets washed into the lake from the catchment as organic matter such as leaves. As bottom-dwelling bacteria feed on the carbon, they use up oxygen in the water; if the lake is stratified for a long time, this process creates an oxygen-depleted (anoxic) environment. Under anoxic conditions, phosphorus can be released from the sediment to become bioavailable. The released, bioavailable phosphorus can be brought to the top layer by diffusion or by mixing of bottom and surface waters as stratification later weakens or breaks down with winds, cool weather or rainfall.

In autumn in Lake Tuggeranong, the top layer of water cools and eventually sinks, forcing the bottom water, with its bioavailable phosphorus, to the surface. This is known as turnover and can cause a late season blue-green algal bloom. These are often of a shorter duration and less severe than summer blooms.

Blue-green algae can also access nutrients in bottom waters by modifying their buoyancy to move up and down through the water column.

University of Canberra researchers monitored phosphorus concentrations in the lake over the 2019/20 dry period and hypothesised that blooms didn't occur during this time because low baseflows meant there was a limited supply of nutrients in the top layer of the lake (Ubrihien et al., 2020). Their data also suggested that lack of carbon inputs may have led to reduced bacteria in the bottom layer, meaning less oxygen was consumed and the phosphorus remained bound to the sediments rather than becoming bioavailable.

One implication of this is that removing sources of phosphorus and carbon in the catchment may have a greater combined impact on reducing the incidence of algal blooms. The influence of dry vs wet weather conditions is also a key part of understanding year-to-year variability in the number, duration and intensity of blue-green algal blooms in Lake Tuggeranong.

The phosphorus content of E. sideroxylon leaves as measured here is comparable to the average phosphorus content of leaves from a variety of deciduous trees measured in northern hemisphere studies (Duan et al. 2014; Hill et al. 2022). The average phosphorus content of leaves from all the eucalypt species studied in the Tuggeranong catchment was generally slightly lower than the average for deciduous leaves.

In the same study the University of Canberra also measured grass clippings deposition (Ubrihien et al. 2024a). It found:

- nutrient deposition from grass clippings varies between seasons (with higher releases in summer) and between different mowing events
- an average 'mowing event' releases 33–76 mg of phosphorus for each square metre of impervious surface next to a mown area. The average varied depending on the season and whether clippings were continuously or intermittently soaked during the experiments.

Booksmythe et al. (2024) extrapolated these estimates to all the road surface within two metres of mown open space in the Lake Tuggeranong catchment, multiplied by the around 11 mowing events per year undertaken by ACT City Services, and found that this equates to clippings contributing between 85–200 kg of phosphorus per year to the lake.

Together, according to these estimates, leaves and grass contribute around 130–240 kg phosphorus per year on average to Lake Tuggeranong.

Urban open space mowing

ACT City Services manage the mowing of all urban open spaces in accordance with Canberra's Lakes and Ponds Land Management Plan and the complementary Urban Open Space Land Management Plan. Together, these plans require that:

- mowing programs aim to improve the ACT's water quality outcomes
- verge managers remove cut vegetation from guttering
- mowing cannot occur within five metres of waterbodies
- verge managers seek the Conservator of Flora and Fauna's advice on mowing areas next to certain waterbodies including Lake Tuggeranong District Park (south) and Isabella Ponds grassland.
- However, some cut vegetation will still end up blowing into gutters. The government is exploring ways to minimise this impact.

Fertiliser

Some residents and businesses use fertilisers to enrich soils with nutrients important for plant growth and health, including phosphorus, nitrogen and potassium. They fertilise residential lawns and gardens as well as public and private green spaces like sports fields, golf courses and gardens. Fertilisers can be a major source of phosphorus pollution of stormwater (Muller at al. 2020).

Fertiliser products come in different forms (manure, compost, chemical/synthetic) and have different release rates. The type of fertiliser used, how much is applied and when it is applied determine how well the plants can take it up, and whether it will stay in (or on) the soil or be transported out of the lawn, turf or garden bed and into waterways.

Nutrients can end up being 'exported' from residences to waterways either in dissolved or particulate form if too much fertiliser is applied (more than can be taken up by soils and plants), it is applied just before rain, or it is applied to soils that don't absorb water well.

Household fertiliser use

A Healthy Waterways funded survey in 2023 heard from 400 Canberra residents about the type and quantity of fertiliser they use (Concepts of Change, 2023). The findings of this survey were that:

- households use an average 84 kg of garden nutrient boosters (fertilisers, manures, compost) annually, which equates to 0.59 kg of phosphorus per household
- 6% of households use a paid gardening service and these accounted for 0.11 kg of annual phosphorus use by households, making a total of 0.70 kg phosphorus applied per household

- around half of Canberra residents use no fertiliser at all, with most of the fertiliser applied by the top 20% of users
- by volume, compost and manure are the most used fertiliser.

There are 21,000 low to medium density residential, detached and semi-detached dwellings with gardens in Tuggeranong (Booksmythe et al. 2024). Survey data on the amount of fertiliser applied by Canberra householders to their blocks combined with data from a literature review on the proportion of phosphorus that leaks into stormwater from different fertilisers (Booksmythe et al. 2024) yields a wide-ranging estimate of around 90–1,200 kg of phosphorus per year entering stormwater from fertilisers applied by householders, with an intermediate estimate of around 550 kg per year. The wide range is because of significant uncertainty in the export rates for phosphorus in fertilisers applied by residents or their gardeners.

Sports field fertiliser use

The Tuggeranong catchment includes approximately 70 hectares of managed sports grounds. Most of these are public grounds managed by ACT City Services Sport and Recreation, with about 7 hectares being privately managed.

The University of Canberra's research in the Tuggeranong catchment found that water samples taken near sports fields had slightly elevated phosphorus concentrations (total and dissolved) (Ubrihien et al., 2020). While they still represent a relatively small component of overall catchment phosphorus, they warrant further investigation.

More work is needed to understand the nutrient transport pathways around sports fields. Soil moisture testing and on-ground observations of public sports fields don't indicate high volumes of surface water runoff, so it's possible the elevated concentrations detected represent historical fertiliser use (going back decades) that is leaching out through the system at a subsurface level.

In general, both public and private sports field managers practice careful application of fertiliser as it represents a significant input cost. In 2022 several private sports field managers were surveyed about their fertiliser application practices (Edmonson, 2022). The survey found that private managers had a detailed knowledge of turf nutrient requirements and, as fertiliser is a major expense, were managing fertiliser application as efficiently and effectively as possible.

ACT City Services Sport and Recreation manage public sports fields in Tuggeranong using practices to improve irrigation efficiency and water retention, prevent surface water runoff and manage the chemical composition of the soil profile to improve nutrient uptake. These help prevent nutrients being exported from sports fields in runoff.

Installing additional bioretention swales between a sports field and the stormwater channel would help intercept and filter any nutrients exported from the sports fields.

Leaky sewerage pipes

Leaking sewers can be a major contributor to water quality issues in urban areas, causing increased nutrients, suspended solids and microbial pollutants to enter waterways. Sewers can become defective and leak from structural problems (broken joints, cracks, fractures and holes), operational problems (root intrusion, sediment accumulation and grease build up) and hydraulic capacity failures (Nguyen & Venohr, 2021). As holes are drilled in urban catchments for a variety of purposes, pipes can be damaged and leak into the stormwater system.

Healthy Waterways has commissioned a study to help characterise how large a problem sewage leaks might be, noting that they might affect not only nutrient concentrations but levels of faecal pollution, which can also result in lake closures. Results will be delivered in 2025 and will be incorporated into later versions of the Plan.

CABINET

Part 4
Identifying solutions to the algal bloom problem

- Form of phosphorus

CABINET

Part 4: Identifying solutions to the algal bloom problem

This report presents a series of analyses to identify and evaluate potential solutions to the problem of algal blooms in Lake Tuggeranong. The analyses were designed to achieve the following:

1. Model the effects of phosphorus inputs from the catchment on in-lake algal responses to help establish a target for reducing phosphorus pollution in Lake Tuggeranong (Part 5).
2. Identify options to either reduce levels of phosphorus in waterways or directly lower algal concentrations within the lake (Part 6).
3. Formulate potential water management scenarios made up of various pollution mitigation options that together reduce the level of phosphorus entering Lake Tuggeranong to the target level (Part 7):
    a. Estimate the costs, effectiveness and cost-effectiveness of a subset of the most feasible pollution mitigation options to help achieve the phosphorus mitigation target.
    b. Define two water quality management scenarios or combinations of workable pollution mitigation options that together reach the phosphorus mitigation target (and thus a substantial reduction in the incidence of blue-green algal blooms in Lake Tuggeranong):
        i. The most cost-effective option to achieve the phosphorus mitigation target.
        ii. A broader benefits option that not only achieves the target but provides stronger benefits than the cost-effective option in relation to supporting health outcomes, amenity and biodiversity, promoting climate resilience by reducing urban heat and recycling stormwater to irrigate sports fields.
    c. Re-configure the catchment water quality model to reflect the two management scenarios to understand the effect of implementing the pollution mitigation options together.
    d. Consider aspects of the feasibility and likelihood of being able to reach the required phosphorus mitigation target.

Based on the analyses, Part 8 plots a path forward.

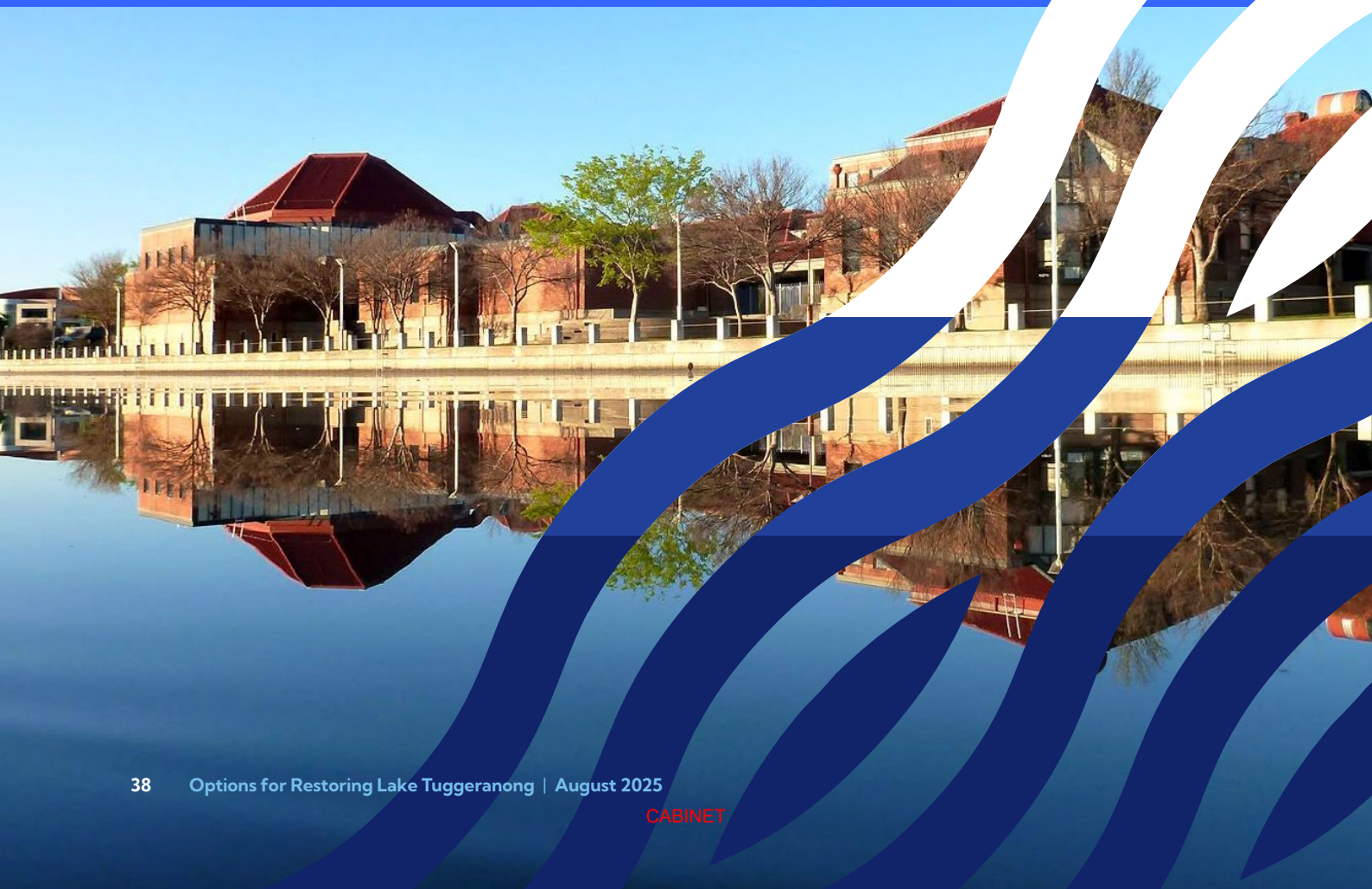
Form of phosphorus

The models and other analyses presented below predict total phosphorus or its effects. There are not enough data to inform what proportion of the particulate fraction of phosphorus in Tuggeranong stormwater is bioavailable, so total phosphorus is used to predict algal responses—and total phosphorus data used in model calibrations—rather than dissolved or bioavailable phosphorus. So, even though algae actually take up dissolved phosphate, in these analyses, ‘phosphorus’ refers to total phosphorus.

CABINET

Part 5
The target – how much phosphorus to mitigate?

- Water quality modelling approach
- Inputs of phosphorus from the catchment
- Current and target supply of phosphorus to the lake
- Reconciling some estimates based on research and modelling



CABINET

Part 5: The target – how much phosphorus to mitigate?

Water quality modelling approach

Dey et al. (2024) developed two coupled water quality models to help estimate how much the supply of phosphorus from the catchment to the lake needs to drop to substantially decrease the incidence of algal blooms in the lake.

The first model is a catchment model that predicts how much water and phosphorus will reach Lake Tuggeranong and how this changes with daily variations in rainfall. The researchers initially used pollution generation rates from different types of land use, derived from the scientific literature, which they then calibrated with observations of water quality and flow in storm events that came from research by the University of Canberra (Ubrihien at al. 2019, 2020).

The second model is a simple in-lake model that predicts how phosphorus concentrations in the lake will change in response to varying runoff and inflow of phosphorus, and then the amount of algae that will grow in response to this. Kahn and Dey (2024) predicted the algal response indirectly using chlorophyll *a* concentration. Chlorophyll *a* is a pigment in many plants and algae that helps them absorb light and is used to assess the amount of algae (ANZECC and ARMCANZ, 2000). They then assigned predicted concentrations of chlorophyll *a* concentration to trophic states: Oligotrophic <5 µg/L, Mesotrophic <15 µg/L, and Eutrophic >15 µg/L.

Inputs of phosphorus from the catchment

The water quality modelling has shown that that the stormwater flowing off the catchment carries very high levels of phosphorus, with an average annual supply to the lake of 1,656 kg phosphorus/yr (Dey et al., 2024; Table 3). This is greater than the annual estimate of 500 kg estimated by Ubrihien, et al. (2019), which was based on data collected in a dry period, with reduced inflows from the catchment.

Based on research data (Ubrihien et al., 2019, 2020), about 50% of this input is in a dissolved form, with most of it ready for uptake by algae. Dey et al. (2024) predict that the seven constructed wetlands built in Stage 1 of Healthy Waterways have reduced the amount of phosphorus entering the lake annually by 214 kg, from 1,656 kg to 1,442 kg.

Table 3. Modelled annual total phosphorus (TP) supply to Lake Tuggeranong (kg/yr) generated for each combination of functional land use and surface type imperviousness: road, hardstand, roof and pervious (from Appendix 5 in Dey et al., 2024).

FUNCTIONAL LAND USE	Road TP (kg/yr)	Hardstand TP (kg/yr)	Roof TP (kg/yr)	Pervious TP (kg/yr)	Total TP (kg/yr)
Suburban	322	169	314	140	945
Commercial	17	45	30	16	108
Open space	243	76	5	88	412
Rural	0	0	1	132	133
Sports field	0	0	0	58	58
Total annual supply (kg/yr)	582	290	350	434	1,656

Current and target supply of phosphorus to the lake

Current supply

Kahn and Dey (2024) used an in-lake algal response model to determine the phosphorus mitigation target (Figure 6). Under current flow and levels of phosphorus supply (Figure 6, 'No Preduction'), their modelling clearly indicates that Lake Tuggeranong will remain in a eutrophic state, with chlorophyll *a* concentrations over 15 mg/L, even in years with relatively little rainfall when smaller amounts of nutrient are transported to the lake. This fits with observations of consistently high levels of phosphorus and frequent blue-green algal blooms in the lake in recent years. It also supports the findings of a 1982 hydrological study of the catchment, which predicted that based on nutrient levels at the time, the lake would exist in a eutrophic state for most of the time (Beer et al., 1982).

A suitable and realistic chlorophyll *a* concentration target range to aim for in Lake Tuggeranong, correlating to a mesotrophic state, is in the range of 5–15µg/L. This target range is based on the following considerations:

- The model predicts that in a predevelopment scenario (when the area was entirely native bushland), Lake Tuggeranong would typically have been in a mesotrophic state, with a chlorophyll *a* concentration in the range of 0–18 µg/L (Figure 6: 'Predevelopment') (Dey et al., 2024).
- The ANZECC guidelines specify a range of 5–15 µg/L for mesotrophic conditions (see Table 8.2.1 in ANZECC and ARMCANZ, 2000).
- In the nearby Googong Reservoir, a water supply with a reduced level of disturbance, chlorophyll a concentrations are typically in the range of 0–28 µg/L, with annual averages consistently in the range of 4–10 µg/L.
- The Australian Environment Council recommends that chlorophyll *a* concentrations in recreational waterbodies be kept below 20 µg/L for recreational lakes and 5 µg/L for water supply reservoirs (AEC, 1987). In the ACT, the Environment Protection Regulation sets a more stringent target of less than 10 mg/L for contact-based activities (noting that direct observations of algal counts rather than chlorophyll a concentrations are used to determine when to close lakes in the ACT).

Target supply to mitigate algal blooms

Kahn and Dey (2024) predict that a mesotrophic state can be achieved in Lake Tuggeranong for most the time if the average annual phosphorus supply to the lake is reduced by 700 kg, having already accounted for the effect of the seven constructed wetlands built in Stage 1 of Healthy Waterways (Figure 6). They did not adopt a higher target because the further reduction in phosphorus would not significantly reduce algal blooms but would cost a lot more to achieve.

A target of 700 kg represents approximately 50–60% of the total supply of phosphorus to the lake from the catchment.

Note that these targets are indicative only, developed for the purpose of supporting the modelling exercise and communicating the benefits of different management scenarios. While the 700 kg target is based on annual averages, the required reductions will be higher in very wet years and lower in dry years.

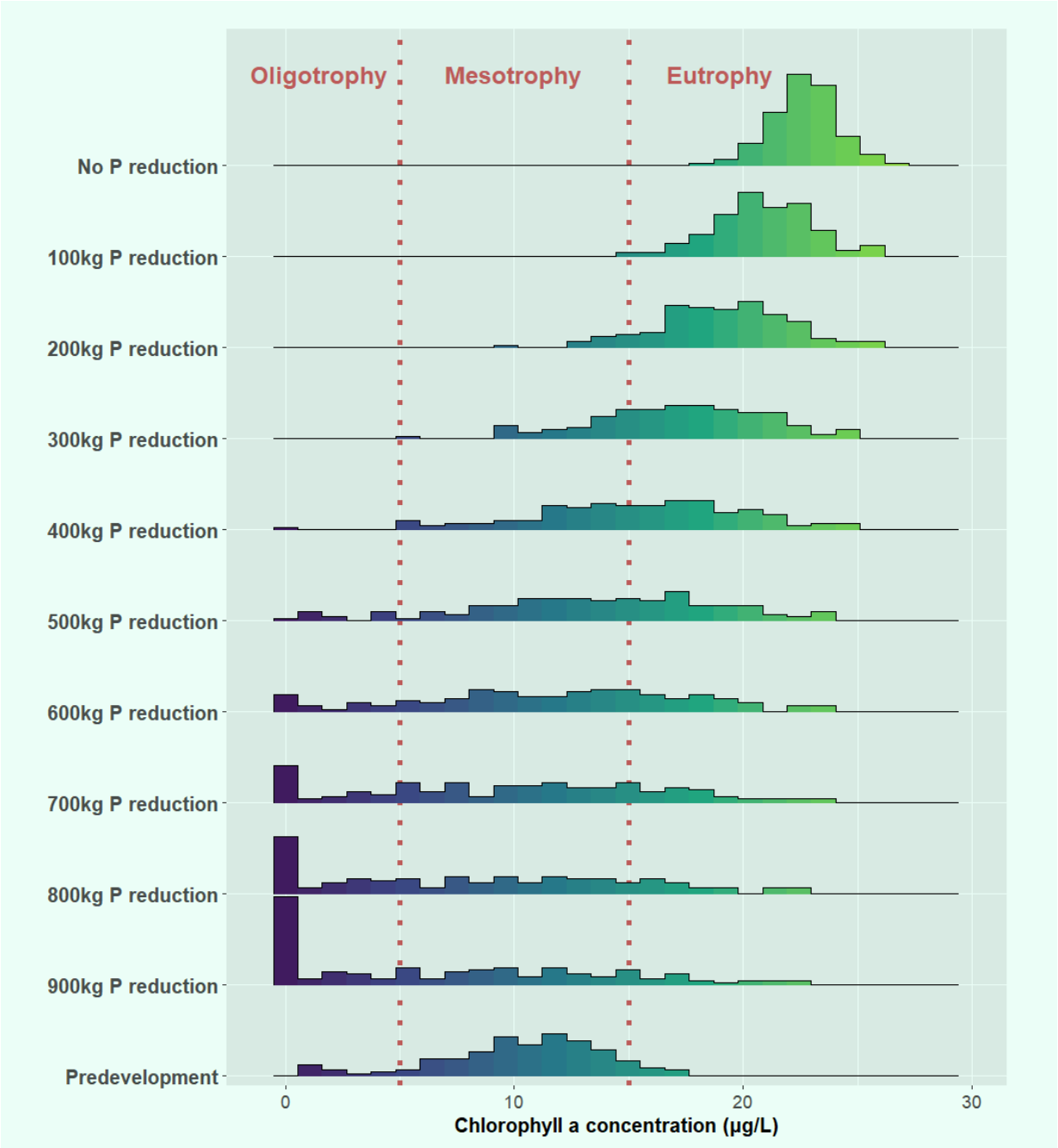


Figure 6. Modelled distribution of predicted chlorophyll *a* concentrations (an indicator of trophic state) in Lake Tuggeranong under varying supply of phosphorus (P). The top row 'No P reduction' shows the lake in its current, eutrophic state. The bottom, 'Predevelopment' row shows the predicted chlorophyll a concentrations if there were no urban development upstream of the lake, indicating that it would have been in a mesotrophic state in most years, but still occasionally have reached a eutrophic state, supporting algal blooms.

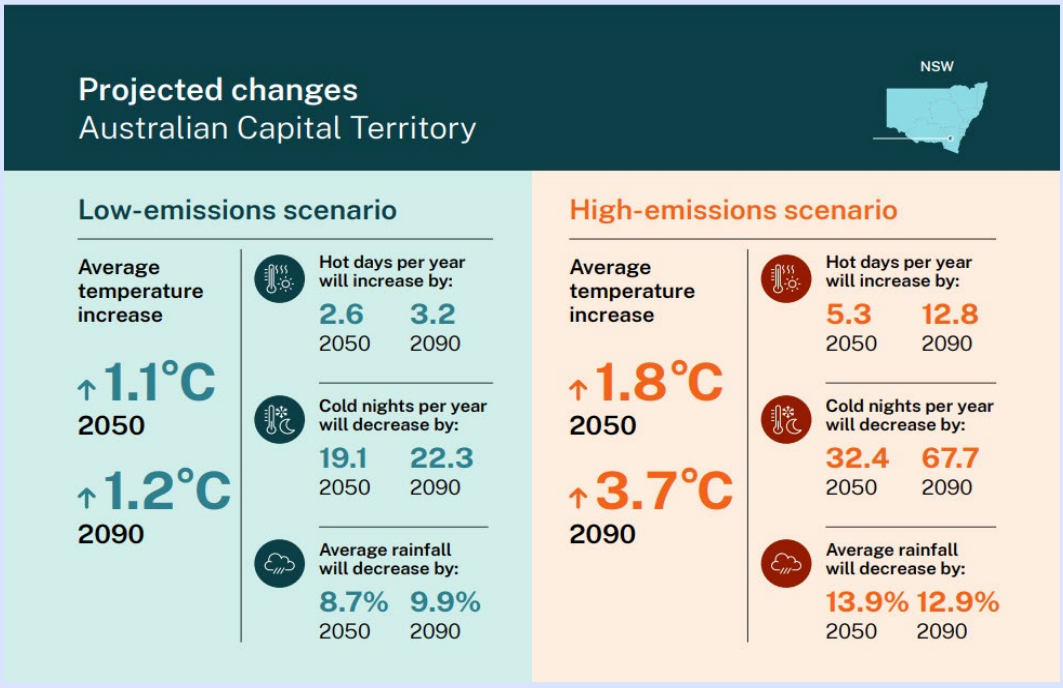
Box 2. How will climate change affect nutrient dynamics and algal blooms?

In the future, the ACT will experience hotter average temperatures, more hot days per year and decreased average rainfall, particularly in spring (NSW Department of Climate Change, the Environment and Water, 2024). Across Australia, including the ACT, extreme rainfall events (storms) will become more intense. The Australian Rainfall and Runoff Guidelines project the biggest increases for very short storms. For example, under scenario SSP3-7.0, storms of under one hour will increase in intensity by 18% by 2030, and by 29% by 2050 (Wasko et al., 2024). More intense localised storms may increase the frequency of 1% Annual Exceedance Probability (AEP) (in layman's terms, 1 in 100 year storms) flooding events in the ACT. The ACT Government's ACTMapi website shows the extent of riverine flooding that would be expected during a 1% AEP flood event.

These changes to temperature, rainfall averages and storm intensity will likely impact nutrient dynamics in the Tuggeranong catchment, for example:

- higher storm intensity will impact streamflow and the way that nutrients are mobilised in, and transported through, the catchment
- hotter temperatures will affect when eucalypt species drop their leaves, how much they drop and the phosphorus content of the leaves
- higher water temperatures will affect in-lake processes like thermal stratification and turnover.

These effects are anticipated but have not yet been studied or quantified in the Lake Tuggeranong context. However, a response framework developed for Victoria's waterbodies argues that climate change will exacerbate blue-green algal blooms through factors including increased temperatures, stronger stratification, increased nutrient levels due to extreme wet/dry periods, longer residence times of water in water bodies and storm events (HydroNumerics, 2020).



Climate change projections for the ACT (NARCliM 2024)

How will the lake behave if the target phosphorus reduction is achieved?

With a 700 kg annual reduction in phosphorus, modelling by Kahn and Dey (2024) suggests the lake will be in a mesotrophic state—or better, in an oligotrophic state—in approximately 75% of years (Figure 7). Under these conditions, some blue-green algae would be present, but the likelihood of problem blooms would be lower than now, and the lake should mainly be in a condition suitable for contact-based activities. Closures may still occur due to elevated levels of faecal indicator bacteria.

The modelling also reveals there will likely always be considerable variation in the concentration of phosphorus in Lake Tuggeranong over time, driven by variation in climatic conditions. Specifically, in very wet years the significant amount of phosphorus coming off the catchment will likely overwhelm any attempts to reduce nutrient levels in the lake, leading to eutrophic conditions.

For example, with a target 700 kg annual reduction in phosphorus, the modelling predicts that in about 25% of years (the wettest years) the lake will still be in a eutrophic state, with sufficient nutrients to promote algal blooms. However, wet years also tend to be relatively cooler, which would reduce the likelihood of severe blooms. Some algae would also flush from the lake in wet years.

Conversely, in relatively dry years, any phosphorus removed from the system represents a relatively larger proportion of the total supply reaching the lake. So, for a target 700 kg annual reduction in phosphorus, modelling by Kahn and Dey (2024) suggests about 25% of years (the driest years) will experience oligotrophic conditions in the lake, with very low concentrations of nutrients, relatively clear water and very little risk of algal blooms occurring.

Caption

Reconciling some estimates based on research and modelling

There are two notable instances where the predictions from catchment water quality modelling and results from catchment research are not fully aligned.

The first relates to the contribution that fertiliser applied on residential gardens makes to phosphorus levels in stormwater. The Lake Tuggeranong catchment water quality model predicts that only around 140 kg/year of phosphorus is generated from pervious suburban land use (Table 3). This is the land use category representing residential yards and gardens, which would include fertiliser use by residents or their gardeners and other sources of phosphorus from residential blocks. The model is based on published literature of phosphorus draining from household blocks and was calibrated to the observed data on phosphorus concentrations in runoff and waterways around the catchment.

In Part 3, the amount of phosphorus entering stormwater from residences, based on surveys of residents, is conservatively estimated at around 90–1,200 kg of phosphorus per year, with an intermediate estimate of around 550 kg per year. The model prediction of around 140 kg/year leakage is within, but at the very lower end, of the estimate of around 90–1,200 kg of phosphorus per year based on the surveys of residents. Since 140 kg/year is well below the middle estimate of 550 kg/year, the difference between the prediction based on modelling and the estimate based on research warrants further investigation.

The second instance where the catchment water quality model and research yield different results relates to the contribution of phosphorus due to leaves and grass. The effect of nutrients leaching from leaf and grass litter—and soils and other road detritus—on roads was assessed through the catchment model as 582 kg/year (Table 3). This is greater than the research estimate of around 130–240 kg/year based on leaf-fall patterns plus biomass of grass on road verges in Part 3 (Ubrihien et al., 2024a). However, there are reasons to believe that the estimates for leaf-fall biomass are underestimated (see Part 3). To date there have been no independent estimates for how much soil and non-leaf debris is on the roads and how much extra phosphorus this contains.

Further research is required to ensure fertilisers applied to household blocks are not making a larger contribution than suggested by the modelling, and to clarify the contribution of leaves and grass. However, both sources of phosphorus pollution are likely to be significant and are preventable so consideration needs to be given to reducing both sources of pollution.

CABINET

Part 6
Options to mitigate phosphorus pollution

- Reduce the amount of phosphorus entering stormwater at the source
- Slow the flow and filter the stormwater
- Treat the polluted water in-lake
- Selection of options for consideration

CABINET

Part 6: Options to mitigate phosphorus pollution

Previous research and programs in the ACT and elsewhere have identified and trialled a range of potential phosphorus mitigation options. For this report, options were shortlisted based on the availability of data to support cost-effectiveness analyses. In some instances, cost-effectiveness data were based on local trials of options. The Healthy Waterways team has yet to evaluate some other very promising options because of a lack of relevant data on which to base cost-effectiveness. These options will be evaluated as data on their cost-effectiveness becomes available through ongoing research and trials.

Conceptually, there are three stages in the 'journey of the stormwater' where phosphorus might be removed from the system or algae may be directly treated through various options (Table 4 and Figure 7). This section describes these options.

Table 4. Pollution mitigation options to remove phosphorus in the 'journey of the stormwater'.

Where to remove phosphorus/treat algae		Mechanism
1	**At the source/s**	Reduce the amount of phosphorus before it enters the stormwater system (phosphorus pollution prevention).
1.1	Enhanced street sweeping	Increase the frequency that streets are swept.
1.2	Pollution prevention partnerships	Promote waterways-friendly gardening practices by working with community and business.
1.3	Water sensitive urban design (WSUD)	Adopt suburb designs—or retrofit elements to existing suburbs—that minimise the impacts of urban development on the natural water cycle and better integrate suburbs into the natural landscape.
2	**In the stormwater system**	Use water sensitive urban design infrastructure to divert runoff in storms, allowing it to slow down, be filtered naturally by wetlands and/or to seep slowly back into the landscape.
2.1	Infrastructure that reduces stormwater peaks	Retain stormwater in green belts, detain it in tanks and/or recycle it.
2.2	Infrastructure that improves stormwater quality	Create various types of constructed wetlands.
2.3	Maximised effectiveness of water quality infrastructure	Sequentially place constructed wetlands and other water quality/ quantity assets along drainage lines and waterways to reach end-of-system targets and maintain the infrastructure in good condition.
3	**In the lake**	Use anti-algal agents that either compete with algae or treat the algae once it grows to bloom proportions.
3.1	Reduction of nutrient levels and/or competition with blue-green algae	Deploy materials or processes that remove nutrients from surface waters, where algae live, or promote natural competitors to algae.
3.2	Direct treatment of algae	Apply algicides or physical mechanisms to destroy or remove algae.

Reduce the amount of phosphorus entering stormwater at the source

There are several ways to prevent waters from becoming polluted in the first place, rather than allowing them to become polluted and then treating the pollution or its effects within the stormwater system.

Street sweeping

The ACT Government's street sweeping program removes leaves and debris from kerbs and gutters along Canberra's urban roads. Every street in Canberra receives at least two full sweeps each year, with additional local sweeps between April and September during the heavy period of leaf-fall (See: https://www.cityservices.act.gov.au/roads-and-paths/road-infrastructure-and-maintenance/street-sweeping).

One option is to increase the frequency of sweeps. As described in Part 4, leaf litter and grass clippings release nutrients quickly as they decompose or are wet. They lose most of their phosphorus within two days of either continuous or periodic inundation (Ubrihien et al., 2024a). The intent of increasing the frequency of street sweeping is therefore to remove leaf and grass litter from gutters before the phosphorus and other nutrients have had a chance to leach out of the litter.

Pollution prevention partnerships

Canberra's residents affect waterway health in the way they manage leaves, grass and fertilisers on their blocks. Through Healthy Waterways, the ACT Government has been building expertise in supporting households to prevent stormwater pollution since 2016. It is working with the community to improve awareness and to support households to adopt practices that promote waterway health, like collecting leaves from the road verge.

Since the evidence began to point strongly to leaf litter in gutters and on paved surfaces as one of the top pollutants, programs have been developed and tested that target leaves directly.

From 2020–23, the government partnered with Griffith University and community stakeholders to test numerous interventions under the project title 'The Leaf Collective'. Three iterations of the program were run—two during autumn and one during summer. In all three campaigns householders reported an increase in the volume of leaf litter they collected from areas draining to stormwater. On average, they collected 20% more than the control groups collected. Attitudes towards the value of leaf litter also changed, with more people adding leaves to compost or using them to create leaf mould, and fewer people disposing of them inappropriately in their general waste bins.

From 2023–25, the government has delivered a smaller program. It features the most popular elements of the earlier pilots, such as the leaf-bag giveaway and leaf cages in schools and is gradually building in more offerings. Community stakeholders and individual community members consistently give positive feedback about these initiatives.

While our understanding of the impacts of fertiliser use on phosphorus pollution in stormwater is less advanced, the ACT Government piloted a 'Love the Lakes' program in May 2024 that aimed to reduce garden fertiliser use in households that use high amounts. Concepts of Change (2023) interviewed 600 households across Tuggeranong and coached householders (via telephone or in-person) about ways they could reduce fertiliser use. When the householders were contacted again in late 2024, they reported an average 36% decrease in fertiliser use during spring.

Through the **Healthy Waterways Plan for Lake Tuggeranong**, we can at look to how to remove phosphorus at three distinct stages in the 'journey of the stormwater'.

Reduce the amount of phosphorus entering the stormwater system:

1. Support the community to help stop leaves and grass from accumulating along our verges and street drains.
2. Work with government, businesses and the community to minimise the amount of fertiliser entering urban stormwater.
3. Working with government and universities to better understand and manage the link between street tree leaves and grass clippings and the amount of nutrients in the stormwater.

Slow the flow and filter – reconnect water back into the landscape and filter nutrients out of the stormwater:

4. Intercept and treat nutrient-laden stormwater running off sports fields. Also reuse stormwater from elsewhere to water the sports fields. This will all reduce the amount of runoff and amount of nutrients flowing into Lake Tuggeranong.
5. Provide opportunities for stormwater to be absorbed and treated in the landscape while improving habitat connectivity, through green infrastructure like swales, raingardens and wetlands.

Manage the in-lake environment

6. Investigate the drivers, habitat enhancements and possible in-lake treatments to reduce the incidence of blue green algal blooms.

Figure 8. Conceptual model showing where phosphorus can be removed from its source to the lake.

Garden service providers were also contacted. They reported applying an average 1.78 kg of phosphorus per garden per year, which accounts for about 15% of the total amount of phosphorus applied across Canberra. Working with garden service providers offers another potential avenue to reduce fertiliser use.

Water Sensitive Urban Design

For many decades, town planning adopted engineering solutions aimed at flood mitigation that turned many ACT waterways into straight pipes and concrete drains. These engineered systems are very efficient at conducting stormwater, and the nutrients it carries, rapidly and directly out of urban landscapes to the natural waterways without opportunities for treatment by catchment soils and vegetation. Studies into urban runoff in storms suggest it has fewer adverse impacts on water quality in natural waterways if there is less direct flow from impervious surfaces, such as roads, to natural waterways (Ladson et al 2006, Walsh et al. 2022).

Water Sensitive Urban Design (WSUD) planning, landscaping and infrastructure promote infiltration of urban stormwater into the soil, increase water retention, reduce flow rates and filter out nutrients from stormwater in the catchment. Using WSUD helps reduce runoff and improve water quality before stormwater enters natural waterways such as Lake Tuggeranong (for example, see Ubrihien et al. 2020).

WSUD infrastructure has been a key feature of Healthy Waterways over its 10 years to date. The program has built 27 water quality assets, predominantly ponds, wetlands, rain gardens and channel restorations across urban Canberra since 2014.

In developing these assets, Healthy Waterways worked across government to ensure the asset designs were either approved against Municipal Infrastructure Standards (MIS) or Municipal Infrastructure Technical Standards (MITS) or are new and effective designs. The new designs allow for an expansion of the MIS and MITS standards, which means there are now more options in the infrastructure toolkit that water managers can use to improve stormwater quality.

Infrastructure that reconnects storm runoff with its catchment

WSUD infrastructure may target either reducing the amount of runoff in storms or improving stormwater quality or both. Features can be added to an urban area to retain water in the landscape or route small streams of stormwater back into green space, such as castellated kerbs and landscape contours (Table 5). This allows stormwater to soak back into natural catchment areas where it is mostly retained (for example, it evaporates or is taken up by plants) or is cleansed by surface vegetation and soils. At one end of the spectrum these features are capital works; for example, Healthy Waterways built some small runoff infrastructure assets such as castellated kerbs to reduce the volume of water in the stormwater system. At the other end of the spectrum, landcare groups can improve stormwater retention simply by roughening drainage lines (Alluvium, 2023). In the case of stormwater recycling, water is diverted from pipes, drains or WSUD infrastructure and usually treated before being used, sometimes to irrigate green space like sports fields and golf courses, and sometimes for other purposes, such as in construction.

Table 5. Types of runoff infrastructure built in the ACT.

Type of infrastructure	How it works
Castellated kerbs	Roadside drains have gaps in them where some of the stormwater is diverted into adjacent green space where the stormwater can be absorbed into the soil.
Landscape roughening	Small mounds are dug into slopes to temporarily capture runoff and allow it to sink into the soil (Alluvium, 2023).
Rainwater tanks	Hold water in the landscape using above or below ground storage tanks for rainwater usually sourced from roofs.
Detention tanks	Built underground to temporarily store stormwater sourced from drains and often used to irrigate sports fields.
Stormwater recycling	Stormwater is diverted to tanks before being cleaned and used instead of potable water; for example, to irrigate sports fields. It may be cleaned by a combination of constructed wetlands, groundwater aquifers, and/or a filtering unit in a shipping container.

Slow the flow and filter the stormwater

Infrastructure that reduces stormwater peaks

Tanks can be used to temporarily store stormwater before the water is either used (for example, to water resident's gardens) or released back into the stormwater system. The delayed release of stormwater reduces peak flows and allows downstream wetlands and ponds more time to process and treat a greater volume of the stormwater.

Infrastructure that improves stormwater quality

WSUD infrastructure is built with a primary function of treating pollutants and improving water quality. This infrastructure includes a variety of constructed wetlands, where plants and soil media filter nutrients and fine sediment particles from the stormwater. Different types of constructed wetlands are shown in Table 6. Constructed wetlands can also have several added benefits such as providing riparian (waters-edge) and aquatic habitat for wildlife within urban areas, reducing urban heat, enhancing Traditional Owner values and contributing to urban amenity. The wetlands, ponds and raingardens built in the Healthy Waterways program are examples of WSUD infrastructure that target improving stormwater quality by removing pollutants.

In the Tuggeranong catchment, research by the University of Canberra has shown that most nutrients are mobilised and transported during big storm events where flow volumes are high (Ubrihien et al., 2020). In this situation, wetlands are only able to treat a small proportion of the nutrient-laden flows, with the remainder bypassing the wetlands. Part 7 further considers the implications of this.

Maximising the effectiveness of WSUD infrastructure

Treatment trains

The effectiveness of water quality assets can be maximised through careful design and sequential placement of different types of assets. A series of assets working in sequence to reduce and improve stormwater quality is known as a treatment train.

Box 3. Urban catchments create more runoff in storms

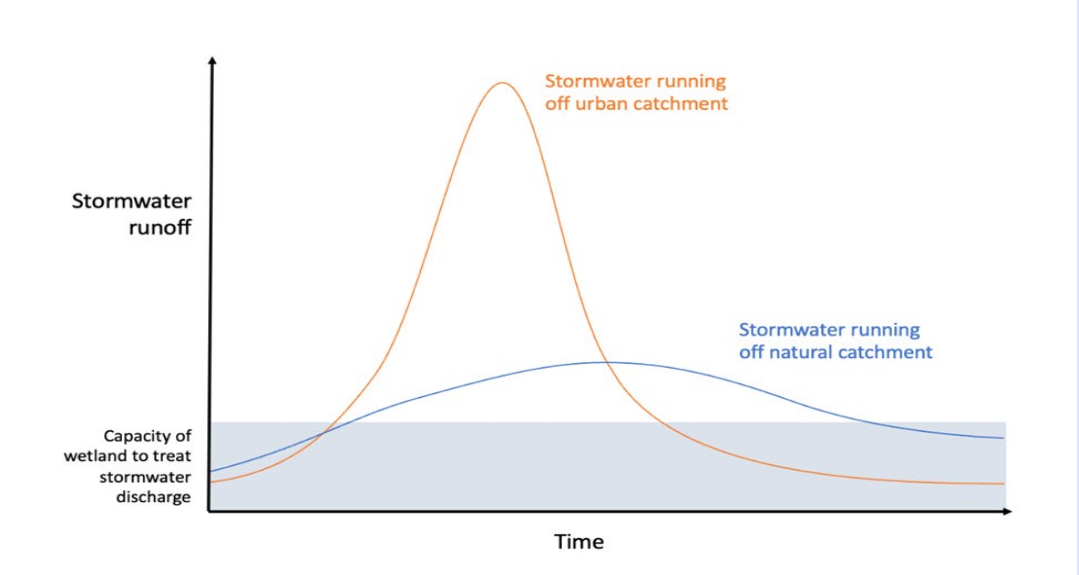
Phosphorus pollution in Lake Tuggeranong is, in large part, a result of urbanisation. Water that flows over the land surface is known as runoff, which in urban areas quickly enters the engineered stormwater system.

In a natural catchment, rain falls on trees and vegetation, which take energy out of the water and allow it to be absorbed into the soil and bedrock. When the ground is saturated, water will eventually start to run off, but at lower volumes and speeds than in an urbanised catchment. When the runoff ceases, water will be slowly released from the landscape, allowing waterways to flow at a gentler rate over a longer period.

The highly urbanised nature of the Lake Tuggeranong catchment means that much of the catchment is covered by buildings, roads, concrete paving and other surfaces that water can't soak into, known as impermeable surfaces (Codner et al., 1988). Rain therefore runs off impermeable surfaces. This runoff washes lots of phosphorus from these impermeable surfaces into the stormwater system, which is also highly impermeable, and on to Lake Tuggeranong. Models estimate that the volume of runoff from the Lake Tuggeranong catchment is three times higher than that of a natural catchment (Dey et al., 2024). Consequently, urban stormwater systems are very 'flashy' waterways, with water levels rising quickly after rainfall, and falling back to baseflow levels almost as quickly (see the hydrograph in the figure below).

Large amounts of runoff in an urban system make it difficult to treat the high levels of phosphorous in stormwater. A wetland only has the capacity to treat a limited amount of stormwater per hour, so the smaller the volume and longer the duration of flow from a storm event, the greater the proportion of stormwater that will be treated.

By reconnecting more runoff and stormwater back into the landscape, we can start to return the catchment to a more natural flow state. This would provide more opportunities for water to be absorbed into the landscape, and for wetlands and their plants to better capture phosphorus from the remaining stormwater and prevent it from reaching Lake Tuggeranong.



Stormwater flow in an urban vs natural catchment and the capacity of a wetland to treat the stormwater. The grey area indicates the volume of water that a wetland can treat over a given period and shows the 'flashy' nature of stormwater coming off an urban catchment.

For example, placing runoff infrastructure such as castellated kerbs higher up in the catchment can divert water back onto grassy areas, which reduces the volume of phosphorus-laden stormwater running down the drains. Detention tanks, like rainwater tanks connected to roofs of houses, can capture stormwater peaks and either release some of the stormwater slowly after the storm has passed (for example, by using a specially designed 'leaky tank') or be used for watering gardens. Around playing fields, smaller swales and raingardens filter out coarse sediments and some nutrients from the stormwater before it flows downstream to bigger wetlands and ponds.

Using a treatment train in this way is particularly effective during big storm events by allowing bigger wetlands downstream to more effectively treat more of a storm event's runoff (and for longer) because flow volumes have been reduced upstream and the first pass through smaller filtering infrastructure that has already filtered some nutrients and sediments, reducing the pressure on the bigger downstream wetland.

Maintenance

When sediments do build up in a constructed wetland and the water plants absorb all the nutrients they can, the wetland needs to be maintained to retain its ability to clean the stormwater. This is an often-overlooked part of managing them for optimal effectiveness. Maintenance can include removing built-up sediments, which reduce the wetland's capacity to hold and filter stormwater and harvesting water plants regularly to remove the nutrients they contain from the system and prevent them from decaying back into the water.

Raingardens are renowned within the stormwater industry as particularly sensitive to poor maintenance. They can become completely dysfunctional if their inlets become blocked and their surface sediments clogged and overgrown with trees or weeds that disrupt their ability to function properly. Operational and maintenance requirements are a key design feature of WSUD infrastructure. The choice of assets and the level of maintenance funding need to be considered before committing to such projects.

Table 6. Types of constructed wetlands built in the ACT.

Type of infrastructure	How it works
Ponds	Stormwater is routed to one or more settling ponds fringed with emergent aquatic plants. The overflow is returned to the stormwater channel.
Traditional wetlands	Stormwater is diverted from channels and routed through a sequence of pools and shallower beds of emergent aquatic plants before being returned to the stormwater drain.
Raingardens	Stormwater floods the soil surface, which has dense growth of emergent aquatic plants, then percolates downwards through the soil and is collected in pipes and returned to the stormwater drain.
Bioretention swales	These smaller, vegetated drains operate in the same way as raingardens and are often targeted at point sources of pollution such as sports fields.
Subsurface wetlands	Stormwater is routed horizontally through gravel beds overlain by soils and emergent aquatic plants. Plant roots extend into the gravel beds. The overflow is returned to the stormwater drain. The aquatic plants remove dissolved nutrients, as in a hydroponic garden.
Channel re-naturalisations	Concrete stormwater open drains or channels are replaced with various combinations of pools, riffles, runs and beds of aquatic plants. In the process, the channels may be reconnected with surrounding floodplain sediments and aquifers.

Box 4. Examples of Water Sensitive Urban Design (WSUD) in Tuggeranong

WSUD infrastructure has been a key feature of Healthy Waterways. Twenty water quality assets, predominantly ponds, wetlands, rain gardens and channel restorations, were built in Healthy Waterways Stage 1. Seven of eight assets have been built in Stage 2, with the final asset slated to be built in 2025.

1. Bioretention swale at Kambah District Playing Fields

2. Pond at Kett St near the Kambah shops

3. Drain naturalisation at Tuggeranong Creek in Calwell – before

4. Drain naturalisation at Tuggeranong Creek in Calwell – after (but before plantings have grown)

Treat the polluted water in-lake

Alongside pollution reduction programs and infrastructure, in-lake treatments are a complementary management tool to further reduce nutrient levels in the system and curb blue-green algal blooms. Blue-green algal blooms are an issue across Australia and globally, affecting drinking water catchments, recreational water bodies and the agricultural industry. Governments, industry and the research community have invested heavily in trying to find solutions and a range of in-lake treatments have been developed (see Table 7).

Broadly, these in-lake treatments try to address blue-green algal bloom by either:

- reducing nutrient levels in a waterbody (adsorptive materials, lake water treated by a lakeside bioretention, biological competitors, water treatment plant) or
- treating the algae directly with chemicals such as algicides or through physical actions or with water treatment plant.

Trials of in-lake treatments—past and future

In 2019–2020 the ACT Government engaged the University of Canberra to conduct in-lake mesocosm experiments using Phoslock™ (adsorptive material), Diatomix™ (modifies the nutrient composition of the water to favour species that promote the growth of diatoms at the expense of blue-green algae) and peroxide (an algicide). The experiments found these methods to be ineffective at reducing established blue-green algal blooms in Lake Tuggeranong. However, the timing of their application, after a bloom was established, may have limited the effectiveness of at least the Phoslock and peroxide treatments. The experiment report suggests that Phoslock offers a promising way to limit internal phosphorus loading, provided catchment sources can be controlled first. It recommends further trials that apply treatments before the onset of a bloom (Ubrihien et al., 2019).

Two floating wetlands have been deployed; one in Lake Tuggeranong and the other outside the Tuggeranong catchment at Yerrabi Pond. The floating wetlands directly compete with algae for light and nutrients. They have yet to be evaluated for their performance.

A range of existing and emerging technologies and methods to treat phosphorus in the lake have been identified, including filtration, sedimentation, floatation, biological and chemical removal (GHD, 2024). This work pointed to potential opportunities to use a combination of bioretention basins and phosphorus adsorptive (chemically binding) material. For example, Poseidon Pellets™ are a patented product made of magnesium carbonate beads, which adsorb phosphorus and ammonia from water. They could be used in a variety of ways; a water-permeable bag containing the beads can be placed in stormwater or suspended in the surface waters of the lake or in a bioretention basin. Once the pellets become saturated with phosphorus they need to be replaced.

Other in-lake treatments may also be trialled in the future through the Healthy Waterways research program, but the immediate priority will be to reduce catchment sources of phosphorus.

Table 7. Different types of in-lake treatments. All have potential adverse environmental impacts and most are likely to have low effectiveness until pollution from the Lake Tuggeranong catchment is reduced. Only a small number of these treatments have been trialled in Canberra, where the focus has been on reducing pollution in the catchment.

Treatment type	How it works
	By reducing nutrient levels and/or competing with blue-green algae
Adsorptive materials	Materials deployed to the lake bind phosphorus strongly, removing dissolved forms from water so the phosphorus is not available for uptake by blue-green algae.
Bubblers	Bubblers increase levels of dissolved oxygen in the water column, which encourages the formation of iron and manganese precipitates that bind dissolved phosphorus. The precipitates then sink and are stored in the lake sediments.
Bioretention	Water from the lake is circulated through raingardens at the edges of the lake, which partially filter the phosphorus by binding it to soil media and incorporating it into plant biomass.
Biological competitors	Competitors promote the growth of water plants or beneficial algae or bacteria that compete with blue-green algae, suppressing their growth.
	By treating algae directly, either in-lake or with water treatment plant
Algicides	Chemical agents aim to selectively kill algae.
Physical	Physical methods either physically break up blue-green algal cells or force them to the surface of the lake where they can be removed by skimming.

Conclusion for in-lake treatments

Unfortunately, there is no treatment that is effective in all contexts or that does not adversely affect the aquatic environment. Since in-lake treatments are unlikely to ever be effective enough to curb nutrient levels that fuel algal blooms, and the excessive use of algicides would present a heightened risk of impacts to non-target organisms, they do not represent a sustainable, stand-alone solution. However, water managers may need to use them both as an interim measure over the next decade, while we work to mitigate the sources of catchment loads, and then as a periodic solution when algal blooms arise despite best efforts to prevent them.

Selection of options for consideration

Booksmythe et al. (2024) analysed a subset of options for mitigating phosphorus pollution for their potential to contribute to solving the algal bloom problem in Lake Tuggeranong (Table 8). They only analysed options if their costs and effectiveness could be well characterised based on local trials or scientific literature. Of the nine selected options to remove phosphorus, five prevent phosphorus entering the stormwater system and four treat it once it's in the system.

They did not select any options for directly treating algae in-lake and selected only one in-lake treatment for reducing nutrient levels and/or competing with blue-green algae (floating wetlands). This is because the initial focus is to mitigate the phosphorus pollution that is driving algal blooms. Other in-lake options will be considered in future once their costs and benefits (and risks) are better understood and phosphorus pollution to Lake Tuggeranong has been reduced.

Table 8. Options considered in this report to reduce phosphorus pollution of stormwater (Booksmythe et al., 2024).

Option	Description
Street sweeping	Increase the amount of street sweeping in the catchment to remove more organic material from the roads, preventing it from leaching phosphorus into the stormwater drains. The implementation level reflects sweeping frequency ranging from 12 to 48 sweeps per year.
Fertiliser management	Identify and target the relatively small number of households that use excessive amounts of fertiliser to help them use either low-phosphorus fertiliser or no fertiliser at all. The implementation level reflects the reach of the program.
Open space mowing	Reduce the amount of grass clippings from municipal mowing that end up on the road, preventing them from leaching phosphorus into the stormwater drains. The implementation level reflects different management approaches, from having designated street sweeping trucks follow immediately after mowing events to towing electric blowers behind mowers to divert clippings away from the road.
Rainwater tanks	Capture stormwater from roofs for reuse on residential blocks. This may aid in removing some phosphorus in the system as well helping to reduce urban runoff. The implementation level reflects the number of houses that would have a tank installed.
Stormwater recycling	Divert and filter stormwater to storage tanks at sports fields for use in irrigating the fields. The implementation level reflects the number of sports field sites at which water managers would install this infrastructure.
Castellated kerbs	Retrofit outlets into road kerbs to divert some of the stormwater to open green space and allow it to filter into the ground. The implementation level reflects the number of outlets installed (water managers are limited by availability of suitable places in the Tuggeranong catchment; that is, areas adjacent to green space).
New water quality infrastructure—sports fields	Build swales around sports fields to potentially capture any phosphorus leaching out from fertiliser. Sports field managers are attempting to use fertiliser optimally and the leaching is more a legacy issue. The investment level reflects the number of sports field sites at which water managers would install this infrastructure.
New water quality infrastructure	Construct more wetlands at suitable locations in the catchment to treat phosphorus in the stormwater. The implementation level reflects the number of wetlands constructed, ranging from the two most effective builds to the ten most effective builds
Maintenance of existing water quality infrastructure	Ensure maintenance (such as dredging out built-up sediment and harvesting plants) of existing WSUD infrastructure in the Lake Tuggeranong catchment to maximise its performance and capture the largest amount of nutrients possible. The implementation level reflects the number of assets maintained.
Floating wetlands	Install more floating wetlands on Lake Tuggeranong to draw phosphorus out of the lake water. The implementation level reflects the number and size of wetlands installed.

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Part 7
Identifying solutions to the problem

- Estimated cost-effectiveness of options
- Management scenarios to solve the problem
- Performance of two scenarios to solve the problem
- Can we reach the phosphorus reduction target?

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Part 7: Identifying solutions to the problem

Booksmythe et al. (2024) derived potential solutions to the problem of phosphorus pollution that drives algal blooms in Lake Tuggeranong by comparing the cost-effectiveness of mitigation options in two ways: first separately and secondly together using the catchment water quality model. The former provides an indication of the most promising pollution mitigation options. The latter is important because it mirrors what will happen in the real world; that is, water managers will implement options together, not in isolation from each other, and implementing one option may affect the cost-effectiveness of other options.

Estimated cost-effectiveness of options

Method for determining cost-effectiveness of options

Booksmythe et al. (2024) defined four investment levels for each pollution mitigation option (Table 8). For example, for the option 'increased street sweeping', the investment levels were 12, 24, 36 and 48 sweeps a year.

They then derived data for costs and effectiveness (in terms of phosphorus reduction) of the investment levels from the scientific literature and the results of local trials. They estimated the benefits (kg phosphorus removed), costs (Net Present Value or 'NPV' over a 30-year period) and cost-effectiveness ($/kg phosphorus removed) of all investment levels. Cost-effectiveness represents the cost/effectiveness ratio of each investment level and was calculated as marginal annual benefit (kg phosphorus removed/year) / marginal annual cost (NPV to implement over 30 years divided by 30).

The researchers used a 30-year timeframe to calculate total costs because it allows for the comparison of options with very different cost schedules. For example, some options have large upfront costs, but low ongoing costs (for example, castellated kerbs) and some options have lower upfront costs, but higher ongoing costs (for example, street sweeping).

Results

Table 9 and Figure 8 present the annual load of phosphorus removed (effectiveness), the 30-year cost and the cost-effectiveness of each option's four levels of investment to mitigate phosphorus pollution. Note that the 30-year cost in Table 9 is the total cost of this option/investment level and any previous investment levels of the option.

It is clear from these data that street sweeping and adding extra water quality assets are the most effective options for reaching the 700 kg target, with the rest of the options bunched below these two in their effectiveness. Street sweeping is the standout option for cost-effectiveness; only the management of grass clippings comes close to the cost-effectiveness of street sweeping. The different pattern of the curve for grass clippings management in Figure 8 is due to the nature of the investment levels, which are effectively a matrix of two levels of assumed cost-effectiveness (low and high) by two separate types of removal, blowers and street sweeping (Booksmythe et al., 2024).

Table 9. Summary of phosphorus (P) removal performance, total cost and cost-effectiveness for four levels of investment for each of ten pollution mitigation options assessed independently (Booksmythe et al., 2024).

P mitigation option and level	Unit	P removed (kg/year)	30-year cost ($)[1]	Cost-effectiveness ($/kg P)
Install additional WSUD 1	Build 2 new WSUD assets	106.21	$22,507,500	$7,064
Install additional WSUD 2	Build 5 new WSUD assets	169.67	$48,369,492	$9,502
Install additional WSUD 3	Build 8 new WSUD assets	226.22	$73,862,467	$10,884
Install additional WSUD 4	Build 10 new WSUD assets	240.46	$84,519,403	$11,716
Maintenance of existing WSUD 1	Enhanced maintenance of 2 assets	35.84	$10,177,128	$9,465
Maintenance of existing WSUD 2	Enhanced maintenance of 3 assets	61.78	$19,086,579	$10,298
Maintenance of existing WSUD 3	Enhanced maintenance of 4 assets	79.93	$26,352,433	$10,990
Maintenance of existing WSUD 4	Enhanced maintenance of 5 assets	88.02	$30,352,433	$11,495
Increase street sweeping 1	12 street sweeps per year	203.70	$7,030,414	$1,150
Increase street sweeping 2	24 street sweeps per year	320.10	$14,060,827	$1,464
Increase street sweeping 3	36 street sweeps per year	372.50	$21,091,242	$1,887
Increase street sweeping 4	48 street sweeps per year	395.80	$28,121,656	$2,369
Manage grass clippings 1	Blow clippings into verge, low P removal estimate	16.40	$2,018,874	$4,103
Manage grass clippings 2	Blow clippings into verge, high P removal estimate	26.10	$2,018,874	$2,578
Manage grass clippings 3	Sweep clippings in verge, low P removal estimate	32.70	$1,521,462	$1,551
Manage grass clippings 4	Sweep clippings in verge, high P removal estimate	52.30	$1,565,956	$998
Sports field fertilizer management 1	Protect 25% of sports fields with bioretention swales	14.93	$4,204,451	$9,387
Sports field fertilizer management 2	Protect 50% of sports fields with bioretention swales	29.85	$11,817,327	$13,196
Sports field fertilizer management 3	Protect 75% of sports fields with bioretention swales	44.78	$19,430,204	$14,463
Sports field fertilizer management 4	Protect 100% of sports fields with bioretention swales	59.70	$31,445,222	$17,557

P mitigation option and level	Unit	P removed (kg/year)	30-year cost ($)[1]	Cost-effectiveness ($/kg P)
Household fertilizer management 1	Low P target (assume cost is $10,000/kg P/year)	20.00	$6,000,000	$10,000
Household fertilizer management 2	Medium P target (assume cost is $10,000/kg P/year)	32.67	$9,800,000	$10,000
Household fertilizer management 3	High target (assume cost is $10,000/kg P/year)	45.33	$13,600,000	$10,000
Household fertilizer management 4	Very high target (assume cost is $10,000/kg P/year)	58.00	$17,400,000	$10,000
Install castellated kerbs 1	Install 1 kerb outlet for every 4 sumps (or 453 outlets)	15.56	$4,532,500	$9,708
Install castellated kerbs 2	Install 1 kerb outlets for every 3 sumps (or 604 outlets)	20.75	$5,990,823	$9,624
Install castellated kerbs 3	Install 1 kerb outlets for every 2 sumps (or 906 outlets)	31.13	$8,539,901	$9,146
Install castellated kerbs 4	Install a kerb outlet for every sump (or 1813 outlets)	62.25	$14,349,291	$7,684
Install floating wetlands 1	Deploy 1000 m^2 of wetland	3.00	$1,226,000	$13,622
Install floating wetlands 2	Deploy 2000 m^2 of wetland	6.00	$2,452,000	$13,622
Install floating wetlands 3	Deploy 3000 m^2 of wetland	9.00	$3,678,000	$13,622
Install floating wetlands 4	Deploy 1000 m2 of wetland	12.00	$4,904,000	$13,622
Stormwater recycling for irrigation 1	Build best 2	8.81	$2,673,863	$10,115
Stormwater recycling for irrigation 2	Build best 4	15.12	$4,588,909	$10,115
Stormwater recycling for irrigation 3	Build best 6	19.19	$7,339,284	$12,748
Stormwater recycling for irrigation 4	Build best 8	21.78	$10,816,870	$16,558
Household rainwater tanks 1	2,500 new households to install water tanks	15.00	$12,500,000	$27,778
Household rainwater tanks 2	2,500 new households to install water tanks	30.00	$25,000,000	$27,778
Household rainwater tanks 3	2,500 new households to install water tanks	45.00	$37,500,000	$27,778
Household rainwater tanks 4	2,500 new households to install water tanks	60.00	$50,000,000	$27,778

1 Total lifecycle cost is the estimated cost of implementing and operating a mitigation option over 30 years, with annual operation and maintenance costs discounted by 7% per annum after the first year.

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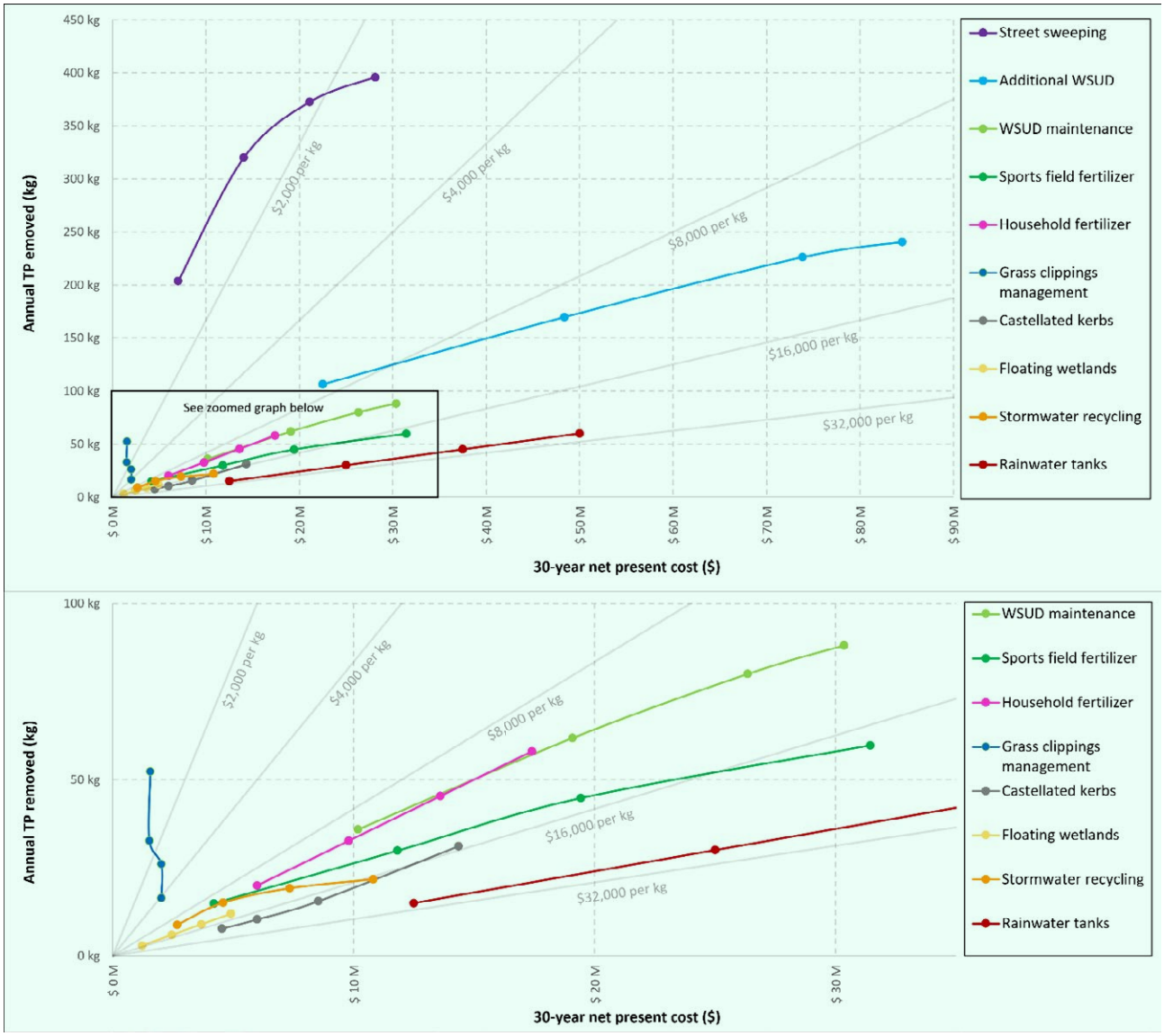

Figure 8. Annual total phosphorus load removed and 30-year lifecycle cost of each incremental investment level for the 10 assessed options for mitigating phosphorus pollution (Booksmythe et al., 2024). Coloured lines connect the four estimates for each option. Grey lines are a guide indicating the cost-effectiveness (cost per kg phosphorus removed) of the estimates. The top panel shows all estimates; the bottom panel shows a zoomed in view of the estimates within the inset box.

An important conclusion of this work is that options to prevent waters from becoming polluted in the first place—street sweeping and ensuring grass clippings from road verges do not enter drains—are more cost-effective than all other options, most notably, the construction of water quality assets. Thus, the most cost-effective way to improve water quality is to prevent waters from becoming polluted rather than relying on water treatment to achieve clean water.

Management scenarios to solve the problem

Booksmythe et al. (2024) define two water quality modelling scenarios: 'cost-effective' and 'broad benefits'. These scenarios are packages of various levels of investment in pollution mitigation options that would theoretically reach the target phosphorus reduction needed to achieve a mesotrophic lake in three out of four years (Dey et al., 2024). These are not the only management scenarios they could imagine but represent two

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common ways of approaching water management. If water managers can successfully implement either of these scenarios, we can expect the lake to be more consistently free of blue-green algal blooms and thus open for the Tuggeranong community to use and appreciate for most of the year. In three out of four years, on average, we would expect no blue-green algal blooms. In the one out of four years where blooms arise, we will develop ways to clear the blooms.

Cost-effective scenario

The cost-effective water management scenario ranked the investment levels of each pollution mitigation option/investment level by its cost-effectiveness and selected the most cost-effective option/investment levels until the total annual phosphorus load removed met the 700 kg target. An increment of an option that represented a higher level of investment was excluded if the increments of lower investment were not also included in the list; that is, managers cannot double a $100,000 investment if they have not already invested $100,000. This resulted in the selection of nine pollution mitigation options (Table 10).

Broad benefits scenario

The 'broad benefits' management scenario started by taking the most cost-effective options and investment levels, as above, but recognised that some lower ranking options should still be included because they provide additional benefits to the community beyond water quality. For example, constructed wetlands can provide:

- Ngunnawal cultural benefits as identified in the Aboriginal Water Assessment (see Part 1), for example:
  - ensuring the locations of living infrastructure—drain re-naturalisations and other constructed wetlands—promote the creation of a cultural and ecological corridor that connects the Lake Tuggeranong catchment, its waterways and areas downstream of the dam at least to the Murrumbidgee River
  - considering the re-naturalisation of concrete drains as options for water quality assets
  - including reeds for weaving among the native seedlings added as water quality plantings
- foundations for residents' wellbeing including opportunities to improve physical and mental health (Lal and Adhikari, 2024)
- greater climate resilience by reducing urban heat (NC Economics, 2019, Tapsuwan et al 2024)
- enhanced amenity of suburbs
- support for urban biodiversity
- a source for recycled stormwater to irrigate sports fields, which relieves pressure on ACT's potable water supply (for example, as implemented at Kambah playing fields).

Under the broad benefits scenario, Booksmythe et al. (2024) considered the level of confidence in their estimates of cost-effectiveness for each pollution mitigation option. They developed confidence criteria for each option based on whether the information and data are robust, from a local source and from a single source or confirmed by multiple sources. Then, to create the broad benefits scenario, they adjusted the cost-effective scenario by increasing levels of investment in options with broader benefits and reducing investment in options with less certainty about their costs or effectiveness.

Compared with the cost-effective scenario, the broad benefits scenario:

- includes a wider variety of pollution mitigation options
- has slightly less street sweeping
- invests less in fertiliser management (because of lower confidence in the estimates of its contribution to phosphorus removal)
- has more investment in WSUD infrastructure because of its broader benefits to the community; for example, a benefit–cost ratio conservatively estimated as 1.66 (NCEconomics, 2019) is conservative because the analysis could not evaluate all benefits including Ngunnawal cultural benefits.

Table 10. Pollution mitigation options for reducing phosphorus in stormwater and levels of investment in these options modelled in the cost-effective and broad benefits scenarios.

	Level of investment	
Mitigation option	**Cost-effective scenario**	**Broad benefits scenario**
Increase street sweeping	48 sweeps uniformly over the year	36 sweeps, seasonally optimised
Improve open space mowing practices	Dedicated street sweeper to sweep after mowers go through	Dedicated street sweeper to sweep after mowers go through
Castellated kerbs	Not included in this scenario	Castellated kerbs retrofitted to replace every 4th sump along roads adjacent to open space (total 453 kerbs)
Improve fertiliser management in households through behaviour change program	Very high investment in program—$17.4 million (NPV, 30 years)	Lower investment in program—$6 million (NPV, 30 years)
Improve maintenance of water quality assets built in Stage 1 of Healthy Waterways	Improve maintenance of four most cost-effective water quality assets	Improve maintenance of five most cost-effective water quality assets
Build and maintain new large constructed wetlands or raingardens, e.g. drawn from the reserve list of assets proposed but not built under Healthy Waterways	Add the two most cost-effective assets	Add the five most cost-effective assets
Build and maintain water quality assets (bioretention swales) on sportsgrounds to capture fertiliser runoff	Add 1,000m^2 of bioretention swales at the biggest four sportsgrounds	Add 5,000 m^2 of bioretention swales at the biggest seven sportsgrounds
Install stormwater recycling tanks at sports fields for irrigation	Tanks installed at four sports fields (Greenway, Calwell, Kambah, Wanniassa)	Tanks installed at six sports fields (Greenway, Calwell, 2 x Kambah, Wanniassa, Gowrie)
Build new floating wetlands	Not included in this scenario	Build new 4000 m^2 of floating wetland in Lake Tuggeranong that is harvested once annually

Analysis of management scenarios

The overall performance of the two scenarios in mitigating phosphorus pollution is analysed in two ways:

1. Summing the costs (net present value, $ over 30 years) and effectiveness (kg phosphorus mitigated) of the pollution mitigation options/investment levels as if they were implemented in isolation, independently of one another. This provides an indication of which are the most promising pollution mitigation options.
2. Summing the costs and effectiveness of the options/investment levels as if they were implemented together at the same time. This is important because, in the real-world, water managers would implement options concurrently, not in isolation from each other, and the implementation of one option may affect the cost-effectiveness of another. Dey et al. (2024) used the catchment water quality model to estimate the combined effects of the options/investment levels on phosphorus supply to or availability in Lake Tuggeranong.

Performance of two scenarios to solve the problem

Options considered independently

The effects of the two scenarios, where the pollution mitigation options/investment level are considered independently of one another, are illustrated in Table 9 and Figures 8 and 9.

The cost-effective scenario is dominated by various investments in pollution prevention options that help prevent stormwater from getting polluted in the first place, such as street sweeping and fertiliser management (Table 9 and Figure 10). Options such as rainwater tanks, floating wetlands and castellated kerbs were less cost-effective (based on available data) than alternatives, so were not included in this scenario.

Only two constructed wetlands were included in the cost-effective scenario because wetlands are only moderately cost-effective in reducing phosphorus (Table 9). In older suburbs like Tuggeranong, there is limited space and it is expensive to retrofit large infrastructure. For example, during Stage 1 of Healthy Waterways, seven different types of constructed wetlands were built in the Lake Tuggeranong catchment at a cost of $30 million. The Lake Tuggeranong catchment water quality model estimates these assets remove 214 kg of phosphorus/year (Dey et al., 2024), approximately 13% of the catchment phosphorus load. While not insignificant, it highlights that wetlands alone will not remove enough phosphorus to reach the target. Even if enough space could be identified to build them, it appears that building more wetlands in the catchment could not reduce total phosphorous by more than 200 kg/year (Figure 8). The cost to attempt to use water quality assets alone to reach the phosphorus mitigation target would be prohibitive and, in medium to large storms, a significant amount of stormwater bypasses them and flows directly to Lake Tuggeranong untreated.

The cost of the cost-effective scenario for mitigating phosphorus pollution in stormwater by 700 kg per year is estimated at around $105 million over 30 years (Table 11).

A broad benefits scenario would remove 64 kg or 9% more phosphorus (Figure 9 and Table 11), while costing $141 million, which is $36 million or 34% more than the cost-effective scenario (Table 11). In both scenarios, street sweeping, water quality assets and WSUD maintenance account for the greatest phosphorus mitigation. In the broad benefits scenario, fertiliser management by households contributes less than at sports fields, and open-space mowing and stormwater recycling contribute more to phosphorus mitigation. Five large water quality assets such as raingardens were included in the broad benefits scenario due to the other benefits they provide in addition to phosphorous removal, as described above.

Raingarden at Isabella Plains

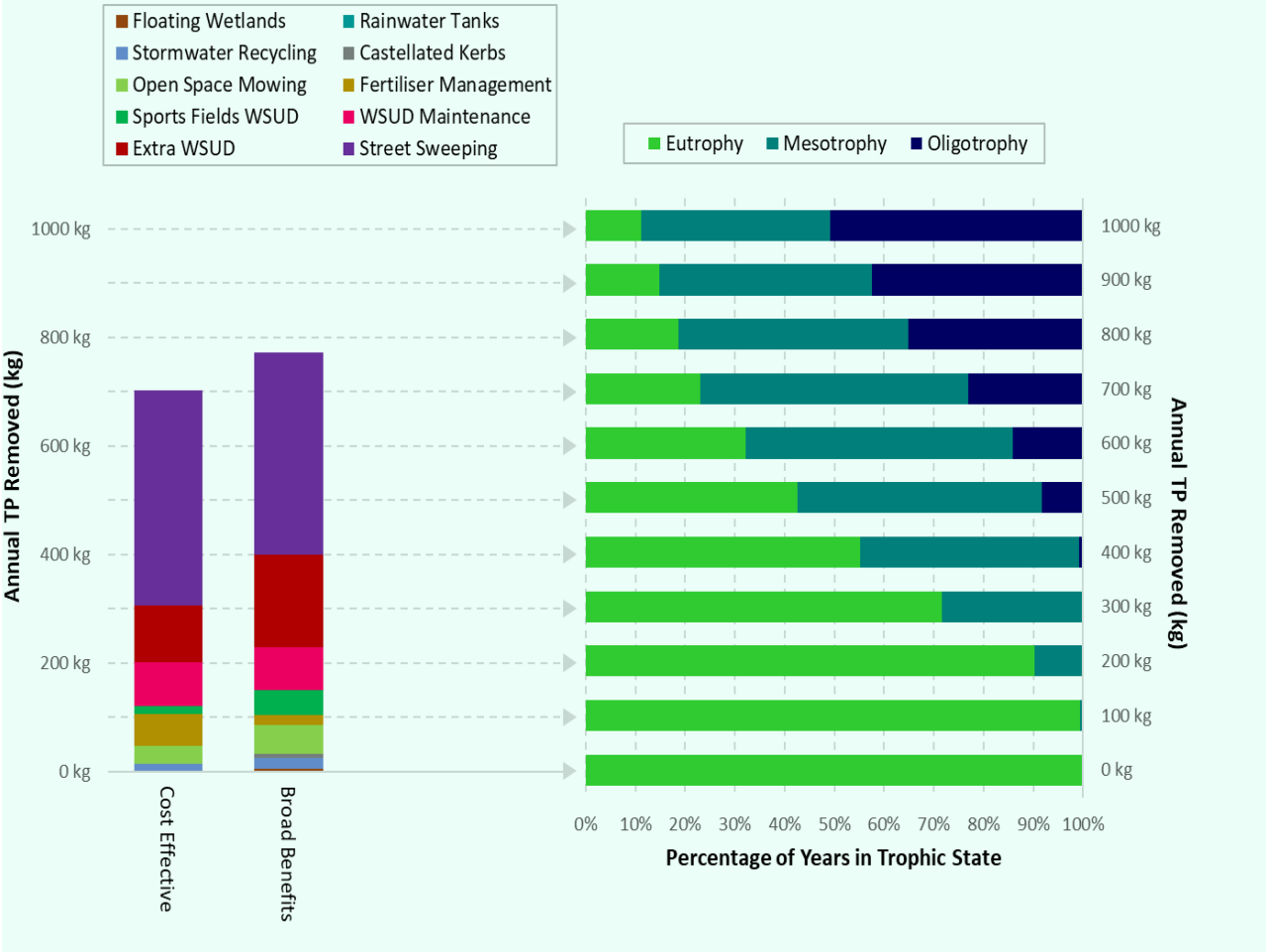

Figure 9. Two scenarios offering of a range of possible phosphorus-reducing options and increments of intensity of implementation, packaged up to reach the 700 kg target for phosphorus mitigation. This will enable Lake Tuggeranong to mostly exist in a mesotrophic state. The effects of the option increments have been analysed independently of one another.

Table 11. Comparison of the cost of two different management scenarios for mitigating phosphorus pollution. NPV is net present value.

Management scenario	Number of pollution mitigation options included	Cost (NPV – $ million over 30 years)	Benefit (kg phosphorus removed / year)	Cost-effectiveness $ / year / kg phosphorus removed
Cost-effective	7	105	703	4,967
Broad benefits	9	141	767	6,241

Options implemented concurrently

In practice, water managers will implement various pollution mitigation options in either of the two scenarios concurrently, and this will affect their combined performance. Dey et al. (2024) used the catchment water quality model to model the two management scenarios to predict any impact to overall phosphorus reduction due to this interactive effect.

Their modelling indicates that when all pollution mitigation options are implemented together, the interactive effect reduces the total phosphorus removed by 14% under the cost-effective approach and by 12% under the broad benefits approach (Table 12, Figure 10). This decrease arises in part because the models assume that the cleaner the stormwater becomes, the less the water quality assets will filter out whatever pollutants remain. Monitoring of asset performance over time at different levels of stormwater flow will help to confirm or clarify this assumption. The decrease is also because some pollution mitigation options partially offset the effects of others. For example, having a dedicated street sweeper follow mowers of road verges would diminish some of the effect of sweeping suburbs 36–48 times a year. However, the uncertainties inherent in all estimates based on research and modelling (see Booksmythe et al. 2024 for details) probably mean that this reduction in supply is indistinguishable from the target of 700 kg (or from a lower level of performance of 400 kg).

Implications

Several key findings emerge from these results:

- There are no silver bullets; no pollution mitigation option has the potential to reach the 700 kg/year phosphorus mitigation target on its own. Managers will need to implement multiple options to reduce phosphorus pollution to a substantial extent and thus restrict the incidence of algal blooms.
- Street sweeping is the most cost-effective option in both scenarios and removes the largest amount of phosphorus (as also indicated in figures 8 and 9).
- Large water quality assets placed low down in catchments are necessary to treat unavoidable pollution but are not sufficient on their own to achieve the target reduction in phosphorus pollution of stormwater. Managers will need to implement options that prevent stormwater from getting polluted in the first place to substantially reduce the incidence of blue-green algal blooms in Lake Tuggeranong.

Table 12, Effects of implementing phosphorus pollution mitigation options together as determined by water quality modelling compared with the sum of benefits when multiple options are considered independently. Source: (Dey et al., 2024). Figures are for average kg phosphorus per year entering Lake Tuggeranong, or percentage decrease in the amount of phosphorus entering Lake Tuggeranong per year.

	Average kg phosphorus/year entering Lake Tuggeranong					
Scenario	Before Stage 1 assets were built	Current (with Stage 1 assets)	Current + added pollution mitigation options considered independently	% decrease from before Stage 1 assets were built	Current + added pollution mitigation options considered together (water modelling)	% decrease from before Stage 1 assets were built
Cost-effective	**1656**	**1442**	**739**	**55%**	**979**	**41%**
Broad benefits	**1656**	**1442**	**662**	**60%**	**859**	**48%**

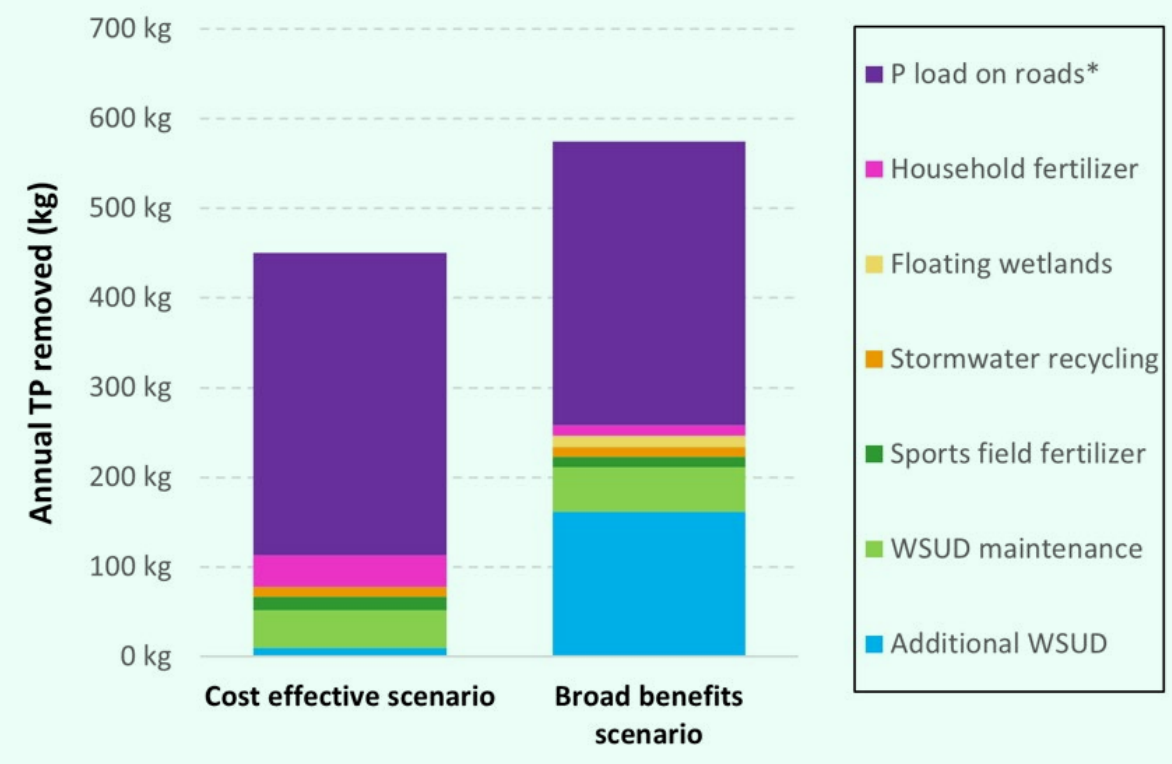

Figure 10. Modelled average annual reduction in the load of total phosphorus (TP) generated in the Lake Tuggeranong catchment under the cost effective and broad benefits management scenarios. Colours indicate the reduction in phosphorus due to different mitigation options in each scenario.

* 'P load on roads' includes the reductions in TP load due to street sweeping, grass clippings management and installation of castellated kerbs.

Box 5. Street sweeping pilot

Based on the research findings that leaves contribute to stormwater pollution (see Part 3), a pilot street sweeping program was conducted over the summer of 2023/24 to better understand how much the leaves and other organic matter from streets contribute to the amount of nutrients in urban stormwater, and to begin to understand the efficacy of increasing the frequency of street sweeping as an option to mitigate pollution.

Over three months, two sub-catchments in the Lake Tuggeranong catchment were swept every fortnight and two sub-catchments were left unswept. Stormwater samples were collected during storm events to see if the fortnightly-swept catchments showed a reduction in nutrient concentrations. Samples of the material swept off the roads by the trucks were also taken to a lab for analysis.

The results indicate that leaves and other organic material on the roads are contributing significant amounts of phosphorus to stormwater in the catchment. Analysis of the material collected by street sweeping trucks (which included leaves, soil, grass clippings, gravel and road material) estimated that 39.2 kg of phosphorus was removed from the roads in the swept sub-catchments during the experiment. Scaled up to the Tuggeranong catchment, this pilot suggests that a fortnightly program of street sweeping could intercept around 300 kg a year of phosphorus, which is more than 40% of the target of 700 kg/year.

Analysis of the stormwater samples showed a modest decrease in phosphorus concentrations in stormwater from the swept sub-catchments over time, compared to the unswept sub-catchments. As there are many other factors that can influence nutrient concentrations in stormwater, the project was repeated in the summer of 2024/25 to strengthen our understanding of how much leaves contribute to phosphorus in the stormwater. Analysis of this second trial is underway.

The street sweeper used in the pilot program.

Can we reach the phosphorus reduction target?

The analyses suggest that the ACT Government can succeed in curbing algal blooms in the lake if it implements a program to reduce phosphorous pollution.

Firstly, a reduction of 500–600 kg/year in phosphorus pollution in the two scenarios presented would substantially reduce the frequency of blue-green algal blooms in Lake Tuggeranong (Figure 6).

Secondly, the management options to mitigate pollution are currently conceived, and thus modelled, in a simple way. Refinement of the options, both during implementation planning and in models, should both decrease their cost and increase their effectiveness. For example, street sweeping in winter, when cold temperatures limit algal growth, may have little impact on lake closures. Eliminating winter street sweeping will reduce costs. Conversely, targeting sweeping efforts in summer, and adding a complementary community program for collecting leaves, may intercept a greater amount of pollution from leaves and grass on verges, reducing the nutrient pollution from these sources beyond that predicted by Dey et al. (2024) for the most intense investment level of this option in the model. There are many nuances to the design of community partnerships and the design and siting of water quality assets that could increase their effectiveness above the average value used in the modelling.

Thirdly, several promising pollution mitigation options have yet to be explored that may help to meet the phosphorus mitigation target. Apart from floating wetlands, in-lake treatments have not been included in the modelled options, and these could contribute to further phosphorus reduction. For example, new products are emerging that draw and capture phosphorus out of stormwater, both in the catchment and in the lake itself. One potential intervention that has shown promising results in trials overseas is Poseidon Pellets™. These pellets consist of porous granules that adsorb dissolved phosphorus from water. They promise a high rate of phosphorous adsorption at a relatively low cost but remain untested locally.

The uncertainty about the extent that fertilisers applied to residents' gardens contribute to stormwater pollution (Part 5) does not preclude taking action now. If it turns out from further research that the fraction of phosphorus attributed to fertiliser use is more than is currently estimated, and the fraction due to leaves and grass is less, there would be a shift in emphasis from options that target leaves to ones that target fertilisers. The same is true if sewer leaks turn out to be an important source of phosphorus; the leaks would need to be fixed but it would still be necessary to deal with leaves, grass and fertilisers.

The main cautionary note is about how quickly algae in Lake Tuggeranong will respond to reduced supplies of phosphorus from the catchment. Algal blooms may persist if the phosphorus in the sediments is able to sustain the blooms. This may mean it takes longer than the goal of a decade to fix the algal bloom problem. The long-term research focus should include investigations into in-lake treatments that reduce the supply of phosphorus from the sediments or compete with algae for phosphorus, such as Poseidon Pellets™.

Key conclusions can be drawn from the analyses in this report:

- There is sufficient knowledge to have confidence that a suite of actions can lead to a substantial reduction in the frequency of blue-green algal blooms in Lake Tuggeranong. Inflows of phosphorus pollution can be reduced by up to 700 kg/year within ten years, but whether this would significantly reduce algal blooms in the same time frame may depend on the development of in-lake treatments to deal with phosphorus stored in lake sediments.
- Algal blooms probably cannot be prevented from forming altogether. The analyses carried out for this report suggest the best that can be achieved is for algal blooms to be prevented in three out of four years on average.
- This means that the ACT Government may need to consider developing ways to treat algal blooms as they arise in the years where pollution levels may permit their formation. These may range from the promotion of algal competitors to the use of algicides (see Part 6).

CABINET

Part 8
The path forward

- Research agenda
- Current priorities for restoration
- Next steps to finalise the Plan

CABINET

Part 8: The path forward

The research findings and modelling work presented in this report provide confidence that the ACT Government can make real progress in addressing the problem of algal blooms in Lake Tuggeranong. The target level of phosphorus reduction is achievable and this would reduce the impacts of blue-green algal blooms. Figure 11 shows a high-level plan for how this could be achieved, from which funding for implementation can be investigated.

Research agenda

Ongoing research and monitoring is critical to refining options to mitigate pollution, to maximise their effectiveness and minimise their costs. The ACT is one of only a small number of jurisdictions in the world actively monitoring constructed wetlands. This is important for testing how well wetland assets perform against design model expectations (including as stormwater entering them becomes cleaner over time) and for informing how the assets are operated and maintained.

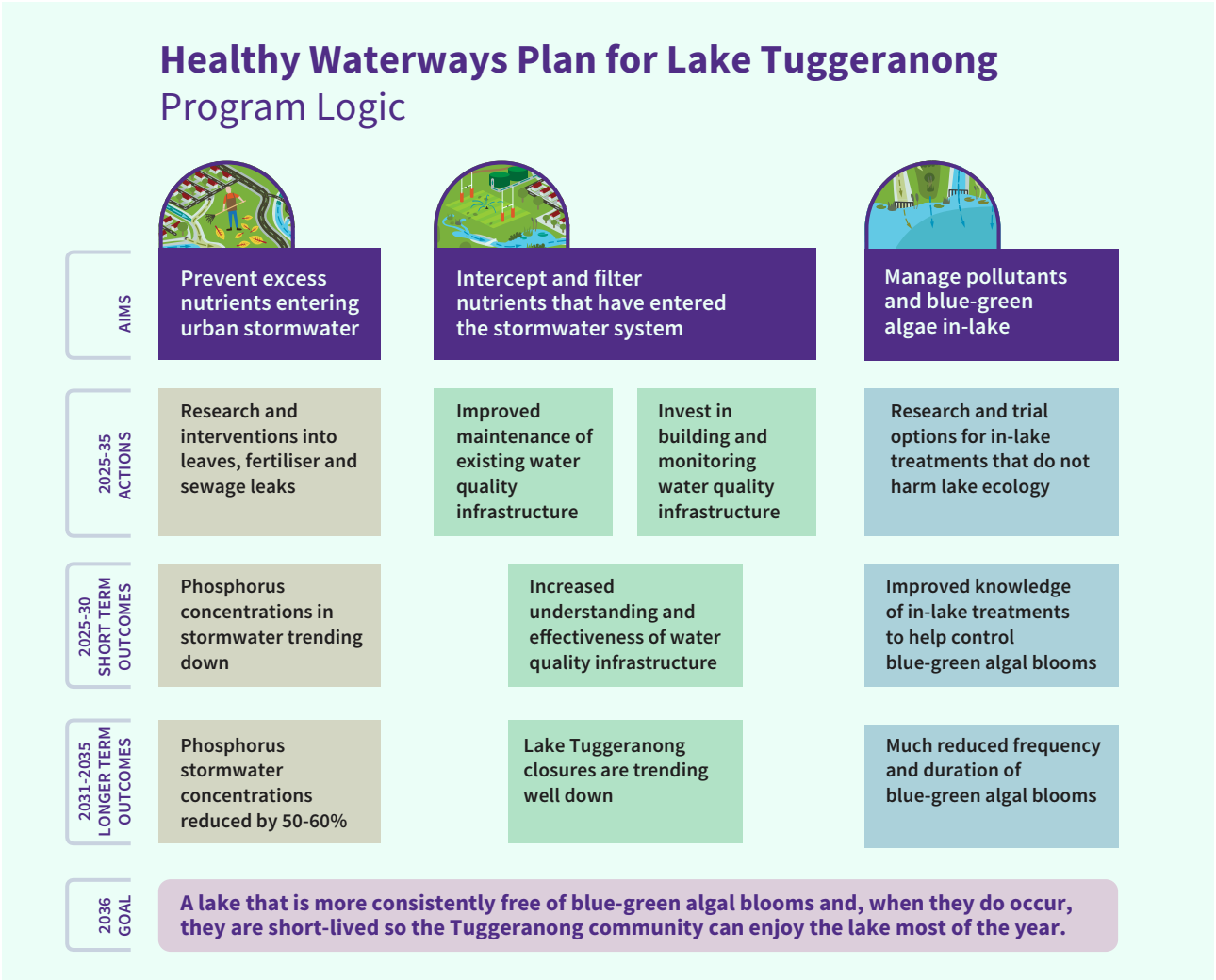

Figure 11. Draft program logic to guide more detailed implementation plan.

The highest priorities for research are to:

- trial promising pollution mitigation options
- investigate, to better understand, the fate of fertilisers applied to residents' blocks
- determine whether sewer cross-connections are a significant source of phosphorus in stormwater.

Table 14 describes the Healthy Waterways research program up to the summer of 2025/26.

Current priorities for restoration

Additional research will continue to refine knowledge and understanding of how to reduce phosphorus in the Lake Tuggeranong catchment, but there is enough evidence already to investigate funding for several priority actions.

Expand street sweeping program to be more often and seasonally optimised

Research by the University of Canberra (Ubrihien et al., 2019) plus the street sweeping pilot by the University of Canberra, Healthy Waterways and City Services demonstrated that leaves contribute a significant amount of phosphorus to catchment loads in the Tuggeranong catchment. Modelling by Booksmythe et al. (2024) indicates that an expanded street sweeping program would remove a significant amount of phosphorus from the catchment. If, for example, streets were to be swept 36 times a year, this would remove up to 316 kg/year or 53% of the target phosphorus reduction amount of 700 kg/year and cost up to around $1.4 million annually (Table 10, noting that the cost of investment level 3 has been annualised).

The Healthy Waterways team and ACT City Services ran a street sweeping pilot again in the summer of 2024/2025 to strengthen findings and inform how best to optimise a future street sweeping program to capture seasonal leaf fall.

New community pollution prevention programs

A successful community pollution prevention program that encourages communities to collect leaves and reduce fertiliser use will complement increased street sweeping by reducing the volume of leaves that make it onto roads. This will reduce the green waste going to landfill and disposal costs since, at present, all waste from streetsweeper trucks is deemed contaminated waste and goes to landfill.

The Leaf Collective and Love the Lakes pilot programs received positive feedback from the community and provide valuable insights into how to engage the community to change their practices around fertiliser use and leaves. In late 2024 a new program that builds upon the successes of the pilots was rolled out as the Waterways Friendly Gardening program.

Build new WSUD infrastructure

WSUD infrastructure cannot solve the problem of blue-green algal blooms on its own and is relatively costly to build and maintain (Table 10). However, there is value in building some additional water quality assets in the Tuggeranong catchment because there will always be some unavoidable pollution of stormwater, which these assets will help to intercept before the pollution reaches the lake. Constructed wetlands also provide other benefits to the community including habitat for native plants and animals, urban cooling (Tapsuwan et al., 2024), public amenity (NC Economics, 2023) and cultural value.

Table 14. Healthy Waterways forward research agenda to 2026 for Lake Tuggeranong.

Area of research	Description	Estimated start date
Investigate potential leaks from sewerage—caffeine tracking study	Use caffeine in stormwater samples from across the catchment as an indicator of sewerage ingress.	Underway
Performance of constructed wetlands	Monitor the performance of four Stage 1 assets: two wetlands and two raingardens.	Underway
Street material content analysis	As part of the street sweeping project, run a study to understand what proportion of road matter phosphorus comes from non-leaf matter sources (e.g. from car tyres).	Summer 2024/2025
Maintenance of channel naturalisations	Develop methods to remove sediments accumulated in plant beds without destroying the plants.	Mid 2025
Investigate potential leaks from sewerage— Microbial Source Tracking	Test and compare the location, quantity and type of faecal matter (animal or human) found in different catchments after rain events, including Lake Tuggeranong.	Mid 2025
Investigate contribution of leaves on roofs to nutrient loads in stormwater	Examine how much leaves that fall on roofs are contributing to stormwater pollution given roofs are the biggest impervious area in the ACT.	Mid 2025
Circular economy—enhancing cost effectiveness of bioretention	Investigate income-generating potential from harvesting of vegetation from stormwater treatment ponds, floating wetlands etc., including when it's combined with swept material being used for biochar feedstock.	Mid 2025
Trial of Poseidon Pellets™	Run small-scale laboratory and field trials to test viability of Poseidon Pellets in the Lake Tuggeranong context.	Spring/Summer 2025/2026
Phosphorus content in leaves and soil	Investigate whether urban street trees of Tuggeranong shed unusually high levels of phosphorus in their leaves and where they access phosphorus from (soil or other sources such as the sewerage network).	Spring/Summer 2025/2026
Fertiliser leaching rates	Investigate runoff from residential blocks or gardens to estimate export rates of nutrients from fertiliser.	Spring/Summer 2025/2026
Maintenance of constructed wetlands	Develop approaches to harvesting macrophytes to increase the export of nutrients from wetlands and stimulate further uptake of nutrients.	Spring/Summer 2025/2026

As with all existing suburbs, space constraints and underground services limit the locations where new water quality assets can be built. However, Healthy Waterways feasibility studies have identified several potential locations that could be investigated further.

Improve maintenance of existing water quality assets

The ongoing performance of all water quality assets relies on good operation and maintenance practices. Modelling by Booksmythe et al. (2024) indicates that improving the maintenance of existing Stage 1 and 2 water quality assets would deliver substantial phosphorus reduction benefits (Table 10). The Healthy Waterways and ACT City Services teams are exploring several ideas for facilitating the operation and maintenance of water quality assets to improve their performance.

Next steps to finalise the Plan

Version 1 of the Healthy Waterways Plan for Lake Tuggeranong will incorporate further inputs from First Nations people and feedback from the community and experts on the proposed approach. An implementation plan will then be developed to set out how the vision will be achieved over the next 10 years. This will consider how the plan will be monitored and evaluated, and include indicators for cultural values.

CABINET

Glossary
References

CABINET

Glossary

Term	As defined in the Plan
Adsorption, adsorbed	The adhesion of a substance (e.g. charged phosphorus ions) to a surface (such as charged clay particles in soil or Poseidon Pellets™).
Bacterial pathogen	Bacteria that can lead to illness.
Baseflow	Streamflow continues between rain events.
Bioavailable	(for plant nutrient–algae relationship) Plant nutrients that are in a form that can be absorbed and used by algae to support growth and metabolism.
Bioretention	Infrastructure (for example, swales or raingardens) comprised of soil, plants and microbes to treat and filter stormwater. Stormwater is spread through the surface of the infrastructure, percolates vertically and is collected in outlet pipes at the base of the asset, leaving behind filtered pollutants.
Bioretention basin	Landscaped depression to manage and treat runoff. See 'Bioretention'
Bioretention swale	Type of bioretention system using linear, vegetated drains in a landscape to capture and filter runoff.
Blue-green algae	A group of photosynthesising, algae-like bacteria that live in freshwater, estuarine and marine environments. Also known as cyanobacteria.
Calibrate, calibration (models)	Adjusting water quality models so they provide a good description of the water quality in Tuggeranong's waterways. This is achieved by comparing model predictions with actual measurements of water quality in the stormwater system and making adjustments to the model to minimise its differences with the observed data.
Catchment	Area of land where precipitation collects and drains to a common outlet (for example, a river or waterbody). May also be known as a drainage basin.
Chlorophyll *a*	A pigment in many plants and algae that helps them absorb light energy and convert it to chemical energy in a process called photosynthesis. Chlorophyll *a* is often used as a proxy to assess algae biomass as it is easier to measure than biomass.
Constructed wetlands	Both a general term for water quality assets comprised of soil, plants and microbes to treat and filter urban runoff, and a reference to a specific type of asset where stormwater that is diverted to the wetland flows laterally to an outlet at its downstream end (as compared to 'bioretention'; see definition above).
Cyanobacteria	See blue-green algae.
Diffuse source	A non-point source, where pollutants are generated from many sources across the catchment.
Deposition rate	(for leaves) The volume of leaves that fall from trees for a given area/time.
Enterococci	Bacteria commonly found in the intestines of humans and animals, used to indicate faecal pollution in waterbodies.
Eutrophic	Water bodies in a eutrophic state are nutrient rich, with highly productive plant growth and high turbidity. They are seasonally deficient in oxygen, which may lead to fish kills. Eutrophic lakes may experience regular algal blooms.
Export rate	% of nutrient (in this case phosphorus) in applied fertilisers lost to runoff.

Term	As defined in the Plan
Hydrograph	A way to display the flow of water over time.
Impervious surface	Water-resistant surface that is a partial or total barrier to water, such as concrete, roofs, roads.
Management scenarios	Packages of phosphorus pollution mitigation options that together are intended to achieve a desirable water quality outcome.
Mesocosm	Enclosure set up in the lake to study aquatic responses under controlled conditions.
Mesotrophic	Water bodies in a mesotrophic state have a moderate amount of nutrients, moderately clear water, some algal blooms in late summer and oxygen depletion at bottom of lake as biomass decomposes. If they do experience algal blooms, it is typically in late summer.
Microbial Source Tracking	Method to identify the sources of faecal contamination in water bodies; that is, whether it comes from humans or animals (domestic pets, wildlife, livestock).
Net Present Value (NPV)	The difference between the present value of cash inflows and outflows over time.
Nitrogen	Key nutrient essential for the growth of aquatic plants and algae. Excess nitrogen can lead to nutrient pollution which can cause algal blooms.
Nutrient load	Refers to the amount of nutrients entering a waterbody in a given time period; for example, kg phosphorus entering Lake Tuggeranong per year.
Oligotrophic	Water bodies in an oligotrophic state have very low nutrient concentrations and tend to have very clear water with little plant or algal growth. High oxygen concentrations depress the release of algal nutrients stored in lake-bottom sediments. Hence, oligotrophic lakes are not prone to algal blooms.
Phosphorus	Key nutrient essential for the growth of aquatic plants and algae. Excess phosphorus can lead to nutrient pollution which can cause algal blooms. Can be either particulate (sediment-bound) or present in dissolved forms. Total phosphorus (TP) is the sum of all forms of phosphorus present in a sample. In this report, phosphorus refers to total phosphorus unless otherwise stated and these terms are used interchangeably.
Phytoplankton	Photosynthesising microscopic organisms that live suspended in water. Blue-green algae/ cyanobacteria are a type of phytoplankton.
Point-source	Where pollutants are generated from specific sources in the catchment such as nutrients from a sewage treatment plant outlet.
Pollutant, Pollution (of water)	A substance (like phosphorus) that is present at levels that can cause harm to life. Phosphorus is not directly harmful but is a pollutant at high concentrations or supply because it promotes the growth of harmful algae.
Pollution mitigation options	Individual approaches to reducing the level of phosphorus in stormwater such as increasing the frequency of street sweeping or building water quality assets.
Raingarden	A water quality asset using bioretention technology in a shallow, landscaped depression to capture and filter urban runoff.
Runoff	Water that flows over the surface of the ground when it cannot sink into the ground.
Runoff infrastructure	Infrastructure or landscaping that holds, redirects and/or slows runoff to allow it to sink into the landscape.

Term	As defined in the Plan
Sediments	In this context, sediments are bits of soil and organic matter eroded from the catchment into stormwater and lake water. Sediments may become deposited in the bottom of lakes.
Stormwater	Water generated through rain that has made its way into the stormwater system.
Stormwater runoff	Rain that isn't absorbed into the ground and flows over the landscape.
Stormwater system	Concrete channels and pipes designed to direct stormwater away from built up areas to reduce flood risk.
Stratification	Formation of distinct thermal layers in the water column, which affect the distribution of oxygen and nutrients within the lake.
Suspended solids	Small particles that remain suspended in water, affecting water quality and aquatic life by reducing light penetration and temperature.
Total dissolved solids	The inorganic and organic substances dissolved in water. They are used as an indicator of water quality.
Treatment train	Water quality infrastructure working in sequence to remove pollutants and manage water flow to a target level.
Trophic state	Describes the biological productivity of a water body and depends on factors such as the concentration of nutrients like phosphorus and nitrogen (see oligotrophic, mesotrophic, eutrophic).
Turnover	Seasonal process where water layers mix resulting in the redistribution of oxygen and nutrients throughout the lake.
Water Sensitive Urban Design (WSUD)	WSUD seeks to minimise impacts of urban development on the natural water cycle by integrating developments with a site's natural features and promoting the integration of stormwater, water supply and sewage management.
Water quality assets	Infrastructure solutions that aim to filter water of pollutants, such as constructed wetlands, raingardens and ponds. Water quality assets are also commonly referred to as 'WSUD infrastructure'.

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Lake Tuggeranong Catchment Model

Technical Report: Configuration and Calibration of the Water Quantity and Quality Model

Water Information Services, ACT Office of Water

December 2024

Environment, Planning and Sustainable Development Directorate

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Executive Summary

Lake Tuggeranong is a small (57 ha) urban lake in southern Canberra. Lake Tuggeranong was constructed in the late 1980s on Tuggeranong Creek, a 66 km^2 catchment that is predominantly (62%) urbanised. In recent decades, Lake Tuggeranong has been plagued by poor water quality. Since 2017, there has been a concerted effort to improve water quality in the lake through the construction of Water Sensitive Urban Design (WSUD) infrastructure throughout the catchment, and a major research program to understand the causes of poor water quality, and sources of pollutants entering the lake. This work has been undertaken as part of the ACT Healthy Waterways program.

The ACT Government has commited to developing Healthy Waterways Plans for priority catchments in the ACT. The draft Lake Tuggeranong plan aims to provide a suite of potential management options to Government to further improve water quality in Lake Tuggeranong. To acheive this, modelling and analyses have been undertaken to examine a broad range of management scenarios and identify cost-effective options to improve water quality in Lake Tuggeranong. To support these analyses, a catchment model was developed in the eWater model platform Source to support the testing of water quality management scenarios, and rank these scenarios based on cost-effectiveness.

This report presents an overview of the development, calibration and outputs of the Lake Tuggeranong catchment model. The underlying rainfall-runoff model chosen for this task was a Sacremento daily timestep model, implemented in Source. Fine-scale delineation of subcatchments, land use and imperviousness, flow regulation infrastructure and WSUD infrastructure were included in the model, to provide a complete, current assessment of the Lake Tuggeranong catchment. A total of 75 subcatchments were delineated to key infrastructure within the catchment, existing monitoring locations, and other features of interest. LIDAR data captured in 2020 was used to quantify surface imperviousness within subcatchments, facilitating an explicit representation of imperviousness in the model.

A comprehensive compilation of water quality data and streamflow data collected in the catchment from 2014 to the present was used to calibrate the Source model. The initial flow calibration is rated as suitable for estimating long-term catchment mean annual flow and long-term mean annual pollutant loads. The water quality model is parameterised against observed end-of-catchment median event concentrations of total phosphorus, total nitrogen, and total suspended solids, in the absence of load-based water quality data. The model estimates pollutant loads generated in the catchment based on land use and imperviousness data.

The parameterised model was used to simulate daily flows and pollutant loads generated in the Lake Tuggeranong catchment between 1889 and 2023, the period for which observed rainfall and climate data was available. Under current catchment land use and management conditions, the modelled average annual inflow to Lake Tuggeranong is 8.8 GL/year. The modelled mean annual loads of pollutants entering Lake Tuggeranong are 1,442 kg/year total phosphorus, 11,894 kg/year total nitrogen, and 397,064 kg/year total suspended solids.

The results provide a robust foundation for future catchment management plans and strategies.

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1. Introduction

Lake Tuggeranong is a small (57 ha) urban lake in southern Canberra. The lake was constructed in the late 1980s on Tuggeranong Creek, a 66 km^2 catchment that is predominantly (62%) urbanised. In recent decades, Lake Tuggeranong has been plagued by poor water quality, with high loads of nutrients (phosphorus and nitrogen) and sediments entering the lake. Since 2017, there has been a concerted effort to improve water quality in the lake through the construction of Water Sensitive Urban Design (WSUD) infrastructure such as wetlands, swales and raingardens throughout the catchment, and a major research program to understand the causes of poor water quality, and sources of pollutants. This work has been undertaken as part of the ACT Healthy Waterways program.

The ACT Government has commited to developing Healthy Waterways Plans for priority catchments in the ACT. The Lake Tuggeranong draft plan aims to provide a suite of potential management options to Government to further improve water quality in Lake Tuggeranong. To acheive this, modelling and analyses have been undertaken to examine a broad range of management scenarios and identify cost-effective options to improve water quality in Lake Tuggeranong. To support these analyses, a catchment model was developed in the eWater model platform Source (Argent, et al., 2005) to support the testing of water quality management scenarios, and rank these scenarios based on cost-effectiveness.

This report documents the development of a new, daily timestep water quantity and quality model for the Lake Tuggeranong catchment. The purpose of the model is to simulate long-term mean annual flows and associated pollutant loads entering Lake Tuggeranong, to inform and support catchment improvement studies and associated management strategies.

The model builds upon and extends previous models describing the Lake Tuggeranong catchment by:

- Including long-term, gap-filled climate data to extend the time period over which simulated results are available (1889-2023);
- Incorporating and combining up-to-date spatial data on land use and land surface imperviousness in the catchment;
- Undertaking hydrological model calibration;
- Adopting a model structure delineated to
    - water quality monitoring points to facilitate water quality model parameterisation;
    - existing and potential water quality improvement infrastructure (i.e., WSUD infrastructure) to facilitate estimation of pollutant load reduction from this infrastructure.

1.1 Overview of previous modelling and monitoring studies in the catchment

The model presented in this report builds on several published and unpublished modelling and monitoring studies undertaken in the Lake Tuggeranong catchment to describe flows and water quality in Lake Tuggeranong. These studies are reviewed briefly below, highlighting how the data has been used to inform the current study.

1.1.1 Modelling studies

Lake Tuggeranong catchment MUSIC 6 model, GHD (2015)

To inform the early stages of the Basin Priority Project, GHD developed a model of the Lake Tuggeranong catchment using the software MUSIC (Model for Urban Stormwater Improvement Conceptualisation) to aid in identifying sources of pollutant loads entering Lake Tuggeranong (GHD, 2015). The Lake Tuggeranong catchment was delineated based on contour information and the ACT stormwater network. Existing WSUD infrastructure in the catchment at the time comprised only gross pollutant traps (GPTs) with or without sedimentation basins, as well as Lake Tuggeranong, Isabella Pond, and Upper Stranger Pond. These assets were each represented as GPT, sedimentation basin, or wetland nodes in the MUSIC model. Land use classification in the model was based on ACT Government land zoning data aggregated to six broad categories, and imperviousness was based on values for each land use category from the published literature. Likewise, water quality parameters (event mean concentration, EMC, and dry weather concentration, DWC, of pollutants) were taken from the literature, rather than derived from existing data in the Lake Tuggeranong catchment.

The MUSIC model simulated flows and pollutant loads in the catchment under rainfall and evaporation conditions for the 10-year period from 1968-1977. It predicted an annual flow volume of 20,600 ML in the Lake Tuggeranong catchment, with an annual average of 2.7 tonnes TP, 31.5 tonnes N, and 2230 tonnes TSS generated given the existing WSUD infrastructure in the catchment at the time.

Lake Tuggeranong catchment MUSIC X model, eWater Ltd (2022)

eWater developed another MUSIC model of the Lake Tuggeranong catchment to assess the potential pollutant load reductions associated with WSUD assets that were constructed up to June 2019 as part of the ACT Healthy Waterways project (eWater Ltd, 2022). The Lake Tuggeranong catchment was delineated to 11 subcatchments, 7 of which drained through WSUD assets. The model operated on a 6-minute time step for the period 2010-2015. Published or MUSIC default values for hydrology and water quality parameters were applied to the model, which adopted a land use -based stochastic EMC/DWC approach to water quality modelling.

Land use was derived from 0.5m LIDAR coverage mapping impervious surfaces in the catchment and was divided into 6 classes (roof, road, hardstand, pervious, bushland, and rural). WSUD assets were incorporated in the model by importing and combining the 7 existing MUSIC models representing the detailed design configurations of each asset. Design configurations are expected to differ slightly from works-as-executed configurations.

The MUSIC model predicted an annual flow volume of 14,284 ML, with an annual average of 4.8 tonnes P, 39.8 tonnes N, and 2320 tonnes TSS generated in the Lake Tuggeranong catchment. However, the model was uncalibrated and over the period 2010-2015 overestimated flows by 57.2%, compared to observed data from the gauge immediately downstream of Lake Tuggeranong (Tuggeranong Creek upstream of Sewer Crossing, gauge 410779). The model is therefore also likely to overestimate pollutant loads in the catchment. However, the percentage removal of pollutants associated with each WSUD asset may be used as a starting point in the current modelling study to represent the treatment performance of existing assets.

Upper Murrumbidgee catchment Source models, Alluvium (2017) and eWater Ltd (2019)

Alluvium (Alluvium, 2017) developed an Upper Murrumbidgee catchment model in Source with the best available data and methods as a part of a project to meet requirements for the Murray-Darlin Basin Plan and the ACT Water Resource Plan. Alluvium's model delineated the Upper Murrumbidgee catchment into 440 subcatchments, using a 20 m digital elevation model (DEM), water management and hydrological boundaries, and stream gauging locations. Current ACT and NSW land use classifications, consistent with the Australian Land Use Mapping (ALUM) codes, were combined into 20 functional units for use in the model. The model used climate data from 1980-2016 and a combination of SIMHYD and GR4J rainfall-runoff models, assigned to urban and agricultural subcatchments, respectively. Observed discharge and water quality data from storages (dams and lakes) and sewage treatment plants (STPs) were used to parameterise the model. The model calibration was moderate for most of the gauges, with missing data at both hydrology and water quality monitoring gauges constituting a major limitation of the model. Moreover, due to the large number of subcatchments, model performance was very slow.

Alluvium's Source catchment model did not estimate flows and pollutant loads entering Lake Tuggeranong, instead providing estimates for the outlet of the Lake Tuggeranong catchment, including the effect of the lake itself on these parameters. The model predicted an annual flow volume of 5,868 ML for the outflow from the Lake Tuggeranong catchment, with an annual average load of 0.29 tonnes P, 5.63 tonnes N and 128.9 tonnes TSS.

In 2019, eWater identified a number of potential improvements to Alluvium's Upper Murrumbidgee catchment model and rebuilt the model (eWater Ltd, 2019). Their updated catchment model defined fewer subcatchments outside the ACT, delineating a total of 163 subcatchments, to improve model performance. eWater's model retained the climate data, land use and functional unit classifications used in Alluvium's model, but used the LASCAM rainfall-runoff model across all subcatchments to enable assessment of the hydrological impacts of land use change. The updated catchment model also incorporated Canberra's water supply, with storages configured to operate, albeit without implementation of operating rules.

Water quality parameters (EMC and DWC) in this model used values taken from the literature, rather than being fitted to observed data. While flow parameters were calibrated to observed data from 32 gauges across the Upper Murrumbidgee catchment, the model did not calibrate end-of-catchment values for the Lake Tuggeranong catchment to the downstream gauge Tuggeranong Creek at Sewer Crossing (410779). Therefore this model configuration cannot provide reliable estimates of the total flow and loads generated from the Lake Tuggeranong catchment.

1.1.2 Monitoring studies

University of Canberra Lake Tuggeranong research project, Stage 3 report (2020)

The University of Canberra's Lake Tuggeranong research project has demonstrated the importance of external sources of nutrients to water quality in Lake Tuggeranong. Stage 3 of the Lake Tuggeranong research project analysed the nutrient contribution from different subcatchments, in order to understand the relative influence of different land uses on nutrient inputs to the lake (Ubrihien, et al., 2020). Water sampling during rainfall events was undertaken in the Kambah Creek and Village Creek subcatchments over two years (2018 – 2020), with more than 2000 grab samples collected and analysed. The monthly total

phosphorus (TP), total nitrogen (TN) and total suspended solids (TSS) loads to Lake Tuggeranong were calculated for each subcatchment.

It was found that event discharge and loads of TP, TN, and TSS were much greater than those from baseflow. Event samples from urban areas of the subcatchments had high concentrations of nutrients with an unexpectedly high proportion in dissolved form. This study was constrained by extremely dry weather conditions over the spring and summer of 2019-20, which limited opportunities to collect event samples in a season of key interest. The movement of water and associated nutrients measured during these extreme conditions are unlikely to be representative of wetter years. Additionally, the lack of streamflow gauging at water quality sampling sites made it difficult to accurately estimate the nutrient loads entering the lake. Flow-weighted mean concentrations of nutrients from event samples were essential to calculate the load.

Despite these limitations, Stage 3 of the Lake Tuggeranong research project provides a significant water quality dataset including manual grab-sampling as well as data from 6 autosamplers at fixed locations on inflows to Lake Tuggeranong. The median measured concentrations of TP, TN and TSS from this work have been used in the parameterisation of our water quality model.

ACT Government water quality data

Several water quality monitoring programs supported or contracted by the ACT Government have measured pollutant (nutrient and sediment) concentrations at sampling sites across ACT waterways, including in the Lake Tuggeranong catchment. These have been collated into a single dataset and used in the parameterisation of our water quality model.

Waterwatch

This dataset includes water quality samples collected from eight different sampling sites in the Lake Tuggeranong catchment from 2017 to the present. The water quality parameters recorded include concentrations of TP and nitrates. Waterwatch data are publicly accessible at https://biocollect.ala.org.au/actwaterwatch. Following review and a focus on event flow water quality samples for model configuration, Waterwatch data were not used in the parameterisation of our water quality model.

Land Use Monitoring program (LUM)

Water quality data was collected from a single site in the Lake Tuggeranong catchment over 2018 and 2019. The water quality parameters recorded include concentrations of TP, TN and TSS.

Basin Plan Phase 1 (BPP1)

Under this program grab-samples were collected from 20 sampling sites in the Lake Tuggeranong catchment and analysed for water quality parameters including concentrations of TP, TN, and TSS.

ACT Lakes and Rivers water quality monitoring program

The ACT Lakes and Rivers water quality monitoring program has maintained two grab-sampling locations on Lake Tuggeranong. While these data were not used explicitly in the Source model calibration, they are

relevant to the in-lake modelling described in the supplement to this report, *Predicting phosphorus concentration and trophic state of Lake Tuggeranong* (Kahn & Dey, 2024).

1.2 Key gaps addressed by this study

The brief review above highlights the considerable amount of new water quality data that is now available for the Lake Tuggeranong catchment, including some event-based concentration data. The new data can be used to refine model water quality parameters that were previously based on values derived from the published literature. The modelling studies described above are limited in their utility as catchment models in the current planning context, as they either did not have the tools or resources available to calibrate model hydrology or were calibrated over a spatial resolution too coarse to investigate detailed catchment management strategies. Additionally, these previous studies simulated results over relatively short timeframes (6 – 36 years).

This study therefore aims to address these gaps by:

1. Preparing a high spatial resolution catchment model that uses a long-term historical climate observations dataset to simulate results over the 133-year period 1889-2023.
2. Calibrating the catchment model to ensure that end-of-catchment observed flows match modelled flows over the long term, so that the model accurately represents long-term water yield.
3. Using available event-based and baseflow water quality data to parameterise land use -based water quality models and derive new estimates of mean annual pollutant loads to Lake Tuggeranong.

Section 2 of this report collates and summarises the input data used to build and parameterise the model including terrain models, land use, water quality assets, hydrological and water quality data. Section 3 describes the model construction and parameterisation procedures and associated results and limitations. Section 4 presents the results of long-term flow and load estimates for the catchment under the current conditions including spatial results and estimated loads to Lake Tuggeranong. Section 5 presents the predevelopment and current scenario analysis of the catchment. Section 6 provides the conclusions and recommendations for next steps to improve model performance through additional data collection or by upgrading the model techniques.

2. Model input data

The Source modelling framework allows the simulation of catchment hydrology and pollutant generation in response to rainfall and climatic processes, catchment characteristics, land use and imperviousness, and waterway management. This requires the input of data describing each of these elements, enabling the catchment to be represented as a connected patchwork of areas for which the conversion of rainfall to runoff, the generation of pollutants, and the flow of surface waters between areas, can be calculated. Dividing the catchment into subcatchments for which flow and water quality data are available allows finer-scale calibration of the model to observed data in the catchment.

This section describes the input data sets used for model creation and parameterisation including:

- Subcatchment delineation;
- Land use classification and imperviousness;
- Water quality data;
- Climate data;
- Lake configuration;
- Streamflow and storage level data;
- WSUD asset configuration.

2.1 Subcatchment delineation

The Lake Tuggeranong catchment is approximately 6,600 hectares and is mostly (62%) urbanised. The southeastern part of the catchment is rural and extends across the ACT border into NSW. Catchment development began in the 1980s (Beer, Young, Humphries, & Burgess, 1982) and continued into the early 1990s. The Lake Tuggeranong catchment is the smallest Water Management Area in the ACT, and also encompasses a small component of the Upper Murrumbidgee water management area due to diversion of the upper Stranger Pond catchment to Lake Tuggeranong at Isabella Pond.

Because the subcatchments delineated to WSUD assets for the eWater (2022) study contained some discrepancies with the ACT Government stormwater network map, a new subcatchment map was created using a pit-filled, 1 m DEM based on high-resolution LIDAR data (ACT Government, 2016) and the ACT Government stormwater network map. Subcatchments within the Lake Tuggeranong catchment were delineated to:

- known water quality monitoring locations;
- known streamflow monitoring locations;
- existing WSUD assets;
- ponds and storages.

This resulted in 75 subcatchments, shown in Figure 1. When identifying water quality monitoring sites for catchment delineation, University of Canberra water quality monitoring sites based on the stormwater network were prioritised.

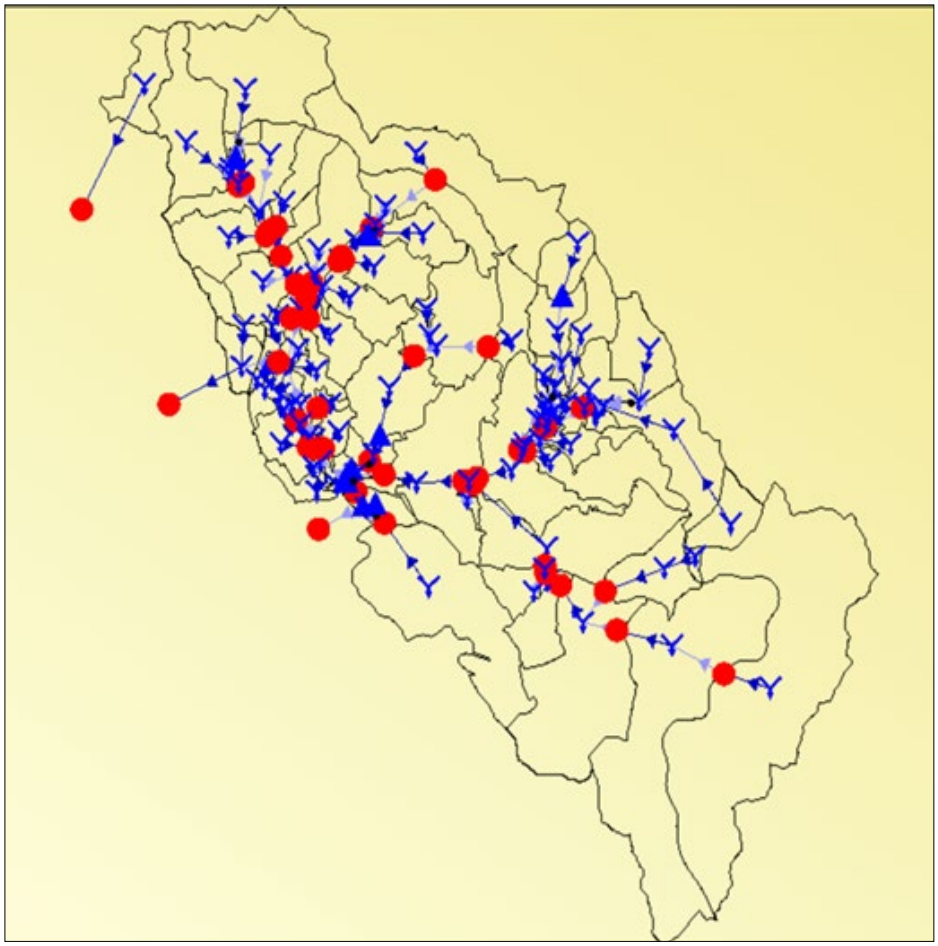

Figure 1. Screenshot of the Source model-generated Lake Tuggeranong subcatchment map, showing nodes defined by flow and water quality monitoring locations (large red points) and WSUD infrastructure (large blue triangles). Blue 'Y' symbols represent flow and pollutant generation within subcatchments and small blue arrows indicate the direction of flow.

2.2 Land use classification and imperviousness

Land use classification for the Lake Tuggeranong catchment model aims to represent a wide range of land uses that could be subject to different structural and non-structural catchment management actions, such as suburban street sweeping, construction of additional WSUD assets, or education around private household fertilizer use. To this end, broad land use classifications adopted for previous modelling studies (eWater Ltd, 2022) were disaggregated to a more granular set of classifications based on ACT Government land zoning. These were combined with data on land surface imperviousness to derive land use for the Lake Tuggeranong catchment model as follows:

1. Aerometrix (2020) LIDAR data at 0.5m pixel resolution was trimmed to the Lake Tuggeranong catchment, mapping 5 land surface imperviousness classes:
    - Impermeable ground level (i.e., roads and hardstand)
    - Impermeable above ground level (i.e., roofs)
    - Permeable ground level (i.e., pervious, unpaved ground)
    - Permeable above ground level (i.e., tree canopy)

- Water

2. The LIDAR data was converted to shapefile and intersected with the 2023 ACT Government land zoning GIS layer trimmed to the Lake Tuggeranong catchment, consisting of 17 land use zones consistent with ALUM codes:
   - Business zone
   - Community Facilities
   - Core zone
   - Leisure and accommodation
   - Local centre
   - Services
   - Services zone
   - Medium density residential
   - Suburban
   - Suburban core
   - Transport
   - Urban open space
   - Restricted access recreation zone
   - Hills ridges and buffer areas
   - Designated
   - River corridor
   - Rural

   The entire NSW portion of the catchment was classed as 'Rural' land use.
3. This cross-classified land use layer was intersected with the ACT Government road edges GIS layer, to identify road area within each land use zone. Areas classified as impermeable ground level that fell outside of the roads boundary were deemed hardstand, and areas classified as permeable above ground level that fell within the roads boundary (i.e. where trees overhung road) were reclassified as road (impermeable ground level). This approach yields a more precise classification of road area than the approach of eWater (eWater Ltd, 2022), where road centrelines buffered by 5m were used to estimate the area of impermeable road surface within the transport classification of the land zoning map, which includes the entire road corridor consisting of largely permeable open space.
4. Finally, visual inspection of aerial imagery was used to identify and manually delineate irrigated sports fields based on their "greenness" relative to nearby open spaces, and assign them a specific land use classification.
5. The land use and imperviousness layer was converted to a 0.5m grid, which was intersected with the Lake Tuggeranong subcatchment map to obtain the area of each land use - imperviousness combination within each subcatchment.
6. The detailed land use types were grouped into six major functional units for incorporation into the Source catchment model: suburban, commercial, open space, rural, bushland and sports field, each containing imperviousness classifications of road, hardstand, roof, permeable ground level, permeable above ground level, and water. The final land use and imperviousness classification schedule, and the area associated with each land use functional unit in the model domain is provided in Appendix C.

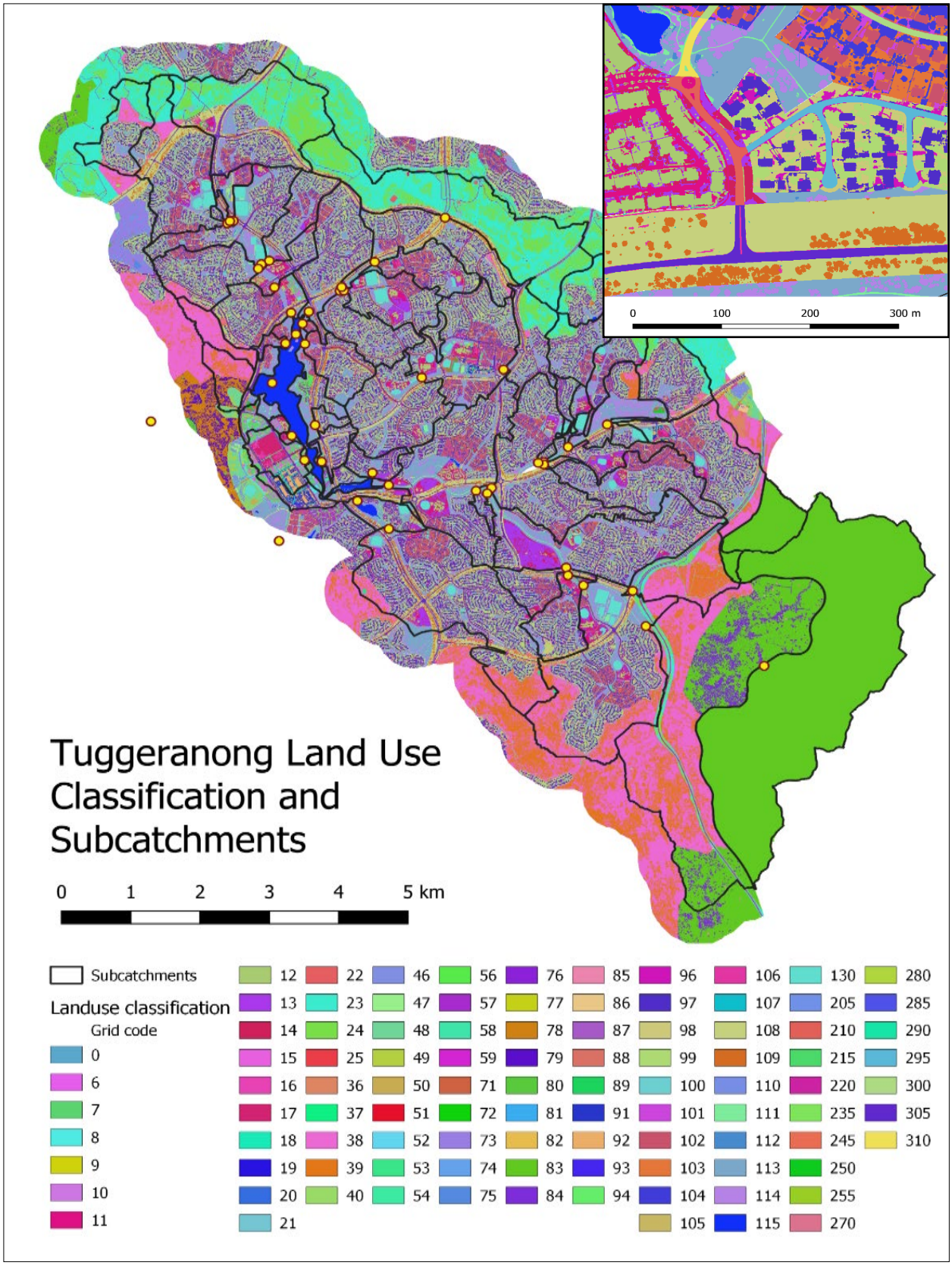

Figure 2. Land use map of the Lake Tuggeranong catchment with colours representing the unique code for each land use - imperviousness combination. Yellow dots indicate water quality or streamflow monitoring locations. **Inset:** close-up detail of a section of the map showing roads, rooftops and open space.

2.3 Water quality data

Water quality data from within the Lake Tuggeranong catchment was collected by a range of programs between 2014 and 2021 (Table 1). Some of the programs entailed event-based monitoring of specific land uses whilst others were focussed on grab sampling from many sites throughout the catchment to try and understand spatial variation of water quality and how it may relate to land use.

Table 1. The number of water quality samples collected across five monitoring programs and analysed for 3 pollutants used in model calibration. TP, total phosphorus; TN, total nitrogen; TSS, total suspended solids.

Monitoring program	Years active	Number of sites	TP	TN	TSS
Basin Plan Phase 1 (event sampling)	2014-2015	19	93	93	93
ACT Government Land Use Monitoring program (event sampling)	2018-2019	1	93	93	93
Lake Tuggeranong Research Project (event sampling)	2017-2018	7	1385	1376	1071
University of Canberra (grab sampling)	2018-2020	29	315	315	316
Upper Murrumbidgee Waterwatch (grab sampling)	2014-2021	8	585		
Total			2471	1877	1573

Table 1 shows there is a large amount of historical water quality data potentially available for use. However, no study in the catchment has converted the measured pollutant concentrations to loads, which requires simultaneously monitoring of flows in order to calculate flow-weighted mean concentrations.

Catchment models typically adopt a land use based EMC/DWC approach to estimate mean annual pollutant load, with model calibration achieved by matching observed loads to modelled loads. As no observed load data is currently available, we adopted the following model parameterisation approach:

1. All pollutant concentration data from the available water quality studies was compiled into a single data frame. For days where multiple samples were collected from a site, the mean of these samples was calculated as an approximation of the mean concentration occurring on that day.
2. Modelled daily flows and modelled pollutant concentrations were compiled into a single data frame and the event flow threshold, defined as the flow threshold that is exceeded in the top 10% of all modelled flow days, was identified.
3. For each day that observed pollutant concentration data was available, we retrieved the modelled flow and associated modelled concentration for the pollutant and monitoring site in question. We split this date-matched data between event and baseflow conditions and calculated the medians of the observed and modelled data for each site.

The median observed pollutant concentration value was compared to the median modelled pollutant concentration value for sites at the six major lake inlet points and a scaling factor estimated to scale the EMC values for that pollutant. The scaling factor was applied across all land uses for that pollutant.

Parameterisation steps 1-3 above were then re-run to test the model fit. This model parameterisation approach preserves the typical difference between land use-based EMC/DWC combinations whilst date-matching median observed lake inflow concentrations to the median modelled concentrations.

Figure 3 provides example plots and data for the monitoring point at the Village Creek inlet to Lake Tuggeranong. Modelled median event-based concentrations of TP exceed observed concentrations, however across all observed data (event and baseflow), median modelled concentrations match observations (n = 275). The time series of modelled concentrations can never attain the variability of observations due to the fixed nature of the EMC/DWC modelling method.

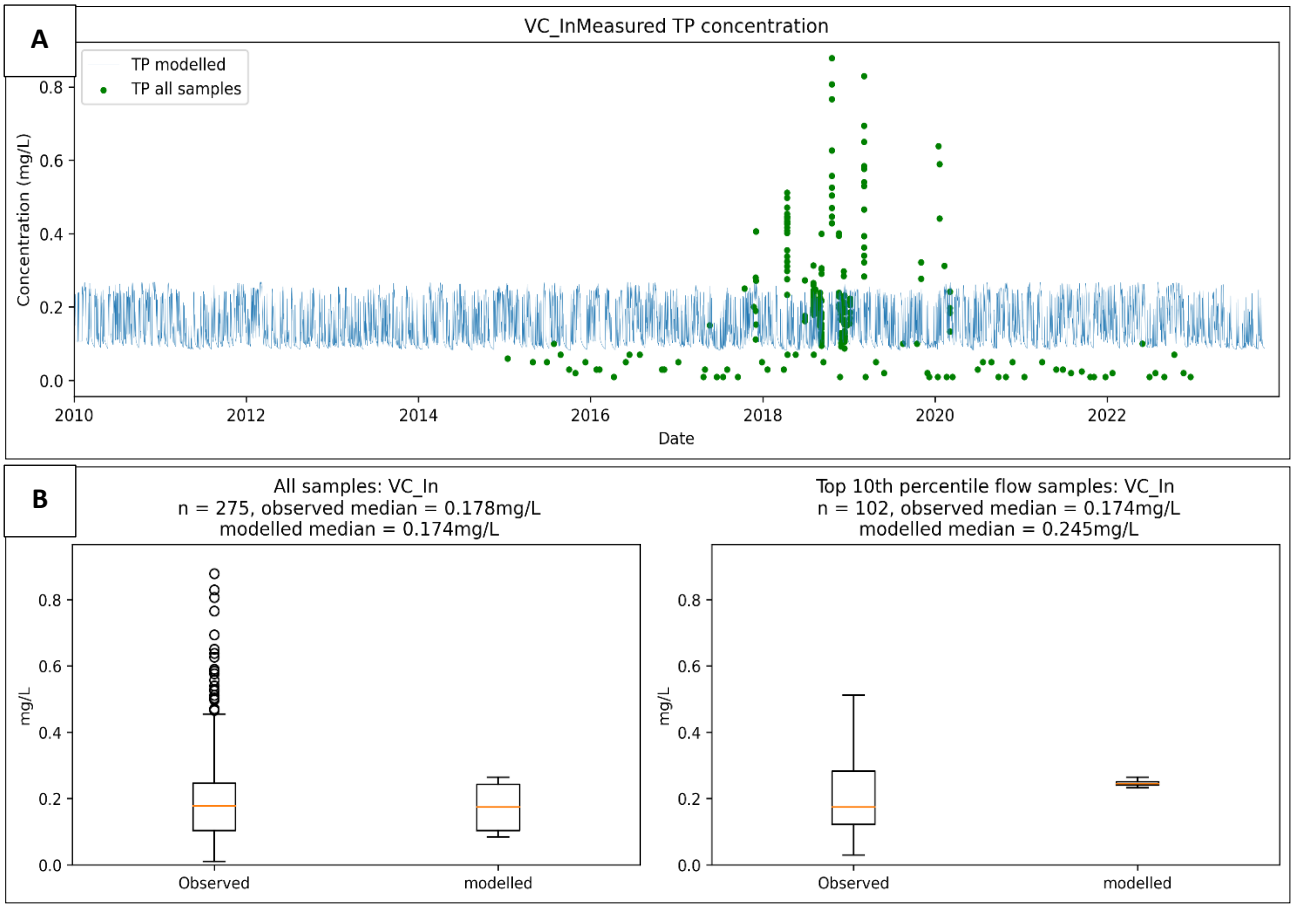

Figure 3. Example of the comparison of observed vs. modelled pollutant concentration data for a single water quality monitoring point. A) Time series of modelled total phosphorus (TP) concentrations (blue line) and date-matched observed median TP concentrations (green points) for the monitoring point at the Village Creek inlet to Lake Tuggeranong. B) Boxplots showing the distributions of modelled and observed median TP concentrations for all samples (left panel) and samples from the top 10th percentile of flow events (right panel) for the monitoring point at the Village Creek inlet to Lake Tuggeranong.

2.4 Climate data

Several climatological stations located within the Lake Tuggeranong catchment could provide data for sub-daily rainfall-runoff modelling. However, to meet the aims of the current model a long-term daily rainfall record without gaps is required. We therefore used patched daily data from the Tuggeranong (Isabella Plains) climatological station (Bureau of Meteorology station number 070339). This station is located within

the Lake Tuggeranong catchment (Figure 4) and has been open since May 1996 - present with 99% completeness of the data record. For this post-1996 period we were able to provide complete observed climate data to the model. To cover the entire period 1889-2023, we used patched data for the pre-1996 period from the SILO (Scientific Information for Land Owners) patch point dataset for this station (https://www.longpaddock.qld.gov.au/silo/).

The following climate variable time series associated with this site were used for catchment modelling:

- Rainfall (mm/d) for rainfall-runoff modelling and water body water balance modelling;
- Morton's wet-environment areal evapotranspiration over land (mm/d) for rainfall-runoff modelling (MWet);
- Morton's shallow lake evaporation (mm/d) for water body water balance modelling (MLake);
- Maximum and minimum temperature for experimental stormwater and lake temperature modelling (Tmax and Tmin) ;
- Evapotranspiration (mm/d) of short crop for irrigation modelling.

2.5 Lake Tuggeranong storage configuration

Lake Tuggeranong is modelled as a completely mixed storage, taking inflows from the whole catchment and releasing flows according to the stage (water level) -discharge relationship of its outflow point at Lake Tuggeranong weir. The lake is also subject to daily rainfall and daily evaporation (MLake), modelled using the SILO daily time-series for the Tuggeranong (Isabella Plains) climatological station (station ID 070339). As Lake Tuggeranong does not have any water supply requirements, no water use is modelled for this storage.

To configure the Lake Tuggeranong storage node, a rating curve was derived from the bathymetry data and imported into the model. This was calculated from the observed water level measured at the Lake Tuggeranong weir (gauge 410784), using the level-volume-area (LVA) relationship for Lake Tuggeranong obtained from bathymetry data collected in 2015 by Steger and Associates Registered Land Surveyors under the Basin Priority Project (data provided in Appendix A).

The lake outlet was configured as an ungated spillway, using the stage-discharge rating table for the Lake Tuggeranong weir (gauge 410784) supplied by ALS Hydrographics via their HYDSTRA database. The stage-discharge data is provided in Appendix B.

2.6 Streamflow and storage level data

2.6.1 Gauge 410779: Tuggeranong Creek upstream of Sewer Crossing

The key streamflow data available for this catchment comes from the gauge at Tuggeranong Creek upstream of Sewer Crossing (gauge 410779; Figure 4) which is located a short distance below the Lake Tuggeranong outflow. Recorded streamflow data is available from 1986 and the gauge remains current. Gauge records show that the maximum recorded flow rate is approximately 200 cumecs, while the maximum rated flow is 108 cumecs or approximately 50% of the maximum recorded flow. Flows greater than 100 cumecs have occurred approximately 6 times since 1990. 216 gaugings (validating measurements) have been undertaken at the site since 1986, with the highest flows being gauged within the first few years of site establishment. Since 2000, the maximum gauged flow has been approximately 6.5 cumecs.

Consequently, higher recorded flows have higher associated uncertainty. However, the gauging record shows a stable relationship with little scatter, with gaugings covering the majority of observed flows at the site, indicating a reliable stage-discharge curve. The site is therefore rated as suitable for model calibration.

2.6.2 Additional short-term streamflow monitoring sites

Additional streamflow records collected by the ACT government for various short-term studies are included in the model:

- 410650 Upper Stranger Pond (1990-1990) Inflow to the pond at GPT
- 410651 Upper Stranger Pond (2017-2018) Outflow from Upper Stranger Pond
- ES1701 Tuggeranong Channel @ Clive Steele (2017-2018)
- ES1702 Monash Channel @ Charleston (2017-2018)

As validation gaugings are generally unavailable for these short-term monitoring sites, they are used for indicative comparison purposes rather than model calibration.

2.7 Water Sensitive Urban Design assets

Geographic location and pollutant reduction performance data were available for eight existing WSUD assets in the Lake Tuggeranong catchment, built under Stage 1 of the ACT Healthy Waterways program. eWater (eWater Ltd, 2022) modelled the flow and water quality performance of these assets using MUSIC (Table 2). Each of these eight WSUD assets is represented in the current Lake Tuggeranong catchment model as a splitter node that diverts flow to the asset, and a storage node that applies a water quality decay function, representing the percentage reduction in pollutant loads (TP, TN, and TSS) achieved by the asset. Splitter nodes are configured with a maximum flow rate that is diverted into the asset, and any flow above this bypasses the asset, based on the MUSIC modelled high-flow bypass threshold. Storage nodes are configured based on asset design information from their respective preliminary sketch plan (PSP) or design acceptance reports, and their pollutant load decay rate was initially set to match the MUSIC modelled percent reduction rate with a default half-life of 1 day. Field observations indicated that some assets are not currently performing to their full capacity, and the pollutant load decay rates were adjusted to reflect the reduced performance of these assets (Table 2).

Table 2. Adjusted efficiencies (% reduction) of water quality parameters for eight Healthy Waterways Stage 1 WSUD assets, matching the current observed working condition of assets. These values were implemented in the Lake Tuggeranong catchment model. Values in parentheses are the predicted efficiencies from MUSIC models in the technical reports for each asset *(eWater Ltd, 2022)*.

Asset	% Flow bypassed	% TP reduction	% TN reduction	% TSS reduction
TG008	41	27 (54)	25 (51)	41 (82)
TG010	28	54 (78)	51 (74)	66 (95)
TG011N	75	39 (66)	31 (53)	45 (75)
TG011S	75	39 (66)	31 (53)	45 (75)
TG012	29	20 (20)	9 (9)	24 (24)
TG017	52	60 (60)	47 (47)	65 (65)
TG029	49	10 (51)	9 (47)	14 (74)
TG030	66	28 (28)	15 (15)	32 (32)

3. Model build and parameterisation

3.1 Hydrology

3.1.1 Lake Tuggeranong catchment model build

A single catchment model representing the Lake Tuggeranong catchment was developed in Source version 5.3 (https://ewater.org.au/ewater-solutions/tools/source/). The model operated on a daily timestep using long-term, gap-filled climate observations from 01/01/1889 to 30/10/2023. Using a 1 m pit-filled DEM and the ACT Government stormwater network, the catchment was delineated into subcatchments based on flow gauging and water quality monitoring sites as well as WSUD asset locations. A node link network of the catchment model was established. Land use classifications and land surface imperviousness data were combined to define functional units implemented in the model.

The gauge downstream of Lake Tuggeranong (Tuggeranong Creek upstream of Sewer Crossing, gauge 410779) was identified as the node for flow calibration. For hydrologic parameterisation for this gauge, daily timestep streamflow data from 06/02/1986 to 30/10/2023 was input to the catchment model. The internal calibration tool using the objective functions square root daily, exceedance, and bias, was implemented to achieve a suitable fit between modelled and measured data. The daily Nash-Sutcliffe efficiency (NSE) coefficient (Nash & Sutcliffe, 1970) was used as the model performance criterion.

3.1.2 Model calibration

SIMHYD and Sacramento rainfall-runoff models were tested for their suitability for model calibration. The initial flow calibration was conducted for the Lake Tuggeranong catchment before delineation into subcatchments, for the period 01/01/1996 to 30/10/2023, with a warm-up period of 10 years (1986-1995). The permanent impervious fraction of the catchment (pctim) for roads, roofs and hardstand was set to 90% impervious in the Sacramento model as these land uses generate more runoff than permeable surfaces. The objective functions used in the calibration were square root daily, exceedance, and bias. Shuffled Complex Evolution (SCE) followed by Rosenbrock were chosen for optimisation, with 5 iterations and a population number of 500. The Sacramento rainfall-runoff model performed better than the SIMHYD model, providing a better fit with the recorded flow data (Table 3).

Table 3. Model performance statistics for the Sacramento and SIMHYD rainfall-runoff models.

Rainfall-runoff model	Daily Nash-Sutcliffe coefficient	% Volume bias
Sacramento	0.803	-0.85
SIMHYD	0.744	0.001

The initial calibration results confirmed the selection of the Sacramento rainfall-runoff model for the Lake Tuggeranong catchment. The calibrated hydrologic parameters for this model are provided in Table 4.

Table 4. Calibrated hydrologic parameters for the Lake Tuggeranong catchment model using a Sacramento rainfall-runoff model.

Parameter	Suburban	Open space	Commercial	Rural	Bushland	Sports field
Soil moisture store (Lztwm) (mm)	75	75	75	75	75	75
Soil moisture store (Lzfsm) (mm)	15	15	15	15	15	15
Soil moisture store (Lzfpm) (mm)	267.5	267.5	267.5	267.5	267.5	267.5
Rate of lateral outflows (Lzsk)	0.03	0.03	0.03	0.03	0.03	0.03
Rate of lateral outflows (Lzpk)	0.003	0.003	0.003	0.003	0.003	0.003
Rserv	0.346	0.346	0.346	0.346	0.346	0.346
Losses (Side)	0	0	0	0	0	0
Time delay in runoff (UH1)	0.88	0.88	0.88	0.88	0.88	0.88
Time delay in runoff (UH2)	0	0	0	0	0	0
Time delay in runoff (UH3)	0	0	0	0	0	0
Time delay in runoff (UH4)	0.0109	0.0109	0.0109	0.0109	0.0109	0.0109
Time delay in runoff (UH5)	0.03	0.03	0.03	0.03	0.03	0.03
Soil moisture store (Uztwm) (mm)	75.44	75.44	75.44	75.44	75.44	75.44
Soil moisture store (Uzfwm) (mm)	75	75	75	75	75	75
Rate of lateral outflows (Uzk)	0.5	0.5	0.5	0.5	0.5	0.5
Water percolation (Zperc)	153.46	153.46	153.46	153.46	153.46	153.46
Water percolation (Rexp)	3.02	3.02	3.02	3.02	3.02	3.02

Parameter	Suburban	Open space	Commercial	Rural	Bushland	Sports field
Impervious runoff (Pctim)	0.5	0.5	0.5	0.5	0.5	0.5
Losses (Sarva)	0	0	0	0	0	0
Losses (Ssout) (mm)	0	0	0	0	0	0
Impervious runoff (Adimp)	0.30	0.30	0.30	0.30	0.30	0.30
Water percolation (Pfree)	0.19	0.19	0.19	0.19	0.19	0.19

Table 4 continued. See caption previous page.

3.1.3 Model verification

To verify the modelled flow generation of the Lake Tuggeranong catchment, a comparison was made with the Jerrabomberra catchment, which has similar geographic features and location.

A model of the Jerrabomberra catchment was set up in Source using the climate variables daily rainfall and Morton's wet-environment areal evapotranspiration over land (MWet). The rainfall data was obtained from SILO, using station ID 70066 for the NSW portion of the catchment, and station 70249 for the ACT portion. The MWet data was obtained from SILO station ID 70072. The gauged flow data used for calibrating this catchment came from Jerrabomberra at Hindmarsh (gauge 410790), obtained from ALS Pty Ltd. The model was calibrated using a Sacramento rainfall-runoff model, and the objective functions square root daily, exceedance, and bias. SCE followed by Rosenbrock were chosen for optimisation, with 5 iterations and a population number of 500. The calibration was a moderate fit with a daily Nash-Sutcliffe coefficient of 0.59 and volume bias of 0%.

The runoff coefficients of both the Lake Tuggeranong and Jerrabomberra catchments were calculated to compare their performance under predevelopment conditions, represented by 100% bushland land use. The runoff coefficient of the Lake Tuggeranong catchment was approximately 7%, and that of the Jerrabomberra catchment was approximately 8.5%. The two catchments performed similarly under pre-development conditions, verifying the flow generation of the Lake Tuggeranong catchment model.

3.1.4 Model uncertainty estimation

At this stage, model uncertainty estimation has not been undertaken.

3.1.5 Flow routing calibration

Due to the small catchment size and largely urban land use, flow routing was not undertaken in any reach in the Lake Tuggeranong catchment model.

3.1.6 Lake water balance

The lake water balance accounted for all inflows, outflows, rainfall, and evaporation from the lake.

3.2 Water quality

Source catchment models are best suited to estimating long-term mean annual catchment pollutant loads rather than daily concentrations. Ideally, empirical measurements of EMC and DWC from different land uses would be used to parameterise the model. However, as described in section 2.3, water quality data from the Lake Tuggeranong catchment has not been collected concurrently with quantitative flow data, precluding the calculation of EMC. As a result of these data limitations, and noting that long-term inflows and pollutant load into the lake are a key predictive output of the model, a simple approach was adopted to adjust land use -based model water quality parameters using available monitoring data:

1. For each water quality monitoring site, daily median event flow concentrations for each pollutant were calculated for all available dates, as described in section 2.3.
2. A baseline simulation run of the model was performed using EMC and DWC values adapted from the literature (Fletcher, Duncan, Poelsma, & Lloyd, 2004), (Witt, Mainwright, & Weber, 2015), (Melbourne Water, 2024), (Blacktown City Council, 2020), and the modelled daily flows and predicted pollutant concentrations for all monitoring sites were extracted.
3. Baseline modelled pollutant concentrations were date-matched with observed median flows and concentrations to allow for later flow stratification (if appropriate) and to account for sample population representativeness (dry periods or wet periods).
4. Median observed and modelled pollutant concentrations for six major lake inflow sites were then calculated, and used to estimate scaling factors to adjust the literature-derived EMC values for majority land uses (roads, roofs, hardstand, and pervious areas of suburban, commercial, and open space land use categories). Where data allowed, inflow-specific scaling factors were applied.
5. The model was re-run using the scaled EMC values (Appendix D), and modelled median concentrations were once again compared against observed median concentrations.
6. When median modelled and observed values were in agreement, the model parameters were checked against literature values to ensure that the model estimate remained in the anticipated range.

4. Results

4.1 Flow calibration

A hydrograph time series for flows in the Lake Tuggeranong catchment over the model calibration period, 1996-2023, is presented in Figure 4. The hydrograph demonstrates good agreement between the timing and magnitude of modelled and observed flows, which are highly correlated with a daily Nash-Sutcliffe coefficient of 0.88 indicating a very good fit (Moriasi, et al., 2007). There is acceptable peak flow matching with an overall low bias, suggesting the model is reliable in simulating high flow events (Table 5). This strong performance across flow magnitudes confirms the robustness of the model calibration and its suitability for simulating the hydrology of the Lake Tuggeranong catchment.

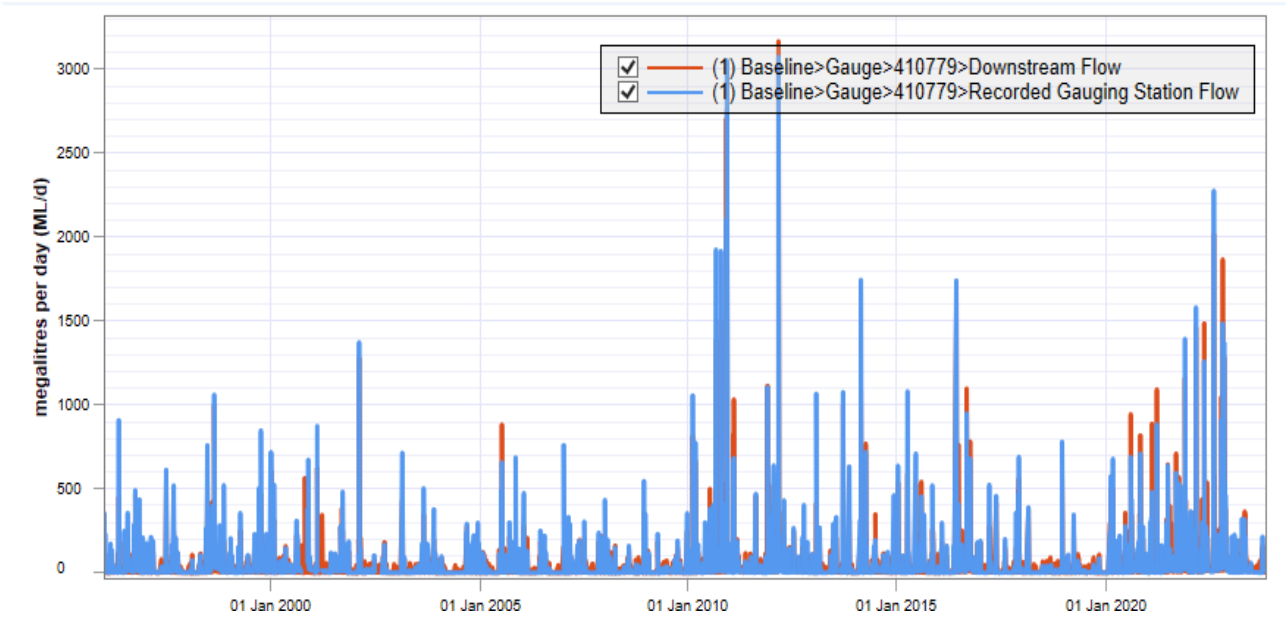

Figure 4. Modelled (red) and observed (blue) flows (daily discharge, ML/d) for Tuggeranong Creek upstream of Sewer Crossing (gauge 410779).

Table 5. Flow calibration model performance statistics for Tuggeranong Creek upstream of Sewer Crossing (gauge 410779).

Performance criterion	
Daily Nash-Sutcliffe Efficiency coefficient	0.88
Monthly Nash-Sutcliffe Efficiency coefficient	0.92
% Volume bias	-0.25

Figure 5 depicts the cumulative flow curve over the calibration period, demonstrating good agreement between modelled and observed flow over the entire period. This agreement indicates that the model accurately captures the total volume of water passing through the catchment, validating its performance in representing the overall hydrological processes.

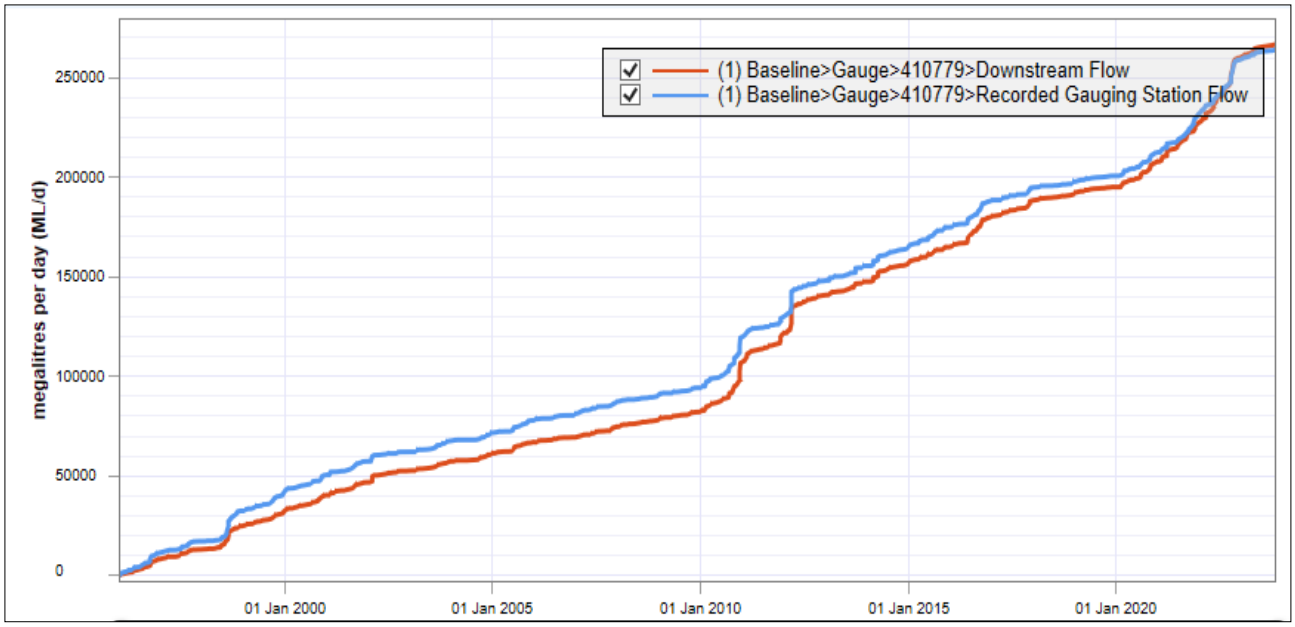

Figure 5. Modelled (red) and observed (blue) cumulative flow for Tuggeranong Creek upstream of Sewer Crossing (gauge 410779), 1996-2023.

Figure 6 illustrates the flow duration curve for flows in the calibration period, showing generally good agreement between modelled and observed flow across most flow conditions. However, discrepancies are noted particularly at low flows. This suggests that while the model performs well overall, there may be areas where the representation of low-flow conditions could be further refined or calibrated.

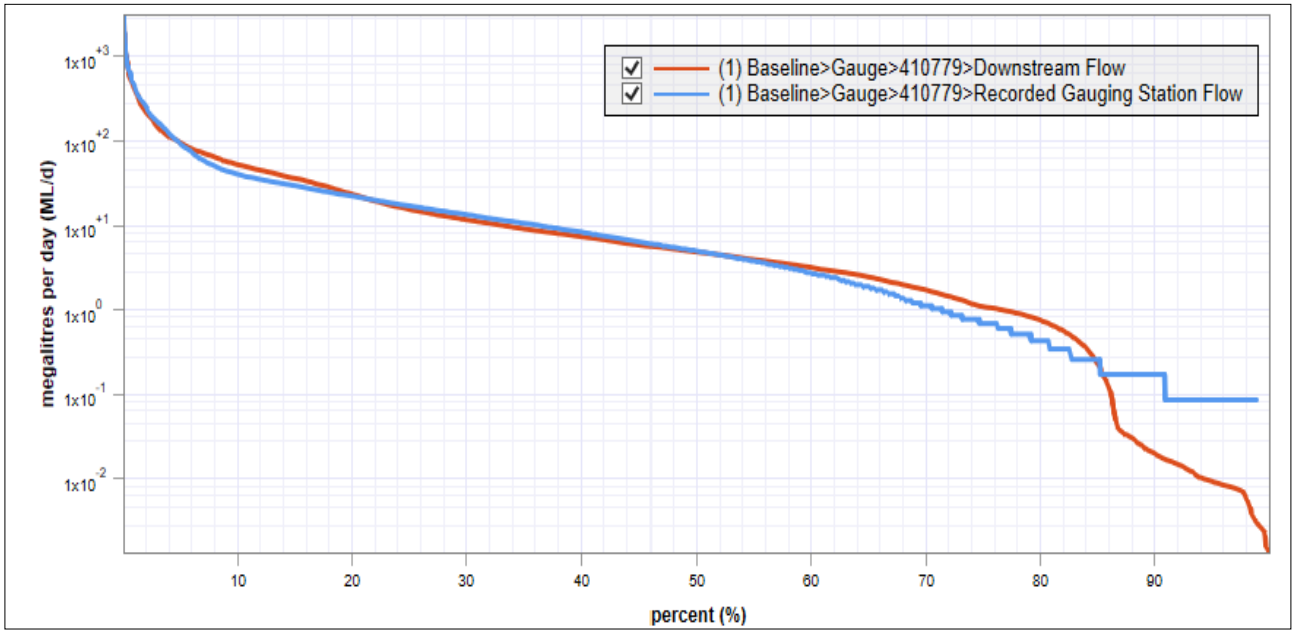

Figure 6. Modelled (red) and observed (blue) flow exceedance curve for Tuggeranong Creek upstream of Sewer Crossing (gauge 410779), 1996-2023.

Figure 7 presents the residual mass curves for observed and modelled flows over the calibration period. The difference between the curves indicates the cumulative difference between observed and modelled flows over time. Ideally, this difference should hover around zero, indicating minimal bias or systematic error in the model.

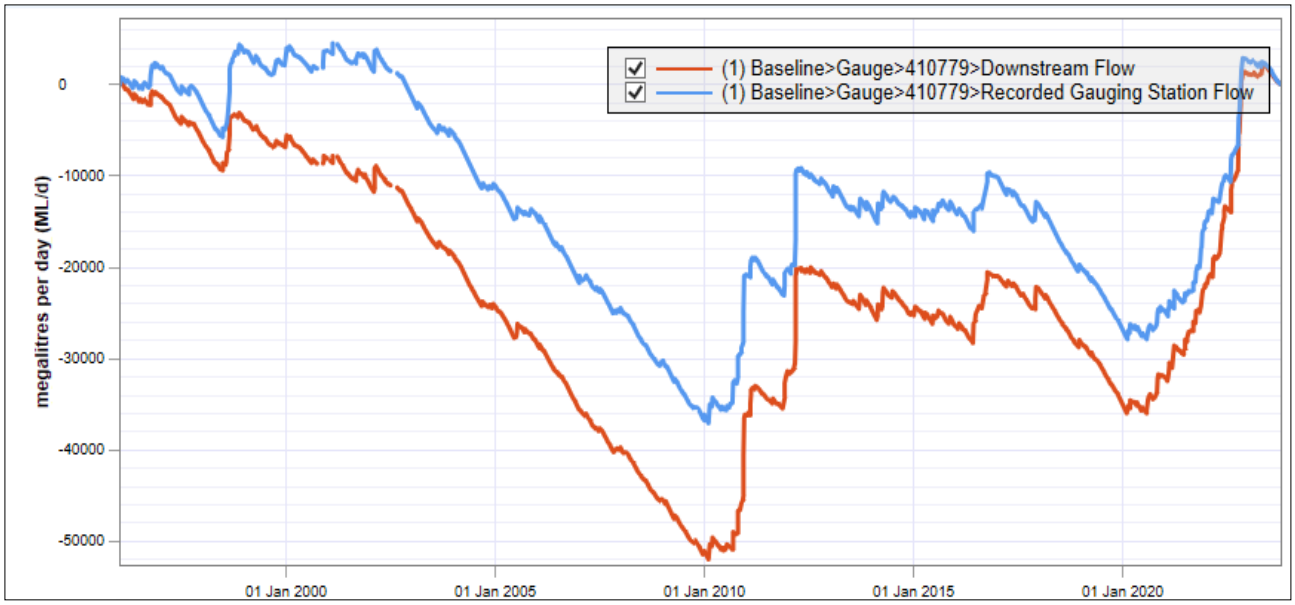

Figure 7. Modelled (red) and observed (blue) residual mass for Tuggeranong Creek upstream of Sewer Crossing (gauge 410779), 1996-2023.

The above plots collectively provide a comprehensive evaluation of the model's performance in simulating hydrological processes in the Lake Tuggeranong catchment, capturing overall flow patterns.

4.2 Water quality calibration

Figure 8 illustrates the comparisons between the median observed and modelled concentrations of TP, TN, and TSS for 34 sites across the Lake Tuggeranong catchment where water quality monitoring was undertaken. These comparisons provide a visual representation of the model's performance in simulating water quality across the catchment. At well-sampled sites, there is generally good agreement between the observed and modelled concentrations. Discrepancies at other sites are primarily due to insufficient sample numbers (Figure 9). Higher median TP concentrations are noted for sites in the Village Creek, Kambah Creek, and Wanniassa subcatchments (site codes beginning with VC, KC, WS respectively) compared to other areas within the Lake Tuggeranong catchment.

As there were multiple sampling locations across the catchment the mean of site medians can provide a robust central tendency measure. The mean of the median modelled concentration for TP is 0.17 mg/L, for TN is 1.33 mg/L, and for TSS is 49.7 mg/L.

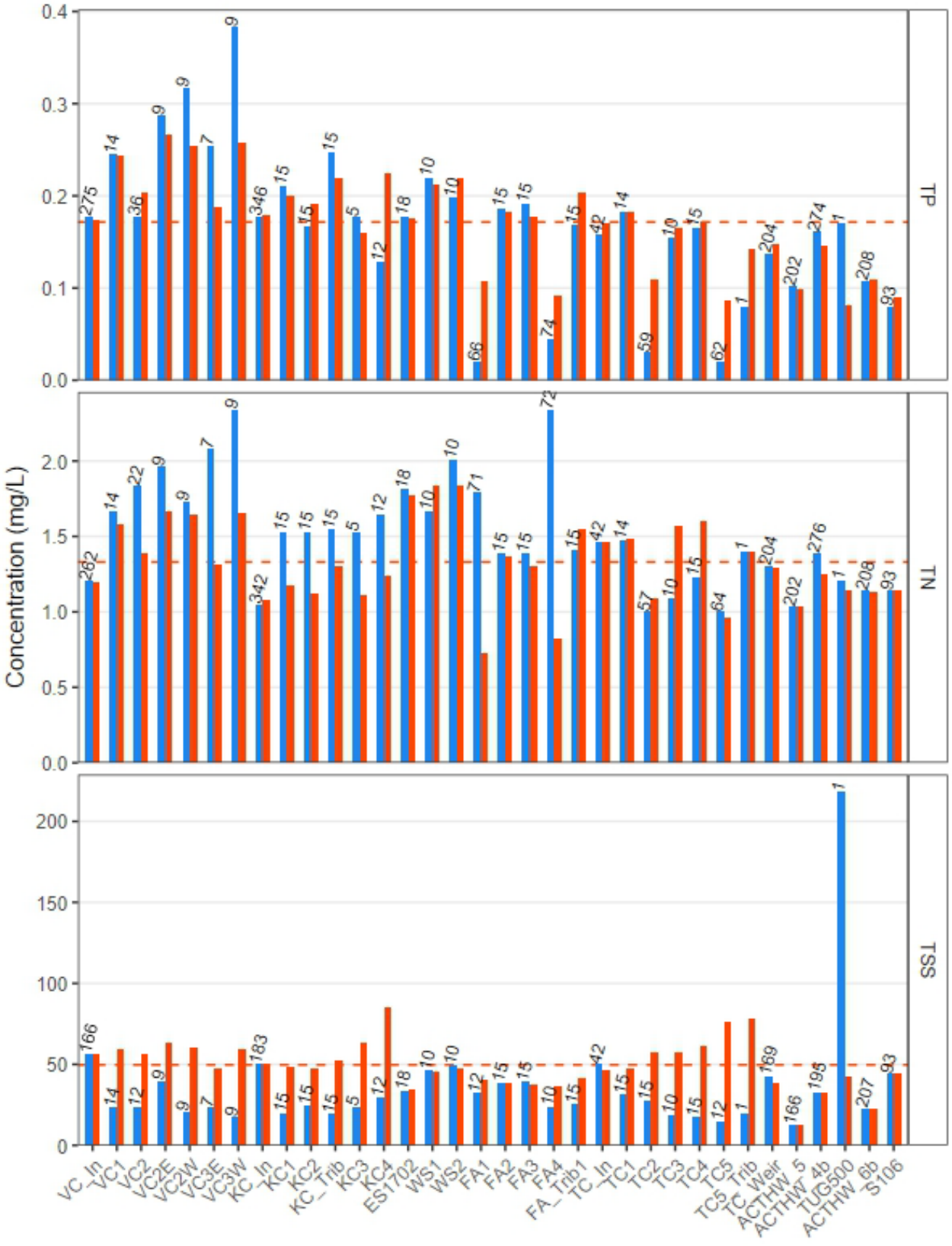

Figure 8. Observed (blue) and modelled (red) median concentrations of total phosphorus (TP; top panel), total nitrogen (TN; middle panel), and total suspended solids (TSS; bottom panel) for each water quality monitoring site in the Lake Tuggeranong catchment. Blue bars are labelled with the number of samples per site analysed for each parameter. The red dashed lines indicate the means of the median modelled concentrations of each pollutant (see text).

Figure 9 illustrates the deviations of modelled from observed site median concentrations for the three water quality parameters, as a function of the number of samples at the monitoring site. A value of zero indicates no bias in the model estimates for that site (i.e. no consistent over- or under-estimation of concentrations, compared to observed values). For all three parameters, deviations decline sharply with increasing sample size. The median deviation for TP is close to zero with a narrow interquartile range, indicating low overall bias. TN deviations are more spread out, with a slight overall positive bias indicated by the median just above zero. TSS deviations have a narrow interquartile range, with a median deviation below zero indicating an overall negative bias, and a notable positive outlier. As for TP and TN, the vast majority of substantial deviations for TSS occur for sites with very low sample sizes.

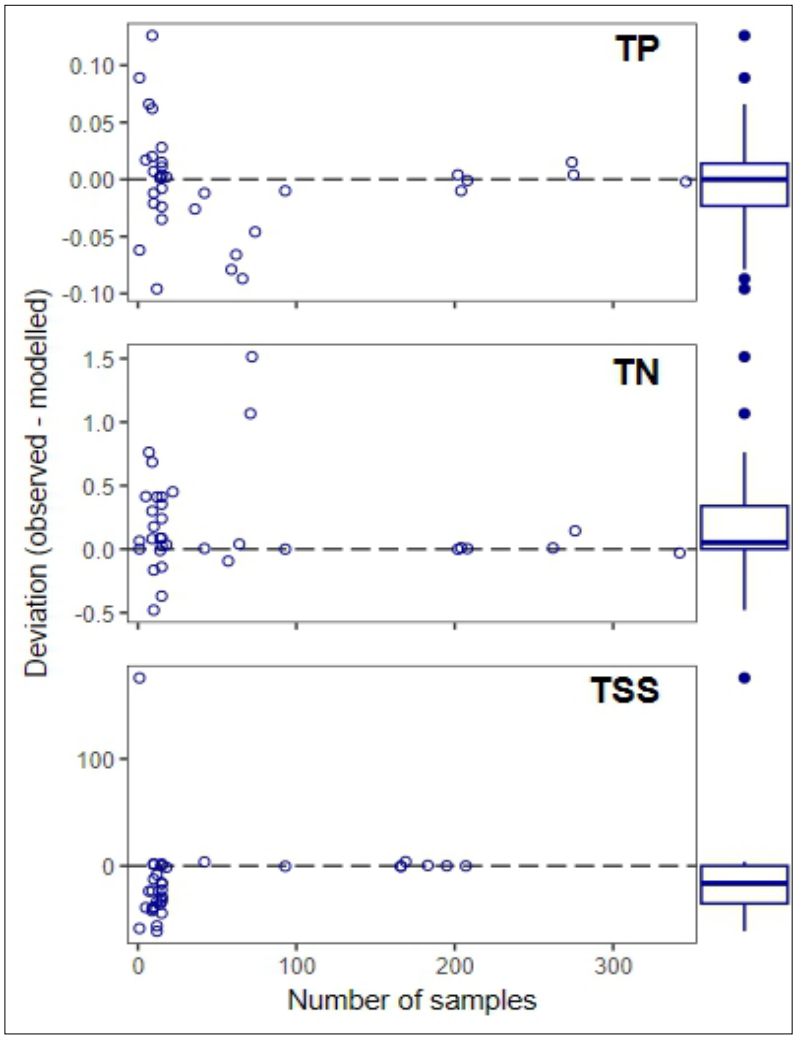

Figure 9. Scatter plots showing the deviation of modelled from observed median concentrations of total phosphorus (TP), total nitrogen (TN), and total suspended solids (TSS) as a function of sample size at 34 water quality monitoring sites in the Lake Tuggeranong catchment. The dashed grey line at zero indicates no bias in the model estimates for a given site. Box-and-whisker plots illustrate the spread of deviations.

4.3 Catchment modelling results

The calibrated catchment model was simulated over the climate period January 1889 – October 2023, and summaries of the total flow and pollutant loads were calculated for each complete year (1889-2022). Under current catchment land use and management conditions, the modelled mean annual inflow to Lake

Tuggeranong was 8.8 GL/year. The modelled mean annual loads of pollutants entering Lake Tuggeranong were 1,442 kg/year total phosphorus, 11,894 kg/year total nitrogen, and 397,064 kg/year total suspended solids.

Figure 10 presents a series of heat maps illustrating the modelled mean annual loads of TP, TN and TSS generated in different subcatchments of the Lake Tuggeranong catchment, with darker shading indicating a higher load. The pollutant load generated depends on the land uses within each subcatchment. The highest mean subcatchment TSS loads fall between 160 – 180 kg/ha/yr. The highest TN loads are between 3.5 – 4 kg/ha/yr, and the highest TP loads are between 0.6 – 0.7 kg/ha/yr. For all three pollutants, higher load generation occurs in more urbanised catchments. This broad visual representation can help in identifying the areas requiring critical attention to improve water quality in the catchment.

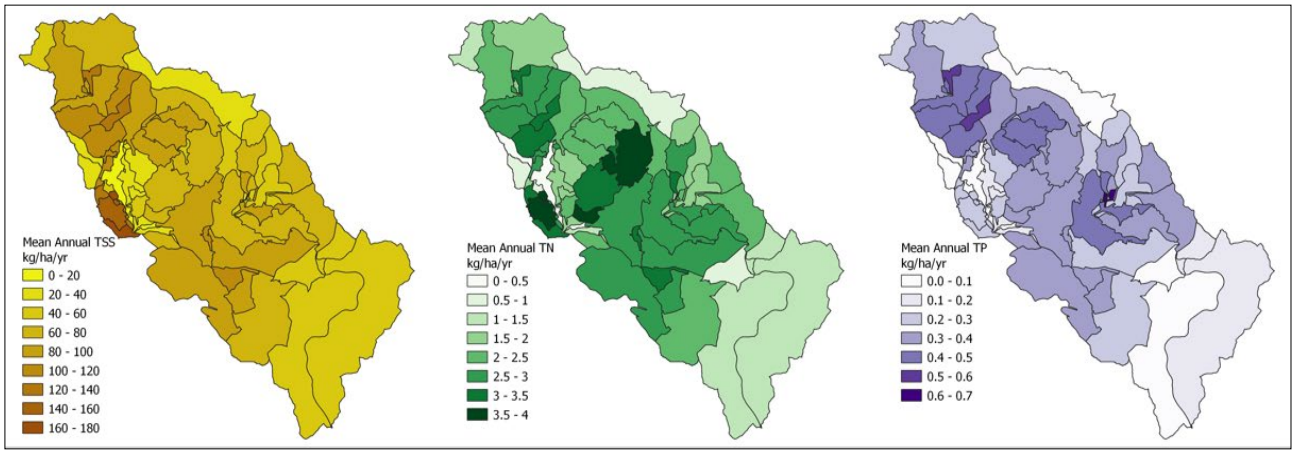

Figure 10. Heat maps of the Lake Tuggeranong catchment for mean annual loads of total suspended solids (TSS, left), total nitrogen (TN, centre) and total phosphorus (TP, right) generated in each subcatchment. Darker shading indicates higher mean annual concentrations.

Figures 11-13 show time-series of modelled daily inflows, pollutant concentrations, and pollutant loads entering Lake Tuggeranong in 2016, a year with a good spread of wet and dry periods. High flow events, likely driven by rainfall, lead to increased runoff, which carries higher concentrations and loads of phosphorus, nitrogen, and suspended solids into the lake. In 2016, the model estimates that the largest flow event saw over 1600 ML enter Lake Tuggeranong in a single day, representing 10% of the total annual inflow that year. This event carried loads of approximately 300 kg TP, 2,500 kg N, and 75,000 kg TSS to the lake, representing 12-13% of the total annual load of each pollutant entering Lake Tuggeranong in 2016. This pattern highlights the impact of storm events on water quality and the importance of managing runoff from the catchment to the lake.

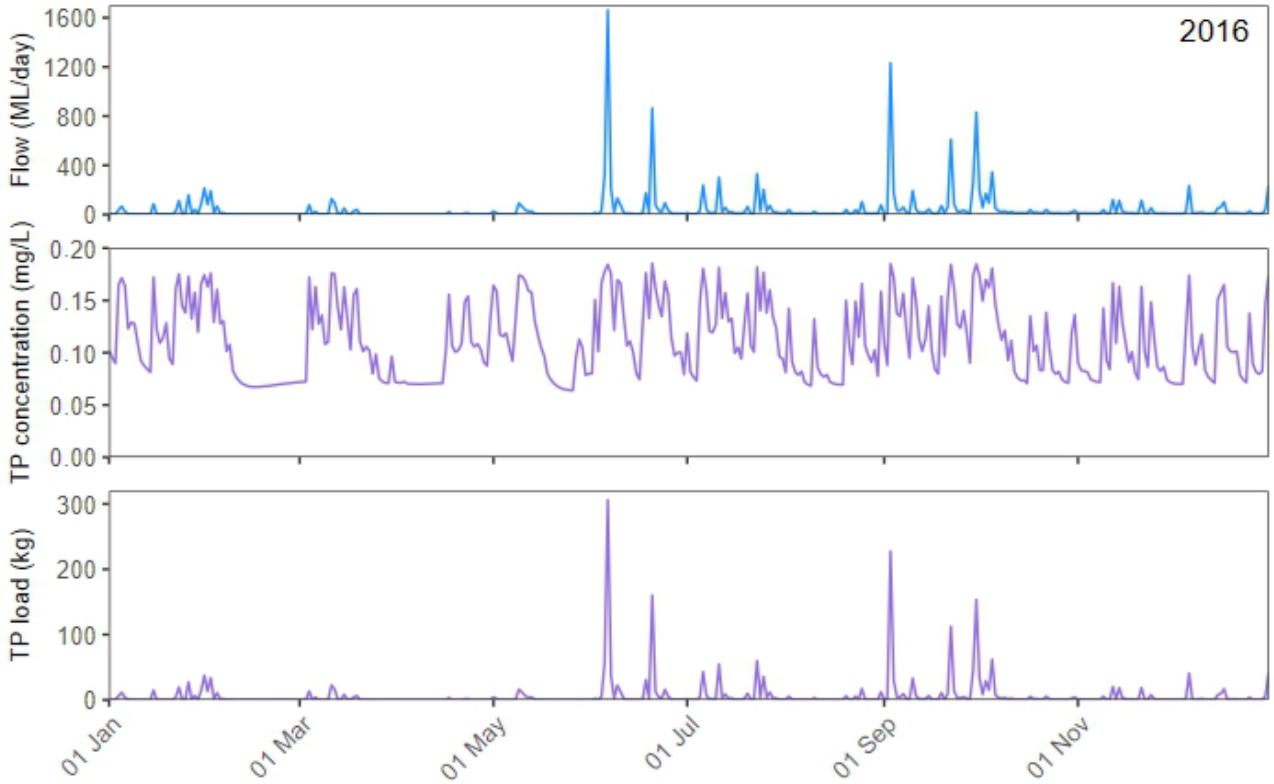

Figure 11. Modelled daily flow and total phosphorus (TP) concentration and load entering Lake Tuggeranong, 2016.

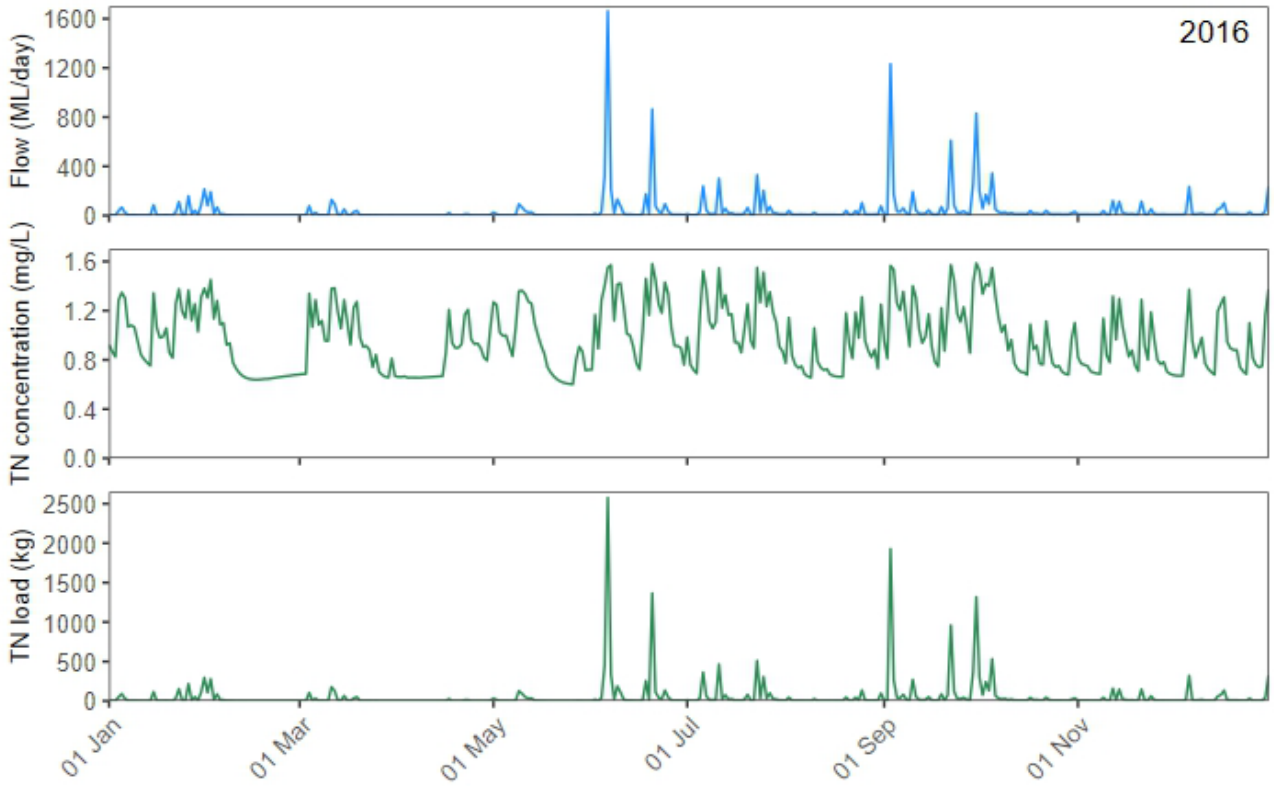

Figure 12. Modelled daily flow and total nitrogen (TN) concentration and load entering Lake Tuggeranong, 2016.

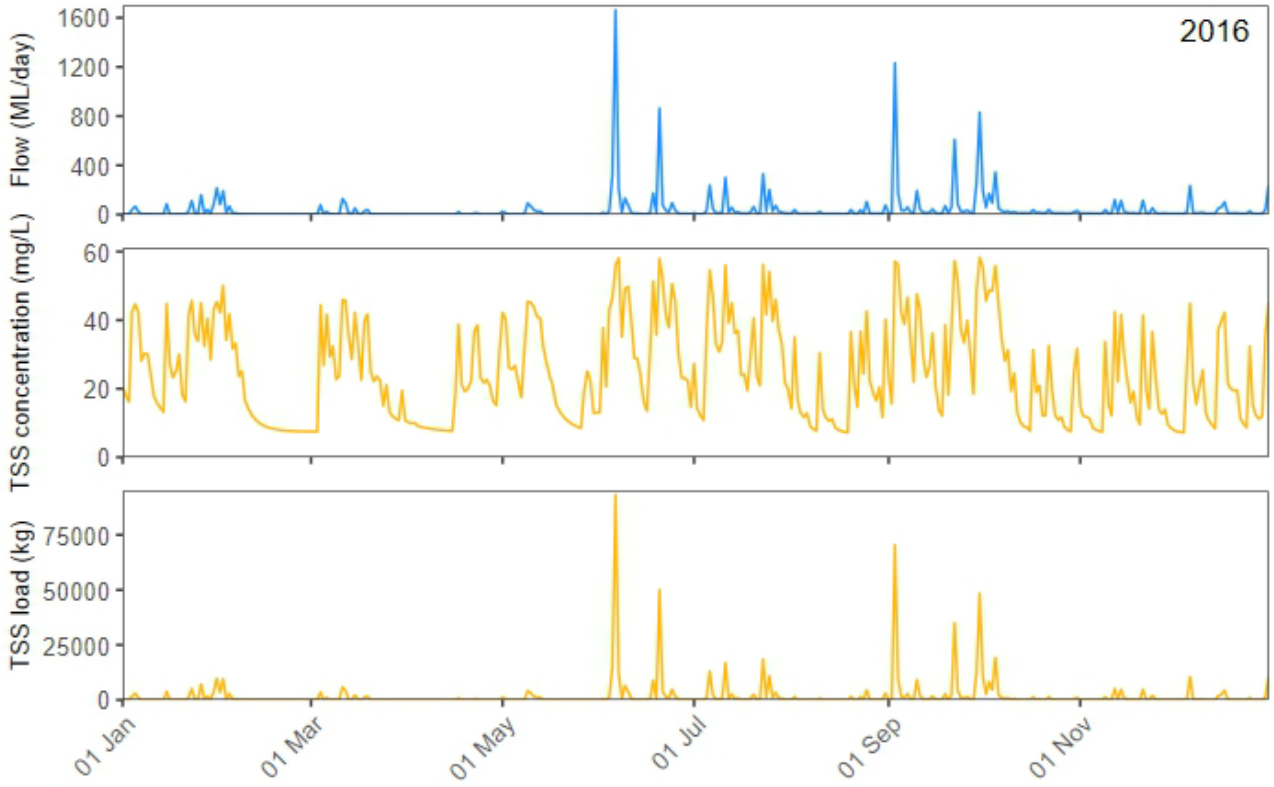

Figure 13. Modelled daily flow and total suspended solids (TSS) concentration and load entering Lake Tuggeranong, 2016.

Figure 14 shows the relationships between daily inflows, concentrations, and loads in 2016 for TP; TN and TSS showed the same patterns in the shape of these relationships.

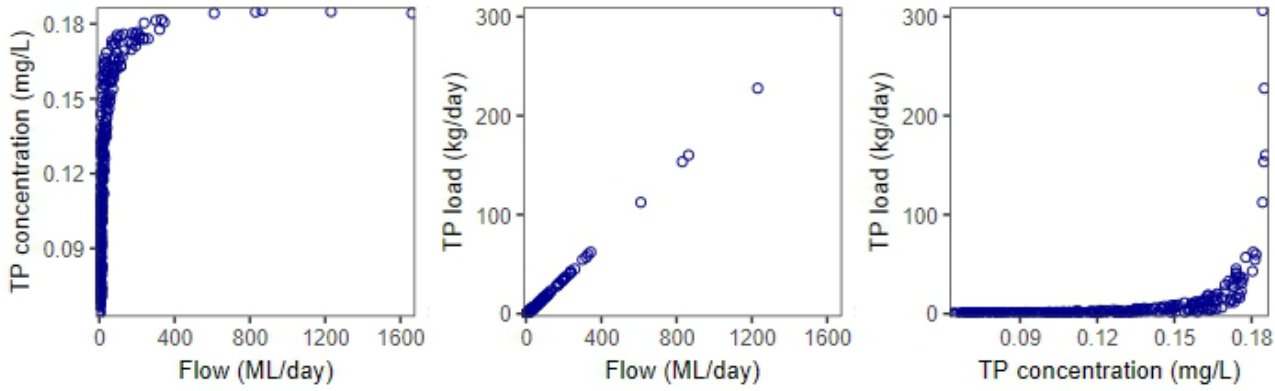

Figure 14. Relationships between the daily inflows and concentrations and loads of total phosphorus (TP) entering Lake Tuggeranong in 2016. The same relationships were seen for total nitrogen and total suspended solids.

4.4 Scenario analysis

4.4.1 Current and predevelopment scenarios

To understand the impact of changes to land use and urban development on the hydrology and water quality of the Lake Tuggeranong catchment, two contrasting land use scenarios were simulated using the

calibrated catchment model. The first, 'current' scenario was the model of current land use and infrastructure conditions described in Section 4.3. Under the current scenario the modelled mean annual inflow to Lake Tuggeranong was approximately 8.8 GL, and the modelled mean annual pollutant loads were 1,442 kg TP, 11,894 kg TN, and 397,064 kg TSS. Figure 15 presents the long-term modelled annual inflow and pollutant loads entering Lake Tuggeranong under the current scenario, for the period 1889-2022.

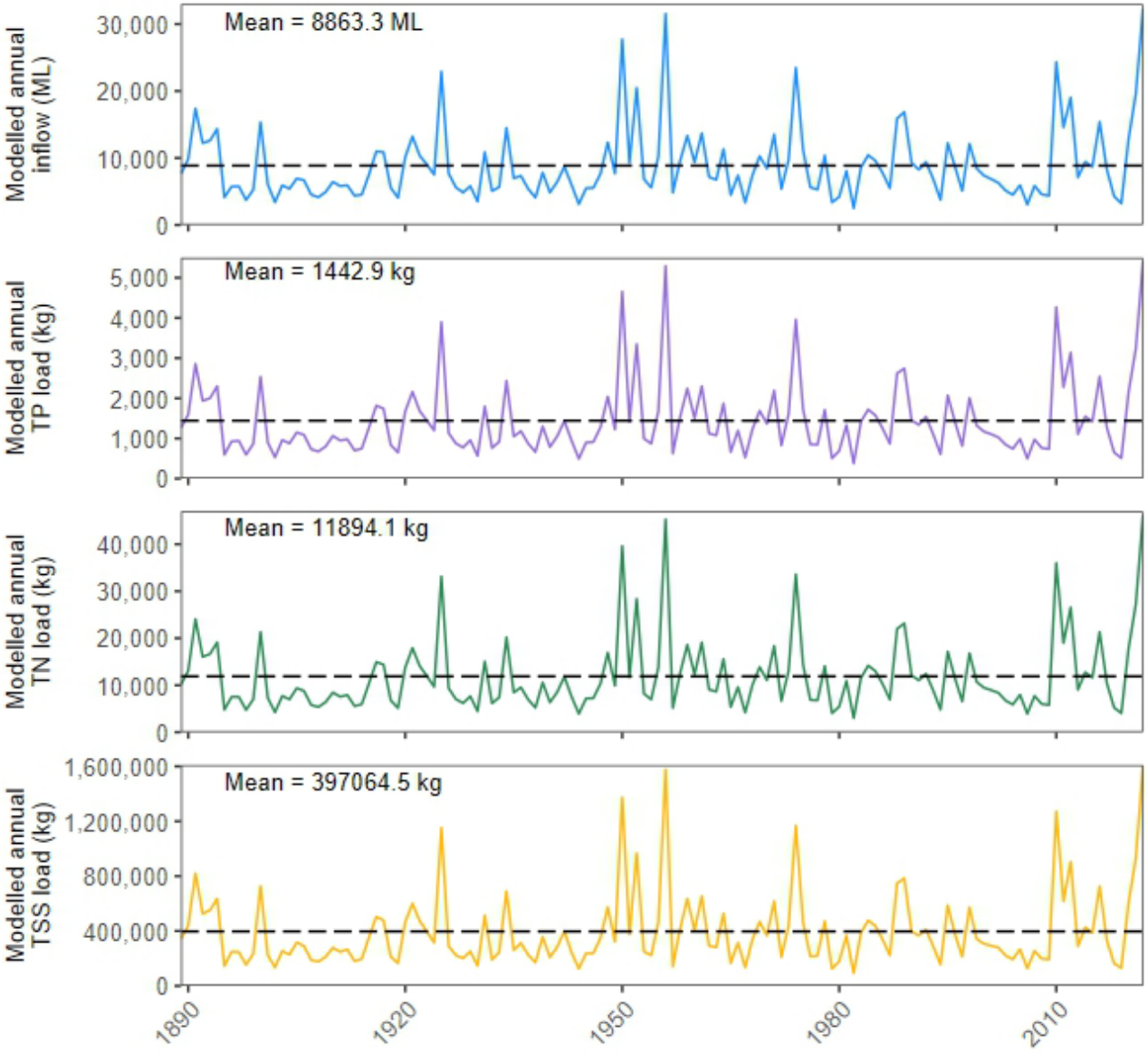

Figure 15. Long-term modelled annual inflows and annual loads of total phosphorus (TP), total nitrogen (TN), and total suspended solids (TSS) entering Lake Tuggeranong under current catchment conditions, for the period 1889 – 2022.

We compared this current scenario to a 'predevelopment' scenario, where all infrastructure (apart from Lake Tuggeranong itself) and developed land uses were removed from the model. Land use for all subcatchments was configured to be entirely bushland, to allow estimation of the runoff and pollutant generation under natural conditions. The results of the predevelopment scenario for the Lake Tuggeranong catchment were validated using the adjacent Jerrabomberra catchment, which has similar geographic conditions, for comparison (see Section 3.1.2). Figure 16 presents the long-term modelled annual inflow and pollutant loads entering Lake Tuggeranong under the predevelopment scenario, for the period 1889-

2022. The mean long-term annual inflow to the lake under predevelopment conditions was approximately 3,268 ML, and the modelled mean annual pollutant loads were 325 kg TP, 2470 kg TN, and 99,673 kg TSS.

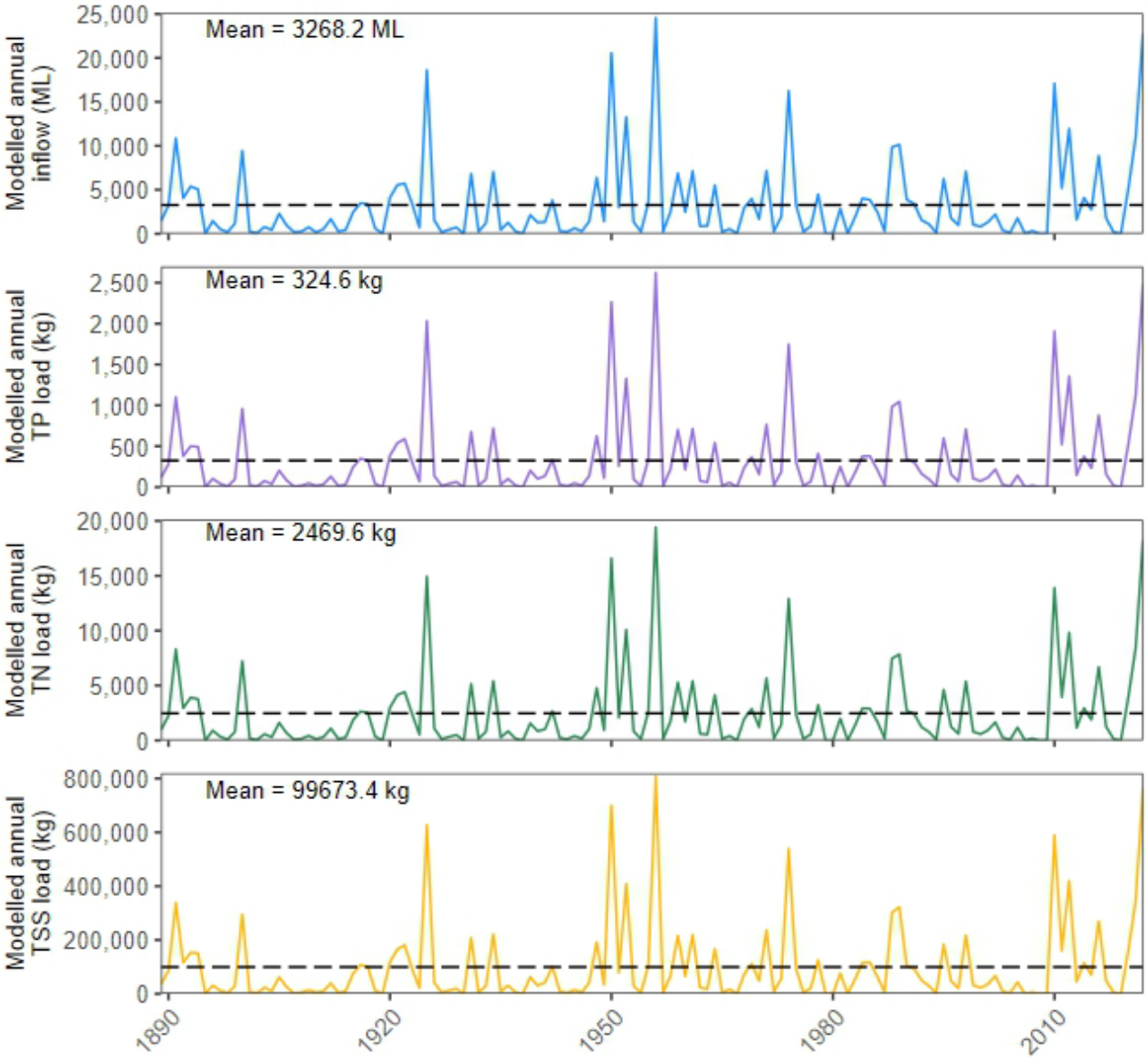

Figure 16. Long-term modelled annual inflows and annual loads of total phosphorus (TP), total nitrogen (TN), and total suspended solids (TSS) entering Lake Tuggeranong under predevelopment catchment conditions, for the period 1889 – 2022.

Table 6 and Figure 17 present comparisons of summary statistics for modelled annual inflows and pollutant loads generated under the current and predevelopment scenarios, for the period 1889-2022. On average, annual inflows to Lake Tuggeranong under predevelopment conditions were 25.5% of annual inflows under current conditions. The reduction in annual inflows, as well as reduced pollution generation modelled from the undeveloped catchment, meant that annual pollutant loads entering Lake Tuggeranong under predevelopment conditions were on average approximately 15% of annual pollutant loads under current conditions.

Table 6. Summary statistics describing modelled annual inflow volumes and loads of total phosphorus (TP), total nitrogen (TN), and total suspended solids (TSS) entering Lake Tuggeranong under the 'current' and 'predevelopment' model scenarios, for the period 1889-2022.

Parameter	Modelled scenario	Minimum	25th percentile	Median	Mean	75th percentile	Maximum
Annual inflow (GL)	Current scenario	2.50	5.39	7.39	8.86	10.37	32.3
Annual inflow (GL)	Predevelopment scenario	0	0.31	1.44	3.27	4.01	24.56
Annual TP load (kg)	Current scenario	377	857	1,176	1,442	1,705	5,412
Annual TP load (kg)	Predevelopment scenario	0	25	133	324	376	2,622
Annual TN load (kg)	Current scenario	3,019	6,893	9,508	11,894	14,100	46,236
Annual TN load (kg)	Predevelopment scenario	0	195	1,041	2,469	2,920	19,420
Annual TSS load (kg)	Current scenario	93,394	221,932	313,352	397,064	471,056	1,607,545
Annual TSS load (kg)	Predevelopment scenario	0	7,558	40,575	99,673	115,094	808,385

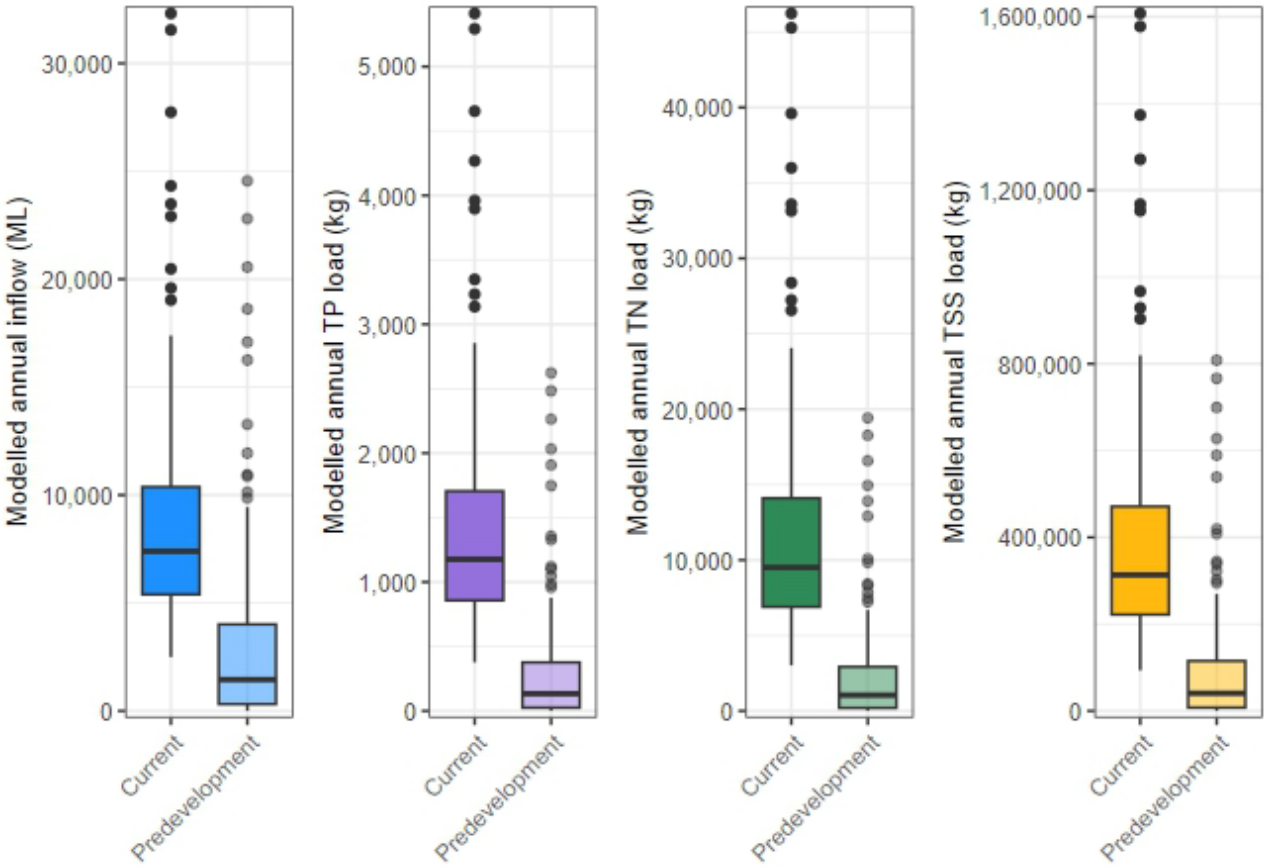

Figure 17. Box-and-whisker plots illustrating the distribution of modelled annual inflows and loads of total phosphorus (TP), total nitrogen (TN), and total suspended solids (TSS) entering Lake Tuggeranong under current and predevelopment catchment conditions, over the period 1889-2022.

Comparing the current and predevelopment scenarios is important for understanding catchment hydrology and pollutant generation before and after development, as well as the impacts of changes in hydrology and pollutant generation on trophic conditions in Lake Tuggeranong. The results from both modelled scenarios were used to parameterise a model of in-lake processes, which estimates the concentrations of phosphorous and chlorophyll a in the lake (Kahn & Dey, 2024). These concentrations were used to predict the distribution of trophic conditions in Lake Tuggeranong under the current and predevelopment scenarios. These analyses help to understand how conditions in the lake are predicted to respond under different inflow and pollutant conditions, and inform management decisions aimed at reducing the occurrence of blue-green algal blooms.

4.4.2 Catchment management option scenarios

The effects of specific management actions aimed at reducing pollutant inputs into the waterways and stormwater network of the Lake Tuggeranong catchment, or filtering or diverting water before it reaches the lake, were investigated in two additional scenarios implemented in the calibrated Source catchment model. Each scenario ('cost-effective' and 'broad benefits') consisted of a combination of different management actions, each with four possible levels of implementation, detailed in the companion to this report, *Lake Tuggeranong Catchment Management Options Assessment* (Booksmythe, Dey, Kahn, Stewart, & Starrs, 2024). The management options included in the two scenarios are detailed in Table 7.

Table 7. Details of the management options included in two scenarios…

Management option	Cost-effective scenario	Broad benefits scenario
Install additional WSUD infrastructure	Investment level 1: install 2 raingardens	Investment level 2: install 5 raingardens
Maintenance of existing WSUD infrastructure	Investment level 3: maintain 4 existing WSUD assets to their designed performance	Investment level 4: maintain 5 existing WSUD assets to their designed performance
Increase frequency of street sweeping	Investment level 4: 48 sweeps per year	Investment level 3: 36 sweeps per year
Manage grass clippings from municipal mowing	Investment level 3: designated street sweeping truck to follow mowers	Investment level 3: designated street sweeping truck to follow mowers
Sports field fertilizer management	Investment level 1: install bioretention swales to intercept 25% of total sports field P	Investment level 3: install bioretention swales to intercept 75% of total sports field P
Household fertilizer management	Investment level 4: very high implementation of community partnership programs aimed at reducing household fertilizer P inputs	Investment level 1: low implementation of community partnership programs aimed at reducing household fertilizer P inputs
Install castellated kerbs	n/a	Investment level 1: install castellated kerb outlets at a rate of 1 per 4 stormwater sumps adjacent to urban open space
Install floating wetlands	n/a	Investment level 4: install 4000 m^2 of floating wetlands
Stormwater recycling for sports field irrigation	Investment level 2: install stormwater recycling infrastructure at 4 sports field sites	Investment level 3: install stormwater recycling infrastructure at 6 sports field sites

Different management actions are implemented in different ways in the catchment model. Some options are explicitly represented by the addition or modification of specified links and nodes in the model:

- **Additional WSUD infrastructure** Proposed raingardens were represented in the catchment model by new storage nodes placed at the locations indicated in the original plans for the raingardens. As for existing assets, each proposed asset was modelled as a splitter node that diverts flow to the asset, and a storage node that applies a water quality decay function, representing the percentage reduction in pollutant loads (TP, TN, and TSS) achieved by the asset. Splitter nodes are configured with a maximum flow rate that is diverted into the asset, and any flow above this bypasses the asset, based on the MUSIC modelled high-flow bypass threshold. The proposed raingarden storage nodes were configured

using the size indicated in the original plans, and the performance details of similar existing WSUD assets.

- **Maintenance of existing WSUD infrastructure** The catchment model includes storage nodes representing each WSUD asset in the Lake Tuggeranong catchment, with the performance of each asset configured to reflect its current phosphorus removal efficiency (Table 2). To represent maintenance of these assets to their designed performance, the performance details were reconfigured to the phosphorus removal rates given in the detailed design reports for each asset.
- **Sports field fertilizer management** For each scenario, we modelled sufficient bioretention swales to intercept the required amount of sports field generated phosphorus (i.e., 25% or 75% of all sports field generated phosphorus, Table 7). We modelled one bioretention swale per subcatchment, starting with the subcatchment containing the largest sports field area, and divided the total swale area across the number of swales included in each scenario, proportionally to the area of sports field in each subcatchment.
    - Each bioretention swale was represented by a storage node configured based on the detailed design of a similar, existing WSUD asset.The percentage removal of TP, TN, and TSS were calculated for each bioretention swale using a MUSIC model consisting of a source, GPT, bioretention, and receiving node.
        - The source node was configured to have the size of the subcatchment's sports field area, and land use set at 100% pervious; remaining parameters used default values.
        - The GPT node was configured with high flow bypass.
        - The bioretention node was configured with size proportional to the subcatchment's sports field area, filter area set to 90% of total swale area, and an extended detention depth of 0.3 m based on recommended MIS08 guidelines; remaining parameters used default values.
        - The MUSIC model for each bioretention swale was run on a 6-minute timestep.
    - As the scale of the catchment model does not delineate sports fields from their subcatchments, a controlled splitter node was added to divert water to the storage node. Because sports fields typically generate higher TP concentrations than the catchment average, but splitters do not allow the adjustment of concentration in the diverted water, we instead increased the load of TP treated by bioretention swales by diverting more water to each sports field storage node. We divided the sports field TP concentration by the subcatchment TP concentration and multiplied this ratio by the proportion of sports field area in the subcatchment, to find the proportion of runoff volume to divert to the storage node.
- **Stormwater recycling infrastructure for sports field irrigation** Each sports field with stormwater recycling infrastructure was represented by a storage node and an irrigator node. A maximum of 1 ML water was diverted to the storage node via a controlled splitter during event flows. The irrigator node was configured as a perennial pasture crop using the crop coefficient from the NSW Environmental Guidelines on the used of effluent by irrigation (NSW Department of Environment and Conservation, 2004), with soil moisture capacity set at 20% and default soil configuration. The subcatchment's sports field area was used to set the size of the irrigated area, determining the water demand for irrigation. Daily rainfall and evapotranspiration (short crop) were obtained from SILO (https://www.longpaddock.qld.gov.au/silo/), covering the climatic period represented in the model (1899 – 2023). During dry periods the irrigation demand specified by the irrigator node was met by the water in the storage node, while in wet periods the demand is first met by rainfall. Excess water was

returned to the stormwater system downstream of the sports field via a link, maintaining water and mass balance.

- **Floating wetlands** To represent floating wetlands in the catchment model, a storage routing link was added just upstream of the Lake Tuggeranong storage node. This was configured using a decay model to reduce the phosphorus concentration in the water passing through the routing link, without affecting water volume. The percentage removal of phosphorus was calculated based on the estimated annual load of TP removed per square metre of floating wetland.

The remaining options cannot be explicitly modelled, and their effects were incorporated in the model by calculating the percentage phosphorus removal attained by each option, compared to the current load of phosphorus available to be intercepted by that option, and adjusting phosphorus concentrations within the catchment model based on these percentage reductions:

- **Household fertilizer management** The percentage reduction in phosphorus concentration due to management of household fertilizer use was applied to all area classified as suburban pervious, and calculated based on the difference in total phosphorus load generated from suburban pervious land across the catchment with and without household fertilizer management.
- **Increase street sweeping frequency | Manage grass clippings from municipal mowing | Install castellated kerbs** The percentage reduction in phosphorus concentration due to these options was applied to all area classified as road. As street sweeping, grass clipping management, and castellated kerbs all act to reduce the load of phosphorus generated from roads, the combined effects of these management options were modelled using a build-up wash-off model (Booksmythe, Dey, Kahn, Stewart, & Starrs, 2024) to predict the total percentage reduction in the phosphorus load from roads for the selected combination of these options in each scenario.

Table 8 presents summary statistics for modelled annual inflows and pollutant loads generated under the cost-effective and broad benefits catchment management scenarios, for the period 1889-2022. The management actions included in these scenarios are not predicted to have a large impact on runoff generation or inflows into Lake Tuggeranong; on average, annual inflows to Lake Tuggeranong under the catchment management scenarios were 97-98% of annual inflows under current conditions. However, the annual TP loads entering Lake Tuggeranong were substantially reduced under the catchment management scenarios. Under the cost-effective scenario annual TP loads were on average approximately 67% of annual TP loads under current conditions, and under the broad benefits scenario annual TP loads were on average approximately 56% of annual TP loads under current conditions.

Table 8. Summary statistics describing modelled annual inflow volumes and loads of total phosphorus (TP) entering Lake Tuggeranong under the 'cost-effective and 'broad benefits' catchment management model scenarios, for the period 1889-2022. Compare to the 'current' scenario, Table 6.

Parameter	Modelled scenario	Minimum	25th percentile	Median	Mean	75th percentile	Maximum
Annual inflow (GL)	Cost-effective scenario	2.36	5.29	7.31	8.76	10.27	32.30
Annual inflow (GL)	Broad benefits scenario	2.31	5.22	7.22	8.64	10.15	31.93
Annual TP load (kg)	Cost-effective scenario	236	551	771	992	1,179	4,076
Annual TP load (kg)	Broad benefits scenario	173	441	639	868	1,041	3,877

5. Summary and future model refinements

5.1 Summary

This report has described the data and methods used to parameterise, configure and calibrate the Lake Tuggeranong catchment model. The model was used to explore four scenarios of different catchment land use and management actions, providing long-term mean annual inflows and pollutant loads to Lake Tuggeranong under each scenario.

The catchment model improves on previous modelling work for the Lake Tuggeranong catchment:

- The model simulates flows and pollutant loads across the Lake Tuggeranong catchment on a daily timestep over 133 years of climate data from 1889-2023.
- The model incorporates updated land use and imperviousness layers to simulate runoff and pollutant generation across six functional land use classes.
- The model is delineated to water quality monitoring locations to facilitate parameterisation with concentrations of three pollutants – total phosphorus (TP), total nitrogen (TN), and total suspended solids (TSS).
- The model is delineated to existing stormwater treatment infrastructure to facilitate estimates of pollutant load reduction after treatment.
- The model hydrology is calibrated to a gauge immediately downstream of Lake Tuggeranong, with a very good fit between observed and modelled flow.
- The model incorporates recently constructed WSUD infrastructure in the Lake Tuggeranong catchment.
- The model incorporates a storage node representing Lake Tuggeranong, simulating flow and pollutant loads entering and leaving the storage.

Key results of the model include:

- Under current catchment land use and management, the model estimates a mean annual inflow to Lake Tuggeranong of approximately 8.8 GL for the period 1889-2022. Under predevelopment conditions, annual flows are on average 75% lower, with an estimated mean annual flow of approximately 3.3 GL.
- Under current catchment land use and management, the model estimates mean annual pollutant loads entering Lake Tuggeranong of 1,442 kg TP, 11,894 kg TN, and 397,064 kg TSS. Under predevelopment conditions, annual pollutant loads to the lake are on average 85% lower.
- By implementing combinations of catchment management options chosen by the ACT Healthy Waterways program, the model estimates that average annual TP loads to Lake Tuggeranong would be reduced to 868-992 kg, a 33-44% decrease compared to current catchment conditions.
- Land use is the major determinant of simulated subcatchment pollutant loads.

5.2 Future model refinements

The reliability and information provided by the Lake Tuggeranong catchment model could be enhanced by improvements to the data used for subcatchment delineation and calibration, and by undertaking assessments of model uncertainty:

- The calibration of water quality (pollutant) estimates in the model was based on observed median concentrations during event flows, which were the only available water quality data. However, observed pollutant loads provide a more robust framework for calibration in Source. Collecting data on pollutant loads requires simultaneous measures of concentration and flow volume and represents a significant change to the water quality and quantity monitoring currently undertaken in the ACT.
- Incorporating observed flow data from additional gauging stations within the Lake Tuggeranong catchment would enhance model reliability by broadening the data available for hydrological calibration.
- Undertaking an uncertainty estimation for the flows and pollutant loads estimated by the catchment model would provide a quantitative assessment of model reliability. Understanding model uncertainty is important when comparing across modelled scenarios, to ensure that differences are explained by modelled management options rather than measurement/estimation error.
- Understanding uncertainty in the model would also allow identification of areas where more hydrological and/or water quality data could improve the reliability of model estimates.

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Appendices

Appendix A: Level-volume-area data for Lake Tuggeranong

To configure the Lake Tuggeranong storage node in the catchment model requires information on the relationship between the water level and volume of the lake. Figure A1 shows the stage-volume rating curve used in configuring the Lake Tuggeranong storage node in the model. The level-volume-area (LVA) relationship for Lake Tuggeranong was derived from bathymetry data collected by Steger and Associates Registered Land Surveyors in 2015, presented in Table A1.

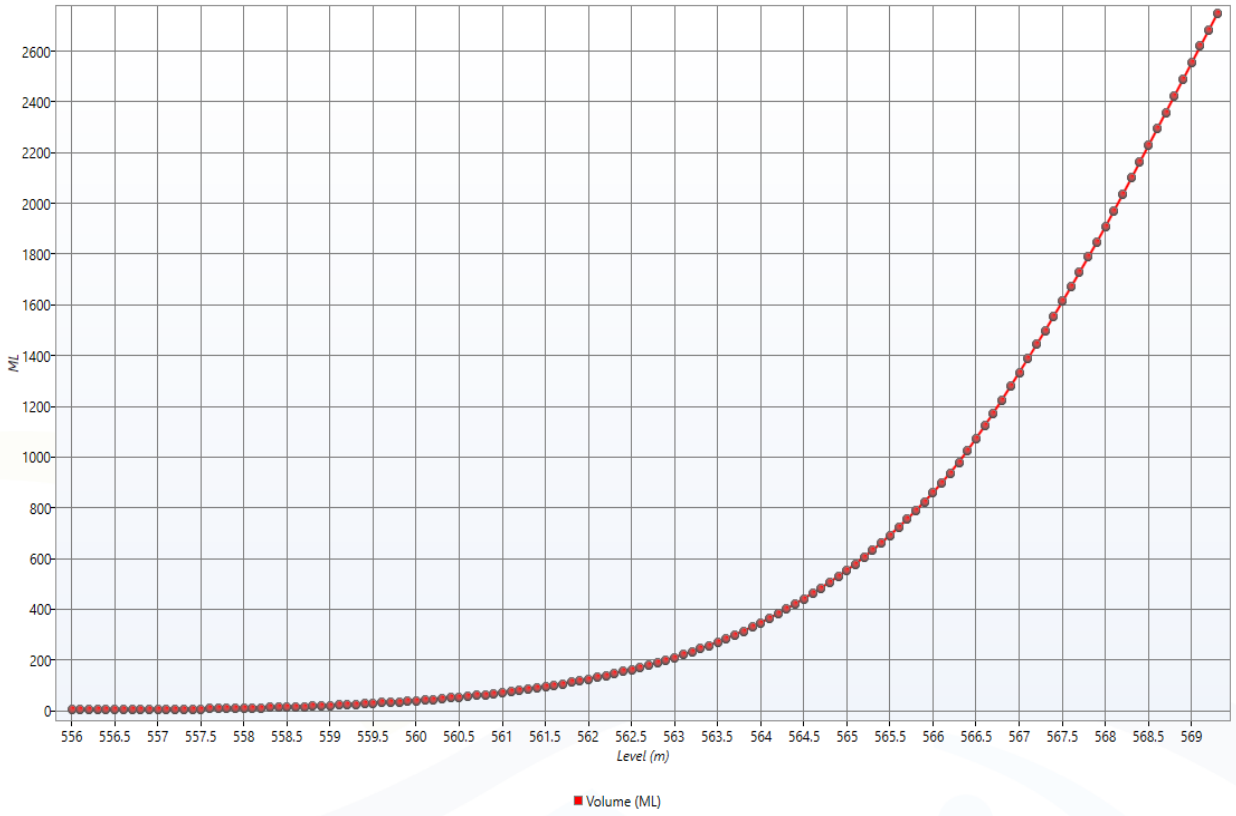

Figure A1. Water level - volume ratings curve for Lake Tuggeranong (gauge 410784) derived from bathymetry data (see Table A1). Source: Steger and Associates Registered Land Surveyors, 2015.

Table A1. Lake Tuggeranong water level, volume, and surface area data. Source: Steger and Associates Registered Land Surveyors, 2015.

Level (m)	Volume (ML)	Surface area (km^2)	Level (m)	Volume (ML)	Surface area (km^2)	Level (m)	Volume (ML)	Surface area (km^2)
556.0	0	0	558.4	10.1361	0.009721	560.8	60.19836	0.035167
556.1	0.014874	0.000119	558.5	11.18874	0.010526	560.9	63.92854	0.037302
556.2	0.036423	0.000215	558.6	12.31101	0.011223	561.0	67.9121	0.039836
556.3	0.072831	0.000364	558.7	13.49978	0.011888	561.1	72.14851	0.042364
556.4	0.122048	0.000492	558.8	14.76326	0.012635	561.2	76.63992	0.044914
556.5	0.222146	0.001001	558.9	16.10082	0.013376	561.3	81.38454	0.047446
556.6	0.374086	0.001519	559.0	17.52169	0.014209	561.4	86.36409	0.049795
556.7	0.570277	0.001962	559.1	19.02266	0.01501	561.5	91.56732	0.052032
556.8	0.808589	0.002383	559.2	20.60679	0.015841	561.6	97.00797	0.054406
556.9	1.104417	0.002958	559.3	22.27321	0.016664	561.7	102.6982	0.056902
557.0	1.442882	0.003385	559.4	24.02014	0.017469	561.8	108.6627	0.059645
557.1	1.824143	0.003813	559.5	25.84861	0.018285	561.9	114.8979	0.062353
557.2	2.241786	0.004176	559.6	27.79639	0.019478	562.0	121.405	0.065071
557.3	2.690724	0.004489	559.7	29.85126	0.020549	562.1	128.2425	0.068375
557.4	3.16953	0.004788	559.8	32.00766	0.021564	562.2	135.4093	0.071668
557.5	3.677818	0.005083	559.9	34.26355	0.022559	562.3	142.8931	0.074838
557.6	4.218615	0.005408	560.0	36.62414	0.023606	562.4	150.7054	0.078123
557.7	4.79095	0.005723	560.1	39.09346	0.024693	562.5	158.8814	0.08176
557.8	5.397505	0.006066	560.2	41.67477	0.025813	562.6	167.4558	0.085744
557.9	6.045165	0.006477	560.3	44.38028	0.027055	562.7	176.4338	0.08978
558.0	6.744306	0.006991	560.4	47.21816	0.028379	562.8	185.8594	0.094256
558.1	7.488318	0.00744	560.5	50.20973	0.029916	562.9	195.7887	0.099293
558.2	8.290076	0.008018	560.6	53.35829	0.031486	563.0	206.241	0.104523
558.3	9.164035	0.00874	560.7	56.6817	0.033234	563.1	217.2403	0.109993

Level (m)	Volume (ML)	Surface area (km²)	Level (m)	Volume (ML)	Surface area (km²)	Level (m)	Volume (ML)	Surface area (km²)
563.2	228.7825	0.115422	565.3	629.1803	0.275842	567.4	1553.159	0.566248
563.3	240.9099	0.121274	565.4	657.9845	0.288043	567.5	1610.312	0.571526
563.4	253.6379	0.12728	565.5	687.9878	0.300033	567.6	1668.006	0.576945
563.5	266.9702	0.133322	565.6	719.1112	0.311234	567.7	1726.277	0.582703
563.6	280.9174	0.139472	565.7	751.5013	0.323901	567.8	1785.19	0.589135
563.7	295.4839	0.145666	565.8	785.1463	0.336449	567.9	1844.844	0.596536
563.8	310.6996	0.152156	565.9	820.0771	0.349308	568.0	1906.38	0.615362
563.9	326.6404	0.159409	566.0	856.4557	0.363786	568.1	1968.905	0.625256
564.0	343.3933	0.167529	566.1	894.2724	0.378167	568.2	2032.357	0.634518
564.1	360.9095	0.175162	566.2	934.0697	0.397974	568.3	2096.546	0.641889
564.2	379.1175	0.18208	566.3	976.8441	0.427744	568.4	2161.172	0.646257
564.3	398.0267	0.189093	566.4	1022.38	0.455357	568.5	2226.008	0.648362
564.4	417.6585	0.196317	566.5	1070.137	0.477574	568.5	2226.008	0.648362
564.5	437.9539	0.202954	566.6	1119.482	0.493452	568.6	2290.955	0.649472
564.6	458.8675	0.209136	566.7	1170.426	0.509434	568.7	2355.947	0.649921
564.7	480.4328	0.215652	566.8	1222.593	0.521672	568.8	2420.965	0.650178
564.8	502.7146	0.222818	566.9	1275.738	0.531451	568.9	2485.993	0.650283
564.9	525.8767	0.231621	567.0	1329.908	0.541698	569.0	2551.028	0.650344
565.0	549.963	0.240863	567.1	1384.869	0.549609	569.1	2616.068	0.650402
565.1	575.1935	0.252304	567.2	1440.435	0.555666	569.2	2681.113	0.650454
565.2	601.5961	0.264027	567.3	1496.534	0.56099	569.3	2746.163	0.650495

Appendix B: Level – discharge data for Lake Tuggeranong outflow

The Lake Tuggeranong outflow was configured as an ungated spillway in the Source model, using the level-discharge relationship from Lake Tuggeranong weir (gauge 410784), presented in Table B1.

Table B1. Lake Tuggeranong weir rating table. *Source: ALS Pty Ltd.*

Level (m)	Discharge (ML/d)	Level (m)	Discharge (ML/d)	Level (m)	Discharge (ML/d)	Level (m)	Discharge (ML/d)
0	0	568.14	740.448	568.43	3957.12	568.72	9072
567.86	0	568.15	809.568	568.44	4121.28	568.73	9244.8
567.87	1.08	568.16	881.28	568.45	4285.44	568.74	9417.6
567.88	6.10848	568.17	959.04	568.46	4458.24	568.75	9676.8
567.89	16.848	568.18	1036.8	568.47	4631.04	568.76	9849.6
567.90	34.56	568.19	1123.2	568.48	4812.48	568.77	10022.4
567.91	41.2992	568.20	1209.6	568.49	4993.92	568.78	10281.6
567.92	48.816	568.21	1296	568.50	5184	568.79	10454.4
567.93	57.1104	568.22	1382.4	568.51	5339.52	568.80	10713.6
567.94	66.096	568.23	1468.8	568.52	5503.68	568.81	10886.4
567.95	76.032	568.24	1563.84	568.53	5667.84	568.82	11059.2
567.96	86.4	568.25	1667.52	568.54	5840.64	568.83	11318.4
567.97	98.496	568.26	1771.2	568.55	6013.44	568.84	11491.2
567.98	110.592	568.27	1874.88	568.56	6186.24	568.85	11664
567.99	124.416	568.28	1978.56	568.57	6359.04	568.86	11923.2
568.00	138.24	568.29	2090.88	568.58	6540.48	568.87	12096
568.01	162.432	568.30	2211.84	568.59	6721.92	568.88	12355.2
568.02	189.216	568.31	2324.16	568.60	6912	568.89	12528
568.03	219.456	568.32	2436.48	568.61	7076.16	568.90	12700.8
568.04	251.424	568.33	2557.44	568.62	7240.32	568.91	12960
568.05	285.984	568.34	2678.4	568.63	7404.48	568.92	13132.8
568.06	323.136	568.35	2808	568.64	7577.28	568.93	13392
568.07	362.88	568.36	2937.6	568.65	7750.08	568.94	13564.8
568.08	406.08	568.37	3067.2	568.66	7922.88	568.95	13824
568.09	451.872	568.38	3205.44	568.67	8095.68	568.96	13996.8
568.10	501.12	568.39	3343.68	568.68	8277.12	568.97	14256
568.11	555.552	568.40	3490.56	568.69	8458.56	568.98	14428.8
568.12	613.44	568.41	3646.08	568.70	8640	568.99	14601.6
568.13	675.648	568.42	3801.6	568.71	8812.8		

Appendix C: Land use and imperviousness classification

Table C1 lists the detailed land use classifications included in each of the six functional land use units defined for the Lake Tuggeranong catchment. Table C2 provides a breakdown of the major and minor subcatchments delineated in the Source catchment model, and Figure C1 shows a map of the major subcatchments. Table C3 provides the subcatchment area breakdown in hectares and area ratio based on land use functional units used in the catchment model.

Table C1. Detailed land use classifications based on ACT Government land zoning grouped into 6 functional units for use in the catchment model.

ACT land zoning	Functional unit
Business zone	commercial
Community Facilities	commercial
Core zone	commercial
Leisure and accommodation	commercial
Local centre	commercial
Services	commercial
Services zone	commercial
Medium density residential	suburban
Suburban	suburban
Suburban core	suburban
Transport	open space
Urban open space	open space
Restricted access recreation zone	open space
Hills ridges and buffer areas	bushland
Designated	bushland
River corridor	bushland
Rural	rural
Sports field (estimated)	sports field

Table C2. Major subcatchments of the Lake Tuggeranong catchment and their component minor subcatchments delineated in the Source catchment model.

Major subcatchment	Minor subcatchments
Village Creek (VC)	VC0, VC1, VC2, VC3, VC4, VC6, VC7, VC8, VC9, VC10, VC11
Kambah Creek (KC)	KC0, KC1, KC2, KC3, KC4, KC5, KC6, KC7
Tuggeranong Creek (TC)	TC0, TC1, TC2, TC3, TC4, TC5, TC6, TC7, TC6_NSW, TC8_NSW
Lake Tuggeranong (Lake T)	
East Lake (EL)	EL1, EL2
West Lake (WL)	WL0, WL1, WL2, WL3, WL4, WL5, WL6, WL7, WL8, WL9, WL10, WL11
Downstream of Lake Tuggeranong (DSL)	DSL1, DSL2
Drakeford Drive South (DDS)	DDS1, DDS2
(DLC)	DLC_N, DLC_S
Stranger Pond (SP)	SP1, SP2
Wanniassa (WS)	WS0, WS1, WS2, WS3, WS4
Fadden stormwater (FA)	FA0, FA1, FA2, FA3, FA5, FA6, FA7, FA8, FA9, FA10, FA11, FA12, FA13, FA14, FA15, FA16, FA17, FA9_NSW

Fig. C1. Map of Lake Tuggeranong catchment showing major subcatchment boundaries. VC, Village Creek; KC, Kambah Creek; WS, Wanniassa; FA, Fadden stormwater; TC, Tuggeranong Creek; DSL, Downstream of Lake Tuggeranong; Lake T, Lake Tuggeranong; DLC, XXX; WL, West Lake; EL, East Lake; DDS, Drakeford Drive South; SP, Stranger Pond.

Table C3. Area of land use functional units within Lake Tuggeranong subcatchments (see Table C2), in hectares (ha) and as a percentage of subcatchment area (%).

Functional unit	VC0 (ha)	VC0 (%)	VC1 (ha)	VC1 (%)	VC2 (ha)	VC2 (%)	VC3 (ha)	VC3 (%)	VC4 (ha)	VC4 (%)	VC6 (ha)	VC6 (%)
Commercial road	1.16654	1.28342	0.55272	1.45670	0.06191	0.06184	0.00053	0.00081	0.00000	0.00000	0.52402	2.40107
Commercial hardstand	2.96745	3.26478	3.54531	9.34381	0.09628	0.09617	0.75895	1.17555	0.72954	0.59131	1.30516	5.98024
Commercial roof	3.62099	3.98381	3.96793	10.45763	0.40466	0.40420	0.96058	1.48785	0.96820	0.78476	1.85026	8.47786
Commercial pervious	3.42116	3.76396	2.91630	7.68602	0.33240	0.33202	2.63463	4.08081	1.87153	1.51694	1.60472	7.35280
Commercial water	0	0	0	0	0	0	0	0	0	0	0	0
Suburban road	3.73592	4.11026	1.45375	3.83141	5.77357	5.76696	3.69303	5.72018	6.43127	5.21276	0.40714	1.86552
Suburban hardstand	5.17332	5.69168	1.37583	3.62604	5.56696	5.56059	2.89318	4.48128	5.92845	4.80520	0.73999	3.39064
Suburban roof	17.15034	18.86877	4.56512	12.03155	22.63823	22.61229	11.73104	18.17036	22.69013	18.39110	2.30035	10.54015
Suburban pervious	29.87385	32.86716	7.64501	20.14873	38.47253	38.42845	20.42040	31.62942	36.44461	29.53956	2.69231	12.33615
Suburban water	0	0	0	0	0.01395	0.01393	2.50E-05	3.87E-05	0.00095	0.00077	0	0
Open space road	4.47567	4.92413	2.24256	5.91036	4.15447	4.14971	2.77265	4.29460	4.04727	3.28044	1.83831	8.42312
Open space hardstand	1.61398	1.77570	0.76704	2.02155	2.45150	2.44869	1.30548	2.02207	3.76469	3.05140	0.72845	3.33773
Open space roof	0.20061	0.22071	0.07460	0.19661	0.48495	0.48439	0.25650	0.39730	0.80075	0.64903	0.14520	0.66532
Open space pervious	14.24994	15.67776	8.83674	23.28958	12.97204	12.95718	16.26664	25.19562	29.51479	23.92272	7.48905	34.31473
Open space water	0.03960	0.04357	0	0	0	0	0	0	0	0	0.19962	0.91466
Bushland road	0	0	0	0	0	0	0	0	0	0	0	0
Bushland hardstand	0.04743	0.05218	0	0	0.24205	0.24177	0	0	0	0	0	0
Bushland roof	0.00363	0.00399	0	0	0.00097	0.00097	0	0	0	0	0	0
Bushland pervious	3.15228	3.46813	0	0	6.44823	6.44084	0	0	0	0	0	0
Bushland water	0	0	0	0	0	0	0	0	0	0	0	0
Rural road	0	0	0	0	0	0	0	0	0	0	0	0
Rural hardstand	0	0	0	0	0	0	0	0	0	0	0	0
Rural roof	0	0	0	0	0	0	0	0	0	0	0	0
Rural pervious	0	0	0	0	0	0	0	0	0	0	0	0
Rural water	0	0	0	0	0	0	0	0	0	0	0	0
Sports field	0	0	0	0	0	0	0.86778	1.34411	10.18341	8.25399	0	0
Total subcatchment area	90.89270	100	37.94290	100	100.11470	100	64.56140	100	123.37560	100	21.82460	100

Table C3 cont. Area of land use functional units within Lake Tuggeranong subcatchments (see Table C2), in hectares (ha) and as a percentage of subcatchment area (%).

Functional unit	VC7 (ha)	VC7 (%)	VC8 (ha)	VC8 (%)	VC9 (ha)	VC9 (%)	VC10 (ha)	VC10 (%)	VC11 (ha)	VC11 (%)	Lake T (ha)	Lake T (%)
Commercial road	0	0	0	0	0.01835	0.00688	0	0	0	0	0	0
Commercial hardstand	0	0	0	0	1.02446	0.38388	1.19452	0.64653	0	0	0	0
Commercial roof	0	0	0	0	0.62828	0.23543	1.79132	0.96955	0	0	0	0
Commercial pervious	0	0	0	0	2.96747	1.11196	4.26940	2.31081	0	0	0	0
Commercial water	0	0	0	0	0	0	0	0	0	0	0	0
Suburban road	0.31054	9.59627	0.00158	0.03398	5.07906	1.90321	10.61841	5.74720	2.75089	3.36567	0	0
Suburban hardstand	0.24232	7.48839	0.00455	0.09815	3.93032	1.47275	6.24872	3.38211	1.53092	1.87306	0	0
Suburban roof	0.71997	22.24891	0.00000	0.00000	17.65425	6.61534	29.89265	16.17935	8.30131	10.15654	0	0
Suburban pervious	1.00224	30.97160	0.09433	2.03477	29.37379	11.00684	51.34650	27.79122	16.30805	19.95268	0	0
Suburban water	0	0	0	0	0	0	0	0	2.50E-05	3.06E-05	0	0
Open space road	0.01912	0.59088	0.73261	15.80361	9.13640	3.42356	3.42844	1.85564	0.08557	0.10470	0.16068	0.22103
Open space hardstand	0.07169	2.21524	0.14298	3.08425	4.31557	1.61712	2.79452	1.51253	0.16162	0.19775	0.31379	0.43165
Open space roof	0.01592	0.49202	0.02103	0.45355	0.45775	0.17152	0.31814	0.17220	0.01235	0.01511	0.30226	0.41579
Open space pervious	0.85420	26.39669	3.63864	78.49169	44.29813	16.59923	34.55149	18.70095	5.38125	6.58389	2.76054	3.79745
Open space water	0	0	0	0	0.17846	0.06687	0	0	0	0	69.15733	95.13407
Bushland road	0	0	0	0	3.77569	1.41481	0.43221	0.23393	1.15907	1.41811	0	0
Bushland hardstand	0	0	0	0	1.75254	0.65671	0.10256	0.05551	0.23837	0.29165	0	0
Bushland roof	0	0	0	0	0.24923	0.09339	0.00665	0.00360	0.11275	0.13795	0	0
Bushland pervious	0	0	0	0	142.00602	53.21198	30.50463	16.51058	45.69143	55.90287	0	0
Bushland water	0	0	0	0	0.02273	0.00852	0	0	0	0	0	0
Rural road	0	0	0	0	0	0	0	0	0	0	0	0
Rural hardstand	0	0	0	0	0	0	0	0	0	0	0	0
Rural roof	0	0	0	0	0	0	0	0	0	0	0	0
Rural pervious	0	0	0	0	0	0	0	0	0	0	0	0
Rural water	0	0	0	0	0	0	0	0	0	0	0	0
Sports field	0	0	0	0	0	0	7.25782	3.92829	0	0	0	0
Total subcatchment area	3.23600	100	4.63570	100	266.86850	100	184.75800	100	81.73360	100	72.69460	100

Table C3 cont. Area of land use functional units within Lake Tuggeranong subcatchments (see Table C2), in hectares (ha) and as a percentage of subcatchment area (%).

Functional unit	KC0 (ha)	KC0 (%)	KC1 (ha)	KC1 (%)	KC2 (ha)	KC2 (%)	KC3 (ha)	KC3 (%)	KC4 (ha)	KC4 (%)	KC5 (ha)	KC5 (%)
Commercial road	0	0	0	0	0	0	0	0	0	0	0.22272	0.32619
Commercial hardstand	0.23590	0.18352	0.10135	0.12613	0.11103	0.12613	0.00800	0.12613	0.00045	0.02089	1.68770	2.47178
Commercial roof	0.46683	0.36317	0.10200	0.12693	0.11174	0.12693	0.00805	0.12693	0.00003	0.00116	1.91152	2.79958
Commercial pervious	0.80327	0.62490	0.02740	0.03410	0.03002	0.03410	0.00216	0.03410	0.01793	0.83192	2.24089	3.28197
Commercial water	0	0	0	0	0	0	0	0	0	0	0	0
Suburban road	7.27826	5.66213	6.20275	7.71915	6.79539	7.71915	0.48981	7.71915	0.00000	0.00000	4.54340	6.65420
Suburban hardstand	7.37201	5.73507	5.85418	7.28537	6.41351	7.28537	0.46229	7.28537	0.02456	1.13940	4.10095	6.00621
Suburban roof	28.02338	21.80082	19.67904	24.49003	21.55926	24.49003	1.55399	24.49003	0.15034	6.97445	14.86127	21.76563
Suburban pervious	45.12123	35.10210	33.59659	41.81005	36.80656	41.81005	2.65302	41.81005	0.19061	8.84250	26.44537	38.73156
Suburban water	0	0	0	0	0	0	0	0	5.00E-05	0.00232	2.50E-05	3.66E-05
Open space road	6.75730	5.25685	2.59264	3.22647	2.84036	3.22647	0.20473	3.22647	0.00375	0.17404	2.08079	3.04750
Open space hardstand	2.98208	2.31991	1.45161	1.80649	1.59030	1.80649	0.11463	1.80649	0.41023	19.03093	1.24580	1.82459
Open space roof	0.23348	0.18164	0.19942	0.24818	0.21848	0.24818	0.01575	0.24818	0.06228	2.88910	0.11700	0.17135
Open space pervious	29.18828	22.70705	10.54832	13.12710	11.55616	13.12710	0.83297	13.12710	1.29149	59.91344	8.08024	11.83421
Open space water	0.01618	0.01258	0	0	0	0	0	0	0	0	0	0
Bushland road	0	0	0	0	0	0	0	0	0	0	0	0
Bushland hardstand	0	0	0	0	0	0	0	0	0	0	0	0
Bushland roof	0	0	0	0	0	0	0	0	0	0	0	0
Bushland pervious	0	0	0	0	0	0	0	0	0	0	0	0
Bushland water	0	0	0	0	0	0	0	0	0	0	0	0
Rural road	0	0	0	0	0	0	0	0	0	0	0	0
Rural hardstand	0	0	0	0	0	0	0	0	0	0	0	0
Rural roof	0	0	0	0	0	0	0	0	0	0	0	0
Rural pervious	0	0	0	0	0	0	0	0	0	0	0	0
Rural water	0	0	0	0	0	0	0	0	0	0	0	0
Sports field	0	0	0	0	0	0	0	0	0.00388	0.17984	0.74094	1.08517
Total subcatchment area	128.54280	100	80.35530	100	88.03280	100	6.34540	100	2.15560	100	68.27860	100

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Table C3 cont. Area of land use functional units within Lake Tuggeranong subcatchments (see Table C2), in hectares (ha) and as a percentage of subcatchment area (%).

Functional unit	KC6 (ha)	KC6 (%)	KC7 (ha)	KC7 (%)	SP1 (ha)	SP1 (%)	SP2 (ha)	SP2 (%)	EL1 (ha)	EL1 (%)	EL2 (ha)	EL2 (%)
Commercial road	0	0	0	0	0.34455	0.09473	0.25623	0.65596	0	0	0.1566	0.8058
Commercial hardstand	0.06448	0.04990	0	0	2.55082	0.70133	0.34418	0.88112	0	0	0.7782	4.0044
Commercial roof	0.08659	0.06701	0	0	2.85592	0.78521	1.33480	3.41714	0	0	1.1017	5.6688
Commercial pervious	0.00426	0.00329	0	0	8.95477	2.46205	1.59170	4.07482	0	0	1.6979	8.7366
Commercial water	0	0	0	0	0	0	0	0	0	0	0	0
Suburban road	6.73670	5.21343	0	0	16.71164	4.59474	0.75529	1.93357	1.96217	3.10053	0	0
Suburban hardstand	6.08694	4.71059	0	0	21.71844	5.97132	2.18503	5.59379	5.25066	8.29684	0	0
Suburban roof	23.68161	18.32684	0	0	73.29687	20.15242	5.26468	13.47782	7.70244	12.17103	0.00198	0.01016
Suburban pervious	41.86302	32.39716	0	0	102.74356	28.24856	5.68414	14.55165	10.69712	16.90309	0.03886	0.19994
Suburban water	0	0	0	0	0.00210	0.00058	0	0	0	0	0	0
Open space road	5.30084	4.10224	2.16018	0.69905	12.17165	3.34650	1.47995	3.78873	1.76602	2.79058	1.38581	7.13058
Open space hardstand	2.65729	2.05644	2.24234	0.72564	5.34020	1.46825	1.23752	3.16811	2.27993	3.60263	0.97812	5.03284
Open space roof	0.16133	0.12485	0.10101	0.03269	0.58110	0.15977	0.09868	0.25262	0.39105	0.61793	0.08547	0.43977
Open space pervious	38.37112	29.69483	13.61355	4.40542	58.24083	16.01287	12.63747	32.35250	32.93501	52.04237	12.78198	65.76885
Open space water	0	0	0	0	0	0	4.32094	11.06181	0.30060	0.47500	0.06847	0.35228
Bushland road	0	0	6.17691	1.99888	0.86652	0.23824	0	0	0	0	0	0
Bushland hardstand	0.00225	0.00174	2.42975	0.78628	0.74172	0.20393	0	0	0	0	0	0
Bushland roof	0.00093	0.00072	1.47904	0.47863	0.70985	0.19517	0	0	0	0	0	0
Bushland pervious	4.20082	3.25095	280.72872	90.84543	52.08091	14.31925	0	0	0	0	0	0
Bushland water	0	0	0.08650	0.02799	0	0	0	0	0	0	0	0
Rural road	0	0	0	0	0	0	0	0	0	0	0	0
Rural hardstand	0	0	0	0	0	0	0	0	0	0	0	0
Rural roof	0	0	0	0	0	0	0	0	0	0	0	0
Rural pervious	0	0	0	0	0	0	0	0	0	0	0	0
Rural water	0	0	0	0	0	0	0	0	0	0	0	0
Sports field	0	0	0	0	3.80112	1.04509	1.87120	4.79037	0	0	0.35953	1.84994
Total subcatchment area	129.21820	100	309.01800	100	363.71260	100	39.06180	100	63.28500	100	19.43470	100

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Table C3 cont. Area of land use functional units within Lake Tuggeranong subcatchments (see Table C2), in hectares (ha) and as a percentage of subcatchment area (%).

Functional unit	WL0 (ha)	WL0 (%)	WL1 (ha)	WL1 (%)	WL2 (ha)	WL2 (%)	WL3 (ha)	WL3 (%)	WL4 (ha)	WL4 (%)	WL5 (ha)	WL5 (%)
Commercial road	4.3703	7.9703	0.8347	3.1681	1.0011	6.7299	0	0	0.62984	11.02963	0	0
Commercial hardstand	11.5970	21.1500	6.8472	25.9884	1.2159	8.1740	0.00085	0.01072	2.13908	37.45934	0	0
Commercial roof	25.6801	46.8340	5.6090	21.2888	4.2901	28.8403	0.00085	0.01072	1.99816	34.99153	0	0
Commercial pervious	4.4233	8.0669	3.4839	13.2230	2.1629	14.5404	0.00355	0.04478	0.60119	10.52793	0.13435	2.80000
Commercial water	0	0	0	0	0	0	0	0	0	0	0	0
Suburban road	0	0	0.01252	0.04754	0	0	0	0	0	0	0	0
Suburban hardstand	0	0	0.10727	0.40713	0	0	0	0	0	0	0	0
Suburban roof	0	0	0.09979	0.37877	0	0	0	0	0	0	0	0
Suburban pervious	0	0	0.23981	0.91019	0	0	0	0	0	0	0	0
Suburban water	0	0	0	0	0	0	0	0	0	0	0	0
Open space road	3.84955	7.02060	3.52733	13.38791	2.07414	13.94361	0.01007	0.12708	0.00397	0.06961	0.76260	15.89337
Open space hardstand	2.01038	3.66643	0.97456	3.69894	1.33538	8.97721	0.81178	10.24202	0.06327	1.10804	0.59875	12.47873
Open space roof	0.65246	1.18991	0.17189	0.65240	0.72916	4.90187	0.14906	1.88065	0.04205	0.73636	0.43773	9.12289
Open space pervious	2.24307	4.09078	4.41994	16.77583	2.06527	13.88395	6.94281	87.59543	0.22977	4.02371	2.82017	58.77550
Open space water	0.00605	0.01103	0.01925	0.07306	0	0	0.00702	0.08861	0.00307	0.05385	0.00874	0.18216
Bushland road	0	0	0	0	0	0	0	0	0	0	0	0
Bushland hardstand	0	0	0	0	0	0	0	0	0	0	0	0
Bushland roof	0	0	0	0	0	0	0	0	0	0	0	0
Bushland pervious	0	0	0	0	0.00130	0.00874	0	0	0	0	0.03586	0.74736
Bushland water	0	0	0	0	0	0	0	0	0	0	0	0
Rural road	0	0	0	0	0	0	0	0	0	0	0	0
Rural hardstand	0	0	0	0	0	0	0	0	0	0	0	0
Rural roof	0	0	0	0	0	0	0	0	0	0	0	0
Rural pervious	0	0	0	0	0	0	0	0	0	0	0	0
Rural water	0	0	0	0	0	0	0	0	0	0	0	0
Sports field	0	0	0	0	0	0	0	0	0	0	0	0
Total subcatchment area	54.83220	100	26.34710	100	14.87520	100	7.92600	100	5.71040	100	4.79820	100

Table C3 cont. Area of land use functional units within Lake Tuggeranong subcatchments (see Table C2), in hectares (ha) and as a percentage of subcatchment area (%).

Functional unit	WL6 (ha)	WL6 (%)	WL7 (ha)	WL7 (%)	WL8 (ha)	WL8 (%)	WL9 (ha)	WL9 (%)	WL10 (ha)	WL10 (%)	WL11 (ha)	WL11 (%)
Commercial road	0.22090	9.12689	0.48320	9.59071	0.10770	9.94735	0	0	0.00152	0.00688	0.00052	0.00688
Commercial hardstand	0.75873	31.34842	0.70091	13.91191	0.09505	8.77898	0.09312	8.05055	0.08472	0.38388	0.02891	0.38388
Commercial roof	1.34172	55.43604	1.17561	23.33390	0.22848	21.10234	0.28581	24.70893	0.05195	0.23543	0.01773	0.23543
Commercial pervious	0.07700	3.18144	0.66586	13.21619	0.21683	20.02632	0.09627	8.32271	0.24539	1.11196	0.08373	1.11196
Commercial water	0.00003	0.00103	0.01950	0.38706	0	0	0	0	0	0	0	0
Suburban road	0	0	0	0	0	0	0	0	0.42001	1.90321	0.14331	1.90321
Suburban hardstand	0	0	0	0	0	0	0	0	0.32501	1.47275	0.11090	1.47275
Suburban roof	0	0	0	0	0	0	0	0	1.45989	6.61534	0.49813	6.61534
Suburban pervious	0	0	0	0	0	0	0	0	2.42902	11.00684	0.82882	11.00684
Suburban water	0	0	0	0	0	0	0	0	0	0	0	0
Open space road	0	0	0.00018	0.00347	0.09565	8.83440	0	0	0.75552	3.42356	0.25779	3.42356
Open space hardstand	0.01015	0.41951	0.59345	11.77910	0.07803	7.20652	0.22165	19.16190	0.35687	1.61712	0.12177	1.61712
Open space roof	0.00730	0.30172	0.15618	3.09997	0.03780	3.49127	0.12877	11.13295	0.03785	0.17152	0.01292	0.17152
Open space pervious	0.00448	0.18496	1.22931	24.39981	0.19978	18.45156	0.30532	26.39594	3.66317	16.59923	1.24992	16.59923
Open space water	0	0	0.01400	0.27789	0.02340	2.16126	0.02576	2.22702	0.01476	0.06687	0.00504	0.06687
Bushland road	0	0	0	0	0	0	0	0	0.31222	1.41481	0.10654	1.41481
Bushland hardstand	0	0	0	0	0	0	0	0	0.14492	0.65671	0.04945	0.65671
Bushland roof	0	0	0	0	0	0	0	0	0.02061	0.09339	0.00703	0.09339
Bushland pervious	0	0	0	0	0	0	0	0	11.74298	53.21198	4.00686	53.21198
Bushland water	0	0	0	0	0	0	0	0	0.00188	0.00852	0.00064	0.00852
Rural road	0	0	0	0	0	0	0	0	0	0	0	0
Rural hardstand	0	0	0	0	0	0	0	0	0	0	0	0
Rural roof	0	0	0	0	0	0	0	0	0	0	0	0
Rural pervious	0	0	0	0	0	0	0	0	0	0	0	0
Rural water	0	0	0	0	0	0	0	0	0	0	0	0
Sports field	0	0	0	0	0	0	0	0	0	0	0	0
Total subcatchment area	2.42030	100	5.03820	100	1.08270	100	1.15670	100	22.06830	100	7.53000	100

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Table C3 cont. Area of land use functional units within Lake Tuggeranong subcatchments (see Table C2), in hectares (ha) and as a percentage of subcatchment area (%).

Functional unit	DDS1 (ha)	DDS1 (%)	DDS2 (ha)	DDS2 (%)	DSL1 (ha)	DSL1 (%)	DSL2 (ha)	DSL2 (%)	DLC N (ha)	DLC N (%)	DLC S (ha)	DLC S (%)
Commercial road	0	0	0	0	0	0	0	0	0	0	0	0
Commercial hardstand	0	0	0	0	0.00817	0.01807	0	0	0	0	0.08175	0.12357
Commercial roof	0	0	0	0	0.00840	0.01857	0	0	0	0	0.14145	0.21382
Commercial pervious	0	0	0	0	6.11195	13.52072	0	0	0	0	0.03060	0.04626
Commercial water	0	0	0	0	0	0	0	0	0	0	0	0
Suburban road	0.89352	7.67025	1.04632	3.69542	0	0	0	0	0.25714	8.61201	3.97777	6.01283
Suburban hardstand	0.63470	5.44849	2.06447	7.29133	0	0	0	0	0.35156	11.77441	5.04227	7.62195
Suburban roof	1.85668	15.93838	4.99336	17.63565	0	0	0	0	1.31517	44.04747	15.13896	22.88422
Suburban pervious	3.18648	27.35385	5.69499	20.11369	0	0	0	0	0.74893	25.08312	22.82264	34.49895
Suburban water	0	0	0	0	0	0	0	0	0	0	0	0
Open space road	0.74070	6.35840	3.08179	10.88433	0	0	0	0	0	0	3.06436	4.63212
Open space hardstand	0.10360	0.88930	1.21974	4.30791	0.00737	0.01631	0.00040	0.00118	0.02711	0.90785	1.28473	1.94201
Open space roof	0.02935	0.25194	0.11342	0.40059	0.00070	0.00155	0	0	0.00355	0.11892	0.17930	0.27103
Open space pervious	4.20409	36.08938	10.09991	35.67110	0.25166	0.55672	0.09442	0.27857	0.28234	9.45621	14.39076	21.75323
Open space water	0	0	0	0	0	0	0	0	0	0	0	0
Bushland road	0	0	0	0	0	0	0	0	0	0	0	0
Bushland hardstand	0	0	0	0	0.65479	1.44850	0.28300	0.83498	0	0	0	0
Bushland roof	0	0	0	0	0.05969	0.13205	0.00107	0.00317	0	0	0	0
Bushland pervious	0	0	0	0	37.96401	83.98318	33.51431	98.88211	0	0	0	0
Bushland water	0	0	0	0	0.13757	0.30434	0	0	0	0	0	0
Rural road	0	0	0	0	0	0	0	0	0	0	0	0
Rural hardstand	0	0	0	0	0	0	0	0	0	0	0	0
Rural roof	0	0	0	0	0	0	0	0	0	0	0	0
Rural pervious	0	0	0	0	0	0	0	0	0	0	0	0
Rural water	0	0	0	0	0	0	0	0	0	0	0	0
Sports field	0	0	0	0	0	0	0	0	0	0	0	0
Total subcatchment area	11.64910	100	28.31400	100	45.20430	100	33.89320	100	2.98580	100	66.15460	100

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Table C3 cont. Area of land use functional units within Lake Tuggeranong subcatchments (see Table C2), in hectares (ha) and as a percentage of subcatchment area (%).

Functional unit	TC0 (ha)	TC0 (%)	TC1 (ha)	TC1 (%)	TC2 (ha)	TC2 (%)	TC3 (ha)	TC3 (%)	TC4 (ha)	TC4 (%)	TC5 (ha)	TC5 (%)
Commercial road	0.58272	0.22654	0	0	0.32153	0.12952	0.06495	0.12948	0.06495	0.12948	0.33632	0.09282
Commercial hardstand	6.51431	2.53251	0	0	1.28484	0.51756	0.77034	1.53569	0.77034	1.53569	3.38792	0.93498
Commercial roof	7.38043	2.86922	0	0	1.32700	0.53454	0.64949	1.29477	0.64949	1.29477	3.90561	1.07785
Commercial pervious	17.78314	6.91338	0	0	32.92973	13.26479	2.22145	4.42849	2.22145	4.42849	9.11530	2.51558
Commercial water	0	0	0	0	0.05460	0.02199	0	0	0	0	0	0
Suburban road	10.77831	4.19018	0.73186	6.26525	12.30299	4.95590	2.64384	5.27054	2.64384	5.27054	12.01325	3.31534
Suburban hardstand	13.56212	5.27241	1.15220	9.86371	14.49177	5.83759	3.18411	6.34758	3.18411	6.34758	12.88176	3.55503
Suburban roof	49.75319	19.34207	3.12461	26.74904	46.70982	18.81570	11.68760	23.29944	11.68760	23.29944	47.17029	13.01776
Suburban pervious	55.40174	21.53800	3.50165	29.97680	72.67577	29.27533	14.37982	28.66642	14.37982	28.66642	77.11695	21.28225
Suburban water	7.51E-05	2.92E-05	0	0	2.51E-05	1.01E-05	0	0	0	0	0.00033	8.97E-05
Open space road	10.01014	3.89155	0	0	5.67404	2.28562	2.44259	4.86935	2.44259	4.86935	6.28860	1.73549
Open space hardstand	6.52754	2.53765	0.53100	4.54575	4.94635	1.99249	1.51306	3.01630	1.51306	3.01630	5.23212	1.44393
Open space roof	0.72237	0.28083	0.00733	0.06271	0.39423	0.15880	0.12290	0.24500	0.12290	0.24500	0.85361	0.23557
Open space pervious	46.04883	17.90196	2.63256	22.53675	49.70804	20.02344	10.34895	20.63080	10.34895	20.63080	50.24425	13.86609
Open space water	0.52547	0.20428	0	0	0	0	0	0	0	0	0	0
Bushland road	0	0	0	0	0	0	0	0	0	0	3.29003	0.90796
Bushland hardstand	0	0	0	0	0	0	0	0	0	0	0.86734	0.23936
Bushland roof	0	0	0	0	0	0	0	0	0	0	0.11853	0.03271
Bushland pervious	0	0	0	0	4	2	0	0	0	0	116.54473	32.16329
Bushland water	0	0	0	0	0	0	0	0	0	0	0	0
Rural road	0	0	0	0	0	0	0	0	0	0	0	0
Rural hardstand	0	0	0	0	0	0	0	0	0	0	0	0
Rural roof	0	0	0	0	0	0	0	0	0	0	0	0
Rural pervious	30.00000	11.66281	0	0	0	0	0	0	0	0	0	0
Rural water	0	0	0	0	0	0	0	0	0	0	0	0
Sports field	1.63753	0.63661	0	0	1.16687	0.47004	0.13350	0.26613	0.13350	0.26613	12.98638	3.58390
Total subcatchment area	257.22790	100	11.68120	100	248.24920	100	50.16260	100	50.16260	100	362.35330	100

Table C3 cont. Area of land use functional units within Lake Tuggeranong subcatchments (see Table C2), in hectares (ha) and as a percentage of subcatchment area (%).

Functional unit	TC6 (ha)	TC6 (%)	TC7 (ha)	TC7 (%)	TC6 NSW (ha)	TC6 NSW (%)	TC8 NSW (ha)	TC8 NSW (%)
Commercial road	0	0	0	0	0	0	0	0
Commercial hardstand	0	0	0	0	0	0	0	0
Commercial roof	0	0	0	0	0	0	0	0
Commercial pervious	0	0	0	0	0	0	0	0
Commercial water	0	0	0	0	0	0	0	0
Suburban road	0	0	0	0	0	0	0	0
Suburban hardstand	0.00375	0.00369	0	0	0	0	0	0
Suburban roof	0.00153	0.00150	0	0	0	0	0	0
Suburban pervious	0.00685	0.00674	0	0	0	0	0	0
Suburban water	0	0	0	0	0	0	0	0
Open space road	0.20877	0.20533	0.04334	0.00706	0	0	0	0
Open space hardstand	0.07513	0.07389	0.03677	0.00599	0	0	0	0
Open space roof	0.01225	0.01205	0.00597	0.00097	0	0	0	0
Open space pervious	4.06725	4.00025	0.25709	0.04191	0.00258	0.02625	2.64149	0.31220
Open space water	0	0	0	0	0	0	0	0
Bushland road	6.02788	5.92859	6.56298	1.06977	0	0	0	0
Bushland hardstand	0.71094	0.69923	1.62155	0.26431	0	0	0	0
Bushland roof	0.27050	0.26604	0.35840	0.05842	0	0	0	0
Bushland pervious	90.27019	88.78316	298.69189	48.68689	0.00055	0.00561	0.00130	0.00015
Bushland water	0.01985	0.01952	0.10036	0.01636	0	0	0	0
Rural road	0	0	0.24039	0.03918	0	0	0	0
Rural hardstand	0	0	0.53294	0.08687	0	0	5.00E-05	5.91E-06
Rural roof	0	0	0.64118	0.10451	0	0	7.50E-05	8.87E-06
Rural pervious	0	0	304.00698	49.55325	9.82337	99.96815	843.45908	99.68764
Rural water	0	0	0.39566	0.06449	0	0	0	0
Sports field	0	0	0	0	0	0	0	0
Total subcatchment area	101.67490	100	613.49550	100	9.82650	100	846.10200	100

Table C3 cont. Area of land use functional units within Lake Tuggeranong subcatchments (see Table C2), in hectares (ha) and as a percentage of subcatchment area (%).

Functional unit	WS0 (ha)	WS0 (%)	WS1 (ha)	WS1 (%)	WS2 (ha)	WS2 (%)	WS3 (ha)	WS3 (%)	WS4 (ha)	WS4 (%)
Commercial road	0	0	0	0	1.54112	0.82442	0	0	0	0
Commercial hardstand	0.22877	0.74891	1.55212	1.03660	6.70734	3.58810	0	0	0.01836	0.02462
Commercial roof	0.36464	1.19371	2.44706	1.63431	8.64741	4.62595	0	0	0.00633	0.00849
Commercial pervious	1.71141	5.60254	3.03841	2.02924	8.14436	4.35684	0	0	0.07058	0.09467
Commercial water	0	0	0	0	0	0	0	0	0	0
Suburban road	1.18540	3.88057	9.03820	6.03629	7.84594	4.19720	0.67185	6.88093	1.71359	2.29845
Suburban hardstand	2.50062	8.18613	9.28827	6.20331	8.99315	4.81090	0.51682	5.29313	2.21056	2.96504
Suburban roof	8.63839	28.27903	32.95523	22.00964	32.99276	17.64954	2.46192	25.21422	8.27366	11.09754
Suburban pervious	8.11016	26.54977	49.31735	32.93733	54.74475	29.28581	4.14976	42.50066	12.91723	17.32601
Suburban water	0	0	2.50E-05	1.67E-05	0.00105	0.00056	0	0	0.00045	0.00060
Open space road	1.26220	4.13198	4.93795	3.29788	9.44718	5.05379	0.16886	1.72939	5.19069	6.96232
Open space hardstand	0.97098	3.17863	3.53733	2.36246	5.75370	3.07795	0.07289	0.74654	1.88015	2.52187
Open space roof	0.11025	0.36091	0.46175	0.30838	1.12409	0.60134	0.00465	0.04762	0.24454	0.32801
Open space pervious	5.43135	17.78029	31.69643	21.16893	35.70274	19.09925	1.71724	17.58751	15.71887	21.08387
Open space water	0.03285	0.10754	0.00560	0.00374	0	0	0	0	0	0
Bushland road	0	0	0	0	0	0	0	0	0.51420	0.68970
Bushland hardstand	0	0	0	0	0.00187	0.00100	0	0	0.06840	0.09175
Bushland roof	0	0	0	0	0	0	0	0	0.02153	0.02888
Bushland pervious	0	0	0	0	0.32207	0.17229	0	0	25.70486	34.47818
Bushland water	0	0	0	0	0	0	0	0	0	0
Rural road	0	0	0	0	0	0	0	0	0	0
Rural hardstand	0	0	0	0	0	0	0	0	0	0
Rural roof	0	0	0	0	0	0	0	0	0	0
Rural pervious	0	0	0	0	0	0	0	0	0	0
Rural water	0	0	0	0	0	0	0	0	0	0
Sports field	0	0	1.45519	0.97187	4.96317	2.65506	0	0	0	0
Total subcatchment area	30.547	100	149.7309	100	186.9327	100	9.764	100	74.554	100

Table C3 cont. Area of land use functional units within Lake Tuggeranong subcatchments (see Table C2), in hectares (ha) and as a percentage of subcatchment area (%).

Functional unit	FA0 (ha)	FA0 (%)	FA1 (ha)	FA1 (%)	FA2 (ha)	FA2 (%)	FA3 (ha)	FA3 (%)	FA5 (ha)	FA5 (%)	FA6 (ha)	FA6 (%)
Commercial road	0.00155	0.00077	0.00178	0.00390	0	0	0	0	0	0	0	0
Commercial hardstand	0.68547	0.33986	1.27610	2.80488	0	0	0.56164	0.42239	0	0	0	0
Commercial roof	1.04842	0.51982	1.47323	3.23817	0	0	0.68604	0.51595	0	0	0	0
Commercial pervious	3.23227	1.60258	6.71763	14.76535	0	0	4.86537	3.65908	0	0	0	0
Commercial water	0	0	0	0	0	0	0	0	0	0	0	0
Suburban road	12.21125	6.05443	3.05012	6.70417	0.26349	3.19399	8.76270	6.59013	0	0	1.31484	1.83693
Suburban hardstand	12.72037	6.30686	2.42518	5.33055	0.25484	3.08907	9.77361	7.35040	0.00222	0.03223	1.43267	2.00154
Suburban roof	48.91619	24.25304	7.39270	16.24915	1.04438	12.65981	33.22342	24.98620	0.05123	0.74231	5.36633	7.49712
Suburban pervious	74.69462	37.03419	11.53219	25.34776	1.75898	21.32205	50.77288	38.18454	0.10458	1.51540	8.99825	12.57116
Suburban water	0.00150	0.00074	0	0	0	0	0.00090	0.00068	0	0	0	0
Open space road	8.37676	4.15327	2.07507	4.56101	0.00935	0.11339	2.20094	1.65525	0.33517	4.85688	1.70013	2.37520
Open space hardstand	4.42618	2.19454	1.77967	3.91171	0.03974	0.48167	1.71507	1.28985	0.20396	2.95548	2.54351	3.55345
Open space roof	0.47688	0.23644	0.10978	0.24129	0.00427	0.05176	0.20312	0.15276	0.04800	0.69560	1.01666	1.42034
Open space pervious	34.29041	17.00146	6.51373	14.31717	0.42130	5.10688	18.91811	14.22766	2.77117	40.15607	40.27044	56.26052
Open space water	0	0	0	0	0.04402	0.53359	0	0	0	0	5.00E-05	6.99E-05
Bushland road	0	0	0	0	0.15460	1.87402	0	0	0	0	0.00000	0.00000
Bushland hardstand	0	0	0	0	0.01489	0.18053	0	0	0	0	0.00713	0.00995
Bushland roof	0	0	0	0	0.01464	0.17746	0	0	0	0	0.01075	0.01502
Bushland pervious	0	0	0	0	4.22510	51.21578	0	0	0	0	8.91775	12.45869
Bushland water	0	0	0	0	0	0	0	0	0	0	0	0
Rural road	0	0	0	0	0	0	0	0	0	0	0	0
Rural hardstand	0	0	0	0	0	0	0	0	0	0	0	0
Rural roof	0	0	0	0	0	0	0	0	0	0	0	0
Rural pervious	0	0	0	0	0	0	0	0	0	0	0	0
Rural water	0	0	0	0	0	0	0	0	0	0	0	0
Sports field	0.60912	0.30201	1.14873	2.52490	0	0	1.28330	0.96513	3.38467	49.04604	0	0
Total subcatchment area	201.69100	100	45.49590	100	8.24960	100	132.96710	100	6.90100	100	71.57845	100

Table C3 cont. Area of land use functional units within Lake Tuggeranong subcatchments (see Table C2), in hectares (ha) and as a percentage of subcatchment area (%).

Functional unit	FA7 (ha)	FA7 (%)	FA8 (ha)	FA8 (%)	FA9 (ha)	FA9 (%)	FA10 (ha)	FA10 (%)	FA11 (ha)	FA11 (%)	FA12 (ha)	FA12 (%)
Commercial road	0	0	0	0	0.96626	0.58898	0	0	0.15920	0.21730	0	0
Commercial hardstand	0	0	0.09825	0.09336	2.87939	1.75511	0.01547	0.62058	0.81899	1.11787	0.84147	7.30903
Commercial roof	0	0	0.28170	0.26767	2.81759	1.71744	0.01910	0.76595	0.99322	1.35568	1.03335	8.97575
Commercial pervious	0	0	1.17809	1.11941	3.34845	2.04102	0.12335	4.94762	2.15616	2.94302	2.27579	19.76764
Commercial water	0	0	0	0	0	0	0	0	0	0	0	0
Suburban road	0.24393	1.83693	3.40824	3.23849	7.53109	4.59051	0	0	2.25456	3.07734	0.05280	0.45865
Suburban hardstand	0.26579	2.00154	4.42791	4.20736	8.06460	4.91570	0	0	2.19261	2.99278	0.08285	0.71968
Suburban roof	0.99555	7.49712	18.40574	17.48898	28.53998	17.39629	0	0	9.76619	13.33023	0.71281	6.19152
Suburban pervious	1.66934	12.57116	29.18282	27.72928	45.86605	27.95723	0	0	14.57372	19.89220	1.08328	9.40943
Suburban water	0	0	0	0	2.49E-05	1.52E-05	0	0	2.50E-05	3.41E-05	0	0
Open space road	0.31540	2.37520	4.65181	4.42011	3.14482	1.91690	0.41795	16.76375	1.63615	2.23324	0.58038	5.04121
Open space hardstand	0.47187	3.55345	2.44401	2.32228	1.98188	1.20804	0.17292	6.93569	1.13037	1.54288	0.57485	4.99321
Open space roof	0.18861	1.42034	0.20423	0.19406	0.18810	0.11466	0.00655	0.26267	0.17858	0.24375	0.09548	0.82934
Open space pervious	7.47089	56.26052	15.52775	14.75434	17.56257	10.70510	1.50429	60.33586	10.68431	14.58340	4.16896	36.21182
Open space water	9.28E-06	6.99E-05	0.01460	0.01387	0	0	0	0	0	0	0.01068	0.09273
Bushland road	0.00000	0.00000	0.14620	0.13892	2.44566	1.49073	0	0	0.18495	0.25245	0	0
Bushland hardstand	0.00132	0.00995	0.74621	0.70904	0.57236	0.34888	0	0	0.12498	0.17059	0	0
Bushland roof	0.00199	0.01502	0.21660	0.20581	0.06938	0.04229	0	0	0.00813	0.01109	0	0
Bushland pervious	1.65440	12.45869	24.30774	23.09701	34.67503	21.13585	0	0	25.02885	34.16279	0	0
Bushland water	0	0	0	0	0.01220	0.00744	0	0	0	0	0	0
Rural road	0	0	0	0	0	0	0	0	0	0	0	0
Rural hardstand	0	0	0	0	0	0	0	0	0	0	0	0
Rural roof	0	0	0	0	0	0	0	0	0	0	0	0
Rural pervious	0	0	0	0	0	0	0	0	0	0	0	0
Rural water	0	0	0	0	0	0	0	0	0	0	0	0
Sports field	0	0	0	0	3.39245	2.06784	0.23356	9.36789	1.37250	1.87337	0	0
Total subcatchment area	13.27909	100	105.24190	100	164.05787	100	2.49320	100	73.26347	100	11.51270	100

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Table C3 cont. Area of land use functional units within Lake Tuggeranong subcatchments (see Table C2), in hectares (ha) and as a percentage of subcatchment area (%).

Functional unit	FA13 (ha)	FA13 (%)	FA14 (ha)	FA14 (%)	FA15 (ha)	FA15 (%)	FA16 (ha)	FA16 (%)	FA17 (ha)	FA17 (%)	FA9 NSW (ha)	FA9 NSW (%)
Commercial road	0	0	0	0	0	0	0	0	0	0	0	0
Commercial hardstand	0	0	0	0	0	0	0.00048	0.00069	0	0	0	0
Commercial roof	0	0	0	0	0	0	0.01188	0.01718	0	0	0	0
Commercial pervious	0.02585	1.29481	0	0	0	0	0.04275	0.06184	0	0	0	0
Commercial water	0	0	0	0	0	0	0	0	0	0	0	0
Suburban road	0	0	0	0	0.99534	6.47445	4.91072	7.10386	2.05614	3.19399	0	0
Suburban hardstand	0	0	0	0	0.98473	6.40548	4.14411	5.99488	1.98860	3.08907	0	0
Suburban roof	0	0	0	0	4.20349	27.34277	16.32055	23.60934	8.14979	12.65981	0	0
Suburban pervious	0	0	0	0	5.84599	38.02693	24.30567	35.16064	13.72613	21.32205	0	0
Suburban water	0	0	0	0	0	0	0	0	0	0	0	0
Open space road	0.02215	1.10948	0	0	0.84631	5.50505	1.22231	1.76820	0.07299	0.11339	0	0
Open space hardstand	0.01945	0.97424	0.01723	4.25808	0.46344	3.01456	1.04693	1.51450	0.31008	0.48167	0	0
Open space roof	0.02070	1.03685	0.00050	0.12360	0.07351	0.47819	0.07243	0.10477	0.03332	0.05176	0	0
Open space pervious	0.62372	31.24084	0.38697	95.61832	1.84850	12.02407	7.92437	11.46341	3.28757	5.10688	0.02229	0.03109
Open space water	0	0	0	0	0	0	0.00198	0.00286	0.34350	0.53359	0	0
Bushland road	0	0	0	0	0	0	0.04578	0.06622	1.20641	1.87402	0	0
Bushland hardstand	0	0	0	0	0	0	0.00348	0.00503	0.11622	0.18053	0	0
Bushland roof	0	0	0	0	0	0	0.00023	0.00033	0.11424	0.17746	2.50E-05	3.49E-05
Bushland pervious	0	0	0	0	0	0	9.02073	13.04941	32.97031	51.21578	0.00283	0.00394
Bushland water	0	0	0	0	0	0	0	0	0	0	0	0
Rural road	0	0	0	0	0	0	0	0	0	0	0	0
Rural hardstand	0	0	0	0	0	0	0	0	0	0	0	0
Rural roof	0	0	0	0	0	0	0	0	0	0	0	0
Rural pervious	0	0	0	0	0	0	0	0	0	0	71.66356	99.96493
Rural water	0	0	0	0	0	0	0	0	0	0	0	0
Sports field	1.28462	64.34376	0	0	0.11200	0.72851	0.05313	0.07685	0	0	0	0
Total subcatchment area	1.99650	100	0.40470	100	15.37330	100	69.12750	100	64.37530	100	71.68867	100

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Appendix D: Literature-derived EMC and DWC values

Baseline values of the event mean concentrations (EMC) and dry weather concentrations (DWC) of total phosphorus (TP), total nitrogen (TN) and total suspended solids (TSS) generated by functional land use units were derived from the literature for initial parameterisation of the model. The EMC values were then scaled based on date-matched observations. Tables D1-D3 present the baseline EMC and DWC values for each functional unit.

Table D1: Baseline total phosphorus (TP) EMC and DWC values (mg/L) derived from the literature for each combination of functional land use and surface imperviousness.

Land surface imperviousness	Suburban	Commercial	Open space	Rural	Bushland	Sports field
Road	EMC: 0.501 DWC: 0.015	EMC: 0.501 DWC: 0.015	EMC: 0.501 DWC: 0.015	EMC: 0.251 DWC: 0.015	EMC: 0.251 DWC: 0.015	
Hardstand	EMC: 0.251 DWC: 0.015	EMC: 0.251 DWC: 0.015	EMC: 0.251 DWC: 0.015	EMC: 0.251 DWC: 0.015	EMC: 0.251 DWC: 0.015	
Roof	EMC: 0.128 DWC: 0.015	EMC: 0.128 DWC: 0.015	EMC: 0.128 DWC: 0.015	EMC: 0.251 DWC: 0.015	EMC: 0.251 DWC: 0.015	
Pervious	EMC: 0.251 DWC: 0.04	EMC: 0.251 DWC: 0.04	EMC: 0.251 DWC: 0.04	EMC: 0.218 DWC: 0.04	EMC: 0.079 DWC: 0.04	EMC: 0.251 DWC: 0.015
Water	EMC: 0 DWC: 0	EMC: 0 DWC: 0	EMC: 0 DWC: 0	EMC: 0 DWC: 0	EMC: 0 DWC: 0	

Table D2: Baseline total nitrogen (TN) EMC and DWC values (mg/L) derived from the literature for each combination of functional land use and surface imperviousness.

Land surface imperviousness	Suburban	Commercial	Open space	Rural	Bushland	Sports field
Road	EMC: 2.187 DWC: 1.0	EMC: 2.187 DWC: 1.0	EMC: 2.187 DWC: 1.0	EMC: 2.187 DWC: 1.0	EMC: 2.187 DWC: 1.0	
Hardstand	EMC: 2.187 DWC: 1.0	EMC: 2.187 DWC: 1.0	EMC: 2.187 DWC: 1.0	EMC: 2.187 DWC: 1.0	EMC: 2.187 DWC: 1.0	
Roof	EMC: 1.995 DWC: 1.0	EMC: 1.995 DWC: 1.0	EMC: 1.995 DWC: 1.0	EMC: 1.995 DWC: 1.0	EMC: 1.995 DWC: 1.0	
Pervious	EMC: 1.995 DWC: 0.4	EMC: 1.995 DWC: 0.4	EMC: 1.995 DWC: 0.4	EMC: 1.995 DWC: 0.4	EMC: 1.995 DWC: 0.4	EMC: 1.995 DWC: 1.0
Water	EMC: 0 DWC: 0	EMC: 0 DWC: 0	EMC: 0 DWC: 0	EMC: 0 DWC: 0	EMC: 0 DWC: 0	

Table D3: Baseline total suspended solids (TSS) EMC and DWC values (mg/L) derived from the literature for each combination of functional land use and surface imperviousness.

Land surface imperviousness	Suburban	Commercial	Open space	Rural	Bushland	Sports field
Road	EMC: 269.15 DWC: 15.849	EMC: 269.15 DWC: 15.849	EMC: 269.15 DWC: 15.849	EMC: 269.15 DWC: 15.849	EMC: 269.15 DWC: 15.849	
Hardstand	EMC: 269.15 DWC: 15.849	EMC: 269.15 DWC: 15.849	EMC: 269.15 DWC: 15.849	EMC: 269.15 DWC: 15.849	EMC: 269.15 DWC: 15.849	
Roof	EMC: 19.95 DWC: 15.849	EMC: 19.95 DWC: 15.849	EMC: 19.95 DWC: 15.849	EMC: 19.95 DWC: 15.849	EMC: 19.95 DWC: 15.849	
Pervious	EMC: 141.25 DWC: 15.849	EMC: 141.25 DWC: 15.849	EMC: 141.25 DWC: 15.849	EMC: 89.12 DWC: 15.849	EMC: 39.81 DWC: 15.849	EMC: 141.25 DWC: 15.849
Water	EMC: 0 DWC: 0	EMC: 0 DWC: 0	EMC: 0 DWC: 0	EMC: 0 DWC: 0	EMC: 0 DWC: 0	

Appendix E: Modelled annual load of total phosphorous

The table below provides total phosphorous generated for each combination of functional land use and surface imperviousness annually.

Table E1: Modelled annual total phosphorus (TP) load (kg/yr) generated for each combination of functional land use and surface imperviousness.

Land surface imperviousness	Road TP (kg/yr)	Hardstand TP (kg/yr)	Roof TP (kg/yr)	Pervious TP (kg/yr)	Water TP (kg/yr)
Suburban	322	169	314	140	0
Commercial	17	45	30	16	0
Open space	243	76	5	88	0
Rural	0	0	1	132	0
Sports field	0	0	0	58	0
Total annual load (kg/yr)	582	290	350	434	0

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Attachment H

ACT Government

Predicting phosphorus concentration and trophic state of Lake Tuggeranong

Technical report supplement to the Lake Tuggeranong Catchment Model

Water Information Services, ACT Office of Water

December 2024

Environment, Planning and Sustainable Development Directorate

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1. Introduction

Vollenweider's (1975, 1976) mass-balance equations, overall, model how the total phosphorous (TP) concentration of a lake ($\mathrm{TP_{lake}}$) is related to the TP concentration of inflows ($\mathrm{TP_{in}}$) and the hydraulic residence/retention time (τ_w). This residence time can be thought of as the average time an incoming water molecule can expect to remain in the lake before leaving the lake through outflow and is calculated by simply dividing the volume of the lake by the outflow rate.

Vollenweider (1976 – Equation 2.13) described this relationship mathematically with the equation below (as re-stated in Brett & Benjamin 2008 – Equation 6):

$$\mathrm{TP_{lake}} = \frac{\mathrm{TP_{in}}}{1+\sigma\tau_w} \qquad (1)$$

Where σ is the first-order rate coefficient of TP loss within the lake due to sedimentation. As this rate is not easily quantified, several different approaches have been proposed to approximate it. Brett & Benjamin (2008) summarised and compared the relative performance of these different approaches using known values from 305 lakes from Europe and North America. They found that all approaches provided a useful fit with real-world values, but that the best-fitting approach was to assume that σ is a function of ${k\tau_w}^x$, where k and x are constants, fitted statistically. This approach was previously used by Larsen & Mercier (1976), who reported a value of x near -0.5.

With this approximation, equation 1 becomes:

$$\mathrm{TP_{lake}} = \frac{\mathrm{TP_{in}}}{1+({k\tau_w}^x)\tau_w} \qquad (2)$$

Brett & Benjamin (2008) found that values of around k=1.12 and x=-0.53 yielded a correlation between predicted and observed TP_{lake} values with r^2>0.8 for the dataset investigated, yielding the following relationship:

$$\mathrm{TP_{lake}} = \frac{\mathrm{TP_{in}}}{1+\left(1.12\times\tau_w^{-0.53}\right)*\tau_w} \qquad (3)$$

If we then approximate k=1 and x=-0.5, equation 3 simplifies to:

$$\mathrm{TP_{lake}} = \frac{\mathrm{TP_{in}}}{1+\sqrt{\tau_w}} \qquad (4)$$

Vollenweider (1976) previously suggested this approximation of the general equation fits with empirical studies, and this relationship was used by Beer *et al.* 1982 in their early work on Lake Tuggeranong.

2. In-Lake Model

2.1 Parameterisation of the modified Vollenweider model

The adjusted Vollenweider model (equation 2) was parameterised using estimates of inflow TP concentrations and inflow and outflow volumes from the Lake Tuggeranong catchment model (Dey et al. 2024), and observed Lake Tuggeranong TP concentrations from the ALS Lakes and Rivers Water Quality Monitoring Program, but with the following caveats:

- The model assumes a steady state of inflows and influent concentrations, which is a limitation to real-world applications, so it is unclear how reliable we should expect its predictions over shorter time periods to be. That being said, past modelling of TP loads has suggested that 3 hydraulic residence times is sufficient for 95% convergence with steady-state predictions (Sonzogni *et al.* 1976), which is <1 year for most years in Lake Tuggeranong. For this reason, our modelling approach will work with annual time steps, with all model inputs and outputs to be interpreted as annual averages.
- In past applications of this model-fitting approach, data across many different lakes were used, with each lake representing a separated datapoint (e.g. Brett & Benjamin 2008, Larsen & Mercier 1976). Here, the datapoints are all from Lake Tuggeranong, just from different years, and are thus pseudo-replicated. However, to provide a Lake Tuggeranong -specific model that will not be applied elsewhere this approach is probably reasonable. It would be informative to repeat this modelling approach in other ACT lakes and compare fitted values later, to investigate the appropriateness of an overall ACT-wide model using data from all different lakes.
- In other applications of Vollenweider model the same value for water inflow and outflow are used (i.e. assumption of no other source of water loss). Since the catchment model have taken into account of the lake water balance.

To parametrise the modified Vollenweider model, we can use annual total TP loads and water inflows and outflows from the Tuggeranong Source Catchment Model. Specifically:

- l_{in}: the annual TP load flowing into Lake Tuggeranong (converted to mg),
- v_{in}: the annual inflow volume of water into Lake Tuggeranong (converted to L)
- v_{out}: the annual outflow volume of water from Lake Tuggeranong (converted to L)

We can then combine these parameters, along with the approximate total volume of Lake Tuggeranong (V= 1,780,000,000L), to calculate the TP concentration of inflows (TP_{in}, measured in mg/L) and the hydraulic residence time (τ_w, measured in years) as follows:

$$\text{TP}_{\text{in}} = \frac{l_{\text{in}}}{v_{\text{in}}} \quad (5)$$

$$\tau_w = \frac{V}{v_{\text{out}}} \quad (6)$$

The predicted annual average TP_{in} and τ_w values from 1990-2022 are summarised in Table 1 and shown in Figure 1.

Table 1. Summary of Lake Tuggeranong annual values of inflow total phosphorus concentration TP_{in} and hydraulic residence time τ_w from 1990-2022.

	$\mathbf{TP_{in}}$ **(mg/L)**	$\boldsymbol{\tau_w}$ **(y)**
Minimum	0.152	0.055
Median	0.163	0.251
Maximum	0.174	0.727

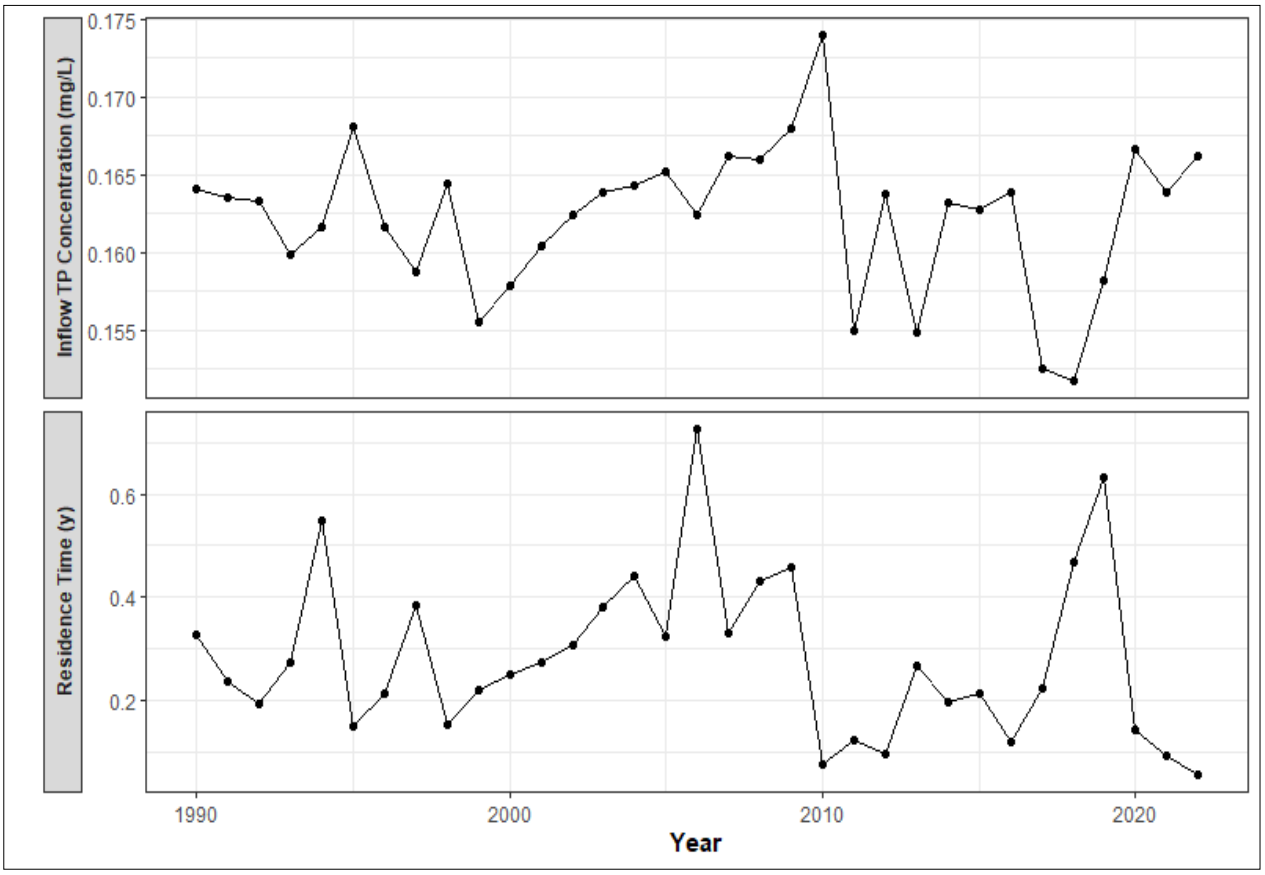

Figure 1. Annual changes in inflow concentrations of total phosphorus (TP_{in}, top panel) and residence time (τ_w, bottom panel) in Lake Tuggeranong, 1990-2022.

2.2 Estimation of total phosphorus and chlorophyll a concentration

Using the modified Vollenweider model (equation 2) $\mathrm{TP_{lake}}$ concentration can be predicted using $\mathrm{TP_{in}}$ and τ_w values. Before estimating the TP_{lake}, fitting of the constants k and x is required such that modelled $\mathrm{TP_{lake}}$ values provide as close-as-possible match to observed $\mathrm{TP_{lake}}$ values. Here, our source of observed $\mathrm{TP_{lake}}$ values come from the ALS Lakes and Rivers Water Quality Monitoring Program from 2005-2022. This period was chosen because it represents the longest run of annual sampling of LT TP concentrations with

relatively constant annual sampling effort (most years had 8 samples from each of two locations within Lake Tuggeranong: LTG248 and LTG249). Other sources of data (e.g. University of Canberra research) did not provide a similar temporal scope, meaning their inclusion would have led to large variability in the underlying sampling effort behind annual averages, which was undesirable here. Waterwatch data was also not used here due to questions about data reliability specifically related to TP measures relative to lab techniques (Harrison *et al.* 2013).

To fit optimal values of k and x to our modified Vollenweider model, an approach similar to Brett & Benjamin (2008) was adopted. Specifically, a function was created in R that would, for given values of k and x, predict lake TP concentrations ($\mathrm{TP}_{\mathrm{predicted}}$) and compare them to average annual observed lake TP concentrations $\mathrm{TP}_{\mathrm{observed}}$ values to calculate the weighted error sum of squares (WESS) as follows:

$$\mathrm{WESS} = \sum \mathrm{weight} \times \left(\mathrm{TP}_{\mathrm{observed}} - \mathrm{TP}_{\mathrm{predicted}}\right)^2 \qquad (7)$$

The number of samples that each annual average was based on as weights was used, such that years that had annual averages based on relatively few datapoints (e.g. 2020 due to lockdowns) contributed relatively less to the WESS. This WESS provides a measure of how closely matched predicted and observed TP values are, with low WESS values indicating a better fitting model.

This function was then used alongside a solver function in R to find a combination of k and x values that minimised the WESS and thus represented the best fit to the observed data. This solver yielded values of $k = 1.093$ and $x = -0.791$. These values are similar to those reported elsewhere (e.g. Brett & Benjamin 2008) and not particularly inconsistent with the unmodified Vollenweider model used by Beer *et al.* 1982 in their early work on LT. Sensitivity analysis of this optimisation was performed by re-calculating the

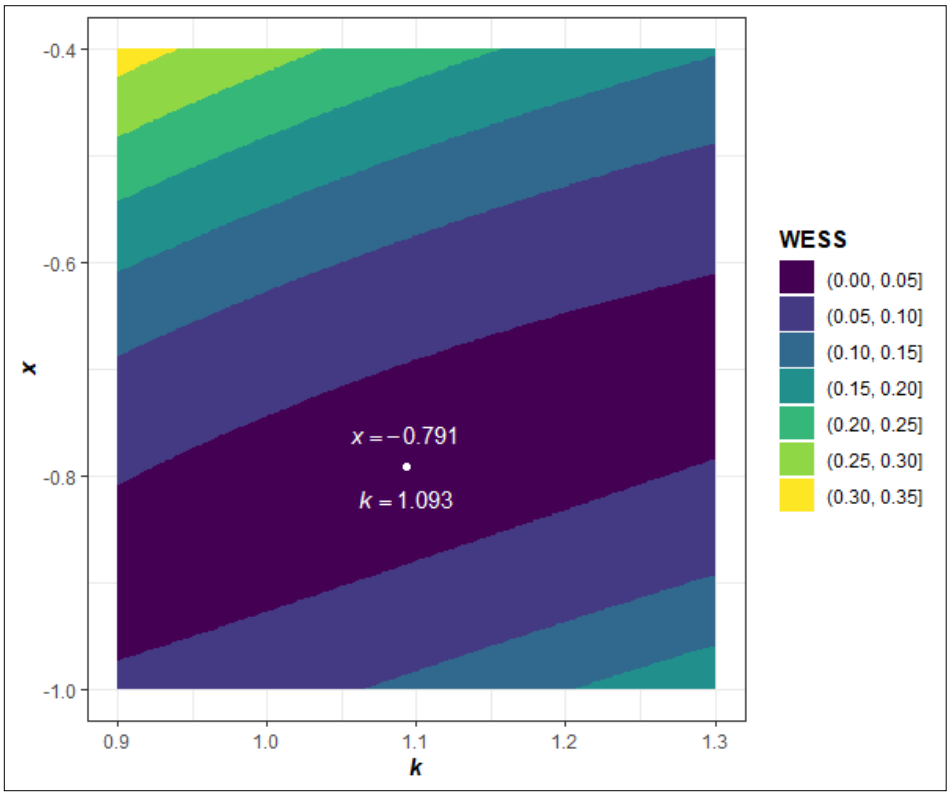

Figure 2. Sensitivity of the Lake Tuggeranong modified Vollenweider model to changes in *k* and *x* in terms of the resultant weighted error sum of squares (WESS). The white point indicates the optimal values.

resultant WESS with a range of k and x values. This analysis indicated that a relatively wide band of k and x values yielded similarly good fits (indicated by relatively low WESS values: Figure 2), which again was consistent with the findings of Brett & Benjamin 2008.

Using the fitted values of k and x, the modified Vollenweider model is represented in equation 8:

$$\mathrm{TP}_{\mathrm{lake}} = \frac{\mathrm{TP}_{\mathrm{in}}}{1+\left(1.093\times\tau_w^{-0.791}\right)*\tau_w} \qquad (8)$$

This yielded predicted $\mathrm{TP}_{\mathrm{lake}}$ values similar to observed values (Table 2, Figure 3).

Table 2. Comparison of observed annual average and predicted total phosphorus concentrations in Lake Tuggeranong (TP_{lake}) from 2005-2022.

	Observed $\mathrm{TP}_{\mathrm{lake}}$ (mg/L)	**Predicted $\mathrm{TP}_{\mathrm{lake}}$ (mg/L)**
Minimum	0.064	0.079
Median	0.086	0.090
Maximum	0.114	0.107

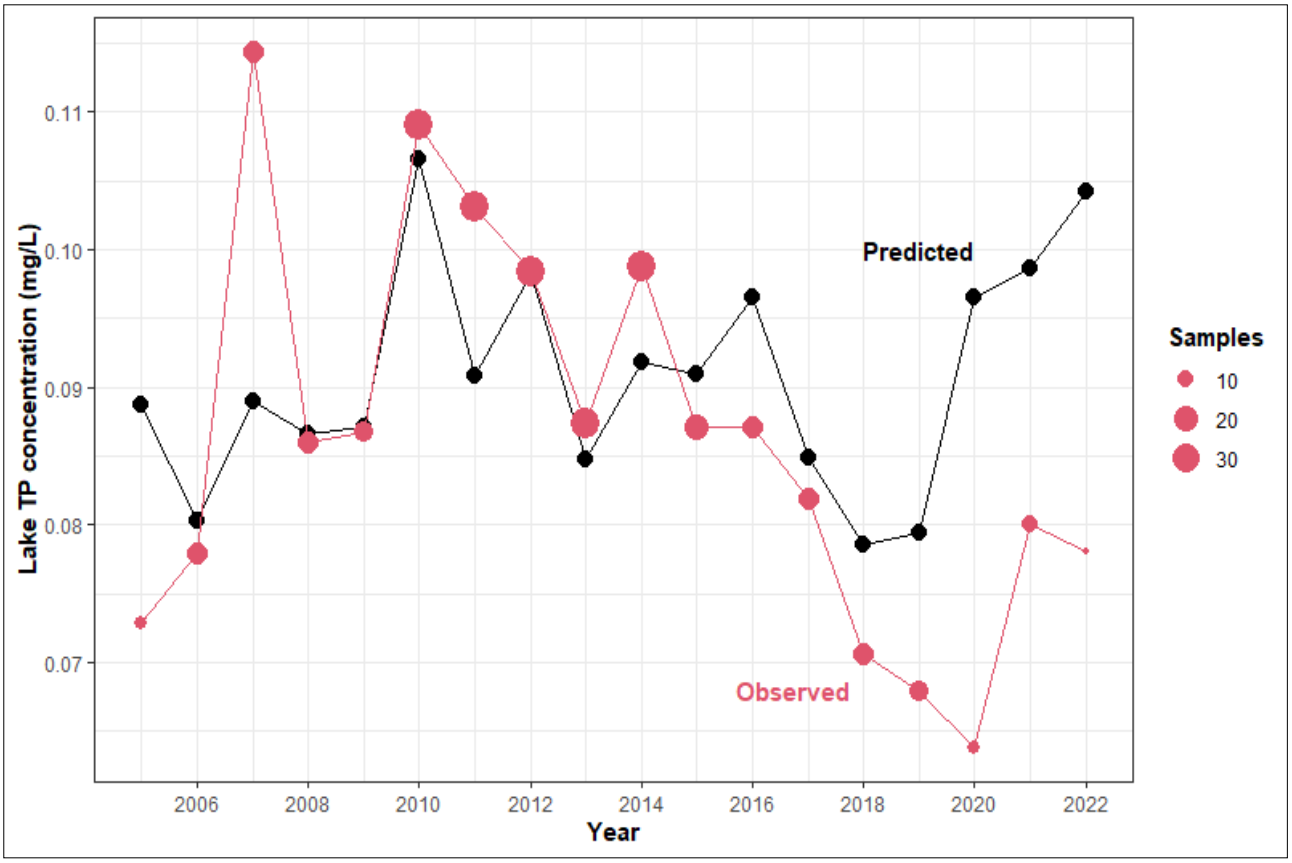

Figure 3. Comparison of observed (red) and predicted (black) annual total phosphorus (TP) concentrations in Lake Tuggeranong from 2005-2022 shows the modified Vollenweider model captures the centre and spread of observed values well with some mirroring of year-to-year trends. Observed values are averages of samples for each year, and data point size represents the number of underlying samples.

The predicted TP concentrations in Lake Tuggeranong had a very similar average and variability to observed TP concentrations, and for many years the two time-series followed similar up/down-wards trajectories (Figure 3). Overall, predicted and observed TP concentrations in Lake Tuggeranong were positively correlated. This was confirmed by a linear regression model relating the two (weighted based on annual sample number), which yielded a significant association between the two variables (ANOVA F-test of slope coefficient: F=8.5889, p=0.0098), and an adjusted r^2 value of 0.3086.

This model can be used to predict the chlorophyll a level using the power relationship described by Lawrence (1980) and applied in Beer *et al.* (1982) in their early work on Lake Tuggeranong:

$$\text{Chlorophyll a} = 0.367 * TP_{Lake}^{0.91} \qquad (9)$$

This relationship was derived from a comparison of several Canberra lakes.

3. Estimation of Lake Trophic State

Using 133 years of annually aggregated Source model output of TP load and inflow water volumes, the above-mentioned models were combined under a range of influent TP reduction scenarios ranging from current/business as usual (BAU: no reduction in TP load), and 100kg to 900kg reduction in annual TP load coming into the lake (with no change to inflow water volumes). Additionally, a predevelopment flow and TP load scenario was considered, which assumed a wholly undeveloped catchment. The Vollenweider model was used to predict annual TP concentrations in the lake for each year under each scenario. This was then converted to predicted chlorophyll a concentration using equation 9. Finally, these predicted concentrations were compared to published cut-offs (e.g. Neil 2012) of chlorophyll a concentration under different trophic states: Oligotrophic <5 µg/L, Mesotrophic <15 µg/L, Eutrophic >15 µg/L.

The predictions for the predevelopment scenario show that, in the absence of development within the catchment, Lake Tuggeranong would likely have experienced a wide range of trophic conditions. In some years the lake would not have received any inflow at all and would likely have reached an oligotrophic state. But in high rainfall years the lake's size and the inflow of TP would have pushed it towards a eutrophic state. This provides a good baseline for considering realistic futures for the lake.

Under the 'current' scenario (BAU), Lake Tuggeranong is predicted to (at the annual, average timescale) remain in a eutrophic state (Figure 4). To avoid a constant eutrophic state, the results of the TP reduction scenarios show that TP load reductions of 600kg or more into Lake Tuggeranong are predicted to result in conditions that are eutrophic less often than not (Figure 4). However, even under high TP load reduction scenarios there will be years of high TP inflow (wet years) where we probably cannot avoid eutrophic conditions developing (as with the pre-development scenario) simply because of the large total TP load entering the lake via stormwater (such that even a >600kg reduction in TP is proportionally fairly insignificant). Conversely, though, dry years with low TP inflows could yield oligotrophic conditions in scenarios with greater than 500kg TP reduction (Figure 4).

Overall, these modelling results suggest that an annual 700kg reduction in TP entering Lake Tuggeranong is an appropriate target for future lake management plans. This level of TP reduction is predicted to lead to

favourable conditions for human recreation in the lake in ~75% of years (~25% oligotrophic, ~50% mesotrophic; Figure 4).

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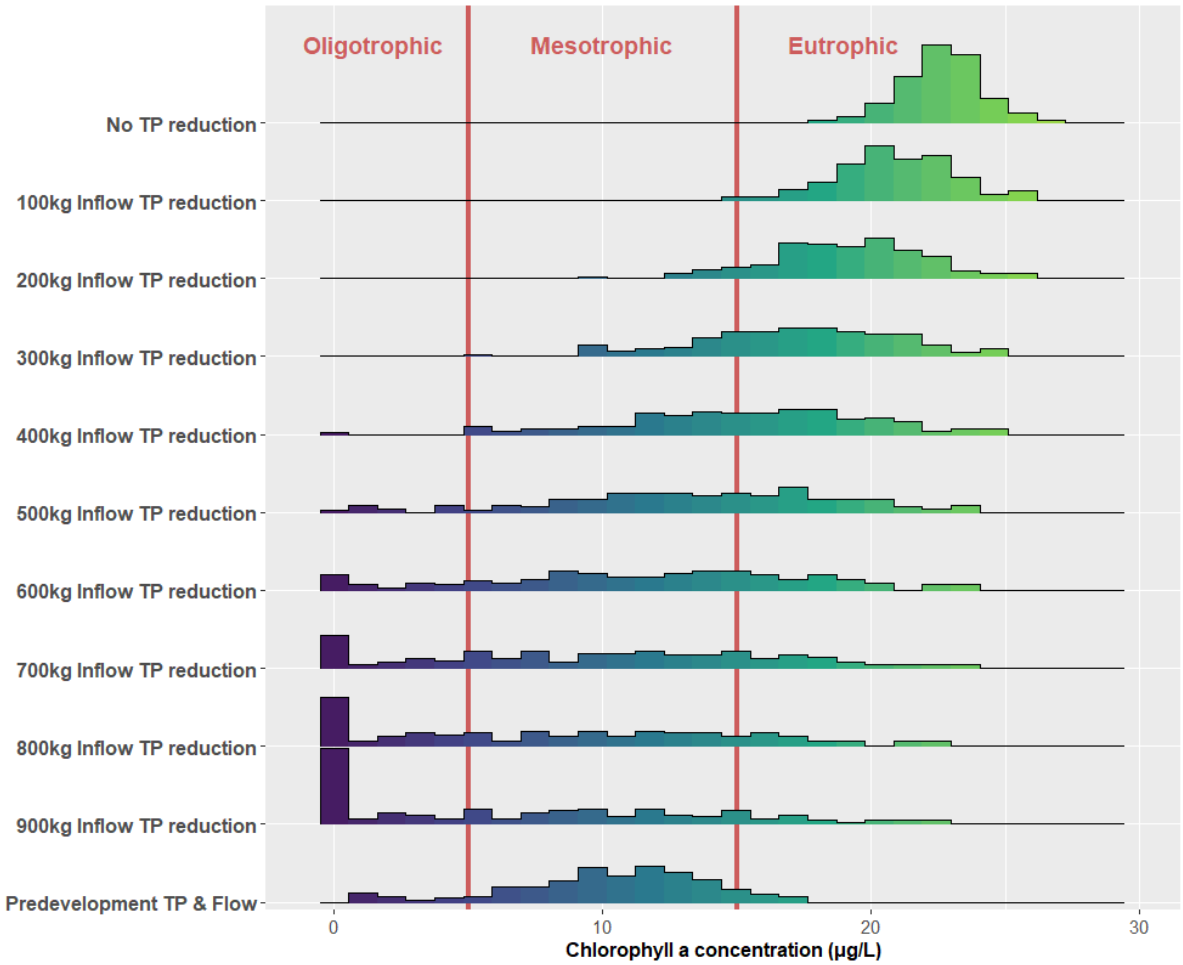

Figure 4. Distribution of annual predicted chlorophyll a concentration (i.e. trophic state) in Lake Tuggeranong under different scenarios of reductions in inflow total phosphorus (TP).

4. Conclusion

Vollenweider's mass-balance model is a simple, but useful, tool for predicting nutrient concentrations in lakes based on influent volumes and concentrations. Whilst they are typically used for comparisons between lakes, in this study the Vollenweider model was modified to derive Lake Tuggeranong specific total phosphorous concentrations. The model produced a reasonable fit with observed values over a 17-year period and could be used in conjunction with catchment model inputs to predict general trends in phosphorous levels in Lake Tuggeranong into the future. The model output was then used to provide an estimate chlorophyll a which is a measure of the trophic state. The estimated chlorophyll a concentration was used to determine the trophic state of the lake under different scenarios. The findings provide an approximate estimate of the target inflow TP load for Lake Tuggeranong to improve the lake trophic conditions, with a target annual reduction of ~700kg of TP yielding favourable predictions.

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Attachment I

ACT Government

Lake Tuggeranong Catchment Management Options Assessment

Technical report supporting the Healthy Waterways Plan for Lake Tuggeranong

Water Information Services, ACT Office of Water

December 2024

Environment, Planning and Sustainable Development Directorate

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Executive Summary

Lake Tuggeranong is a small (57 ha) urban lake in southern Canberra. Lake Tuggeranong was constructed in the late 1980s on Tuggeranong Creek, a 66 km^2 catchment that is predominantly (62%) urbanised. In recent decades, Lake Tuggeranong has been plagued by poor water quality. Since 2017, there has been a concerted effort to improve water quality in the lake through the construction of Water Sensitive Urban Design (WSUD) infrastructure throughout the catchment, and a major research program to understand the causes of poor water quality, and sources of pollutants entering the lake. This work has been undertaken as part of the ACT Healthy Waterways program.

The ACT Government has commited to developing Healthy Waterways Plans for priority catchments in the ACT. The Lake Tuggeranong draft plan provides a suite of potential management options to Government to further improve water quality in Lake Tuggeranong. To acheive this, modelling and analyses have been undertaken to examine a broad range of management scenarios and identify cost-effective options to improve water quality in Lake Tuggeranong, with a focus on reducing the annual load of phosphorus entering the lake.

This report documents the approach taken to assess the predicted performance and cost of 10 proposed catchment management options for reducing the load of phosphorus entering Lake Tuggeranong. For each management option identified, details of the data and information used to calculate the estimates of performance and cost are presented, and summarised in an assessment of cost-effectiveness. To provide a comparison of cost-effectiveness both across and within management options, the cost-effectiveness of four different levels of investment was calculated for each option, ranging from relatively low to relatively high investment. An evaluation of the quality of evidence supporting these estimates and its impact on our confidence in specific values is provided for each management option.

These assessments found that increasing the frequency of municipal street sweeping and the construction of additional WSUD infrastructure were the management options predicted to remove the greatest loads of phosphorus, with street sweeping the most cost-effective option at all levels of investment.

The assessments of management option cost-effectiveness were provided to the ACT Healthy Waterways team who chose options to combine into two proposed management scenarios, with the aim of reducing the phosphorus load entering Lake Tuggeranong (currently ~ 1440 kg/year) by approximately 700 kg/year. A reduction of this amount is predicted to maintain Lake Tuggeranong in a predominantly mesotrophic state, substantially reducing the frequency, extent and duration of blue-green algal blooms (Kahn & Dey, 2024). The proposed management scenarios were then implemented in the catchment model for the Lake Tuggeranong catchment (Dey, Stewart, Kahn, Booksmythe, & Starrs, 2024), to estimate their average annual phosphorus load reductions, accounting for interactive effects of the different options included in a scenario.

Modelling the proposed management scenarios revised down the estimated annual load of phosphorus they were predicted to remove,from 700-750 kg/year to 450-575 kg/year. This is mainly due to the large impact of street sweeping on reducing the concentration of phosphorus in stormwater, which alters the rate of phosphorus removal estimated for management options involving WSUD infrastructure.

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1. Introduction

Lake Tuggeranong is a small (57 ha) urban lake in southern Canberra. The lake was constructed in the late 1980s on Tuggeranong Creek, a 66 km^2 catchment that is predominantly (62%) urbanised. In recent decades, Lake Tuggeranong has been plagued by poor water quality, with high loads of nutrients (phosphorus and nitrogen) and sediments entering the lake, leading to frequent, extensive blue-green algal blooms that result in lake closures. Since 2017, there has been a concerted effort to improve water quality in the lake through the construction of Water Sensitive Urban Design (WSUD) infrastructure such as wetlands, bioretention swales and raingardens throughout the catchment, and a major research program to understand the causes of poor water quality, and sources of pollutants. This work has been undertaken as part of the ACT Healthy Waterways program.

The ACT Government has commited to developing Healthy Waterways Plans for priority catchments in the ACT. The Lake Tuggeranong draft plan aims to provide a suite of potential management options to Government to further improve water quality in Lake Tuggeranong (ACT Government, 2025). To achieve this, modelling and analyses have been undertaken to examine a broad range of management scenarios and identify cost-effective options to improve water quality in Lake Tuggeranong, with a focus on reducing the annual load of phosphorus entering the lake. The availability of phosphorus is the main controllable factor limiting blue-green algal growth (Ubrihien, et al., 2020). While large amounts of phosphorus are bound to sediments on the lake bottom, reducing the phosphorus inputs to the lake is necessary before this in-lake source of phosphorus can be effectively addressed.

This report documents the approach taken to assess the predicted performance and cost of proposed catchment management options for reducing the load of phosphorus entering Lake Tuggeranong. For each management option identified, details of the data and information used to calculate the estimates of performance and cost are presented, and summarised in an assessment of cost-effectiveness. An evaluation of the quality of evidence supporting these estimates and its impact on our confidence in specific values is provided for each management option.

Government experts identified a range of potential management options for mitigating phosphorus pollution. They then narrowed their consideration of options based on the availability of data to support cost-effectiveness analyses. In some instances, cost-effectiveness data were based on local trials of mitigation options.

Ten management options are assessed in this report:

- Construction of additional WSUD infrastructure
- Improved maintenance of existing WSUD assets
- Increased frequency of street sweeping
- Improved management of grass clippings from municipal mowing
- Management of public sports field fertilizer use practices
- Management of household fertilizer use practices
- Installation (retrofitting) of castellated kerbs
- Installation of in-lake floating wetlands

- Installation of stormwater recycling infrastructure for sports field irrigation
- Installation of household rainwater tanks

The assessments used to generate estimates of the cost-effectiveness of each of these management options is detailed in section 2 of this report. Sections 3.1 and 3.2 describe the process of comparing management options and combining them into proposed management scenarios with the aim of reducing the phosphorus load entering Lake Tuggeranong by approximately 700 kg/year. A reduction of this amount is predicted to maintain Lake Tuggeranong in a predominantly mesotrophic state, substantially reducing the frequency, extent and duration of blue-green algal blooms (Kahn & Dey, 2024). Section 3.3 outlines the results of implementing the proposed management scenarios in the catchment model for the Lake Tuggeranong catchment (Dey, Stewart, Kahn, Booksmythe, & Starrs, 2024).

1.1 Management option performance

The performance of each management option is assessed in terms of the amount of total phosphorus (TP) it is predicted to prevent from entering Lake Tuggeranong in a year. To facilitate comparison between different types of management option, we assume a 30-year lifecycle for each option. Total lifecycle performance is estimated by multiplying the annual TP removal by 30.

Phosphorus reduction has been chosen as the primary quantitative metric for management option performance due to its key role in promoting blue-green algal blooms in Lake Tuggeranong. Further assessment could consider other aspects of water quality improvement (e.g. the reduction of total nitrogen, TN, and total suspended solids, TSS), along with non-water quality benefits, as part of performance.

1.2 Management option costs

Costs are estimated in Australian Dollars (AUD) as at 2024. Costs are broken down into three components:

- Capital costs (in 2024 currency; assumed to be incurred in the first year of implementation)
- Annual operating costs (in 2024 currency)
- Total 30-year lifecycle costs (capital costs + annual operating costs over 30 years, using an annual discount rate of 7% after the first year (Infrastructure Australia, 2021))

We assume that management options have no residual value at the end of lifecycle, facilitating a like-for-like comparison between management options with vastly different cost profiles (e.g. infrastructure vs. non-infrastructure options).

1.3 Management option cost-effectiveness

By calculating an estimate of cost-effectiveness we aim to provide a metric allowing direct comparison of different management options. The cost-effectiveness of each management option is calculated by dividing the total lifecycle cost by the total lifecycle performance (TP removal). This produces a standardised metric for comparison between disparate management options in a consistent unit ($/kg). To provide a comparison of cost-effectiveness both across and within management options, the cost-effectiveness of

four different levels of investment was calculated for each option, ranging from relatively low to relatively high investment.

1.4 Quality of supporting evidence

With any process of estimation comes uncertainty. In assessing the cost-effectiveness of phosphorus-reducing management options in the Lake Tuggeranong catchment, uncertainty may arise through three main channels:

- Uncertainty about estimates of the cost of implementing a management option
- Uncertainty about estimates of the efficacy of the management option in removing phosphorus (e.g., uncertainty about the amount of leaf litter prevented from entering the stormwater system by street sweeping)
- Uncertainty about estimates of the amount of phosphorus available for removal by a particular management option (e.g., uncertainty about the pollutant load generated from leaf litter on roads)

We use both quantitative and qualitative approaches to address these sources of uncertainty in our assessment of management options.

1.4.2 Quantitative assessment of estimate uncertainty

A wide range of data and information were collated to estimate the phosphorus-removal performance and cost of each assessed option. In some cases, when incorporating multiple sources of information about the same aspects of performance or cost, a range of estimates was obtained. We assessed this range of estimates statistically, to understand whether it was likely to represent a realistic range of possible variability in outcomes, or to over- or under-estimate the expected variability.

1.4.2 Qualitative assessment of estimate uncertainty

We developed a rubric to systematically assess the quality of evidence sources contributing to the cost-effectiveness estimates of each management option (Appendix A). The data informing the calculations of predicted cost and performance were scored on nine criteria and the scores summed to give an overall uncertainty rating for the cost-effectiveness estimate.

Box 1. Key definitions and abbreviations used in this report

- Annual operating cost – the estimated annual cost of day-to-day operation of a management option, including routine maintenance and staff costs unless otherwise specified.
- Capital cost – the cost of capital works (i.e. construction planning, materials and delivery) of a management option, excluding operation and maintenance costs. Some management options do not have a capital cost (e.g. community partnership programs).
- Discount rate – the interest rate at which future dollar values are adjusted to represent their value in today's dollars. This adjustment is made to account for the fact that money today is more valuable than money in the future.
- EPSDD – Environment, Planning and Sustainable Development directorate, ACT Government
- Gross pollutant trap (GPT) – infrastructure installed upstream of stormwater management infrastructure to capture large debris and prevent it from causing blockage of the infrastructure.
- Model for Urban Stormwater Improvement Conceptualisation (MUSIC) – software that simulates rainfall, stormwater runoff, flows, and pollution. Used to simulate flow reduction and pollution removal through stormwater management infrastructure such as wetlands, bioretention, and sediment ponds.
- O&M – Operation and maintenance
- TCCS – Transport Canberra and City Services directorate, ACT Government
- Total lifecycle cost – the estimated cost of implementing and operating a management option over 30 years, with annual (O&M) costs discounted by 7% per annum after the first year.
- Total phosphorus (TP) – the sum of all forms of phosphorus present in a sample. In this report the term phosphorus refers to total phosphorus (TP) unless otherwise specified, and these terms may be used interchangeably.
- Water-sensitive Urban Design (WSUD) assets – infrastructure such as constructed wetlands, bioretention, and sediment ponds, for the management of stormwater and its pollutants using natural biological and physical processes including sediment settlement, filtration, and uptake by plants.

2. Management option assessments

2.1 Construction of additional WSUD infrastructure

2.1.1 Background

Stages 1 and 2 of the ACT Healthy Waterways program saw the construction of several different types of water-sensitive urban design (WSUD) infrastructure across urban Canberra waterways, including 8 assets in the Lake Tuggeranong catchment. WSUD infrastructure, including constructed wetlands, raingardens, and bioretention swales, can be situated directly on a branch of the stormwater network (online) or receive inflows diverted from the stormwater network (offline), or be positioned to intercept runoff before it enters the stormwater network (at-source). While water is within the infrastructure, a proportion of the nutrient and sediment pollutants in the water are removed through processes including natural settling, filtration, and uptake by plants. Outflows from the infrastructure are returned to the stormwater network. This section assesses the cost-effectiveness of installing additional WSUD infrastructure in the catchment.

The amount of total phosphorus (TP) available for removal by additional WSUD infrastructure is that which is intercepted by the infrastructure as it travels through the catchment. The catchment model for the Lake Tuggeranong catchment estimates the load of TP generated and entering the stormwater network in each subcatchment, allowing calculation of the accumulated load that would be received by a new WSUD asset depending on its location in the catchment (Dey, Stewart, Kahn, Booksmythe, & Starrs, 2024).

2.1.2 Phosphorus removal performance

We estimate the TP removal performance of additional WSUD infrastructure based on the performance of similar existing infrastructure. MUSIC models were developed for each of the WSUD assets constructed as part of Stage 1 of the ACT Healthy Waterways program. These models are configured to reflect the final design of each asset and model the predicted TP removal for each asset over a known climatic period, adopting MUSIC's default TP concentrations for stormwater runoff generated from different land uses in the catchment. The models for the 8 WSUD assets installed in the Lake Tuggeranong catchment were reviewed and updated by eWater (eWater Ltd, 2022), which estimated annual mean percentage reductions in TP of between 15-80% for these assets. These percentage reductions were applied in the Lake Tuggeranong catchment model (Dey, Stewart, Kahn, Booksmythe, & Starrs, 2024) to estimate the TP load removed by each asset. The total annual load of TP removed depends on the type, size, and location of assets. The two constructed wetlands in the Lake Tuggeranong catchment remove an estimated 0.003-0.01 kg TP per square metre of wetland per year. However, we excluded wetlands from the infrastructure used to estimate the performance of additional WSUD infrastructure, as there is very little scope to build further wetlands in the Lake Tuggeranong catchment, and modelling smaller assets is more realistic. For the 6 non-wetland assets (bioretention swales, raingardens, and channel restorations) in the catchment, the annual load of TP removed ranges between 0.0048-0.014 kg TP per square metre of asset area (Table 1).

The installation of additional WSUD infrastructure, and the size of infrastructure that can be built, is limited by the availability of suitable locations in the catchment. This means that specific asset designs, of known type, size, and location, are needed when estimating the impact of additional WSUD infrastructure on reducing the TP load entering Lake Tuggeranong. Here, the size and possible locations of additional WSUD infrastructure were determined from design reports for 10 proposed raingardens in the Lake Tuggeranong

catchment (Alluvium, 2015), undertaken as part of the ACT Healthy Waterways program Stage 1, that were not selected as priorities for construction during that project (Table 2). As there may be planning and feasibility constraints that determined why these particular raingardens were not built at the time, the estimates in this section should be read as an example of the kind of infrastructure that could be installed in the Lake Tuggeranong catchment, not a specific proposal.

Table 1. Summary statistics for the performance of 6 existing non-wetland WSUD assets in the Lake Tuggeranong catchment.

Parameter	Total annual TP removed (kg/m^2)
Minimum	0.0048
Median	0.0074
Mean	0.0081
Maximum	0.0142

We assigned each of these hypothetical assets an annual TP removal rate, assuming that raingarden performance efficacy improves with increasing treatment area. To implement this relationship, we ranked the raingardens by size, and applied the maximum TP removal rate from Table 1 to the largest two assets, the mean TP removal rate to the next three largest assets, the median TP removal rate to the next three largest assets, and the minimum TP removal rate to the two smallest assets (Table 2).

Table 2. Size, assigned rate of TP removal, and estimated total annual TP removed for 10 proposed raingardens in the Lake Tuggeranong catchment.

Asset	Asset size (m^2)[1]	Annual TP removed (kg/m^2)	Total annual TP removed (kg)
TG018	4,800	0.0142	68.16
TG014	2,700	0.0142	38.34
TG004	2,600	0.0081	21.06
TG013	2,600	0.0081	21.06
TG015	2,600	0.0081	21.06
TG016	2,600	0.0074	19.24
TG031	2,600	0.0074	19.24
TG005	2,459	0.0074	18.20
TG007B	1,500	0.0048	7.20
TG009	1,440	0.0048	6.91

1 Assets with no projected treatment area were assigned an area of 2,600 m^2, the average area for a raingarden in the catchment.

2.1.3 Costing

G2W Pty Ltd were engaged to review the capital and ongoing operation and maintenance costs associated with existing WSUD infrastructure in the Lake Tuggeranong catchment (G2W Pty Ltd, 2024). Bioretention assets (raingardens and swales) in the Lake Tuggeranong catchment ranged between 765 - 5,270m^2 in size, and between $774 - 2,532/m^2 in capital construction cost, with a strongly negative relationship between

size and cost such that on average, larger assets had a lower capital cost per square metre. We used this size - capital cost relationship to estimate the capital cost of constructing the 10 proposed raingardens based on the sizes presented in Table 2. We used the capital cost of the cheapest existing raingarden as a lower limit for the cost estimates of the proposed raingardens. Similarly, the annual operation and maintenance (O&M) cost of existing bioretention assets ranged between \$62 – 170/m^2, with larger assets having a lower O&M cost per square metre. We used the asset size - O&M cost relationship to estimate the annual maintenance cost of the 10 proposed raingardens, again using the lowest existing O&M cost as a lower limit for our estimates. We used the capital and O&M cost estimates to calculate the 30-year lifecycle cost of the 10 proposed raingardens, assuming an annual discount rate of 7% each year on the O&M costs.

2.1.4 Cost-effectiveness

We calculated the individual cost-effectiveness of each of 10 proposed raingardens based on the assigned rate of TP removal for each asset (Table 3).

Table 3. Capital costs, annual operation and maintenance costs, 30-year lifecycle costs, and individual cost-effectiveness of 10 proposed raingardens in the Lake Tuggeranong catchment.

Asset	Capital cost	Annual operation and maintenance cost	Total 30-year lifecycle cost[1]	Cost per unit TP removed ($/kg)
TG018	$4,882,560	$338,496	$13,025,856	$6,388
TG014	$4,226,310	$261,846	$8,878,356	$7,740
TG004	$4,137,640	$255,424	$8,620,664	$13,585
TG013	$4,137,640	$255,424	$8,620,664	$13,585
TG015	$4,137,640	$255,424	$8,620,664	$13,585
TG016	$4,137,640	$255,424	$8,620,664	$14,969
TG031	$4,137,640	$255,424	$8,620,664	$14,969
TG005	$4,003,746	$245,941	$8,248,021	$15,143
TG007B	$2,817,750	$168,150	$5,424,900	$24,882
TG009	$2,727,590	$162,513	$5,231,543	$24,995

1 Total lifecycle cost is calculated over 30 years using a discount rate of 7% per annum on O&M costs.

To provide four levels of investment in the additional WSUD infrastructure management option, we grouped the 10 proposed raingardens by their size and cost-effectiveness and created four tiers of installation: to either build the two, five, 8 or 10 most cost-effective of these assets. We re-calculated the overall 30-year lifecycle cost and cost-effectiveness for the group of assets included in each investment level (Table 4), incorporating additional cost scaling factors to account for total construction size, number of assets to be constructed and the number of gross pollutant traps required (we assumed that each asset would need one gross pollutant trap).

Table 4. Costing summary for four levels of investment in additional WSUD infrastructure in the Lake Tuggeranong catchment.

Investment level	Number of assets built	Total annual TP removed (kg/year)	Total 30-year lifecycle cost[1]	Cost per unit TP removed ($/kg)
1	Build 2 assets	106.21	$22,507,500	$7,064
2	Build 5 assets	169.67	$48,369,492	$9,502
3	Build 8 assets	226.22	$73,862,467	$10,884
4	Build 10 assets	240.46	$84,519,403	$11,716

1 Total lifecycle cost is calculated over 30 years using a discount rate of 7% per annum on O&M costs.

2.1.5 Quality of supporting evidence

Using the evaluation rubric (Appendix A), the above estimates of cost-effectiveness of installing additional WSUD infrastructure scored 13/14 for confidence in cost estimates, and 9/16 for confidence in performance estimates.

2.2 Maintenance of existing WSUD infrastructure

2.2.1 Background

WSUD infrastructure requires ongoing maintenance to function at its designed phosphorus removal efficiency. Transport Canberra and City Services (TCCS) undertake this maintenance for the 8 existing WSUD assets in the Lake Tuggeranong catchment.

2.2.2 Phosphorus removal performance

Six of the 8 WSUD assets in the Lake Tuggeranong catchment were visually assessed for their current level of maintenance and treatment efficacy in February 2024. Five of these assets were assessed as performing at between 20% and 70% of their designed efficiency due to maintenance shortfalls. The estimated reduction in performance of each asset was incorporated into the baseline run of the catchment model, used to calculate the current (business-as-usual) annual load of TP entering Lake Tuggeranong (Dey, Stewart, Kahn, Booksmythe, & Starrs, 2024). To estimate the amount of TP that could be removed if all existing assets were maintained to 100% of their designed efficiency, the catchment model was then run without applying the asset performance reductions. The total difference in TP load between the business-as-usual and optimal asset maintenance model runs was 88 kg/year (Table 5).

Table 5. Current asset total phosphorus (TP) removal performance efficiency as a percentage of designed performance, and the additional annual TP load that could be removed if assets were maintained to designed performance.

Asset	Current TP removal performance	Marginal increase in TP removed with optimal maintenance (kg/year)
TG011N – wetland	60%	23.28
TG029 – raingarden	20%	12.56
TG010 – raingarden	70%	25.94
TG011S – wetland	60%	18.15
TG008 – raingarden	50%	8.09

2.2.3 Costing

The costs provided for asset operation and maintenance are based on annualised operational cost estimates from TCCS budget requests, and incorporate costs of major renewal activities such as cleaning GPTs, mucking out sediment forebays and replacing raingarden filter media at regular intervals. We used the costs provided without modification, to calculate the 30-year lifecycle cost of each asset assuming an annual discount rate of 7% after the first year.

2.2.4 Cost-effectiveness

Our estimates of cost-effectiveness assume that there is currently no funding provided for WSUD asset maintenance, and that if the estimated O&M costs (Table 6) *were* to be spent on these assets, the marginal gains in TP removal (Table 5) would be achieved.

Table 6. Annual operation and maintenance costs, 30-year lifecycle costs, and cost-effectiveness of maintaining 5 existing WSUD assets to their designed performance.

Asset	Annual operation and maintenance cost	Total 30-year lifecycle cost[1]	Cost per unit TP removed ($/kg)
TG011N – wetland	$485,352	$6,508,917	$9,320
TG029 – raingarden	$221,091	$3,668,211	$9,735
TG010 – raingarden	$340,432	$8,909,451	$11,449
TG011S – wetland	$541,800	$7,265,925	$13,344
TG008 – raingarden	$235,739	$3,999,929	$16,481

1 Total lifecycle cost is calculated over 30 years using a discount rate of 7% per annum on O&M costs.

To provide four levels of investment in the WSUD maintenance management option, we grouped the five assets by the cost-effectiveness of their maintenance and created four tiers of implementation: to maintain either the two, three, four or five most cost-effective of these assets. We re-calculated the overall 30-year lifecycle cost and cost-effectiveness for the group of assets included in each investment level (Table 7).

Table 7. Costing summary for four levels of investment in maintenance of existing WSUD infrastructure in the Lake Tuggeranong catchment.

Investment level	Number of assets maintained	Total annual TP removed (kg/year)	Total 30-year lifecycle cost[1]	Cost per unit TP removed ($/kg)
1	Maintain 2 assets	35.84	$10,177,128	$9,465
2	Maintain 3 assets	61.78	$19,086,579	$10,298
3	Maintain 4 assets	79.93	$26,352,433	$10,990
4	Maintain 5 assets	88.02	$30,352,433	$11,495

1 Total lifecycle cost is calculated over 30 years using a discount rate of 7% per annum on O&M costs.

2.2.5 Quality of supporting evidence

Using the evaluation rubric (Appendix A), the above estimates of cost-effectiveness of maintaining existing WSUD infrastructure scored 4/14 for confidence in cost estimates, and 8/16 for confidence in performance estimates.

2.3 Increased frequency of street sweeping

2.3.1 Background

In the Lake Tuggeranong catchment, research by the University of Canberra (Ubrihien, et al., 2020) indicates that a large amount of nutrients enter the waterways from diffuse, rather than point, sources – i.e. from widespread land uses across the catchment such as residential blocks and roads. One potential contributing factor found across these land uses is leaf litter (here defined as fallen leaves and other plant and soil matter) on impervious surfaces like roads, footpaths and driveways. Water passing over this leaf litter can take up nutrients in both dissolved and particulate forms, and enter the stormwater system via street gutter sumps. Dissolved nutrients may be leached out of leaf litter by the passing water, while particulate nutrients are chemically bound to particles such as soil and leaf fragments. In addition, with sufficient flows intact leaf litter may be washed into the stormwater system and transported to the lakes and waterways where they will break down and release nutrients into the water.

The primary function of the municipal street sweeping program is to prevent blockage of the stormwater system and ensure its effectiveness in flood mitigation. While increasing the frequency of street sweeping is often raised as a possible action to reduce leaf litter as a source of nutrient pollution, the impact of street sweeping on reducing nutrient inputs into the urban waterways of the ACT has not previously been quantified.

Phosphorus generated from leaf litter on roads

The amount of TP available for removal by street sweeping is that which originates as leaf litter on roads. The Lake Tuggeranong catchment model estimates the total annual TP load that runs off roads in the Lake Tuggeranong catchment as 582 kg TP/year (Dey, Stewart, Kahn, Booksmythe, & Starrs, 2024), and we use this as an estimate of the maximum available load of TP generated by leaf litter on roads.

There is strong seasonal variation in leaf fall in *Eucalyptus* species, which are predominant among the street tree and other public tree assets in the Lake Tuggeranong catchment (Ubrihien, et al., 2024), with most leaves falling in the warmer months (Crockford & Richardson, 1998). This variation, as well as seasonal variation in rainfall, will affect the accumulated load of leaf litter on the roads at any given time, and means that not just the frequency but also the timing of street sweeping can impact the amount of TP removed by this management option.

2.3.2 Phosphorus removal performance

We created a simple build-up wash-off model ('leaf load calculator') to incorporate these sources of seasonal variation in TP load, and the influence of sweeping frequency and timing, into our estimate of the TP removal performance of street sweeping. The calculator is based on 24 years of daily rainfall data from the Tuggeranong (Isabella Plains) climatological station (Bureau of Meteorology station ID 070339). It allows manual adjustment of variability in leaf fall, and specification of the frequency and timing of street sweeping. Using these inputs it calculates the cumulative load of leaf litter each day:

Load today = load yesterday + new fall today – load swept today – load washed away by rain today.

We used data from University of Canberra research into the leaf fall and TP content of four *Eucalypt* species in urban Canberra (Ubrihien, et al., 2024) to generate an approximate seasonal leaf fall pattern for the Lake Tuggeranong catchment. We input this seasonal pattern into the leaf load calculator, scaling the daily maximum leaf fall rate to be consistent with the average annual load of 582 kg TP on roads in the catchment estimated by the catchment model (Dey, Stewart, Kahn, Booksmythe, & Starrs, 2024). We then compared different annual street sweeping schedules, from two sweeps per year (business-as-usual) to 48 sweeps per year. We explored schedules of sweeping evenly spaced throughout the year, as well as seasonally focused schedules with increased frequency during high leaf fall periods and reduced or no sweeping during low leaf fall periods. For all schedules we assumed a minimum of one week between sweeps.

To compare each sweeping schedule explored using the leaf load calculator, we calculated their monthly and annual statistics on the leaf litter load on roads, the load collected by street sweeping trucks (and the approximate number of truckloads), and the load washed away into the stormwater network, over the 24 years of rainfall data.

2.3.3 Costing

To find the cost of a single sweep event for the Lake Tuggeranong catchment, we multiplied the current daily cost of one street sweeping truck by the number of truck-days needed to sweep the entire catchment once. We then added the cost of transporting and disposing of the swept material in landfill. We assume an expansion of the current operational model based on leasing trucks, so no capital cost (e.g. outright purchase of trucks) is included in our costings for this management option.

Days needed for one catchment sweeping event A pilot experiment investigating the impact of frequent street sweeping on nutrient concentrations in stormwater included a 12-week period of fortnightly street sweeping in two subcatchments of the Lake Tuggeranong catchment, comprising 10% of the total catchment road area. From records of the number of shifts needed to complete sweeping of this area each

fortnight during the experiment, we calculate that on average 24.17 truck-days would be needed to sweep the entire Lake Tuggeranong catchment.

Daily truck cost An estimate of daily cost per truck, based on the current running costs of a truck in the ACT street sweeping fleet, was provided by the TCCS Street Sweeping team. The fleet runs 5 days per week, with up to two staff shifts per truck per day, allowing each truck to operate for up to 10 hours per day. At the maximum (2 shift/day) rate of operation, the cost of one truck, including leasing, staff, running and maintenance costs, is $1,200-$1,500/day. Here we conservatively use the higher cost estimate. Over 24.17 truck-days, the estimated truck cost to sweep the entire Lake Tuggeranong catchment is $36,255.

Disposal costs The total cost of disposing of material to landfill in 2024 currency is $181/tonne. Of this, tip fees comprise $171/tonne and the cost of transporting collected material to landfill sites is $10/tonne (both excluding GST).

From data provided by TCCS, the estimated tonnage of material removed in one year (260 weekdays) by the fleet of 6 trucks is 2,364 tonnes, or an average of 9.1 tonnes/day. Assuming that each truck spends about 10% of its time non-operational (due to breakdowns, time out for servicing, etc.), this equates to an estimated average of 1.7 tonnes of material removed per truck per day (9.1 / (6 * 0.9)). Given 24.17 truck-days per catchment sweeping event, the disposal cost per sweeping event is $7,437. The total combined truck and disposal cost to sweep the Lake Tuggeranong catchment is $43,692 per street sweeping event. These estimates assume a constant load of material collected at each sweeping event (i.e., no seasonality or decrease due to sweeping frequency is included in disposal cost estimates, due to a lack of data on these possible effects).

2.3.4 Cost-effectiveness

To provide four levels of investment in the street sweeping management option, we considered four sweeping schedules ranging between 12 - 48 sweeping events in a year (1 - 4 per month). The three lower-frequency schedules account for the seasonality of leaf fall to obtain the best performance for each level of investment. The 48-sweep schedule is essentially equivalent to sweeping every week, so no seasonal adjustment is made. We calculated the 30-year lifecycle cost of each schedule using an annual discount rate of 7% on annual program costs after the first year.

Table 8. Costing summary for four levels of investment in increased frequencies of street sweeping in the Lake Tuggeranong catchment.

Investment level	Sweeping schedule	Total annual TP removed (kg/year)	Annual program cost	Total 30-year lifecycle cost[1]	Cost per unit TP removed ($/kg)
1	12 sweeps – seasonal focus	203.7	$524,304	$7,030,414	$1,150
2	24 sweeps – seasonal focus	320.1	$1,048,608	$14,060,827	$1,464
3	36 sweeps – seasonal focus	372.5	$1,572,912	$21,091,242	$1,887
4	48 sweeps – weekly	395.8	$2,097,216	$28,121,656	$2,369

1 Total lifecycle cost is calculated over 30 years using a discount rate of 7% per annum on annual costs after the first year.

2.3.5 Quality of supporting evidence

Using the evaluation rubric (Appendix A), the above estimates of cost-effectiveness of increasing the frequency of street sweeping scored 10/14 for confidence in cost estimates, and 9/16 for confidence in performance estimates.

2.4 Management of grass clippings from municipal mowing

2.4.1 Background

Grass clippings resulting from mowing of public open space can be blown onto adjacent roads, from where they can enter the stormwater system. Public perception is that large amounts of clippings end up on the roads, and if so these clippings may be a sizeable contributor to nutrient pollution of the waterways. Preventing or reducing the input of phosphorus from this source could be achieved by installing catchers on lawnmowers, using blowers to return clippings to the verge, or running designated street sweeping trucks along mown roadsides.

Phosphorus export from municipal mowing activity

The total area of pervious, ground-level (i.e., likely grassed and subject to TCCS mowing) public open space in the Lake Tuggeranong catchment is 928.5 ha. We assume that clippings from areas within 2m of a road are likely to end up on the road - this is probably an overestimate, and gives an area of 98.1 ha of mown area from which grass clippings will reach the road.

The estimated amount of clippings generated from this area in a year is between 327,000 - 523,000 kg dry mass. This is based on a 2016 report for the South Australian Government investigating the effect of watering regime on turf grass yields (Barton, 2016). University of Canberra research (Ubrihien, et al., 2024) estimates the phosphorus content of grass clippings at 0.1% of the dry weight of clippings, which gives between 327 - 523 kg TP for the estimated annual load of clippings on roads in the Lake Tuggeranong catchment.

When considered in light of information from the street sweeping pilot experiment (see section 2.3), this estimate appears unrealistically high. At this rate, the TP load from 12 weeks' worth of grass clippings on the road in the subcatchments monitored in the experiment would comprise around 50% of the total TP load estimated from the experiment. Furthermore, the mass of these clippings would be around 100 times greater than the total mass of material collected during the experiment. Rough visual estimates suggest that only between 0-10% (by volume) of the swept material was grass clippings. To reconcile these different estimates, we assume that current mowing management practices are 90% effective in keeping clippings off the road, so clippings contribute 32.7 - 52.3 kg TP/year (at this rate, TP loads from clippings would comprise around 5% of the total TP load measured in the street sweeping experiment).

2.4.2 Phosphorus removal performance

Only two of the three suggested management methods for municipal grass clippings are assessed here. Through consultation with the Transport Canberra and City Services mowing team, the use of catchers has

been discounted – most of the current fleet of mowers cannot accommodate a catcher, and the team does not have the capacity (time or resources) to dispose of collected clippings.

Management method 1 is to adopt the use of electric blowers towed behind mowers to move clippings away from road edges. This option is assumed to improve current practices to be 95% effective at keeping clippings off the roads, reducing TP inputs by 50% (removing between 16.4 - 26.1 kg TP/year).

Management method 2 is to use street sweeping trucks to immediately remove all remaining grass clippings on roads. A suggestion to do this by coordinating with the current street sweeping program has previously been trialled and found to be logistically infeasible. This option would instead require the lease of a designated street sweeping truck(s) to run immediately after mowing and is assumed to remove the entire TP load from clippings (removing 32.7 - 52.3 kg TP/year).

2.4.3 Costing

Management method 1 To achieve the full reduction in phosphorus inputs estimated for this method would require enough blowers to provide operational coverage to current municipal mowing activities in the Lake Tuggeranong catchment. Based on consultation with the TCCS mowing team, the purchase of two blowers and their ongoing operation and maintenance are costed:

- Capital purchase (2 blowers) = $160,000
- Annual cost (2 staff at $65,000/year + maintenance at $5,000/year) = $140,000/year

Management method 2 Here we assume that operational coverage for current municipal mowing activities in the Lake Tuggeranong catchment would require the lease of one dedicated street sweeping truck running full time (2 shifts per day, 5 days per week). Costing is based on leasing and operational cost information provided by the TCCS street sweeping team:

- No capital cost
- Annual operational cost (truck lease, staff, fuel, and maintenance) = $108,996/year
- Additional annual cost (landfill charges at $171/tonne ex. GST, for 32,700-52,300 kg material) = $5,592-$8,943/year

2.4.4 Cost-effectiveness

These two methods for the management of grass clippings from municipal mowing are predicted to remove between 16 - 52 kg TP per year at a cost of between $998 - $4,103 per kg P removed, over 30 years. We use the high and low estimates of TP removal performance for each method to provide four levels of investment in this management option (Table 9).

2.4.5 Quality of supporting evidence

Using the evaluation rubric (Appendix A), the estimates of cost-effectiveness of managing grass clippings from municipal mowing scored 9/14 for confidence in cost estimates, and 7/16 for confidence in performance estimates.

Table 9. Estimated annual load of total phosphorus (TP) prevented from entering Lake Tuggeranong, total 30-year lifecycle cost, and cost-effectiveness of options for management of grass clippings from municipal mowing.

Investment level	Management method and level of TP removal	Total annual TP removed (kg/year)	Total 30-year lifecycle cost[1]	Cost per unit TP removed ($/kg)
1	Method 1 (blowers) – low TP removal estimate	16.4	$2,018,874	$4,103
2	Method 1 (blowers) – high TP removal estimate	26.1	$2,018,874	$2,578
3	Method 2 (sweeping) – low TP removal estimate	32.7	$1,521,462	$1,551
4	Method 2 (sweeping) – high TP removal estimate	52.3	$1,565,956	$998

1 Total lifecycle cost is calculated over 30 years using a discount rate of 7% per annum on annual costs after the first year.

2.5 Management of sports field fertilizer use practices

2.5.1 Background

The use of fertilizers containing phosphorus on sports grounds and other 'managed' green space is undertaken by both government and private managers. The Lake Tuggeranong catchment includes ~60 ha of actively managed (irrigated and fertilized) sports grounds, and a few additional privately managed assets: Vikings Club football ground, and three school sports grounds (Trinity Christian School, St Mary Mackillop College, Erindale College) with an estimated combined total of 7.5 ha.

Interviews with Canberra sports field and turf managers (Edmondson, 2022) suggest that in general, sports field managers are motivated to use fertilizer efficiently within the constraints of their management priorities. There is likely little to be gained in trying to further reduce fertilizer application rates. An additional option to address fertilizer export from sports fields is to install bioretention swales to intercept runoff from sports fields, and this is the management option we assess here.

Phosphorus application and export rates from sports field fertilizer use

TCCS provided information on the fertilizer application of the public sports grounds in the catchment. Estimates of fertilizer application regimes of privately managed sports grounds are based on information from interviews with Canberra sports turf managers (Edmondson, 2022). Export rates of phosphorus from different fertilizer products (Table 10) were estimated based on a review of experimental studies of TP export rates (Booksmythe, 2023).

Table 10. The amount of phosphorus (P) applied in fertilizers, and literature-derived rates of P export for the fertilizers applied, for three categories of sports field management in the Lake Tuggeranong catchment. Lower, medium, and upper estimates of P export rates are provided, based on the range of values reported for each fertilizer type in the literature.

Sports field type	TP applied (kg/year)	Lower TP export rate (kg/ha/year)	Medium TP export rate (kg/ha/year)	Upper TP export rate (kg/ha/year)
Public sports field	10	0.2	1.2	2.5
'Elite' public sports field	36	0.72	4.32	9
Private sports field	3	0.06	0.36	0.75

We multiplied the annual amount of P applied by the export rates given in Table 10 to calculate a range of estimates of the total P load exported from sports fields in the Lake Tuggeranong catchment (Table 11).

Table 11. The total area of three categories of sports field management in the Lake Tuggeranong catchment, and the estimated total annual load of total phosphorus (TP) exported from each category.

Sports field type	Total area (ha)	Lower total TP exported (kg/year)	Medium total TP exported (kg/year)	Upper total TP exported (kg/year)
Public sports field	58.7	11.74	70.44	146.75
'Elite' public sports field	2.3	1.66	9.94	20.7
Private sports field	7.5	0.45	2.7	5.63
Total	68.5	13.85	83.08	173.08

The median and upper estimates of the total TP exported from sports fields (based on the upper bound of estimates of TP export rate from the literature) are larger than the total TP load of 57.9 kg/year from sports field land use estimated by the Lake Tuggeranong catchment model (Dey, Stewart, Kahn, Booksmythe, & Starrs, 2024).

2.5.2 Phosphorus removal performance

We assess the TP removal performance of installing bioretention swales below public managed sports fields in the Lake Tuggeranong catchment based on the performance of similar existing WSUD infrastructure in the catchment (see Section 2.1.2). We calculated the swale area required to remove the total TP load from sports fields, 57.9 kg P/year, across the range of performance rates in Table 1. In the absence of explicit scoping work investigating possible locations and designs for swales, we made a simplified assumption of the range of TP removal performance: of the total infrastructure required to remove 57.9 kg TP/year, 25% would perform at the highest rate, 25% would perform at the lowest rate, and 50% would perform at the average rate (Table 12). Based on this assumed performance range, the total swale area required to remove the total TP load from sports fields is 7,882 m^2.

Table 12. Phosphorus removal performance bands assumed for bioretention swales installed below sports fields in the Lake Tuggeranong catchment

Performance band	Annual TP removal ($kg/m^2/year$)	TP load addressed (kg)	Swale area required (m^2)
High performance (25% of assets)	0.0142	14.93	1,016
Average performance (50% of assets)	0.0077	29.86	3,878
Low performance (25% of assets)	0.0048	14.93	2,988

2.5.3 Costing

G2W Pty Ltd were engaged to review the capital and ongoing operation and maintenance costs associated with existing WSUD infrastructure in the Lake Tuggeranong catchment (see section 2.1.3) (G2W Pty Ltd, 2024). Bioretention assets (raingardens and swales) in the Lake Tuggeranong catchment ranged between 765–5,270m^2 in size, and between \$774 - 2,532/m^2 in capital cost, with a strongly negative relationship between size and cost such that on average, larger assets had a lower capital cost per square metre. Similarly, the annual operation and maintenance (O&M) cost of existing bioretention assets ranged between \$62 – 170/m^2, with larger assets having a lower annual O&M cost per square metre. We used these asset size - cost relationships to estimate the capital and O&M costs of constructing between 4 and 24 swales with a total combined area of between 1,016 - 7,882 m^2, and used these capital and O&M cost estimates to calculate the 30-year lifecycle cost, assuming an annual discount rate of 7% each year for O&M costs.

2.5.4 Cost-effectiveness

To provide four levels of investment for this management option, we used the performance bands described in Section 2.5.2 to define four tiers of implementation: to build the best-performing 25%, 50%, 75% or 100% of the swales required to remove the TP load from sports fields (Table 13). Investment option 1 is to build all assets in the 'high performance' band, addressing 25% of the sports field TP load. Investment option 2 builds the assets from option 1, and additionally half the assets in the 'average performance' band, in total addressing 50% of the sports field TP load. Investment option 3 builds all the assets in the 'high' and 'average performance' band, addressing 75% of the sports field TP load, and investment option 4 builds all the assets in all performance bands, addressing 100% of the sports field TP load.

Table 13. Costing summary for four levels of investment in constructing bioretention swales below managed sports fields in the Lake Tuggeranong catchment.

Investment option	Costing level	Total annual TP removed (kg/year)	Total 30-year lifecycle cost[1]	Cost per unit TP removed ($/kg)
1	Build best 25%	14.93	$4,204,451	$9,387
2	Build best 50%	29.85	$11,817,327	$13,196
3	Build best 75%	44.78	$19,430,204	$14,463
4	Build all	59.70	$31,445,222	$17,557

1 Total lifecycle cost is calculated over 30 years using a discount rate of 7% per annum on O&M costs.

2.5.5 Quality of supporting evidence

Using the evaluation rubric (Appendix A), the above estimates of cost-effectiveness of installing bioretention swales below managed sports fields scored 13/14 for confidence in cost estimates, and 9/16 for confidence in performance estimates.

2.6 Management of household fertilizer use practices

2.6.1 Background

Household use of fertilizer products was investigated as a source of TP in the catchment that may be exported from residential blocks. The loss of fertilizer TP from residential blocks could be reduced by community partnership programs designed to alter how people use fertilizer on their block, and/or by legislating to reduce the TP content of fertilizer products, e.g. (Environmental Protection (Packaged Fertiliser) Regulations, 2010).

Concepts of Change were contracted to survey Canberra households on their fertilizer use (including purchased compost, manures, and 'chemical' fertilizer products). Based on the detailed information the survey obtained about the usage rates of different types of fertilizer products, Concepts of Change estimated the amount of phosphorus applied to residential properties (Concepts of Change, 2023). Export rates of phosphorus from different fertilizer products were estimated based on a review of experimental studies of TP export rates (Booksmythe, 2023).

Phosphorus application and export rates from household fertilizer use

Survey respondents lived on residential blocks with garden space - i.e. RZ1 or RZ2 -zoned blocks. The total per-household rate of TP application in fertilizer products estimated from the survey was 0.59 kg TP/year (Table 14).

Table 14. Average annual amounts of total phosphorus (TP) applied to residential blocks in the ACT from chemical fertilizers, commercial composts and raw manures, and literature-derived rates of TP export for these products. Lower, medium, and upper estimates of TP export rates are provided, based on the range of values reported for each fertilizer type in the literature.

Product type	TP applied (kg/household/year)	Lower TP export rate (% of applied)	Medium TP export rate (% of applied)	Upper TP export rate (% of applied)
Fertilizers	0.15	2%	12%	25%
Composts	0.36	0.2%	1%	2.5%
Raw manures	0.07	1%	9%	17%

There are ~21,000 RZ1 and RZ2 -zoned blocks (low to medium density residential, detached and semi-detached dwellings with garden) in the Lake Tuggeranong catchment comprising ~1030 hectares of permeable area (out of 1950 ha total area of RZ1 and RZ2 blocks). Chemical fertilizers account for about 25% of the TP applied to household gardens, but their higher export rates compared to composts and manures mean they are estimated to account for about 65% of the exported TP (Table 15).

Table 15. Annual amounts of total phosphorus (TP) from fertilizer products applied to and exported from residential blocks (RZ1 and RZ2) in the Lake Tuggeranong catchment.

Product type	Total TP applied in catchment (kg/year)	TP applied (kg/ha/year)	Lower total TP exported (kg/year)	Medium total TP exported (kg/year)	Upper total TP exported (kg/year)
Fertilizers	3192	3.10	0.06	0.37	0.78
Composts	7644	7.42	0.02	0.07	0.19
Raw manures	1533	1.49	0.02	0.13	0.25
Total	12369	12.01	0.09	0.58	1.21

The Lake Tuggeranong catchment model (Dey, Stewart, Kahn, Booksmythe, & Starrs, 2024) estimates the total TP load from suburban pervious land in the Lake Tuggeranong catchment to be ~0.12 - 0.16 kg/ha/year, or in the vicinity of the lower estimate from the survey data. The catchment model estimate includes all TP inputs from suburban pervious land (e.g. any TP from leaves & grass clippings, pet waste, etc.) so it suggests that our estimates from the survey data might be too high (even the lower value). Caveats to our current understanding of the TP inputs contributed by household fertilizer use include:

- Although the survey was very detailed and thorough, and estimates of fertilizer use included correction factors based on on-the-ground verification of reported product use, these estimates may still over-estimate the amount of fertilizer applied to residential blocks. Information on Bunnings' annual ACT fertilizer sales suggest rates of 'chemical' fertilizer use are between 12 - 20 times lower than survey estimates.
- Estimates of export rates obtained from the literature varied widely between studies and depend on a large number of factors (e.g. soil type, 'rainfall' intensity and duration, vegetation type and presence). The highest export rate reported in the literature for a given type of fertilizer product was used as the upper estimate in these calculations. This is similar to assuming a 1-in-10 year rain event occurring immediately after fertilizer is applied. The lower estimates may be more realistic, and are more

consistent with the catchment model estimates of the TP load generated by suburban pervious land use in the Lake Tuggeranong catchment.

- The reported rates of phosphorus application suggest that we should see far more phosphorus exported from residential blocks than current water quality data indicates. If the survey-derived estimates of phosphorus application are broadly correct, several further avenues of investigation are required to understand what is happening to this phosphorus, e.g.:
  - how long has phosphorus been applied at this rate?
  - how much phosphorus can be stored in the soil?
  - is excess phosphorus taken up by trees?

2.6.2 Phosphorus removal performance

The management option assessed here is to use specialised community partnership approaches to encourage households to reduce the amount of phosphorus fertilizer products they apply to residential blocks.

To estimate the potential TP reduction resulting from this approach, we assume a community partnership program that gets the top 20% of P-inputting households to reduce their inputs by 20% (this outcome is chosen based on advice from Concepts of Change). Using the fertilizer survey data and TP export rates from the literature, the amount of TP applied and exported by the top 20% of users can be calculated. Reducing these inputs by 20% and adding the unaltered inputs from the remaining 80% of users, gives a reduction of 17% of the current total household P exports.

To calculate the estimated TP load reduction of this option, we assume that household fertilizer TP exports occur in event flows, and any reduction will not affect the baseflow TP loads coming from suburban pervious areas in the Source catchment model. This baseflow TP load is estimated to be 0.018 kg/ha/year. This is subtracted from the total modelled TP load from suburban pervious areas (~0.12 - 0.16 kg/ha/year) to give the estimated event flow TP load, of between 0.103 - 0.142 kg/ha/year.

We also assume that the catchment model estimates represent the upper limit of current household fertilizer TP exports. This means that the median and upper TP export estimates (Table 13) based on the survey data and export rates from the literature are too large to be consistent with the model. In providing an estimated range of the TP load reduction from banning phosphorus in fertilizers, we use the lower TP export estimate from the survey and literature review as the lower bound, and the catchment model estimate of suburban pervious event flow load as the upper bound (Table 16).

To calculate the percent reduction in the suburban pervious TP load resulting from this community partnership program, we add the baseflow loads to the new event flow loads from fertilizer and divide this by the current total suburban pervious load. This gives an estimated maximum TP reduction of between 14 - 41% of the current load contributed by suburban pervious areas, or the removal of between 20 - 58 kg of the current 140.3 kg TP/year.

Table 16. Estimating the reduction in TP load from suburban pervious land use resulting from a 17% reduction in current TP inputs from household fertilizer use. The range of values in each cell reflects the range of estimated TP export rates from the fertilizer applied to residential blocks.

Total TP load from suburban pervious land use (kg/ha/year)[1]	Current event-flow TP load from fertilizer (kg/ha/year)[2]	Reduced event-flow TP load from fertilizer (kg/ha/year)	Reduced event-flow TP load from fertilizer, plus baseflow load (kg/ha/year)	Percent reduction in total TP load from suburban pervious land use (kg/ha/year)
Lower estimate: 0.121	0.092 – 0.103	0.076 – 0.085	0.094 – 0.103	14.5 – 22.2%
Upper estimate: 0.160	0.092 – 0.142	0.076 – 0.118	0.094 – 0.136	15.1 – 41.2%

1 Estimated from the catchment model for the Lake Tuggeranong catchment (Dey, Stewart, Kahn, Booksmythe, & Starrs, 2024).

2 Estimates for the event-flow TP load from household fertilizer use are capped at the model-estimated total event-flow TP load from all suburban pervious land use, 0.103 or 0.142 kg TP/ha/year.

2.6.3 Costing

The lower cost estimate is based on the cost of a 6-month Concepts of Change community partnership program implemented in 2024, scaled up to run over 5 years and reach all households in the Lake Tuggeranong catchment. The higher cost estimate is based on expert opinion provided by Concepts of Change for the cost of a 5-year intensive campaign to achieve the reductions described in this section across all of Canberra. 30-year costings use a discount rate of 7% per annum after the first year, and assume that the intensive 5-year campaign runs twice (years 0-4 and 15-19), and that for all intervening years, maintenance costs of $350,000/year are required for both costing levels.

2.6.4 Cost-effectiveness

Based on the above, management of household fertilizer use by way of a community partnership program aimed at reducing the TP inputs of the top 20% of users by 20% is predicted to remove between 20 - 58 kg TP per year at a cost of between $3,700 - $24,000 per kg TP removed, over 30 years (Table 17).

Table 17. Estimated annual program and maintenance costs, total 30-year lifecycle cost, and cost-effectiveness of options for management of household fertilizer use.

Costing level	Annual program cost (2 x 5-year programs in 30-year lifecycle)	Annual maintenance cost (non-program years)	Total 30-year lifecycle cost[1]	Cost per unit TP removed ($/kg) – low performance	Cost per unit TP removed ($/kg) – high performance
Lower cost estimate	$637,000	$350,000	$6,362,682	$10,604	$3,657
Higher cost estimate	$2,000,000	$350,000	$14,509,794	$24,183	$8,399

1 Total lifecycle cost is calculated over 30 years using a discount rate of 7% per annum on O&M costs.

However, how cost estimates relate to the efficacy of this option is uncertain. We have no information on whether cost-effectiveness would increase or decrease with the scale of investment in a community partnership program to manage household fertilizer use.

In providing four levels of investment for this management option, we therefore assumed a uniform cost-effectiveness of $10,000/kg TP removed at all four levels of investment. This value was chosen as it falls within the cost-effectiveness estimates generated from both cost estimates above, and results in a realistic range of total program costs (between $6 and $17 million) when applied to the lower and upper estimates of the reduction in TP achieved by such a program. We used the lower and upper estimates of TP removal as the amount that would be removed by the lowest and highest levels of investment in this management option, respectively, and interpolated two evenly-spaced levels of TP removal between these extremes (Table 18).

Table 18. Costing summary for four levels of investment in community partnership programs aimed at managing household fertilizer use to reduce TP inputs in the Lake Tuggeranong catchment.

Investment level	Assumed program implementation	Annual TP removed (kg)	Total 30-year lifecycle cost[1]	Cost per unit TP removed ($/kg)
1	Low implementation	20	$6,000,000	$10,000
2	Medium implementation	32.67	$9,800,000	$10,000
3	High implementation	45.33	$13,600,000	$10,000
4	Very high implementation	58	$17,400,000	$10,000

1 Total lifecycle cost is calculated over 30 years using a discount rate of 7% per annum on annual costs after the first year.

2.6.5 Quality of supporting evidence

Using the evaluation rubric (Appendix A), the above estimates of cost-effectiveness of community partnership programs aimed at managing household fertilizer use scored 9/14 for confidence in cost estimates, and 7/16 for confidence in performance estimates.

2.7 Installation of castellated kerbs

2.7.1 Background

The stormwater network of the Lake Tuggeranong catchment was designed and built to be extremely efficient at directing stormwater into the piped network. The prevailing paradigm at the time was to minimise flood risk by getting stormwater out of residential areas as efficiently as possible. Consequently, the Lake Tuggeranong catchment stormwater network is dominated by concrete drains and a significant underground stormwater pipe network.

Almost all stormwater that ends up on sealed roads is diverted directly into the underground stormwater pipe network via the sumps along the kerbs. A small number of sealed roads in the Lake Tuggeranong catchment divert stormwater directly to public open space.

Castellated kerbs are concrete kerbs that include engineered breaks or channels diverting water to adjacent pervious land. Retrofitting castellated kerbs on roads adjacent to public open space in the Lake Tuggeranong catchment has two potential benefits for improving water quality in the lake. Firstly,

stormwater diverted to public open space is able to infiltrate the soil, allowing the capture of nutrients and sediment from the water. Secondly, the flow of the portion of stormwater diverted to public open space is slowed, and the volume of water remaining in the stormwater network is reduced. These effects reduce the hydrological flashiness in downstream areas of the catchment, with benefits for the function of other WSUD infrastructure. Estimating these secondary effects on downstream hydrology is extremely complex and beyond the capability of this assessment. Here, phosphorus removal performance estimates are estimates of the amount of stormwater and pollution diverted from sealed roads.

The Lake Tuggeranong catchment model estimates that 582 kg TP/year is generated from the 388 ha of impervious road surface area in the catchment (Dey, Stewart, Kahn, Booksmythe, & Starrs, 2024). Using ACT Government GIS layers for land zoning and roads, the surface area of road that is adjacent to public open space is 166.15 ha, or 43% of the total road area. Assuming that pollutant generation is uniform, the amount of TP generated on roads adjacent to public open space is calculated as 249 kg/year (43% of the total road TP load). However, in some instances, the road will slope away from the adjacent open space – here we assume that on average, half of the road area adjacent to public open space has a slope suitable to allow drainage towards the open space, and so half of the TP generated on this road area – 124.5 kg TP/year – is currently received by the 1813 stormwater sumps located along kerbs bordering public open space.

2.7.2 Phosphorus removal performance

Not all of the TP currently received by stormwater sumps bordering open space would be diverted to castellated kerb outlets, as these outlets are not able to receive as much road runoff as stormwater sumps, and will be bypassed when the pervious land is saturated. Here we conservatively assume that a castellated kerb outlet can receive half as much runoff as a stormwater sump.

Under these assumptions, if a castellated kerb outlet was installed immediately ‘upstream’ of each of the 1813 stormwater sumps located on kerbs bordering public open space, intercepting half of the road runoff received by each sump, 62 kg TP/year would be diverted from the stormwater network. This represents an upper limit to the amount of TP removed, as it is likely an unrealistically high rate of installation, and does not take into account logistical considerations for construction or issues such as changes to the road flooding risk. Lower rates of installation result in proportionally lower rates of TP removal: installing a castellated kerb outlet for every second, third, or fourth sump would remove 31, 20.75, or 15.5 kg TP/year, respectively.

2.7.3 Costing

The cost to retrofit castellated kerb outlets was reported as $6,872 per outlet in the preliminary sketch plan (PSP) report by Construction Control Australia for a project to construct 36 outlets in the Lake Tuggeranong catchment as part of Stage 2 of the ACT Healthy Waterways project (Construction Control Australia Pty Ltd, 2022). We used this figure as our lower estimate of the cost of this management option. An alternative costing estimate of $10,000 per outlet is is derived from the estimated cost in 2024 for the construction of 51 outlets of $18,802 per outlet (GW2, 2024), and assumes an economy of scale to achieve a reduced per unit cost.

2.7.4 Cost-effectiveness

We assume a lifecycle of 30 years for castellated kerbs, consistent with other management options. However, no reliable estimate of the maintenance costs of castellated kerb outlets was obtained, and our estimates of cost-effectiveness of this management option are based solely on the capital cost of installation.

In calculating the cost-effectiveness of castellated kerbs as a management option, we incorporated a range of installation frequencies (an outlet for every sump – an outlet for every 4 sumps) and costs (between the lower and higher cost estimates obtained, above). We assumed an economy of scale such that installing outlets at the lower rate of one for every four sumps incurs the highest per-outlet cost of $10,000, but there is a marginal decrease in per-outlet costs as more outlets are installed (Table 19).

2.7.5 Quality of supporting evidence

Using the evaluation rubric (Appendix A), the estimates of cost-effectiveness of installing castellated kerb outlets scored 11/14 for confidence in cost estimates, and 7/16 for confidence in performance estimates.

Table 19. Estimated annual load of total phosphorus (TP) prevented from entering Lake Tuggeranong, cost per castellated kerb outlet installed, total 30-year lifecycle cost, and cost-effectiveness of for four levels of investment into retrofitting castellated kerb outlets to divert road runoff from the stormwater network.

Investment level	Number of outlets installed	TP removed (kg/year)	Cost per outlet	Cumulative total lifecycle cost[1]	Cost per unit TP removed ($/kg)
1	453 (1 per 4 sumps)	15.56	$10,000	$4,532,500	$9,708
2	604 (1 per 3 sumps)	20.75	$9,652	$5,990,823	$9,624
3	906 (1 per 2 sumps)	31.13	$8,957	$8,539,901	$9,146
4	1813 (1 per sump)	62.25	$6,872	$14,349291	$7,684

1 Cumulative total lifecycle cost is calculated based on the assumed marginal improvement in per-unit cost between installation tiers. For example, the total cost of installing 453 outlets (the lowest installation rate) is equal to 453 times the unit cost of $10,000. The total cost of installing 604 outlets (the second-lowest installation rate) is equal to the cost of installing 453 outlets at $10,000, plus 153 outlets at the unit cost of $9,652.

2.8 Installation of floating wetlands

2.8.1 Background

Once nutrients are transported into a waterbody, they may become available for uptake by plants, algae, and bacteria, including blue-green algae. Fringing and in-lake vegetation can help to limit blue-green algae blooms by competing with them for these nutrients, particularly phosphorus. One approach to increasing in-lake vegetation is to install floating wetlands.

Floating wetlands are floating structures supporting beds of emergent wetland vegetation, deployed in lakes and ponds to remove nutrients from the water. The plants take up the nutrients they need as they grow, and regular harvesting of the plants prevents the recycling of those nutrients back into the water. The ACT Healthy Waterways program contracted Atlan Stormwater to trial floating wetlands in Lake Tuggeranong in 2023 (Atlan Stormwater, 2023). Three floating platforms totalling 500m^2 were installed, with three species of wetland plants compared for their nutrient uptake rates. The data from this trial inform the estimates of TP removal performance and cost of this management option.

2.8.2 Phosphorus removal performance

In the trial, the floating wetland plants were harvested once, after a year of deployment, and the increase in their TP content was recorded as a measure of the amount of TP they removed from the lake. From this we can calculate the amount of TP removed from the lake per square metre of floating wetland area for each plant species separately. The worst-performing species removed 0.001kg TP/m^2/year, and the best-performing species removed 0.005kg TP/m^2/year. The average amount of TP removed by all three species was 0.003kg TP/m^2/year, and we used this as our estimate of floating wetland TP removal performance.

2.8.3 Costing

G2W Pty Ltd were engaged to review the costs associated with existing WSUD infrastructure in the Lake Tuggeranong catchment (G2W Pty Ltd, 2024). The average capital cost of the trialled floating wetlands was \$1,049/m^2, and the annual maintenance cost was \$13.24/m^2.

2.8.4 Cost-effectiveness

We calculated the cost-effectiveness of floating wetlands based on the above TP removal performance and costs over a 30-year lifecycle, as \$13,622.2/kg TP removed. We assume that both cost and performance scale linearly with floating wetland area, so cost-effectiveness remains the same for any size of wetland. To provide four levels of investment in this management option, we used four sizes of floating wetland area (Table 20).

Table 20. Wetland area, estimated TP removal performance, estimated capital cost and annual operation and maintenance costs, 30-year lifecycle costs and cost-effectiveness for four levels of investment in installation of floating wetlands in Lake Tuggeranong.

Investment level	Wetland area (m^2)	Total annual TP removed (kg)	Capital cost	Annual operation and maintenance costs	Total 30-year lifecycle cost[1]	Cost per unit TP removed ($/kg)
1	1000	3	$1,049,000	$13,240	$1,226,000	$13,622.2
2	2000	6	$2,098,000	$26,480	$2,452,000	$13,622.2
3	3000	9	$3,147,000	$39,720	$3,678,000	$13,622.2
4	4000	12	$4,196,000	$52,960	$4,904,000	$13,622.2

1 Total lifecycle cost is calculated over 30 years using a discount rate of 7% per annum on O&M costs.

2.8.5 Quality of supporting evidence

Using the evaluation rubric (Appendix A), the above estimates of cost-effectiveness of installing floating wetlands in Lake Tuggeranong scored 10/14 for confidence in cost estimates, and 9/16 for confidence in performance estimates.

2.9 Installation of stormwater recycling infrastructure

2.9.1 Background

Urban stormwater contains high concentrations of nutrients because the large area covered by impervious surfaces in the urban environment prevents water from soaking into the ground and being naturally filtered through the soil. Diverting some stormwater for use in the irrigation of public sports fields removes nutrients from the stormwater system. It also slightly reduces the volume of stormwater that continues through the system, reducing hydrological flashiness to the benefit of downstream WSUD infrastructure.

In the Lake Tuggeranong catchment, a stormwater recycling system for sports field irrigation has been installed at one publicly managed sports field (TCCS ID: Kambah 3). A further ten publicly managed sports fields at 8 sites in the Lake Tuggeranong catchment are currently irrigated using potable water, with a combined irrigation water demand of 194 ML/year, at an average cost of $5,478/ML. Here we assess the TP removal performance and cost of installing stormwater recycling infrastructure for sports field irrigation across these sites.

2.9.2 Phosphorus removal performance

As we assume that 100% of the P in stormwater is removed when water is used for irrigation, the amount of TP removed depends on the amount of stormwater used for irrigation. TCCS provided data on the average annual water demand for 10 irrigated sports fields at 8 sites in the Lake Tuggeranong catchment (Table 18). In wet years, irrigation water demand is low and stormwater is abundant, conditions that make it likely that 100% of demand can be met using recycled stormwater. In dry years, however, water demand is high and stormwater is relatively scarce. This, combined with the flashy nature of stormwater hydrographs, make it unlikely that all the irrigation demands will be met by stormwater. We therefore assume that overall, 75% of average annual potable water demands would be met using stormwater (Table

20). We assume a TP concentration of 0.15mg/L to calculate the potential load of TP removed by harvesting stormwater to irrigate these sports fields (Table 21). This value is the average median observed TP in the University of Canberra research data used to calibrate the catchment model (Ubrihien, et al., 2020).

Table 21. Annual irrigation demand, estimated demand met by recycled stormwater, and estimated annual TP load in recycled stormwater, for 8 sports field sites[1] in the Lake Tuggeranong catchment.

Sports field ID	Total annual irrigation water demand (ML)	Demand met by stormwater = 75% of total (ML)	TP load in stormwater used for irrigation (kg)
Calwell 1, 2, 3[1]	47.15	35.36	5.30
Kambah 1	31.18	23.38	3.51
Wanniassa 2	28.40	21.30	3.19
Greenway 1	27.70	20.77	3.12
Gowrie 1	18.68	14.01	2.10
Kambah 2	17.49	13.12	1.97
Chisholm 1	15.21	11.41	1.71
Isabella 1	7.76	5.82	0.87
Total	193.57	145.17	21.78

1 TCCS provided a combined irrigation demand for three Calwell sports fields, which are treated as a single site.

2.9.3 Costing

The estimated costs of installing stormwater recycling infrastructure are based on the realised cost of the infrastructure installed at Kambah 3 (GW2, 2024) and assume that each system will include the same components, namely:

- Stormwater treatment train (gross pollutant trap, sediment forebay, and wetland/pond/raingarden)
- Pumps and pipe infrastructure
- Water treatment plant (sand filter and UV filter)
- Water holding tanks (1 ML capacity)
- Operation and maintenance

These costs will be offset by the savings accrued as a result of the 75% reduction in the use of potable water and its associated cost of $5,478/ML.

The infrastructure installed at sports field Kambah 3, which has an average annual water demand of 26.6 ML, had capital costs of approximately $1,500,000, and annual operation and maintenance costs of $65,000. This site had existing water tanks for irrigation, which is not the case for all of the sites costed here. We therefore take these as the lower bound of cost estimates, and assign this minimum cost to sports fields with an average annual water demand equal to or less than that of Kambah 3. We assume that more infrastructure will be required to divert, filter, store, and irrigate more water, and that operation and maintenance of larger facilities will increase similarly. Both the capital costs and O&M costs for stormwater

recycling infrastructure installed at sports fields with larger water demands than Kambah 3 are scaled up in proportion to their demand (Table 22).

2.9.4 Cost-effectiveness

While sports fields with the highest annual irrigation demands have the highest capital and O&M costs, they also experience the largest savings from reduced potable water expenses and remove the largest TP loads, representing the most cost-effective options (Table 22).

Table 22. Capital cost, annual operation and maintenance cost, savings from reduced potable water use, 30-year lifecycle cost, and cost-effectiveness for the installation of stormwater recycling infrastructure for irrigation at 8 sports field sites in the Lake Tuggeranong catchment.

Sports field ID	Capital cost	Annual operation and maintenance cost	Savings from potable water expenses	Total 30-year lifecycle cost[1]	Cost per unit TP removed ($/kg)
Calwell 1, 2, 3	$2,661,034	$115,311	-$193,726	$1,609,575	$10,115
Kambah 1	$1,759,537	$76,247	-$128,096	$1,064,288	$10,115
Wanniassa 2	$1,602,639	$69,452	-$116,681	$969,446	$10,115
Greenway 1	$1,563,316	$67,744	-$113,811	$945,600	$10,115
Gowrie 1	$1,500,000	$65,000	- $76,748	$1,342,472	$21,295
Kambah 2	$1,500,000	$65,000	- $71,868	$1,407,903	$23,850
Chisholm 1	$1,500,000	$65,000	- $62,496	$1,533,578	$29,875
Isabella 1	$1,500,000	$65,000	- $31,887	$1,994,008	$74,221

1 Total lifecycle cost is calculated over 30 years using a discount rate of 7% per annum on both annual O&M costs and savings from reduced potable water expenses.

To provide four levels of investment in this management option, we grouped the 8 sports field sites by size and cost-effectiveness and created four tiers of installation: either build the best two, best four, best six, or all 8 stormwater recycling systems (Table 23).

Table 23. Costing summary for four levels of investment in installing stormwater recycling infrastructure for sports field irrigation in the Lake Tuggeranong catchment.

Investment option	Costing level	Total annual TP removed (kg/year)	Total 30-year lifecycle cost[1]	Cost per unit TP removed ($/kg)
1	Build best 2	8.81	$2,673,863	$10,115
2	Build best 4	15.12	$4,588,909	$10,115
3	Build best 6	19.19	$7,339,284	$12,748
4	Build all 8	21.78	$10,816,870	$16,558

1 Total lifecycle cost is calculated over 30 years using a discount rate of 7% per annum on O&M costs.

2.9.5 Quality of supporting evidence

Using the evaluation rubric (Appendix A), the above estimates of cost-effectiveness of installing stormwater recycling infrastructure for sports field irrigation scored 10/14 for confidence in cost estimates, and 10/16 for confidence in performance estimates.

2.10 Installation of household rainwater tanks

2.10.1 Background

Residential properties make up a large proportion of the Lake Tuggeranong catchment area, and consist of large areas of impervious surface in the form of rooftops. Residential properties are therefore expected to be a significant contributor to the generation of nutrient pollutants and runoff in the catchment.

Encouraging the installation of plumbed household rainwater tanks on residential properties, by covering some or all of the associated costs to property owners, is a potential approach to reducing this source of runoff. Installation of plumbed rainwater tanks at residential properties diverts runoff, and the phosphorus it carries, from the stormwater system, instead directing it to non-potable household uses and on to the wastewater (sewage treatment) system, or to garden uses from where it completes the water cycle either via evapotranspiration or by entering the groundwater. When properly plumbed in and used, household rainwater tanks help to reduce the intensity of rises in water level and flow during rainfall events (i.e. flatten the hydrograph), which should be beneficial for the TP removal performance of downstream WSUD infrastructure. Rainwater tanks provide some opportunity to directly capture phosphorus when particulate forms are deposited within the tanks, although this effect is likely to be small.

2.10.2 Phosphorus removal performance

To calculate the amount of TP diverted from the stormwater system by rainwater tanks we used estimates of the annual amount of water captured and used by plumbed rainwater tanks, from a study that modelled the savings in potable water offered by residential rainwater tanks in Canberra (Imteaz, Yilmaz, Santos, & Ahsan, 2023). Their estimates account for seasonal variability in rainfall, the typical non-potable water demands of a household, and the spillover of water to the stormwater system when tanks are over capacity, and are broadly summarised for a range of roof and tank sizes in Table 24.

Table 24. Potable water savings from plumbed household rainwater tanks, estimated by Imteaz et al. 2023.

Roof size (m^2)	Tank size (L)	Water saved – dry year (L/year)	Water saved – average year (L/year)	Water saved – wet year (L/year)
100	2,500	35,000	50,000	55,000
200	5,000	40,000	55,000	60,000
100	2,500	50,000	60,000	65,000
200	5,000	60,000	75,000	80,000

These estimated water savings represent the amount of residential runoff diverted from the stormwater system by plumbed rainwater tanks. By multiplying these by the estimated concentration of TP in runoff from suburban roof area in the Lake Tuggeranong catchment (from the calibrated catchment model) we can calculate the approximate load of TP removed per household (Table 25).

Table 25. Estimated loads of TP diverted from the stormwater system by plumbed household rainwater tanks.

Roof size (m^2)	Tank size (L)	TP removed – dry year (L/year)	TP removed – average year (L/year)	TP removed – wet year (L/year)
100	2,500	3.82	5.45	5.99
200	5,000	4.36	5.99	6.54
100	2,500	5.45	6.54	7.09
200	5,000	6.54	8.18	8.72

While the annual load of TP removed from the stormwater system per household is small, ranging between approximately 4-8 g/year, multiplying by the number of residential properties in the Lake Tuggeranong catchment (~21,000 RZ1- and RZ2-zoned blocks) gives an upper estimate of annual TP removal of between 84-168 kg/year.

However, this assumes 100% uptake in rainwater tank installation, which is unlikely for several reasons. An estimated 36% of households in the ACT already have rainwater tanks installed, and therefore do not contribute to this source of TP (Schirmer & Dale, 2023). Some households may not be willing or able to install rainwater tanks, and others may not make full use of the water captured by their tanks, which increases spillover and reduces the amount of water diverted from the stormwater system. In costing this option we assume that the highest rate of uptake of new household rainwater tanks would be 10,000 households, or around 50% of residential properties in the Lake Tuggeranong catchment.

2.10.3 Costing

For this management option we estimate costs for a government grant scheme that covers the capital cost of rainwater tank installation for residential properties in the Lake Tuggeranong catchment. Rainwater tanks installed on suburban residential properties are typically of 1,000 - 3,000 L capacity, and cost between $1,000 - $2,000. Adding the costs of installation and plumbing, here we assume a total cost per household of $5,000 that would be provided by government funding. Rainwater tanks are fairly low maintenance, and we assume any operation and maintenance costs would be left to property owners in costing this management option.

2.10.4 Cost-effectiveness

We assume an average rainwater tank TP removal performance of 6 g/year, at a cost of $5,000 per tank installed. Over a 30-year lifecycle, this gives a cost-effectiveness estimate of $27,778 per kg TP removed. To provide four levels of investment in this management option, we costed rates of uptake of rainwater tank installation of between 2,500 and 10,000 households (Table 26).

Table 26. Costing summary for four levels of investment in installing household rainwater tanks on residential properties in the Lake Tuggeranong catchment.

Investment level	Number of households	Total TP removed (kg)	Total 30-year lifecycle cost[1]	Cost per unit TP removed ($/kg)
1	2,500	15	$12,500,000	$27,778
2	5,000	30	$25,000,000	$27,778
3	7,500	45	$37,500,000	$27,778
4	10,000	60	$50,000,000	$27,778

1 30-year lifecycle cost is the capital cost of tank installation, as we assume no operation and maintenance costs for this option.

2.10.5 Quality of supporting evidence

Using the evaluation rubric (Appendix A), the above estimates of cost-effectiveness of a government grant scheme that covers the capital cost of rainwater tank installation for residential properties in the Lake Tuggeranong catchment scored 6/14 for confidence in cost estimates, and 9/16 for confidence in performance estimates.

3. Designing management scenarios

3.1 Comparing the cost-effectiveness of management options

Table 27 presents the annual load of TP removed, the 30-year cost, and the cost-effectiveness of the four levels of investment for the management options assessed in Section 2. We plotted the range of TP removal performance and cost of each management option across the levels of investment to provide a visual comparison of the management options and the range of cost-effectiveness for each option (Fig. 1). Increasing street sweeping frequency and constructing additional WSUD infrastructure were estimated to remove the largest amounts of phosphorus annually, in the range of 100-400 kg/year. Street sweeping was the more cost-effective of these two approaches, estimated at $1,000-2,500 per kg TP removed, while constructing WSUD infrastructure had costs of between $7,000-12,000 per kg P. The remaining options all had lower total annual TP removal performances and ranged in cost-effectiveness up to $28,000 per kg TP.

Table 27. Summary of phosphorus removal performance, total cost, and cost-effectiveness for four levels of investment for each of 10 management options assessed in this report. See Section 2 for details of the investment levels for each management option.

Management option and level	TP removed (kg/year)	30-year cost ($)[1]	Cost-effectiveness ($/kg TP)
Install additional WSUD 1	106.21	$22,507,500	$7,064
Install additional WSUD 2	169.67	$48,369,492	$9,502
Install additional WSUD 3	226.22	$73,862,467	$10,884
Install additional WSUD 4	240.46	$84,519,403	$11,716
Maintenance of existing WSUD 1	35.84	$10,177,128	$9,465
Maintenance of existing WSUD 2	61.78	$19,086,579	$10,298
Maintenance of existing WSUD 3	79.93	$26,352,433	$10,990
Maintenance of existing WSUD 4	88.02	$30,352,433	$11,495
Increase street sweeping 1	203.7	$7,030,414	$1,150
Increase street sweeping 2	320.1	$14,060,827	$1,464
Increase street sweeping 3	372.5	$21,091,242	$1,887
Increase street sweeping 4	395.8	$28,121,656	$2,369
Manage grass clippings 1	16.4	$2,018,874	$4,103
Manage grass clippings 2	26.1	$2,018,874	$2,578
Manage grass clippings 3	32.7	$1,521,462	$1,551
Manage grass clippings 4	52.3	$1,565,956	$998
Sports field fertilizer management 1	14.93	$4,204,451	$9,387
Sports field fertilizer management 2	29.85	$11,817,327	$13,196
Sports field fertilizer management 3	44.78	$19,430,204	$14,463

Management option and level	TP removed (kg/year)	30-year cost ($)[1]	Cost-effectiveness ($/kg TP)
Sports field fertilizer management 4	59.70	$31,445,222	$17,557
Household fertilizer management 1	20	$6,000,000	$10,000
Household fertilizer management 2	32.67	$9,800,000	$10,000
Household fertilizer management 3	45.33	$13,600,000	$10,000
Household fertilizer management 4	58	$17,400,000	$10,000
Install castellated kerbs 1	15.56	$4,532,500	$9,708
Install castellated kerbs 2	20.75	$5,990,823	$9,624
Install castellated kerbs 3	31.13	$8,539,901	$9,146
Install castellated kerbs 4	62.25	$14,349,291	$7,684
Install floating wetlands 1	3	$1,226,000	$13,622.2
Install floating wetlands 2	6	$2,452,000	$13,622.2
Install floating wetlands 3	9	$3,678,000	$13,622.2
Install floating wetlands 4	12	$4,904,000	$13,622.2
Stormwater recycling for irrigation 1	8.81	$2,673,863	$10,115
Stormwater recycling for irrigation 2	15.12	$4,588,909	$10,115
Stormwater recycling for irrigation 3	19.19	$7,339,284	$12,748
Stormwater recycling for irrigation 4	21.78	$10,816,870	$16,558
Household rainwater tanks 1	15	$12,500,000	$27,778
Household rainwater tanks 2	30	$25,000,000	$27,778
Household rainwater tanks 3	45	$37,500,000	$27,778
Household rainwater tanks 4	60	$50,000,000	$27,778

1 Total lifecycle cost is calculated over 30 years using a discount rate of 7% per annum on annual (O&M) costs after the first year.

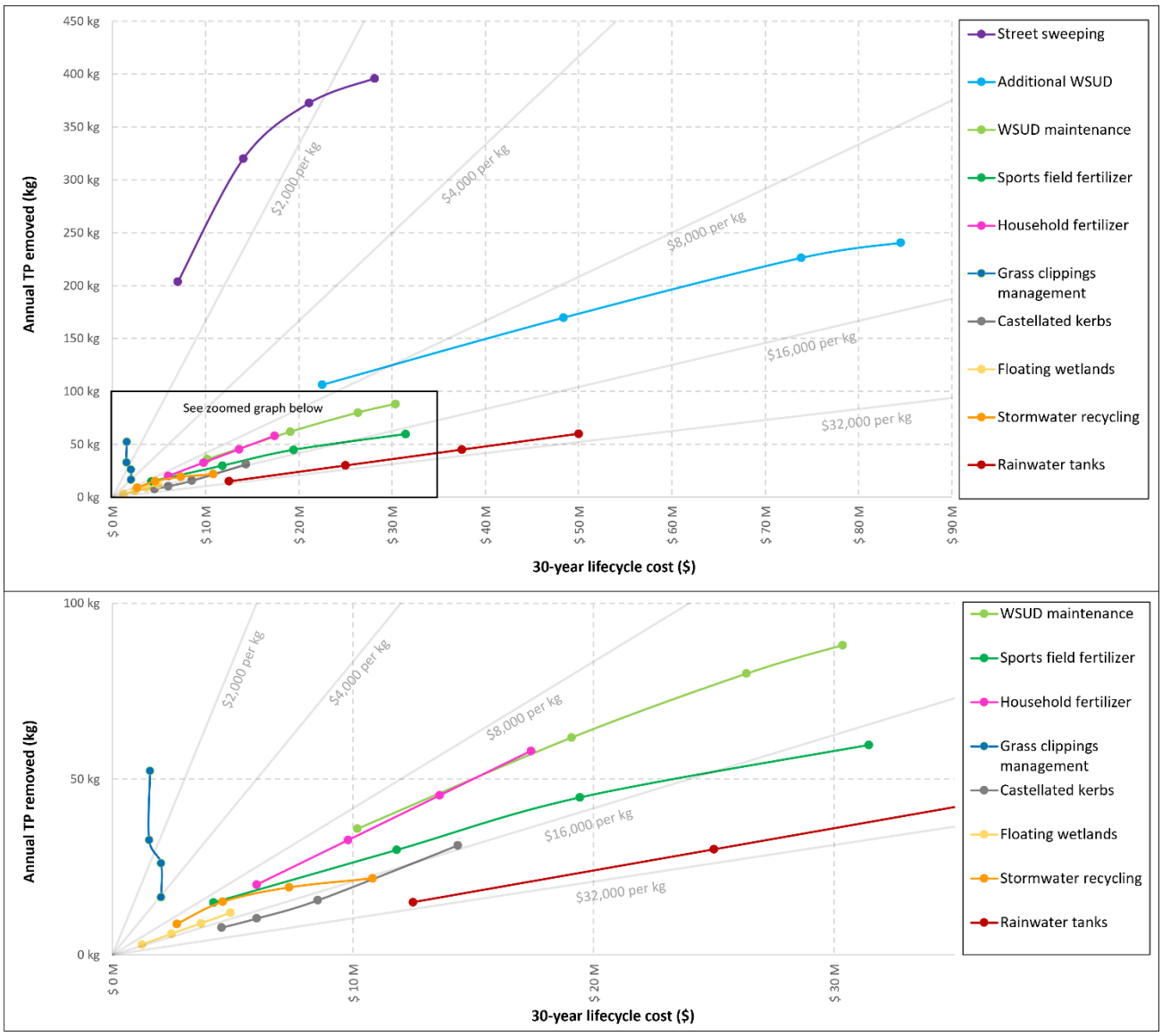

Figure 1. Annual total phosphorus load removed, and 30-year lifecycle cost, of each investment level for the 10 management options assessed in Section 2. Coloured lines connect the four estimates for each management option. Grey lines are a guide indicating the cost-effectiveness (cost per kg TP removed) of the estimates. The top panel shows all estimates; the bottom panel shows a zoomed in view of the estimates within the inset box.

The results of the management option assessments show that there is no single option capable of achieving the estimated ~700 kg reduction in annual phosphorus load required to maintain Lake Tuggeranong in a predominantly mesotrophic state (Kahn & Dey, 2024). To approach this target reduction, a combination of several management options aimed at reducing and intercepting catchment sources of phosphorus will be necessary.

3.2 Combining options to build management scenarios

The Healthy Waterways planning team used the information in Section 2, Table 27 and Figure 1 to create two scenarios, consisting of different combinations of management options, that achieved a reduction in the total annual phosphorus load entering Lake Tuggeranong of around 700 kg (Table 28).

Table 28. Comparison of the investment levels of management options selected for inclusion in the Cost-effective and Broad benefits scenarios designed to achieve a 700 kg reduction in the annual phosphorus load entering Lake Tuggeranong.

Management option	Cost-effective scenario	Broad benefits scenario
Install additional WSUD infrastructure	Investment level 1	Investment level 2
Maintenance of existing WSUD infrastructure	Investment level 3	Investment level 4
Increase frequency of street sweeping	Investment level 4	Investment level 3
Manage grass clippings from municipal mowing	Investment level 3	Investment level 3
Sports field fertilizer management	Investment level 1	Investment level 3
Household fertilizer management	Investment level 4	Investment level 1
Install castellated kerbs	n/a	Investment level 1
Install floating wetlands	n/a	Investment level 4
Stormwater recycling for sports field irrigation	Investment level 2	Investment level 3
Sum of annual TP removed	702.65 kg	766.62 kg
Total 30-year cost	$104,696,482	$143,540,616

The **Cost-effective scenario** systematically ranked the investment levels of each management option by cost-effectiveness, and selected the most cost-effective investment level of the most cost-effective options until the total annual phosphorus load removed met the 700 kg target. This scenario prioritized management options that prevent pollutants from entering the stormwater system, such as street sweeping and fertilizer management, as these have high cost-effectiveness. Options involving WSUD infrastructure were given lower priority under this approach, as they tend to have high costs for more limited phosphorus removal capacity. Some options, including rainwater tanks, floating wetlands, and castellated kerbs, were not considered to be sufficiently cost-effective for inclusion in this scenario.

The **Broad benefits scenario** considered additional information, as well as cost-effectiveness, when selecting management options to meet the 700 kg phosphorus removal target. This approach took into account the quality of evidence underlying each management option assessment, avoiding large investments into options with less certainty around their cost or performance estimates. Broader community and government values, including wellbeing, climate resilience, and public amenity, were also considered when selecting options to include in this scenario. This led to a wider variety of options being

selected for the broad benefits scenario compared to the cost-effective scenario, including more options involving WSUD infrastructure (Table 28).

The TP removal and cost-effectiveness estimates obtained for each management option do not consider the way that options may interact and affect each other's performance. For example, decreasing the load of phosphorus entering stormwater by frequent street sweeping in the catchment should result in lower phosphorus concentrations in the stormwater intercepted by a raingarden further downstream, reducing the phosphorus available for the raingarden to remove. Some of these interacting effects can be estimated by implementing combinations of management options in the catchment model, and calculating the total reduction in the phosphorus load entering Lake Tuggeranong under different combinations.

3.3 Modelling management scenarios

The two scenarios summarised in Table 28 were implemented in the catchment model, to generate estimates of the total annual load of phosphorus entering Lake Tuggeranong under each scenario, while accounting for interactive effects of different management options (Dey, Stewart, Kahn, Booksmythe, & Starrs, 2024).

Different management options are implemented in different ways in the catchment model. Some options are explicitly represented by the addition or modification of specified links and nodes in the model:

- **Additional WSUD infrastructure** Proposed raingardens were represented in the catchment model by new storage nodes placed at the locations indicated in the original plans for the raingardens. The raingarden nodes were configured using the size indicated in the original plans, and the performance details of similar existing WSUD assets.
- **Maintenance of existing WSUD infrastructure** The catchment model includes storage nodes representing each WSUD asset in the Lake Tuggeranong catchment, with the performance of each asset configured to reflect its current phosphorus removal efficiency. To represent maintenance of these assets to their designed performance, the performance details were reconfigured to the phosphorus removal rates given in the detailed design reports for each asset.
- **Sports field fertilizer management** For each scenario we modelled sufficient bioretention swales to intercept the required amount of sports field-generated phosphorus (i.e., 25% or 75% of all sports field generated phosphorus). We modelled one swale per subcatchment, with swale size proportional to the area of sports field in each subcatchment. Bioretention swale performance was configured using the performance details of similar existing WSUD assets. As the scale of the catchment model does not delineate sports fields from their subcatchments, a controlled splitter was used to divert water to the node representing each swale, in proportion to the swale : subcatchment area ratio.
- **Stormwater recycling infrastructure for sports field irrigation** Each sports field with stormwater recycling infrastructure was represented by a storage node and an irrigator node. A maximum of 1 ML water was diverted to the storage node via a controlled splitter during event flows. The water in the storage node was used to meet the irrigation demand specified by the irrigator node. Excess water was returned to the stormwater system downstream of the sports field.
- **Floating wetlands** To represent floating wetlands in the catchment model, a storage routing link was added just upstream of the Lake Tuggeranong storage node. This was configured using a decay model to reduce the phosphorus concentration in the water passing through the routing link.

The remaining options were implemented in the model by calculating the percentage phosphorus removal attained by each option, compared to the current load of phosphorus available to be intercepted by that option, and adjusting phosphorus concentrations within the catchment model based on these percentage reductions:

- **Increase street sweeping frequency** The percentage reduction in phosphorus concentration due to increased street sweeping was applied to all area classified as road, and calculated based on the difference in total phosphorus load generated from roads across the catchment with and without an increase in street sweeping frequency.
- **Manage grass clippings from municipal mowing** The percentage reduction in phosphorus concentration due to management of grass clippings from municipal mowing was applied to all area classified as road, and calculated based on the difference in total phosphorus load generated from roads across the catchment with and without management of grass clippings.
- **Install castellated kerbs** The percentage reduction in phosphorus concentration due to the installation of castellated kerbs was applied to all area classified as road, and calculated based on the difference in total phosphorus load generated from roads across the catchment with and without the installation of castellated kerbs.

  As street sweeping, grass clipping management, and castellated kerbs all act to reduce the load of phosphorus generated from roads, the combined effects of these management options were modelled using a build-up wash-off model as described in 2.3.2 and used to predict the total percentage reduction in the phosphorus load from roads due to the selected combination of these options in each scenario.
- **Household fertilizer management** The percentage reduction in phosphorus concentration due to management of household fertilizer use was applied to all area classified as suburban and permeable, and calculated based on the difference in total phosphorus load generated from suburban pervious land across the catchment with and without household fertilizer management.

The catchment model for the Lake Tuggeranong catchment estimates the current load of phosphorus entering Lake Tuggeranong at 1,442 kg/year (Dey, Stewart, Kahn, Booksmythe, & Starrs, 2024). Under the cost-effective scenario, the model estimates that this load would be reduced to 992 kg TP/year (a reduction of 450 kg/year) and under the broad benefits scenario, the model estimates that the load would be reduced to 868 kg TP/year (a reduction of 574 kg/year; Figs. 2, 3).

The estimated reductions in TP load for each proposed management scenario generated by the catchment model are substantially lower than the reductions calculated by adding the individual estimated reductions for each management option (~ 450-575 kg/year vs. ~ 700-750 kg/year, respectively). The major interactive effects explaining this difference are those between management options that prevent TP from entering the stormwater system, such as street sweeping and household fertilizer management, and options that intercept and remove TP from stormwater, such as WSUD infrastructure. Options that prevent TP from entering stormwater have the effect of reducing TP concentrations in the stormwater that will be intercepted by WSUD-type options, which lowers the rate at which these can remove P. Considering management options that act to reduce runoff generation and flatten the peaks of storm flows, might help to improve the performance of WSUD management options in these scenarios.

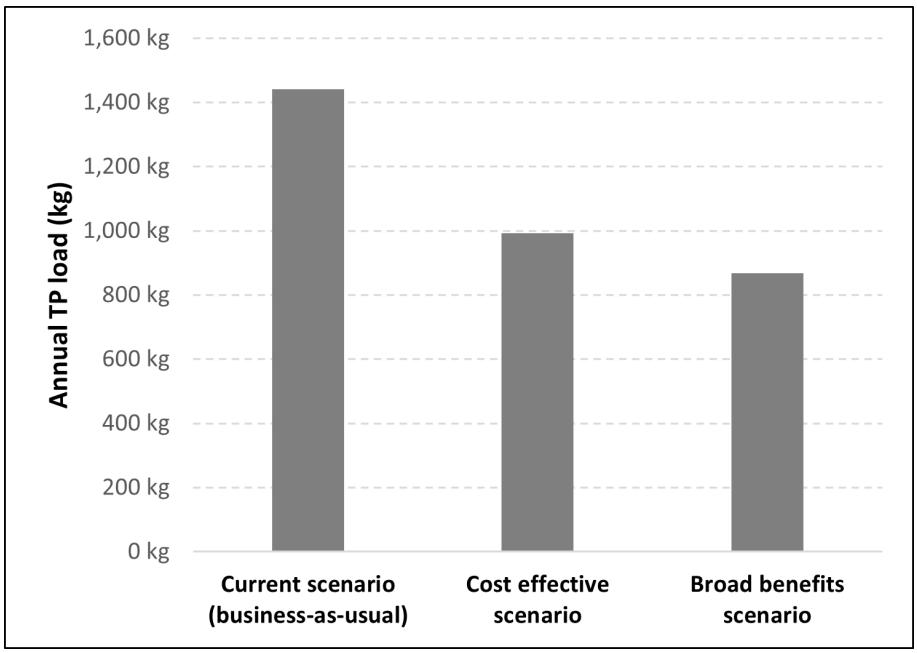

Figure 2. Modelled average annual load of total phosphorus (TP) generated in the Lake Tuggeranong catchment under three management scenarios.

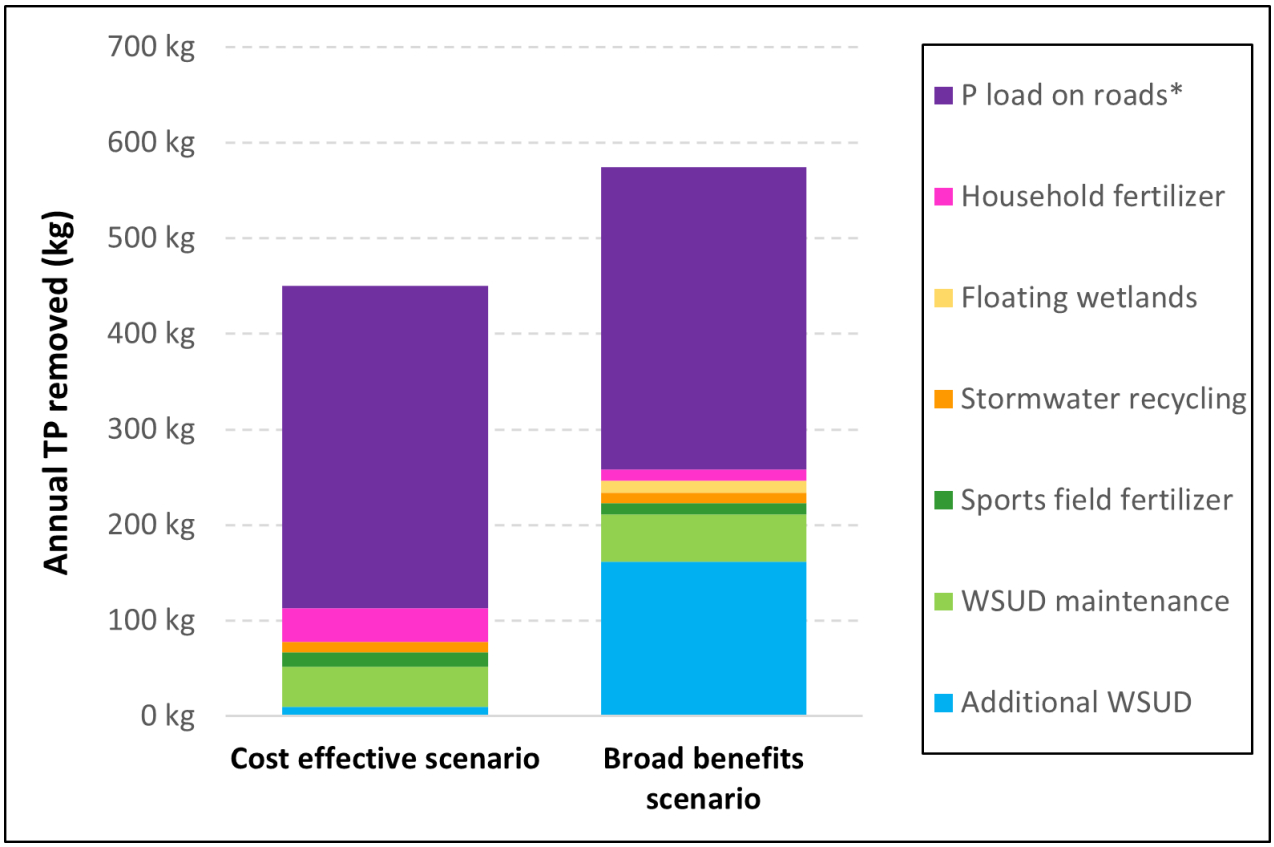

Figure 3. Modelled average annual reduction in the load of total phosphorus (TP) generated in the Lake Tuggeranong catchment, under the cost effective and broad benefits management scenarios. Colours indicate the reduction due to different management options in each scenario. * P load on roads includes the reductions in TP load due to street sweeping, grass clippings management and installation of castellated kerbs.

3.4 Summary

This report has described the approaches used to estimate the phosphorus removal performance and implementation cost of proposed management options for the Lake Tuggeranong catchment. These estimates were used to compare the cost-effectiveness of different management options, and create combinations of options aimed at achieving a ~700 kg reduction in the annual phosphorus load entering Lake Tuggeranong. The Lake Tuggeranong catchment model was used to simulate the effects of these combinations of management options and estimate long-term mean annual inflows and phosphorus loads to Lake Tuggeranong under each scenario.

The management option assessments aimed to provide evidence-based estimates of cost-effectiveness:

- Estimates of the phosphorus removal performance and implementation costs of management options were based on multiple sources, including local implementation of similar management options wherever possible.
- Estimates of the cost of implementation were calculated over a 30-year lifespan for all management options, to allow for the comparison of options with disparate cost distributions.
- A range of estimates was produced for both performance and cost wherever possible, to understand and incorporate uncertainty in the predicted cost-effectiveness of each management option.
- Cost-effectiveness was calculated for each option at four levels of investment to allow its assessment within as well as between management options.
- Confidence in the estimates provided by these assessments was evaluated systematically using a rubric to score the quality of supporting evidence for both the performance and cost estimates for each management option.

Key results of the management options assessment exercise include:

- Increasing the frequency of street sweeping and installing additional WSUD infrastructure are the management options with the largest predicted impacts on reducing phosphorus loads entering Lake Tuggeranong each year.
- Increasing the frequency of street sweeping is estimated to be the most cost-effective management option of those assessed.
- Management scenarios created by combining management options with the aim of achieving a 700 kg reduction in the annual load of phosphorus entering Lake Tuggeranong are estimated to have a total 30-year cost of between $100-145 million.
- Simulating these management scenarios in the Lake Tuggeranong catchment model allows estimation of the predicted reduction in phosphorus entering the lake while accounting for interactions between the different management options included. The model estimates that the average annual phosphorus load to Lake Tuggeranong would be reduced to between 868-992 kg, a 33-44% decrease compared to current catchment conditions.

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5. Appendices

5.1 Appendix A: Quality of evidence assessment rubric

To evaluate the sources of evidence used to inform our assessments of the cost-effectiveness of catchment management options, we designed a rubric to score each option against 9 criteria addressing the information on option cost (4 criteria) and option efficacy (5 criteria) (Table A1).

Table A1. Rubric used to score the quality of evidence informing the assessments of cost-effectiveness of the 10 catchment management options included in this report.

Criterion	Maximum score	1 (weak)	2 (fair)	3 (good)	4 (very good)
Estimates of cost	14				
C1: How recent are cost estimates?	4	Based on implementation 5-10 years ago; **not** 2024 currency	Based on implementation 5-10 years ago; 2024 currency	Based on implementation within the last 5 years; **not** 2024 currency	Based on implementation within the last 5 years; 2024 currency
C2: Source of cost estimates?	4	Not based on previous implementation	Based on implementation overseas	Based on implementation in Australia	Based on implementation in the ACT
C3: Number of independent sources of cost estimates?	3	Costs inferred, from a single source	Based on implementation, from a single source	Based on implementation, from multiple independent sources	
C4: How is variability in cost estimates considered?	3	Based on a single point estimate (+/- 50% or more)	Based on a limited range of estimates (+/- 20-50%)	Based on a substantial range of estimates (+/- 20% or less)	
Estimates of performance	16				
P1: Source of pollutant estimates?	4	Poorly understood	Indirectly inferred from Australian/ overseas data	Indirectly inferred from local empirical data	Directly quantified from local empirical data
P2: Source of performance estimates?	3	Not based on empirical data	Indirectly inferred from local data, or quantified elsewhere	Directly quantified from local empirical data	

Criterion	Maximum score	1 (weak)	2 (fair)	3 (good)	4 (very good)
P3: Is the option explicitly modelled?	3	Represented indirectly in the catchment model, conceptually inconsistent	Represented indirectly in the catchment model, conceptually consistent	Represented explicitly in the catchment model	
P4: Confidence in scaleability of performance?	3	Not understood or not explicitly represented	Inferred from conceptual understanding, explicitly represented	Based on empirical data, explicitly represented	
P5: How is variability in performance estimates considered?	3	Based on a single point estimate (+/- 50% or more)	Based on a range of estimates (+/- 20-50%)	Based on statistical analysis of empirical/ modelled data (+/- 20% or less)	

CABINET

ACT Government

City and Environment Directorate

Ministerial Brief

To:	Minister for Climate Change, Environment, Energy and Water	**Tracking No.: 25/222**
Date:	07/10/2025	
From:	Executive Group Manager, Climate Change, Energy and Water	
Subject:	Final lodgement of 'Options for restoring Lake Tuggeranong', a draft of the 'Healthy Waterways Plan for Lake Tuggeranong'	
Critical Date:	ASAP	
Critical Reason:	The supplementary paper was due to Cabinet Office on 8 October 2025 for cabinet consideration on 16 October 2025	

Recommendations

<

That you:

1. **Sign** and agree for CED to lodge the final Supplementary Paper at Attachment 1 and associated documents with the Cabinet Office; and

Signed/ Not Signed / Please Discuss

2. **Annotate** if an CED official is required to attend.

Required / Not Required / Please Discuss

Suzanne Orr MLA 08/10/25

Minister's Feedback

Background

1. On 10 September 2025, Cabinet considered the draft Healthy Waterways Plan for Lake Tuggeranong.

Issues

2. Cabinet requested a comeback following concerns that wording in the draft Plan will raise expectations in the community of services and works that City Operations (or the ACT Government) does not have fiscal capacity to provide.

3. The City and Environment Directorate (CED) have made edits to the communication materials to strengthen the messaging in line with the concerns raised. The Supplementary paper at Attachment 1 and associated documents are attached for your agreement to lodge with Cabinet Office for Cabinet on 16 October 2025.

Financial Implications

4. Nil for the purpose of this brief.

Consultation

5. Nil for the purpose of this brief.

Work Health and Safety

6. Nil for the purpose of this brief.

Benefits/Sensitivities

7. Nil for the purpose of this brief.

Communications, media and engagement implications

8. There are high community expectations for the restoration of Lake Tuggeranong. Joint involvement in the decision for the future investment to improve the lake is an important consideration.

9. Changes to the consultation approach and activities have been aligned with the cabinet decision. A communications and engagement strategy has been prepared with consultation now scheduled to run for 6 weeks, concluding before Christmas 2025.

Signatory Name:	Kieran Lawton
Action Officer:	Ralph Ogden

Attachments

ACT Government

1 – Final Supplementary Paper

A – Table of comments

E – Community Consultation paper (replaces Snapshot)

F – Options for restore Lake Tuggeranong (updated)

2 – Cabinet meeting brief

CABINET SUPPLEMENTARY PAPER

Cabinet number:	**25/222**
Title:	**Healthy Waterways Plan for Lake Tuggeranong**
Meeting type:	Cabinet (COMEBACK)
Minister:	Suzanne Orr MLA Minister for Climate Change, Environment, Energy & Water
Co-Sponsoring Minister/s:	N/A
ERC date:	Tuesday, 26 August 2025
Previous Consideration date:	Wednesday, 10 September 2025
Cabinet date:	Thursday, 16 October 2025

Status	**FINAL**	
Relationship to previous decisions	2023/24 ERC EPSDD CO2 Expanding Healthy Waterways – Consolidating Gains	
Submission type:	Agree to public consultation	Click here to enter text.
Purpose:	To approve release of 'Options for Restoring Lake Tuggeranong' (Options Paper) and a Community Consultation Paper for public consultation	
Category:	Category 1 - Government Priorities	
Treasury agreement:	Yes	28/04/2025
	Date of Treasury agreement:	Click here to enter a date.
Digital Canberra consultation	No	Click or tap to enter a date.
Access Canberra consultation	No	Click or tap to enter a date.
Legislative change:	No - change to legislation not required	
PCO/JACS HR	No - change to legislation not required	Click here to enter a date.
Regulatory impact	No	
Wellbeing Impact Assessment		Yes
Primary Wellbeing Domain		Environment and climate
Closing the Gap - Priority Reforms	Not in Scope for Closing the Gap Priority Reform	

Minister's signature_____ Date 08/10/2025

RECOMMENDATIONS

1) I recommend Cabinet agree:

   a. To release the revised 'Healthy Waterways Plan for Lake Tuggeranong – Community Consultation Paper' (Attachment E) for public consultation using the Communications Strategy outlined in Attachment D, supported by the publication of the technical report 'Options for Restoring Lake Tuggeranong' (the Options Paper) (Attachment F).

   b. The Minister for Climate Change, Environment, Energy and Water finalise any minor amendments prior to public consultation.

   c. Supporting communications and consultation materials will be approved by the Minister for Climate Change, Environment, Energy and Water following Cabinet agreement.

2) I recommend Cabinet note:

   a. The final 'Healthy Waterways Plan for Lake Tuggeranong' (the Plan) will be brought to Cabinet following the public consultation period, likely early 2026.

   b. The Plan will deliver a part of the 2024 election commitment to *'develop and deliver a 10-year plan for a healthier Lake Tuggeranong'*.

   c. The Options Paper is underpinned by three comprehensive technical reports detailing modelling and other analyses. These will be made publicly available on the City and Environment website at the time of the public consultation period (Attachments G, H, I).

   d. The proposed release of the following Cabinet Decision and Wellbeing Impact Summaries as required under Section 23 of the *Freedom of Information Act 2016*:

      i. Cabinet agreed to the release of the 'Healthy Waterways Plan for Lake Tuggeranong – Community Consultation Paper' and 'Options for Restoring Lake Tuggeranong' Options (Options Paper) for public consultation. The Options Paper describes current knowledge about what is causing blue-green algal blooms in Lake Tuggeranong, and, using modelling of catchment water quality and mitigation costs, presents options for addressing them.

      ii. Lake Tuggeranong's frequent blue-green algal blooms have negative visual and smell impacts, present health risks, and prevent people from recreating in and around the lake. Using current scientific understanding of what's causing Lake Tuggeranong's algal blooms, the Options Paper presents options to improve water quality in the catchment to reduce the frequency and severity of blooms. This will have positive wellbeing benefits for the Tuggeranong community through reducing health risks, providing access to blue-green space, and enhancing cultural and biodiversity values.

SUPPLEMENTARY INFORMATION

3) The Options Paper and associated communications material were considered by Cabinet on 10 September 2025. Cabinet asked for further development of the Options Paper and associated materials to ensure that consultation does not inappropriately commit Government to actions or investment at this time.

4) There were concerns that wording in the Options Paper will raise expectations in the community of services and works that City Operations (or the ACT Government) does not have fiscal capacity to provide.

   a. The options presented will enable the Government to eliminate algal blooms in Lake Tuggeranong three out of four years, and manage them in-lake in the one in four years they arise.

   b. There is not an expectation that current budgets for the relevant sections in City Operations and other CED divisions could deliver the proposed services and works. The Options Paper makes it clear that restoration would require new funding to the delivery sections.

   c. The Government can expect increased income as lakeside businesses become more viable and residences increase in value that can be used to offset the costs of implementing the Plan.

   d. City Operations has nominated several staff to work with the Office of Water to prepare a 2026-27 business case to support consideration and implementation of the Plan, and the indicative costs of proposed changes to the street sweeping regime will be refined through this process.

5) Cabinet recommended changes to the communications material, specifically to emphasise the improvement of street sweeping outcomes without committing to increased resourcing in advance of budget consideration.

   a. Changes have now been made to strengthen the messaging in line with the concerns raised:

      i. The term **increased sweeping** (i.e. frequency of sweeping) has been changed to **targeted street sweeping** in the communications materials.

      ii. The same change has been made within the Options Paper except where specific reference is made to the performance of different frequencies of increased street sweeping, which is what was modelled and evaluated in the Paper.

      iii. Key messages have also been updated in the Community Consultation Paper to highlight that the focus must shift from more expensive options like building new infrastructure towards more effective options to stop pollution at the source – including actions that residents can apply (to do with leaves, fertilisers) and the interventions the Government is already undertaking (street sweeping, maintenance).

FINANCIAL IMPACT

Nil

TECHNOLOGY IMPACT

Nil

SERVICE DELIVERY IMPACT

Nil

WELLBEING IMPACT SUMMARY

Nil

CLOSING THE GAP - PRIORITY REFORMS

Nil

CONSULTATION

External stakeholders

Nil for this paper

ACT Government Agencies

Nil for this paper

MEDIA AND COMMUNICATIONS

6) A communications and engagement strategy has been prepared with consultation now scheduled to run for 6 weeks, concluding before Christmas 2025. It is anticipated that the consultation will attract media coverage and Tuggeranong community commentary.

7) The updated materials will be graphically designed following Cabinet agreement.

IMPLEMENTATION

Nil

HUMAN RIGHTS IMPACT

Nil

ATTACHMENTS

Updated or new attachments:

Attachment A – Table of comments

Attachment D – Communications strategy

Attachment E – Community Consultation Paper (word version)

Attachment F – Options to restore Lake Tuggeranong - revised language

ACT Government

MINISTER'S CABINET BRIEF

Cabinet Number	**25/222**
Title	Draft Healthy Waterways Plan for Lake Tuggeranong - Public Consultation
Minister	Suzanne Orr MLA
Portfolio	Minister for Climate Change, Environment, Energy & Water
Cabinet date	Wednesday, 1 October 2025
Recommended position	SUPPORT

Submission recommendations

This is your submission – the City and Environment Directorate (CED) recommends you support all recommendations.

Issues/comment

The Minister for City and Government Services may raise concerns around the presentation of city operations costs (street sweeping) in the *Options* report and backing technical reports; whether the costs have been developed in consultation with City Operations; and the risk that public consultation on the *Options* report will raise expectations in the community of services and works that City Operations (or the ACT Government) does not have fiscal capacity to provide.

The Office of Water has and continues to work closely with City Operations in the development of the options and costings, informed in part by street sweeping trials over the last two summers.

CED has revised key communications documents to emphasise options that residents can apply (preventing pollution at the source) and targeting the interventions (street sweeping, maintenance) the Government is already undertaking, rather than more expensive options like infrastructure investment. You could seek agreement that any further requested changes be settled between relevant Ministers.

Wellbeing Impact Assessment

Implementation of the Healthy Waterways Plan will have a positive impact on the wellbeing of residents in Tuggeranong and visitors to Tuggeranong within the domains of, primarily, Environment and Climate and secondarily, Health, Social connection, Economy and Governance and institutions.

Context and consultation

The *Options* report is not a statement of government commitment nor a proposal for investment. The method for costing enhanced street sweeping is based on figures provided by the former TCCS, was conservatively interpreted, and was appropriate as an indicative estimate for comparison with other options.

The *Options* report is consistent with the expectations raised by the election commitment to *Develop and deliver a plan to restore the health of Lake Tuggeranong*.

Cleared:	David Clapham, Executive Branch Manager, Office of Water
Prepared by:	Ralph Ogden, Healthy Waterways program manager

There are high community expectations for the restoration of Lake Tuggeranong. Joint involvement in the decision for the future investment to improve the lake is an important consideration.

A future Lake Tuggeranong Plan would be supported by a business case for funding, co-developed with City Operations and EPA. Costings for all options will be refined at this time, supported by an external analysis.

Restoring Lake Tuggeranong is not a 'set and forget' initiative. The *Options* report makes it clear that the Government will monitor and evaluate the cost and benefits of different management options and continuously refine and improve the suite of options applied to ensure the greatest benefit for the least cost.

ACT Government

TABLE OF COMMENTS

Attachment A

EXPOSURE DRAFT COMMENTS – 25/222

Exposure circulation undertaken: Full exposure circulation

Dates circulated: 19-26 May 2025

Directorate	Comment	Response
CMTEDD	Support with comment The Environment Protection Authority (EPA) suggests that the cabinet submission, draft plan and attachments be amended to: • provide formal acknowledgment of the role of government agencies including the EPA in the protection of lake Tuggeranong to date and into the future. • formally acknowledge and include the EPA and other government agencies in the development of the consultation process • highlight and address resourcing implications for additional regulatory work that will result from the proposed activities	Text has been added to the draft plan (Attachment F - p16) noting the role of the EPA administering the *Environment Protection Act 1997,* and *Lakes Act 1976.* A summary of agency responsibilities regarding management of Lake Tuggeranong has been added to the draft plan (Attachment F - p17). The Cabinet Submission has been amended to note proposed consultation with other agencies in the development of the final plan (Para 31 – Implementation). Text has been added to the 'Cross-portfolio collaboration and partnerships' section of the Wellbeing Impact Assessment to note collaboration with the EPA (Attachment C p4). No changes to Cabinet Submission regarding resourcing implications for additional regulatory work since additional regulatory work has

		not yet been identified. This will be discussed with EPA at the stage of budget bid development and implementation planning and.
JACS	Supported.	
HD	Supported.	
CHS	Supported.	
EDU	Supported.	
TCCS	Supported.	
CSD	Supported.	
EPSDD	Supported.	
MPC	Supported.	
Statutory Office Holder	Supported.	

FINAL COMMENTS – 25/222

Final circulation undertaken: Yes

Dates circulated: 13/08/2025 to 18/08/2025

Directorate	Comment	Response
CMTEDD	Supported.	
HCSD	Supported.	
CHS	Supported.	
EDU	Supported.	
DCBR	Supported.	

CSD	Supported.	
CED	Lead Directorate.	
MPC	Supported.	
Statutory Office Holder	Supported.	

Communications Plan

Project: Community consultation – Options for Restoring Lake Tuggeranong
Directorate: Environment, Planning and Sustainable Development Directorate
Release date: October 2025 **Attachment D**

What is government's involvement/interest?	The ACT Government is seeking feedback from Tuggeranong residents and Canberrans who use, or take an interest in, Lake Tuggeranong on proposed options to restore the Lake.
Why are we communicating on this issue?	• **To inform and educate** the Tuggeranong community about the importance of improving water quality in Lake Tuggeranong and how they can help. • **To engage** with a range of stakeholders who may be substantially impacted by the water quality of Lake Tuggeranong and/or the proposed methods to improve the lake. • **To drive participation** throughout the engagement process to make sure the Healthy Waterways Plan for Lake Tuggeranong has incorporated feedback from the community, experts and First Nation's people. The condition of Lake Tuggeranong has been a contentious issue for many years. We need to engage with the community as early as possible, acknowledge the community and stakeholder feedback that has been received to date, and ensure that they feel their voice is being heard. It will be important to demonstrate that long-term action has been undertaken but there needs to be more work done. The new plan seeks to take more preventative action at the source. The community will also have an important role to play in implementing the plan to improve the water quality of Lake Tuggeranong.
Background/research/insights	• **The Planning Act (2023)** prioritises management objectives for all public land (including waterways) as (1) prevent and control floods, (2) prevent and control pollution, (3) provide for public recreation and (4) habitat for flora and fauna. Since there is little urban infrastructure downstream of Lake Tuggeranong to protect from floods, the highest priority management objective for Lake Tuggeranong under the Planning Act is to prevent and control pollution. • **The ACT Water Strategy 2024–2044 Striking the Balance** sets a 20-year vision for ACT water management as: 'A community working together, managing water wisely to support a vibrant, sustainable and thriving region'. Outcome 1 of the Strategy—Healthy Catchments and Waterbodies—aims to achieve 'Well managed, functioning catchments that provide sufficient clean water for the environment and human consumption, support healthy waterbodies, and contribute to liveability of the ACT community'. • **The ACT and Region Catchment Strategy 2016-2046**. This Strategy establishes a 30-year vision to guide priority actions for a healthy Upper Murrumbidgee River region (upstream of Burrinjuck Dam to Tantangara Dam in NSW).

<table>
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A 2002 Legislative Assembly commitment to manage downstream water quality through an agreed motion that the water leaving the ACT via the Murrumbidgee River should be of no less quality than the water flowing into the ACT (ACT Legislative Assembly motion 5 June 2002 9.1(b)).
The Canberra Urban Lakes and Ponds Land Management Plan's vision is to 'enrich local communities through the aesthetic, recreational, sporting, tourism, cultural and ecological values of lakes and ponds, and to provide opportunities for people to be involved in their use, care, and management'. Under this Plan, 'recreation' and 'visual landscape' are listed as Lake Tuggeranong's highest values (Figure 3, ACT Government, 2022b).
The ACT's Water Resource Plan, developed under the Murray-Darling Basin Plan, contains a Water Quality Management Plan that sets locally relevant water quality targets.
A 2016 survey of over 7000 people on Canberra's urban lake use found that the lake use activity most often rated as 'highly important' was walking with other people, followed by picnics/barbeques, cycling, and using playground areas (Schirmer & Mylek, 2016).
In community engagements as part of developing the Tuggeranong District Strategy, the Tuggeranong community expressed that they value the lake for a range of recreational activities throughout the year, including walking, cycling, swimming, fishing and windsurfing (ACT Government, 2023).
In the findings of an ACT 'Better Suburbs' community survey from 2018, the citizen forum's first recommendation (out of 14) was to increase funding for lakes, ponds, wetlands, stormwater and water quality. This was ranked as more important for community members than issues such as street trees, roads, footpaths and public libraries (ACT Government, 2018).
A report commissioned by the ACT Government in 2023 explored ACT residents' willingness to pay for environmental amenity and recreational use of Canberra's lakes (NCEconomics, 2023). ACT residents surveyed indicated that they were prepared to pay up to $70/pp/quarter (or $280/pp/year, to greatly improve the environmental—visual and smell—amenity of Lake Tuggeranong (NCEconomics, 2023).
In a 2024 Tuggeranong Community Council annual community survey, 'improved water quality in Lake Tuggeranong', was one of the top four priorities for the general community, and the number one priority for young people

</td></tr>
<tr><td>Does it cross over other Directorates/ agencies?</td><td>Transport Canberra and City Services
Environment Protection Authority
ACT Health</td><td>Spokesperson</td><td>Ms Suzanne Orr, Minister for Climate, Change, Environment, Energy and Water
Fiona Wright, Executive Group Manager, Climate Change, Energy & Water
David Clapham, Executive Branch Manager, Office of Water</td></tr>
</table>

			Dr Ralph Odgen, Director, Healthy Waterways Program
Communications tier	Tier 2		

Engagement areas of influence	The research shows that the water quality can be improved in Lake Tuggeranong and the instances of lake closures due to algae blooms can be significantly reduced by employing a range of nutrient pollution mitigating actions.
	
	• The focus areas of these actions are:
	  ○ Stop pollution at the source
	  ○ Treat stormwater before it reaches the lake
	  ○ Treat the lake itself
	
	• The strongest focus and area of influence for this consultation falls within the 'Stop pollution at the source' area.
	
	• This focus area is the most effective at preventing algae blooms but also has the most impact on community members as it will require residents to take action to reduce pollution entering the lake.
	
	• A lesser focus will be on 'Treat stormwater before it reaches the lake', and even less feedback needed for 'Treat the lake itself'. The former will be a focus of engagement during implementation of the plan. The latter will be a focus of awareness raising—that we need to curb pollution from the catchment before considering lake treatments.
	
	• The engagement will also seek to educate community on what actions can be taken to improve the health of the lake and how they prioritise and value the water quality of the lake.		

CED Strategic Indicators	**Deliver a compact, efficient and sustainable city to be enjoyed now and into the future** (*Access and connectivity, Economy, Environment and climate, Health, Housing and home, Identity and belonging, Governance and institutions, Time)* **Enhance Canberrans wellbeing by conserving and experiencing nature and culture** (*Environment and climate, Social Connection, Health, Education and life-long learning, Identity and belonging, Governance and institutions, Safety)* **Create our climate-ready city** (*Economy, Environment and climate, Social Connection, Health, Education and life-long learning, Housing and home, Governance and institutions, Safety*) **Respect our Ngunnawal Traditional Custodians' history, knowledge and aspirations and work in partnership with Ngunnawal people to build a strong and shared future that respects and values Ngunnawal Country. Acknowledge and celebrate the diverse First Nations peoples and their unique cultures through shared opportunities, respecting and valuing their knowledge and contributions to the work we do** (*Economy, Environment and climate, Education and life-long learning, Housing and home, Identity and belonging, Governance and institutions, Safety*)		

Target audiences

A detailed stakeholder engagement matrix is included at the end of this document.

Primary	• Residents that live near the lake • Tuggeranong District residents • Lakeside residents, businesses, and other organisations. • Lake users including Tuggeranong Sea Scouts, Rowing Club
Key influencers/stakeholders	• **Tuggeranong Community Council** • **Lake users:** Tuggeranong Sea Scouts, Rowing Club, Park Run, Seniors Centre, Leisure Centre, Arts Centre • **Entities that operate near the lake:** Lake Tuggeranong College, Seniors Centre, Leisure Centre, Arts Centre, businesses, Playgroups and childcare centres on lake edge • **Aboriginal and Torres Strait Islander community:** Representative Aboriginal Organisations (RAOs), United Ngunnawal Elders Council, Aboriginal and Torres Strait Islander Elected Body. • **Water catchment groups:** Southern ACT Catchment Group (primary), Ginninderra Catchment Group, Molonglo Conservation Group, Upper Murrumbidgee Catchment Group • **Environmental groups:** Conservation Council ACT Region, Landcare ACT, ACT Australian Conservation Foundation Community, SEE Change. • **ACT Government advisory bodies and reference groups:** ACTNRM Advisory Group, ACT and Region Catchment Coordination Group, Environment and Planning Forum, Office of the Commissioner for Sustainability and the Environment, ACT Climate Change Council • **Tuggeranong residents** that live near the lake and further afield. • **Wider Canberra community** who may use the lake or take an interest in the health of Lake Tuggeranong**.** • **Academics and universities** who research water quality and take an active interest in water quality strategies and plans.
ACTPS (if relevant)	• Transport Canberra and City Services • Treasury • Traditional Custodian Engagement (EPSDD) • ACT Health

Key Messages

General about the consultation

- Lake Tuggeranong is under pressure from nutrient pollutants that wash off gardens, driveways and road gutters. Fallen leaves, fertiliser, grass clippings and soil end up in stormwater drains increasing the risk of blue green algal blooms and lake closures.
- We know that the community has provided significant feedback to Government already on initiatives and challenges over a number of years.
- The Tuggeranong community is now invited to share feedback on proposed options to improve Lake Tuggeranong, helping the ACT Government shape a 10-year restoration plan.
- ACT Government will be consulting with the Tuggeranong community, residents and stakeholders who live, work and use Lake Tuggeranong to seek their feedback on options to improve the water quality and restore the health of Lake Tuggeranong, so the community can enjoy a lake which is more consistently free of unhealthy algal blooms by 2035.
- The Tuggeranong District Strategy envisions Tuggeranong Town Centre as a thriving hub for jobs, shopping, and services, supported by a clean and healthy lake that enhances the area's appeal, attracts visitors, boosts local businesses, and strengthens the ACT economy.
- Lake Tuggeranong is at the heart of the region, and the ACT Government has been working to improve the lake's water quality and is committed to creating a long-term plan to restore Lake Tuggeranong.
- This consultation is open from [XX to XX] for an 6-week period.
- For more information and find out how to have your say, visit YourSay Conversations:
    - Read the Community Consultation Paper to find out more about the proposed options.
    - If you'd like to read about the research which has informed these proposed options, read the Options for Restoring Lake Tuggeranong Report.
- Your feedback will help the ACT Government take steps to develop the 10-year plan to restore Lake Tuggeranong. This includes consideration of which of the potential options Government may use to improve outcomes.

What are we consulting on

- To improve the water quality of Lake Tuggeranong, the ACT Government has delivered wetlands, raingardens, ponds and other water quality improvement features.
- This has greatly improved the health of the lake and recreational opportunities in Tuggeranong, but more must be done.
- An excess of plant nutrients (fallen leaves, grass clippings and fertilisers) makes its way down drains via our stormwater systems and pollute our lakes, stimulating algal blooms.
- The consultation seeks feedback on proposed options along the journey of stormwater where nutrient reduction can occur:
    - At its source - by preventing nutrient pollution from occurring in the first place
    - Within the stormwater system - by slowing the flow and filtering pollution from the stormwater
    - In the lake - we can build wetlands or use substances that compete with algae, or use chemicals that kill algae
- We know that it will take a variety of actions to improve the health of the lake.
- The research shows there is not one single solution and that a combination of proposed options will be required across the journey of the stormwater.

- Through extensive modelling and research, we have evaluated 10 possible ways to improve the health of the lake.
- The most effective way to reduce nutrients in the lake is to prevent nutrient pollution at its source. This means that we must now shift from mainly building infrastructure once the nutrients have entered the system, to also including more options to stop pollution at its source.

Why we are consulting

For Tuggeranong residents

- Every proposed option may impact the local community. It could mean changing your routine to accommodate targeted street sweeping, adjusting gardening habits, or the construction of local wetlands.
- As a Tuggeranong resident, you are likely to benefit from a clean and healthy lake that can provide enhanced recreational space, decreased health risks, help to boost local economy and community pride.
- You will also continue to have in important role to play in keeping the lake clean by keeping leaves and fertilisers out of the stormwater system.

For lake users

- The consultation is your opportunity to provide your input to shape the Plan.
- As a lake user, you'll benefit from a cleaner, fresher environment with little to no unpleasant odours and fewer health risks.
- With time the lake will be available for recreational activities most of the time throughout the year and if we do have lake closures, they will be short lived.

For lakefront residents and businesses and other entities operating on the lakefront

- The consultation is your opportunity to provide your input to shape the Plan.
- As someone who is close to the lake, you are likely to benefit from the implementation of the plan.
- A clean lake has the potential to attract more visitors, boost local businesses and make the Tuggeranong town centre a prime location for jobs, shopping, and services.

Public consultation action plan

Date	Communications tactic and collateral	Distribution	Responsibility
Pre-launch of consultation			
August	**Engage Ngunnawal Water Policy Officer and First Nations consultant**, and co-design engagement approach to ensure the voice of First Nations people is included.		Office of Water CED Comms
October	**Set up YourSay page** - Survey - Quick comments - Written submissions (using consultation/survey questions).		CED Comms
Week prior to launch	**Key Stakeholder pre-briefing** 4-5 key stakeholders pre-briefing to get an outline of what the consultation process will look like and key areas of influence. This would include the Tuggeranong Community Council. Briefings of other ACT MLAs and local MPs will occur as requested. - Powerpoint presentation		Options for Office of Water CED Comms
Day prior to launch	**Media pre-briefing** A pre-briefing is recommended to ensure media are able to understand the subject matter within the consultation. - Powerpoint presentation - Media release - Talking points - Q&A		Office of Water CED Comms
Day of Consultation launch			
October (Date TBC)	**Media release** with supporting talking points and Q&As		CED Comms
October (Date TBC)	**YourSay project page** published YourSay conversations		CED Comms
October (Date TBC)	**Social media post** on ACT Government social media channels		CED Comms
October	**Direct emails** to stakeholder list and EPF to formally notify of the consultation being launched. This will include a partnership pack which will allow them to share promotional material through their owned channels.		Office of Water
During the Consultation period – 6 weeks			

November	**Community Events** - 1 x in-person information session for Tuggeranong Community Council - 2 x Stakeholder information workshops - 1 x online (and recorded) information session for Tuggeranong residents and general public - 2-4 pop-ups at different areas around the lake and broader Tuggeranong district. **Targeted stakeholder events** - Workshop/s with Tuggeranong Community Council, Southern ACT Catchment Group, Landcare, ACT NRM, ACTCMCG		Office of Water CED Comms

October – November	**Communications**
	- Development and distribution of a range of print collateral:
	  ○ Poster for community noticeboards and lakeside businesses
	  ○ Postcards at businesses
	  ○ Temporary Corflutes installed around lake
	- Article in the October edition - OurCanberra print, online and digital newsletter
	- Social media posts, including geotargeted dark posts for Tuggeranong district
	- Physical display at Tuggeranong Library
	- Stakeholder emails
	- Letterbox drop for homes near the lake
	- Easy English translation
			CED Comms

Following consultation			
December	**Media Release** wrapping-up the consultation (if appropriate)		CED Comms

December	**Direct emails** to the stakeholder list and EPF including the Listening Report.		Office of Water
January	**Listening Report** – upload the to the YourSay project page		CED Comms

Stakeholder Engagement Matrix

Community or Stakeholder Group	Level of impact on policy direction (low, moderate, high)	Level of interest (low, moderate, high)	Engagement needs or expectations	Level of engagement (inform, involve, collaborate)	How we will engage	Responsibility (line area/comms team)
Tuggeranong Community Council	High	High	Participate in workshops, be presented a detailed draft plan and be provided an opportunity to provide feedback on proposed options.	Collaborate	Will write to council and invite the opportunity to present the Plan at council meeting and seek feedback from council members.	Office of Water
Southern ACT Catchment Group	High	High	Participate in workshops, be presented a detailed draft plan be provided an opportunity to provide feedback to the Healthy Waterways team.	Collaborate	Contact the SACG and host a workshop with members of the group to run through details of the Plan and consultation.	Office of Water
Lake users e.g. Tuggeranong Sea Scouts, Rowing Club	Low	High	Opportunity to participate in YourSay or take part in a “Pop up” event to talk about the consultation. They like to be kept informed about health risks, likelihood of future blooms under Plan and how the plan might impact lake usage.	Involve (YourSay)	Email targeting these groups with information about the consultation, link to YourSay provide snap-shot doc and provide information about upcoming pop-up events.	EPSDD Comms
Around the lake users	Low	High	To provide input by YourSay, to be kept informed about	Involve (YourSay)	Email targeting these groups with	EPSDD Comms

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e.g. Park Run, Seniors Centre, Leisure Centre, Arts Centre,			health risks. May want to participate in a pop-up event.		information about the consultation, link to YourSay provide snap-shot doc and provide information about upcoming pop-up events.	
Lake Tuggeranong College	Low	High	To provide input via YourSay, to be kept informed about health risks and any future blooms under plan. May take part in a pop-up event to understand the consultation better.	Involve (YourSay)	Email targeting the college with information about the consultation, link to YourSay provide snap-shot doc and provide information about upcoming pop-up events as well as links to learning resources.	EPSDD Comms
Playgroups and childcare centres on lake edge	Low	High	To provide input by YourSay, to be kept informed about health risks, they would like to know about algae blooms in future. They would like information and resources about how to care for Lakes and Waterways to aid teaching.	Involve (YourSay)	Email targeting this group with information about the consultation, link to YourSay provide snap-shot doc and provide information about upcoming pop-up events as well as links to learning resources.	EPSDD Comms
Lakeside businesses	Low	High	To provide input by YourSay, and to be kept informed about health risks, and future blooms under the Plan. Could provide information on how their businesses have	Involve (YourSay)	Email targeting local business. Provide information about the consultation, link to YourSay provide snap-shot doc and provide	EPSDD Comms Office of Water to hold workshops.

			been impacted by blooms over years. May want to participate in a pop-up event.		information about upcoming pop-up events.	
Ngunnawal people	High	Moderate	This group will want to participate in design of assets to enhance cultural values.	Collaborate (targeted workshops, Aboriginal Waterway Assessments)	Engage with a consulting firm who specialises in first nation consultations.	Office of Water to manage First Nations engagement
Residents that live near the lake [need to define boundary]	Moderate	High	To provide input into YourSay, to be kept informed about health risks, to understand how they can participate in waterway friendly gardening	Involve	Letterbox drop postcards that contain a snapshot of the consultation and QR code linking to YourSay.	EPSDD Comms
Tuggeranong Residents and Canberra residents further afield	Moderate	Moderate	To provide input by YourSay, information about how they can participate and be interested in waterway friendly gardening	Involve	Dark posts on social media geo-targeting Tuggeranong residents with links to YourSay.	EPSDD Comms
Other Catchment groups	Low	Moderate	Will be keen to understand approach in Tuggeranong and how it may be rolled out in other catchments in future	Collaborate	Email targeting Catchments groups to participate in pop-up events or in a dedicated workshop.	Office of Water
Landcare ACT	Moderate	Moderate	Membership is Ngunnawal community, rural landholders, catchment groups. May be helpful to coordinate input from these interests.	Collaborate	Email with information about the Plan and consultation. Provide information to take part in You-Say or attend a workshop.	Office of Water

ACT Government

ACTNRM Advisory Group	Moderate	Moderate	Membership includes various experts, landholders, urban parks volunteering. May be helpful to coordinate input from these interests.	Collaborate	Email with information about the Plan and consultation. Provide information to take part in You-Say or attend a workshop.	Office of Water
ACT and Region Catchment Coordination Group	Moderate	Moderate	Membership includes ACT, NSW Government, water experts. Dr Maxine Cooper is Chair.	Collaborate	Email targeting Catchments groups to participate in pop-up events or in a workshop	Office of Water
University of Canberra ANU, CSIRO and other academics in the sector	High	High	Participate in workshops, be presented a detailed draft plan be provided an opportunity to provide feedback to the Healthy Waterways team.	Collaborate	Contact academics and host a workshop to run through details of the Plan and consultation.	Office of Water

Lake Tuggeranong

The Tuggeranong valley landscape has changed dramatically in the past 200 years, shifting the ~~traditional~~ life patterns that Traditional Custodians have understood and worked with for thousands of years. Sheep and cattle stations were established in the early 1800s, and suburban development began in the 1970s. Now, around 50% of the lake's catchment is urbanised.

Lake Tuggeranong was built in 1987 as a focal point for the growing town centre and to protect the downstream areas from the effects of urban development on flooding and water quality.

Around the same time, to protect urban areas from flood risk, a stormwater system was built by converting natural creek lines such as Tuggeranong Creek into concrete channels. This has had lasting implications for lake water quality by reducing the permeability of the landscape and rapidly channelling catchment nutrients to the lake rather than allowing them to be processed within the catchment.

Lake Tuggeranong is highly valued by the community, but for more than a decade it has experienced frequent blue-green algal blooms, caused by elevated nutrient levels.

This has had a significant impact on the Tuggeranong community and those who value and use the lake: the blooms smell unpleasant, are unsightly and close the lake to activities such as swimming and water sports due to health risks.

Algal blooms may also pose health risks to residents of suburbs surrounding the lake who are exposed to aerosolised lake water on windy days.

The ACT Healthy Waterways Program has invested in improving water quality in the Lake Tuggeranong catchment over the past decade by building wetlands, working with the community, and investing in research to better understand the source of nutrients causing the algal blooms. Through this dedicated research, we are now confident that:

- There are actions we can take to substantially reduce the frequency and severity of algal blooms in Lake Tuggeranong.
- To succeed, we need a suite of pollution mitigation options to prevent nutrients entering the lake.
- Algal blooms can't be prevented entirely: the best that can practically be achieved is to prevent algal blooms in three out of four years on average.
- We may therefore still need to develop management options to treat algal blooms when they do arise.

This consultation paper summarises current knowledge and understanding about what's causing the algal blooms, and what Government, business and ~~the community~~residents can do about it. It's supported by a detailed report and a series of technical reports that can be found on the YourSay Conversations website

Following feedback from the community, the Government will develop a ten-year plan to restore the lake's health by reducing algal blooms – the *Healthy Waterways Plan for Lake Tuggeranong*.

This plan will deliver on the ACT's Government's commitment for the 11th

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Assembly to *Develop and deliver a 10-year plan for a healthier Lake Tuggeranong*.

Community consultation

We are sharing a range of possible management options that Government, business and residents may use to improve water quality in Lake Tuggeranong.

Your feedback will help the ACT Government take steps to develop the 10-year plan to restore Lake Tuggeranong. This includes consideration of which of the potential options Government may use to improve outcomes.

The consultation will be open from XX to XX for 6 weeks. There will be several ways you can have your say both in person and online.

Have your say!

Share: Your feedback online or in person

Engage: Help us understand how the possible management options may impact you and your community

Visit: A pop up and chat to our project team or join us for an information session to share your feedback

What causes algal blooms?

Blue-green algae are present in virtually all aquatic environments across the world. They are only a problem when they reproduce rapidly to become super-abundant, which is referred to as an algal bloom.

The plant nutrient phosphorus i~~A~~s a key food source for algae, ~~phosphorus is the key nutrient~~ driving algal blooms in Lake Tuggeranong.

Research has found that algal blooms in Lake Tuggeranong are driven primarily by phosphorus coming off the catchment rather than by phosphorus released from sediment at the bottom of the lake, although sediment-released phosphorus ~~released from the sediments~~ also contributes to the problem (Ubrihien et al. 2019; Ubrihien et al. 2020). This means that to solve the problem, we need to first reduce the supply of catchment-based nutrients to the lake before turning our attention to sediment-released phosphorus.

There are many potential sources of nutrients and other pollutants from urban catchments. Research in the Tuggeranong catchment (Ubrihien et al. 2019; Ubrihien et al. 2020; Upper Murrumbidgee Waterwatch, 2023; Concepts of Change, 2023) has found that:

- phosphorus is mainly coming from urban, not rural, areas
- phosphorus is coming from many small sources across the whole catchment (diffuse sources), rather than from one or two large, concentrated locations (point-source)
- around 50% of the phosphorus in stormwater is in dissolved, bioavailable forms, meaning it is readily available for uptake by blue-green algae once it reaches the lake
- leaves, grass clippings, fertiliser products (including composts and manures), soil and sewage are all contributing to catchment-based phosphorus.

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The challenge

If we take no further action, under current flow and levels of phosphorus supply, Lake Tuggeranong will continue to experience frequent algal blooms ~~events~~.

If we can reduce current levels of nutrients, then this will decrease the risk of blue-green algal blooms arising. This could be achieved in Lake Tuggeranong if the average annual phosphorus supply to the lake is reduced by 700 kg (Kahn and Dey (2024). This represents approximately 50–60% of the total supply of phosphorus to the lake from the catchment.

This would reduce ~~how much the lake has to be closed~~lake closures due to algal blooms (but closures may still occur due to elevated levels of faecal indicator bacteria).

Can we make a difference?

With a 700 kg annual reduction in phosphorus, Kahn and Dey (2024) suggest the lake will be in a mesotrophic state or better in an average of 3 out of 4 years.

Under these conditions, some blue-green algae would be present, but the likelihood of problem blooms would be lower than now, and the lake should mainly be in a condition suitable for contact-based activities.

It's important to note that there will be considerable variation through time in the concentration of phosphorus in Lake Tuggeranong, driven by variation in climatic conditions.

Specifically, in very wet years the significant amount of phosphorus coming off the catchment will likely overwhelm any attempts to reduce nutrient levels in the lake, leading to increased risk of algal bloom events.

However, wet years also tend to be relatively cooler, which would reduce the likelihood of severe blooms. Some algae would also flush from the lake in wet years.

Conversely, in relatively dry years, any phosphorus removed from the system represents a relatively larger proportion of the total supply reaching the lake.

The potential impact of climate change on nutrient dynamics and algal blooms is discussed in Box 1.

Faecal indicator bacteria

Lake closures can also be due to the presence of faecal indicator bacteria, with Tuggeranong Town Beach showing a higher incidence of closures due to this cause.

ACT Health routinely tests ACT lakes for faecal contamination using the faecal indicator bacteria enterococci. These are a group of bacteria found in the intestines of humans and animals; their presence in water may indicate domestic sewage leaks or contamination from diffuse sources of human and animal waste. Water managers use enterococci as the standard faecal indicator bacteria to test water quality in recreational waters in Australia because they are well understood, easy to detect and their presence reliably predicts health risks associated with exposure to waterborne bacterial pathogens.

Monitoring work using Microbial Source Tracking is currently underway to understand the extent the faecal matter is coming from human or animal sources. Findings from this work will inform future iterations of the Plan. In the meantime, many of the interventions proposed to reduce ~~algal blooms~~phosphorus will also remove faecal bacteria and other pollutants, such as excess carbon, nitrogen and total dissolved solids, that are potentially causing issues in the catchment.

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~~future iterations of the Plan. In the meantime, many of the interventions proposed to reduce algal blooms will also remove bacteria and other pollutants, such as excess carbon, nitrogen and total dissolved solids, that are potentially causing issues in the catchment.~~

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Box 1. How will climate change affect nutrient dynamics and algal blooms?

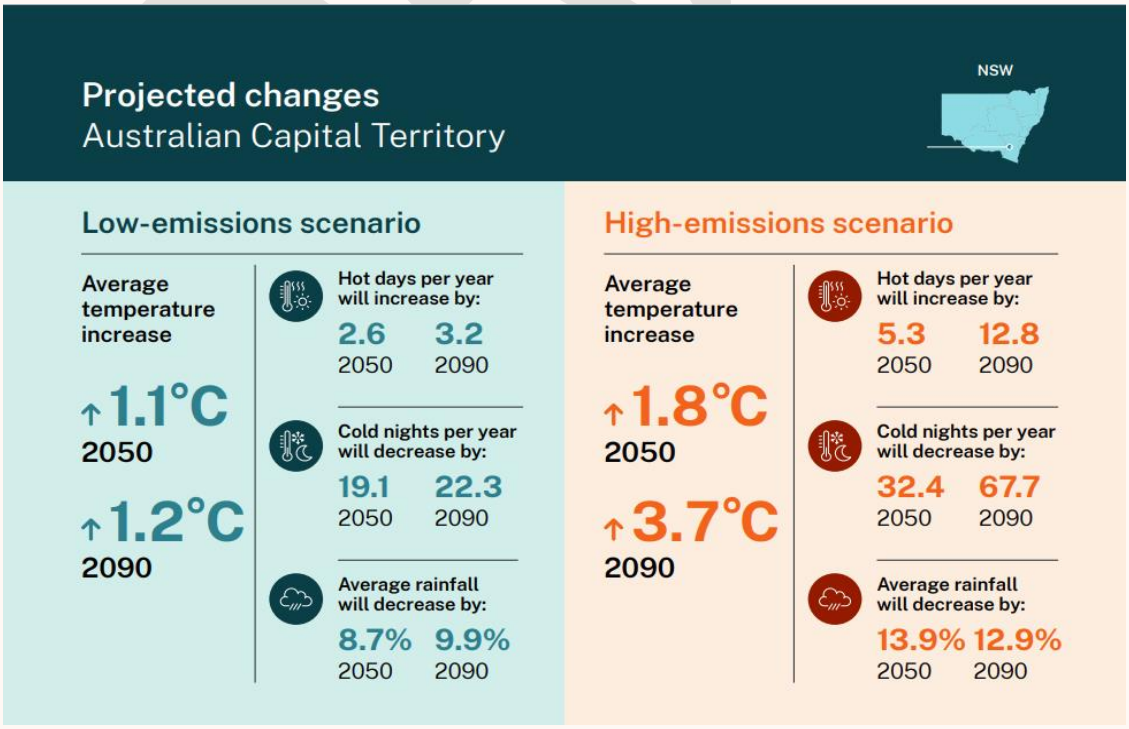
In the future, the ACT will experience hotter average temperatures, more hot days per year and decreased average rainfall, particularly in spring (NSW Department of Climate Change, the Environment and Water, 2024). Across Australia, including the ACT, extreme rainfall events (storms) will become more intense.

The Australian Rainfall and Runoff Guidelines predicts the biggest increases will be in very short storms. For example, under scenario SSP3-7.0, storms of under one hour will increase in intensity by 18% by 2030, and by 29% by 2050 (Wasko et al., 2024). More intense localised storms may increase the frequency of 1% Annual Exceedance Probability (AEP) (in layman's terms, 1 in 100-year storms) flooding events in the ACT. The ACT Government's ACTMapi website shows the extent of riverine flooding that would be expected during a 1% AEP event.

These changes to temperature, rainfall averages and storm intensity will likely impact nutrient dynamics in the Tuggeranong catchment, for example:

- higher storm intensity will impact streamflow and the way that nutrients are mobilised in, and transported through, the catchment
- hotter temperatures will affect when eucalypt species drop their leaves, how much they drop and the phosphorus content of the leaves
- higher water temperatures will affect in-lake processes like thermal stratification (i.e. where warmer water sits on top of colder layers of water) and turnover, both of which increase the supply of nutrients from lake bottom sediments to the lake water.

These effects are anticipated but have not yet been studied or quantified in the Lake Tuggeranong context. However, a response framework developed for Victoria's waterbodies argues that climate change will exacerbate blue-green algal blooms through factors including increased temperatures, stronger stratification, increased nutrient levels due to extreme wet/dry periods, longer residence times of water in water bodies and storm events (HydroNumerics, 2020).



Climate change projections for the ACT (NARCliM 2024)

What we can do

There are three points in the 'journey of stormwater' where phosphorus may be removed or algae treated directly:

1. At the sources of phosphorus pollution, by preventing nutrient pollution from occurring in the first place.

2. Within the stormwater system, by slowing the flow of water and allowing it to ~~,~~ be filtered naturally by wetlands and/or to seep slowly back into the landscape ~~-~~ where it is naturally cleansed ~~and filtering nutrient pollution from the stormwater~~.

3. In the lake, using ~~with floating wetlands or by using agents that compete with algae for nutrients, or by using algicides.~~ anti-algal agents that either compete with algae or treat the algae once it grows to bloom proportions

These are ~~described~~ illustrated in Figure 1 and described in Table 1 ~~below.~~

Figure 1. Management options for preventing and treating pollution and algal blooms. Numbers refer to specific management options in Table 1.

~~As with many environmental problems, efforts at prevention will yield the greatest, most cost-effective results. In Tuggeranong, that means preventing phosphorus pollution from entering the stormwater system rather than trying to either clean polluted water within pipes, drains or the lake itself, or to treat algal blooms once they form in the lake.~~

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Table 1. ~~Management interventions~~ -Management options for preventing and treating pollution and algal blooms in the context of the 'journey of the stormwater'. Numbers refer to the graphic in Figure 1.

~~Management interventions~~ Available management option ~~in 'journey of stormwater'~~	Description	Aspect(s) of option evaluated
At the sources of pollution~~s~~ **~~Reduce the amount of phosphorus before it enters the stormwater system (phosphorus pollution prevention).~~**		
(1) ~~Targeted street sweeping~~New management practices for roadside drains and verges	Optimise street sweeping ~~(~~for frequency, location and seasonality to remove more organic material from the roads, preventing it from leaching phosphorus into the stormwater drains~~)~~ Reduce the amount of grass clippings from municipal mowing that end up on the road	Increase the frequency of street sweeping in the catchment. Either street sweepers or electric blowers follow mowers, ensuring clippings stay out of drains.
(2) Pollution prevention partnerships	Promote waterways-friendly gardening practices—targeting leaves, grass clippings and fertilisers—by working with community and business.	Identify and target the relatively small number of households that import excessive amounts of fertiliser and manures to help them have fantastic gardens using little or no-phosphorus fertiliser.
(3 & 4) Water sensitive urban design (WSUD)	Adopt suburb designs—or retrofit elements to existing suburbs—that minimise the impacts of urban development on the natural water cycle and better integrate suburbs into the natural landscape.	Capture storm runoff from roofs for reuse on residential blocks. This may aid in removing some phosphorus in the system as well helping to reduce urban runoff and peak stormflows, allowing wetlands to function better. Retrofit 'castellated kerbs' –outlets in road kerbs adjacent to green space to divert some of the stormwater to open green space and allow it to filter into the ground
In the stormwater system **~~Use water sensitive urban design infrastructure to divert runoff in storms, allowing it to slow down, be filtered naturally by wetlands and/or to seep slowly back into the landscape.~~**		
(5) Stormwater recycling~~Infrastructure that reduces stormwater peaks~~	Capture and re-use stormwater~~Retain stormwater in green belts (nature strips), detain it in tanks and/or recycle it.~~	Divert and filter stormwater to storage tanks at sports fields for use in irrigating the fields.
(6) Infrastructure that improves stormwater quality	~~Create~~ Build ~~various types of~~ constructed wetlands (including ponds and raingardens)~~.~~	Increase the area of wetlands in the catchment to capture and treat phosphorus in the stormwater.
(7) Maximised effectiveness of water quality infrastructure	Sequentially place ~~constructed~~ wetlands and other water quality/ quantity assets along drainage lines and waterways to reach end-of-system targets and maintain the infrastructure in good condition.	Optimise maintenance of existing constructed wetlands —such as dredging out built-up sediment and harvesting plants—to maximise their pollutant filtering capacity.
In the lake	**~~Use anti-algal agents that either compete with algae or treat the algae once it grows to bloom proportions.~~**	
(8) Infrastructure that improves stormwater quality ~~Floating wetlands~~	Deploy wetlands ~~Wetlands floating~~ in or adjacent to the lake with plants	Install floating wetlands on Lake Tuggeranong, which directly compete with algae for nutrients and light.

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MAvailable management interventionsoption in 'journey of stormwater'	Description	Aspect(s) of option evaluated
	that draw phosphorus out of lake water.	
(9) Products that compete with Reduction of nutrient levels and/or competition with blue-green algae	Deploy materials or processesproducts that remove nutrients from surface waters, where algae live, or promote natural competitors to algae.	Preliminary investigations only.
(10) Direct treatment of algae	Apply algicides or physical mechanisms to destroy or remove algae.	Preliminary investigations only.

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Through the **Healthy Waterways Plan for Lake Tuggeranong**, we can at look to how to remove phosphorus at three distinct stages in the 'journey of the stormwater'.

Reduce the amount of phosphorus entering the stormwater system:

1. Support the community to help stop leaves and grass from accumulating along our verges and street drains.
2. Work with government, businesses and the community to minimise the amount of fertiliser entering urban stormwater.
3. Work with government and universities to better understand and manage the link between street tree leaves and grass clippings and the amount of nutrients in the stormwater.

Slow the flow and filter – reconnect water back into the landscape and filter nutrients out of the stormwater:

4. Intercept and treat nutrient–laden stormwater running off sports fields. Also reuse stormwater from elsewhere to water the sports fields. This will reduce the amount of runoff and amount of nutrients flowing into Lake Tuggeranong.
5. Provide opportunities for stormwater to be absorbed and treated in the landscape while improving habitat connectivity, through green infrastructure like swales, raingardens and wetlands.

Manage the in-lake environment

6. Investigate the drivers, habitat enhancements and possible in–lake treatments to reduce the incidence of blue green algal blooms.

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What we've done to date

To improve the water quality of Lake Tuggeranong, through the Healthy Waterways Program the ACT Government has delivered wetlands, raingardens, ponds and other water quality improvement features, trialled programs to engage with residents and businesses to ~~clean up waterways~~keep leaves and grass off road verges and reduce fertiliser use, and explored or implemented various ways that the Government can manage road verges and drains.

These actions have begun to improve the health of the lake and provided new recreational opportunities in Tuggeranong. However, the infrastructure projects have together only reduced catchment phosphorus loads by around~~bout~~ 13-15%. More must be done to reduce phosphorus to a level that will meaningfully shift the lake's susceptibility to algal blooms.

2017/18

Wetlands built flanking the north and south sides of Isabella Pond

A raingarden built at Isabella Plains

2019

Three raingardens built at Gowrie Playing Fields, Fadden Pines, Wanniassa

A concrete drain naturalised in Monash

A pond built below Kambah Shops

2021

A set of floating wetland platforms deployed in the north arm of Lake Tuggeranong

'Leaf Collective' community education program launched in Tuggeranong

2022

Four bioretention swales installed in drains around Playing Fields in Kambah

2023

ACT Healthy Waterways public information campaign on managing leaves commences

45 roadside kerb outlets to water green space created in Kambah

2024

'Love the Lakes' community education program targeting Tuggeranong

A major concrete drain naturalised in Calwell

A filtration unit added to Kambah Playing Fields to recycle stormwater to irrigate the fields

Benefits and costs of management options

Booksmythe et al (2024) evaluated ~~To understand~~ how effective different management options are at reducing phosphorus pollution, and the~~ir~~ cost of this. They were only able to evaluate options, or aspects of the options, where their costs and benefits could be quantified. The options (or their aspects) evaluated ~~, Booksmythe et al (2024) examined a subset of ten specific option~~are detailed in the third column of ~~s (~~Table 1~~2)~~. ~~These represent a subset of possible management options for which the costs and benefits can be quantified.~~

~~*Table 2 Phosphorus reduction options*~~

~~Phosphorus reduction option~~	~~Description of modelled option~~
~~Street sweeping~~	~~Increase the amount of street sweeping in the catchment to remove more organic material from the roads, preventing it from leaching phosphorus into the stormwater drains.~~
~~Fertiliser management~~	~~Identify and target the relatively small number of households that use excessive amounts of fertiliser to help them use either low-phosphorus fertiliser or no fertiliser at all.~~
~~Open space mowing~~	~~Reduce the amount of grass clippings from municipal mowing that end up on the road using either street sweepers or electric blowers, so preventing clippings from leaching phosphorus into the stormwater drains.~~
~~Rainwater tanks~~	~~Capture stormwater from roofs for reuse on residential blocks. This may aid in removing some phosphorus in the system as well helping to reduce urban runoff.~~
~~Stormwater recycling~~	~~Divert and filter stormwater to storage tanks at sports fields for use in irrigating the fields.~~
~~Castellated kerbs~~	~~Retrofit outlets into road kerbs adjacent to green space to divert some of the stormwater to open green space and allow it to filter into the ground.~~
~~New water quality infrastructure — sports fields~~	~~Build special swales (a shallow ditch that collects rainwater) around sports fields to potentially capture any phosphorus leaching out from fertiliser. (Note: Sports field managers are attempting to use fertiliser optimally and the leaching is more a legacy issue).~~
~~New water quality infrastructure~~	~~Construct more wetlands at suitable locations in the catchment to treat phosphorus in the stormwater.~~
~~Maintenance of existing water quality infrastructure~~	~~Ensure maintenance (such as dredging out built-up sediment and harvesting plants) of existing constructed wetlands in the Lake Tuggeranong catchment to maximise their performance so they can capture the largest amount of nutrients possible.~~
~~Floating wetlands~~	~~Install more floating wetlands on Lake Tuggeranong to draw phosphorus out of the lake water.~~

For the cost modelling, four levels of investment were developed for each option to provide an indication of expected reduction in phosphorus at different levels of investment. Figure 2 indicates results at all four investment levels and ~~Table 3~~Table 2 shows an excerpt of the results (at the highest and lowest investment levels)~~, and Figure 1 indicates results at all four investment levels~~.

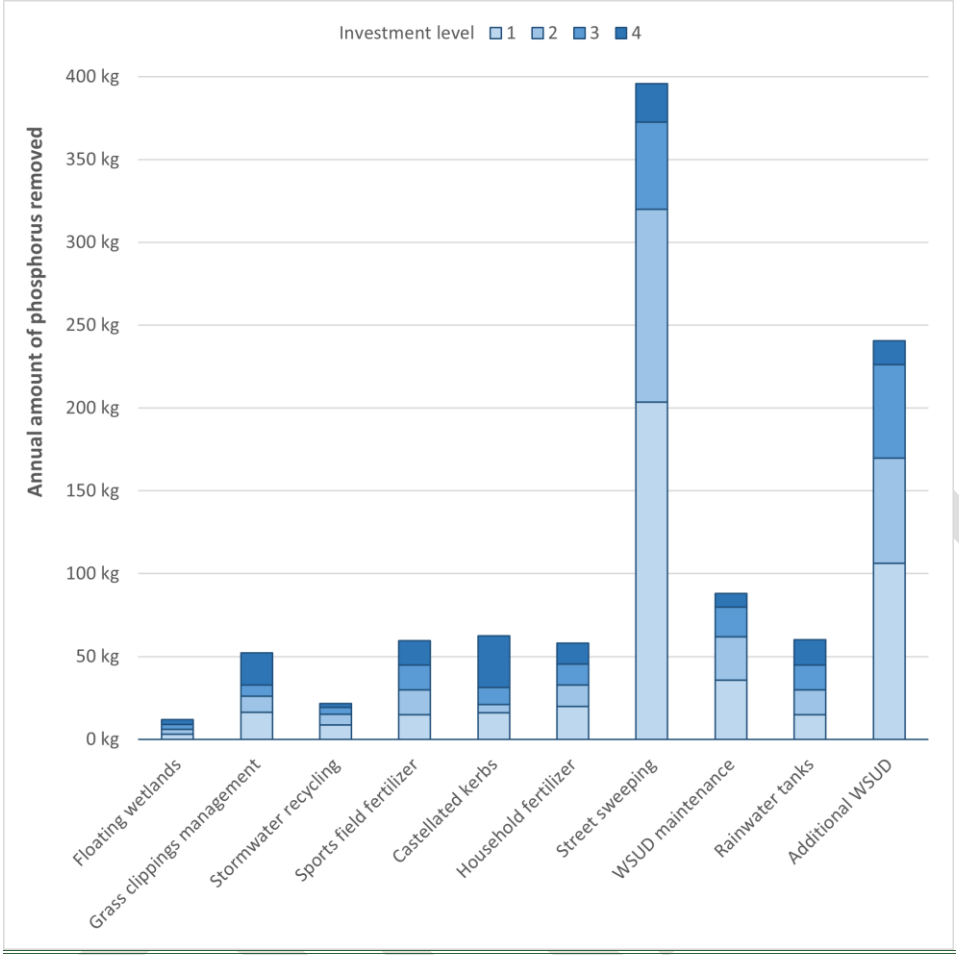

Figure ~~1~~2. ~~-~~Amount of phosphorus removed for four different levels of investment in ten different mitigation options (based on figures from Booksmythe et al 2024).

Table ~~3~~2. Summary of phosphorus (P) removal performance, total cost and cost-effectiveness for two indicative levels of investment (high and low) in ten pollution mitigation options (Booksmythe et al., 2024).

Phosphorus (P) reduction option and level	Unit	P removed (kg/year)	30-year cost ($)[1]	Cost-effectiveness ($/kg P)
Install additional WSUD 1	Build 2 new WSUD assets	106.21	$22,507,500	$7,064
Install additional WSUD 4	Build 10 new WSUD assets	240.46	$84,519,403	$11,716
Maintenance of existing WSUD 1	Enhanced maintenance of 2 assets	35.84	$10,177,128	$9,465
Maintenance of existing WSUD 4	Enhanced maintenance of 5 assets	88.02	$30,352,433	$11,495
Increase street sweeping 1	12 street sweeps per year	203.70	$7,030,414	$1,150

Phosphorus (P) reduction option and level	Unit	P removed (kg/year)	30-year cost ($)[1]	Cost-effectiveness ($/kg P)
Increase street sweeping 4	48 street sweeps per year	395.80	$28,121,656	$2,369
Manage grass clippings 1	Blow clippings into verge, low P removal estimate	16.40	$2,018,874	$4,103
Manage grass clippings 3	Sweep clippings in verge, low P removal estimate	32.70	$1,521,462	$1,551
Sports field fertilizer management 1	Protect 25% of sports fields with bioretention swales	14.93	$4,204,451	$9,387
Sports field fertilizer management 4	Protect 100% of sports fields with bioretention swales	59.70	$31,445,222	$17,557
Household fertilizer management 1	Low P target (assume cost is $10,000/kg P/year)	20.00	$6,000,000	$10,000
Household fertilizer management 4	Very high target (assume cost is $10,000/kg P/year)	58.00	$17,400,000	$10,000
Install castellated kerbs 1	Install 1 kerb outlet for every 4 sumps (or 453 outlets)	15.56	$4,532,500	$9,708
Install castellated kerbs 4	Install a kerb outlet for every sump (or 1813 outlets)	62.25	$14,349,291	$7,684
Install floating wetlands 1	Deploy 1000 m^2 of wetland	3.00	$1,226,000	$13,622
Install floating wetlands 4	Deploy 1000 m^2 of wetland	12.00	$4,904,000	$13,622
Stormwater recycling for irrigation 1	Build best 2	8.81	$2,673,863	$10,115
Stormwater recycling for irrigation 4	Build best 8	21.78	$10,816,870	$16,558
Household rainwater tanks 1	2,500 new households to install water tanks	15.00	$12,500,000	$27,778
Household rainwater tanks 4	2,500 new households to install water tanks	60.00	$50,000,000	$27,778

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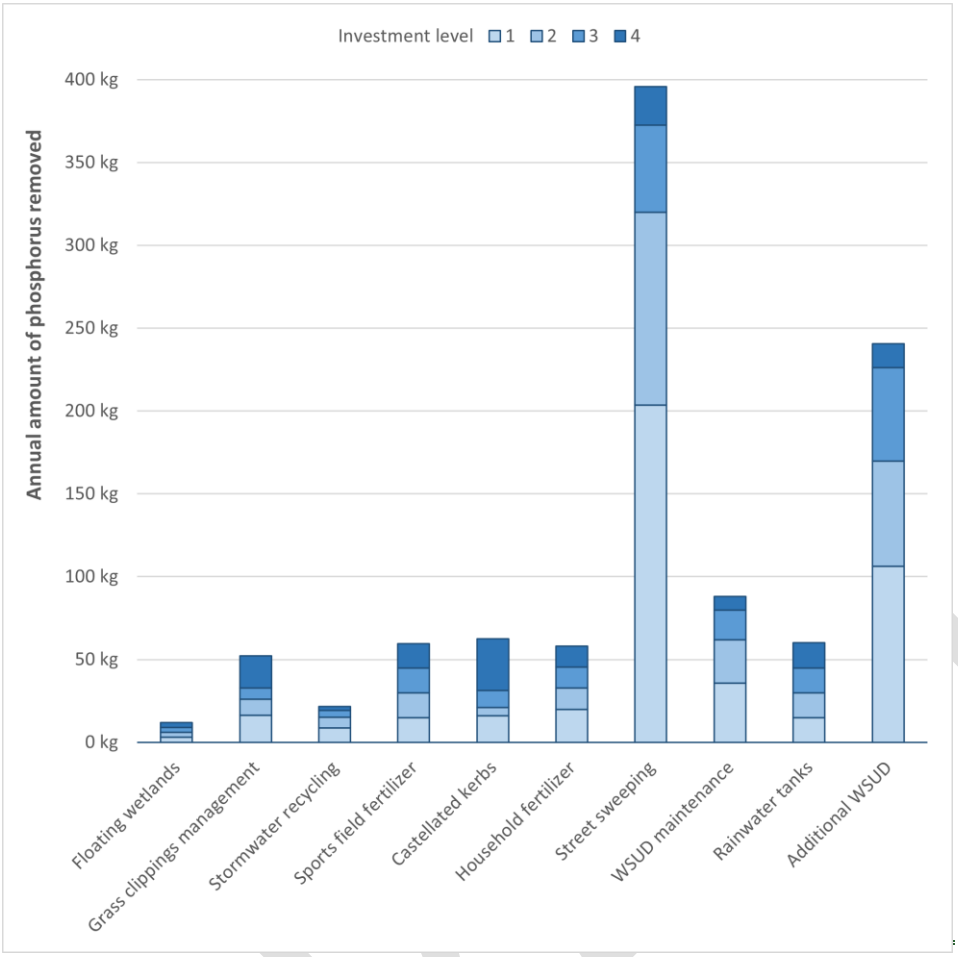

~~*Figure 1 Amount of phosphorus removed for four different levels of investment in ten different mitigation options (based on figures from Booksmythe et al 2024).*~~

Implications

There are several key findings from the cost-benefit analyses:

- It is possible to reach the phosphorus reduction option of 700 kg/year. However, t~~T~~here are no silver bullets; no single ~~phosphorus reduction option can reach the 700 kg/year~~ phosphorus reduction option will reach the target on its own. Managers will need to implement multiple options to reduce phosphorus pollution to a level where it materially restricts the incidence of algal blooms.
- The construction of l~~L~~arge wetlands and other water quality assets ~~(shown as 'Additional WSUD' in Figure 1)~~, which has been the main focus of management efforts so far, ~~are~~ is necessary to treat unavoidable nutrients that make their way into large stormwater drains. However, ~~but~~ on ~~their~~ its own, ~~they~~ this management option won't solve the problem. ~~Options that prevent stormwater from getting polluted in the first place are needed to substantially reduce the incidence of blue-green algal blooms in Lake Tuggeranong.~~
- Options that prevent stormwater from getting polluted in the first place are needed to substantially reduce the incidence of blue-green algal blooms in Lake Tuggeranong. ~~There are no silver bullets; no single phosphorus reduction option can reach the 700 kg/year~~

~~phosphorus reduction target on its own. Managers will need to implement multiple options to reduce phosphorus pollution to a level where it restricts the incidence of algal blooms.~~

-

An optimised regime of s~~The modelling showed that an S~~treet sweeping is both the most beneficial (in terms of total phosphorus removed) and cost-effective management option ~~yet found~~found yet~~considered in this process (Figure 1)~~. Subsequent analyses of the effects of targeting street sweeping efforts in the summer leaf-fall season and on streets with a greater density of trees are likely to further reduce the costs of this option. These analyses will inform ~~be included in~~ the subsequent Plan for Lake Tuggeranong.

- Residents have an important role to play in preventing stormwater from getting polluted. This means helping to keep leaves and grass clippings, which are rich in phosphorus, out of driveways and roadside drains. ~~For example, it is not reasonable to expect that street sweepers can keep up with all leaves that fall or blow onto streets.~~ There will be leaves that end up on streets in between sweeps and our research has shown that, like a tea bag, the majority of nutrients seep out of fallen leaves the first time they are wetted. ~~So, when a storm occurs, any leaves on the road will contribute to pollution.~~ Government, business and residents need to work together to prevent leaves from accumulating on impervious surfaces like driveways and roadside gutters. Residents using large amounts of fertilisers are also encouraged to join the many Canberrans with fantastic gardens who use little or no fertiliser.
- Algal blooms can't be prevented entirely: the best that can practically be achieved is to prevent algal blooms in three out of four years on average. We may therefore still need to develop management options to treat algal blooms when they do arise.
- The management options evaluated so far are not the only ones available to help solve the problems of phosphorus pollution and algal blooms. There will be ongoing research and analyses of the benefits of other management options, or ways to ~~target~~ optimise existing ones~~such as targeting activity~~ ~~, will require consideration as the Plan is developed~~to ensure that Lake Tuggeranong is cleaned up at least cost to the Canberra community~~have yet to be evaluated~~.

~~• Finally, in considering the findings from the analyses, it should be noted that there are that we have not yet been able to evaluate These should also be considered as the Plan is developed~~

Conclusion

This work suggests that there are a range of management options available to reduce ~~catchment phosphorus that, if implemented, could reduce~~ phosphorus pollution in Tuggeranong to a level that significantly reduces the incidence of blue-green algal blooms in Lake Tuggeranong.

As with any natural system, there remains a level of uncertainty about the nature and timing of the system's response. The main cautionary note is that it may take time – a decade or more – for algal blooms to be greatly diminished, but we expect improvements in water quality to be observable before then.

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How the community can help

We know that it will take a variety of actions to improve the health of the lake – there is no one single solution.

The most effective way to reduce nutrients in the lake is to prevent nutrient pollution at its source. This means that we must now shift our focus from ~~mainly~~ just building ~~infrastructure~~ wetlands and other assets ~~once~~ that treat ~~the nutrients have entered the system~~stormwaters once they have become polluted, to also includ~~eing~~ more options to stop pollution at its source.

This will take efforts by government, businesses and residents. Community action can greatly contribute to stopping pollution from entering our waterways by reducing fertiliser use and ensuring grass clippings and leaves end up in composts or~~in~~ green bins, not in stormwater drains.

Next steps

Following feedback from the community and further inputs from First Nations people, a Healthy Waterways Plan for Lake Tuggeranong will be produced to present the strategy that the Government has adopted to tackle the problem of blue-green algal blooms in the lake.

An implementation plan will then be developed to set out how the vision will be achieved over the next 10 years~~, including how it will be monitored and evaluated.~~. The plan will include a robust program of monitoring and evaluation of the benefits of the management options implemented. This will enable management options to be refined over time so that the incidence of algal blooms can be minimised at the least cost to the community (Figure 3).

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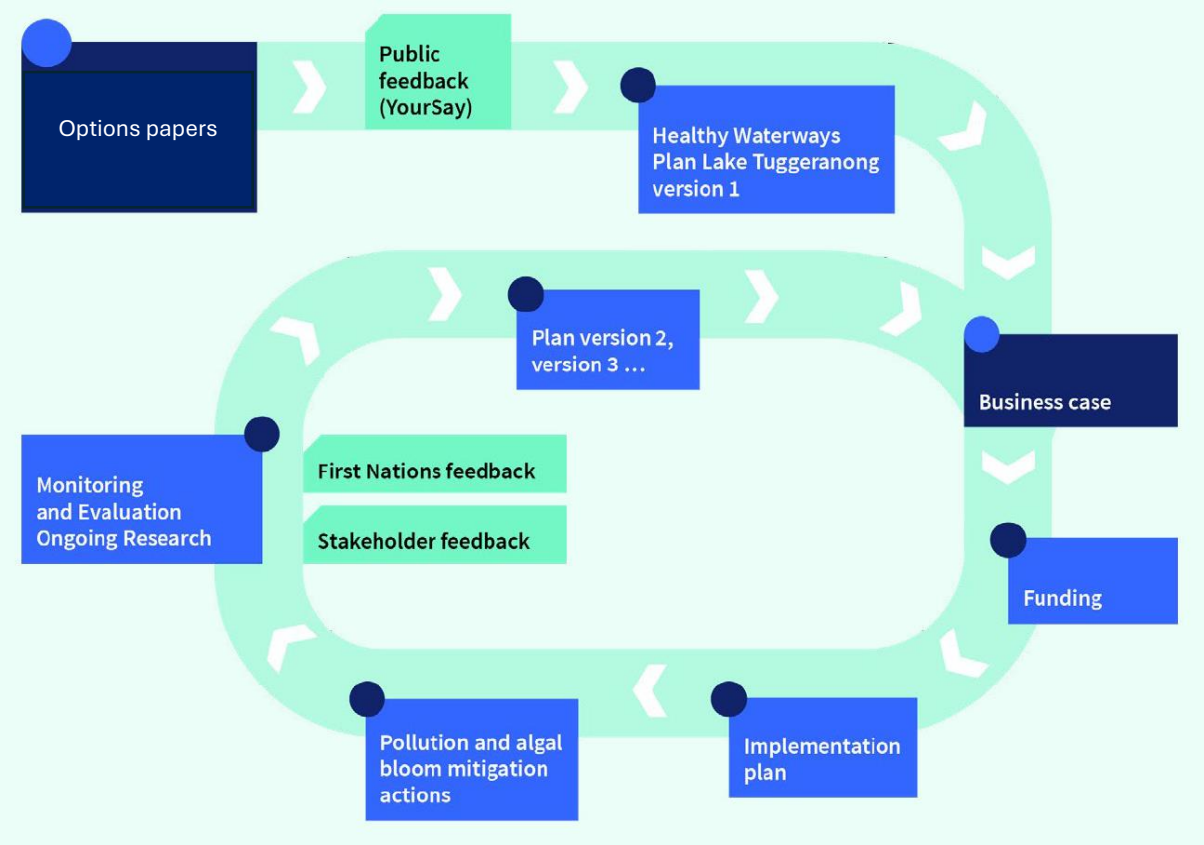

Figure 3. Current papers and how they can help government to progress towards an adaptive management cycle for reducing pollution in the Lake Tuggeranong catchment and algal blooms in the lake.

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Attachment F

Options for Restoring Lake Tuggeranong

August 2025

ACT Government

ACT Healthy Waterways

Acknowledgement of Country

Yuma
Dhawura nguna ngurumbangu gunanggu Ngunnawal. Nginggada dindi dhawura Ngunnawalbun yindjumaralidjinyin.
Mura bidji mulanggaridjindjula.
Naraganawaliyiri yarabindjula.

Hello,
This country is Ngunnawal (ancestral/spiritual) homeland. We all always respect elders, male and female, as well as Ngunnawal country itself.
They always keep the pathways of their ancestors alive.
They walk together as one.

We acknowledge the Ngunnawal people as traditional custodians of the ACT and recognise any other people or families with connection to the lands of the ACT and region. We acknowledge and respect their continuing culture and the contribution they make to the life of this city and this region.

Privacy

Any personal information provided during your submission will be used solely for the purpose of this community engagement process. Submissions may be partially or fully published on an ACT Government website or incorporated into a subsequent consultation report. As the ACT operates under a pro-release policy, citizens and others have the right to access information obtained through this engagement process under the Freedom of Information Act 2016. While the names of organisations may be disclosed, individuals' identities will be de-identified unless explicit prior consent has been obtained.

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Contributors

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Options for Restoring Lake Tuggeranong

Executive summary

There is a rich history of Aboriginal use of the Tuggeranong valley and its waterways, with evidence of the Ngunnawal people occupying the valley for more than 20,000 years. The name 'Tuggeranong' comes from a Ngunnawal word for 'cold place' or 'cold plains'.

The valley has changed dramatically in the past 200 years, shifting the traditional life patterns that Traditional Custodians have understood and worked with for thousands of years. Sheep and cattle stations were established in the early 1800s. Since suburban development started in the 1970s, around 50% of the water catchment has been urbanised. Lake Tuggeranong was built in 1987 as a focal point for the growing town centre and to protect the downstream Murrumbidgee River from the water quality effects of development. Around the same time, a stormwater system was built to manage flood risk by converting natural creek lines such as Tuggeranong Creek into concrete channels.

Lake Tuggeranong has experienced elevated nutrient levels for more than ten years, which has led to frequent blue-green algal blooms. The algal blooms smell unpleasant, are unsightly and require the government to close the lake to activities such as swimming and water sports due to health risks. They also may pose health risks to residents of suburbs surrounding the lake who are exposed to aerosolised lake water on windy days.

Several key conclusions can be drawn from the analyses in this report:

- There is sufficient knowledge to have confidence that better water management can lead to a substantial reduction in the frequency of blue-green algal blooms in Lake Tuggeranong.
- A suite of pollution mitigation options to prevent nutrients entering the lake will be needed for success.
- Further research and adaptive management in implementation will lead to a refined suite of management options for Government to choose from and increase the overall cost-effectiveness of the restoration effort.
- There will be a limit to what can be done to prevent algal blooms; the best that can be achieved is to prevent algal blooms in three out of four years on average.
- Water managers may need to develop options to treat algal blooms when they do arise.

This report presents our current knowledge of options for preventing algal blooms in terms of impact and cost-effectiveness. This report builds on previous Healthy Waterways work in the Lake Tuggeranong catchment that saw the construction of nine important wetlands and funded research and community engagement to reduce the sources of nutrient pollutants.

Following consideration of community feedback on the report, the Government will present its preferred options for achieving a healthier Lake Tuggeranong as a *Healthy Waterways Plan for Lake Tuggeranong* (the Plan).

The vision

This report and the Plan that will follow, address an ACT Government commitment for the 11th Assembly to *Develop and deliver a 10-year plan for a healthier Lake Tuggeranong*.

The 10-year vision is:
By 2035, Lake Tuggeranong is more consistently free of blue-green algal blooms and, when they do occur, they are short-lived so the Tuggeranong community can enjoy the lake most of the year.

The underpinning research and analyses

Research and modelling funded through the ACT Healthy Waterways program over the past decade has greatly improved understanding of blue-green algal blooms in Lake Tuggeranong. It is now well established that the inflow of phosphorus and other nutrients from the catchment is the main factor driving the blooms. They effectively feed the blooms.

There is currently far more phosphorus entering the lake from its catchment than is released to the water column from lake-bottom sediments. Phosphorus is generated from many diffuse sources across the urban catchment such as leaves, grass clippings, fertiliser products (including composts and manures), soil and sewage. Roughly half of it is in a dissolved form that is readily taken up by algae.

The stormwater flowing off the catchment carries an average annual generation of 1,656 kg phosphorus/year. The seven constructed wetlands built in Stage 1 of Healthy Waterways have reduced this by about 214 kg a year (to 1,442 kg). However, under current flow and levels of phosphorus supply, Lake Tuggeranong will remain in a eutrophic state—which means it is primed for algal growth.

Research shows that we can significantly reduce blue-green algal blooms if we curb or 'mitigate' the supply of phosphorus to the lake by about 50%, or around 700 kg a year. Once this happens, any further algal blooms can be prevented through in-lake actions. If the average annual amount of phosphorus entering the lake can be reduced by another 700 kg, the water quality models predict a eutrophic state can be avoided for an average of three out of four years.

The 700 kg target is based on annual averages. In very wet years the reductions in phosphorus will need to be higher, while in dry years they can be lower. Some blue-green algae will be present in all years—it naturally occurs in, but if the 700 kg target can be achieved, the likelihood of problem blooms would be lower than at present and the lake should usually be available for contact-based activities.

Options for removing phosphorus

It is possible to remove phosphorus from the system, or to treat algae directly, at three stages during the 'journey of the stormwater':

1. At the sources of pollution, by preventing pollution from occurring in the first place.
2. Within the stormwater system, by slowing the flow and filtering pollution from the stormwater.
3. In the lake, by using agents that compete with algae for nutrients, or by using algicides.

Some potential options are identified for reducing or mitigating phosphorus levels (pollution mitigation options) or directly treating algal blooms. A subset of ten options and variants of options are examined in

detail. These were chosen because their costs and effectiveness could be well characterised based on local trials or the scientific literature.

The analyses clearly show that the most effective options for reducing phosphorus pollution are an increased frequency of street sweeping and building extra water quality assets, such as wetlands, which cleanse stormwater of pollutants. Street sweeping is by far the most cost-effective mitigation measure, decreasing phosphorus by 200–400 kg per year, depending on the frequency of sweeps. Constructing more water quality assets would decrease phosphorus by 100–200 kg per year, depending on the scale of the wetlands and other water quality assets already in the system.

Commented [DC1]: Minister a) asked for this section to be included in the consultation document and b) struck this paragraph out. This is not in the consultation document, but I had a discussion with the MO who advised that the intent was not to expunge all findings that street sweeping is the most cost effective option. We have left here in the technical report, as it simply reports the findings of the analyses but does not commit to a course of action.

However, no single option is a 'silver bullet' that has the potential to reach the phosphorus mitigation target on its own. Multiple options will be needed. Notably, options to prevent stormwater from getting polluted in the first place will be needed to substantially reduce the frequency of blue-green algal blooms.

Future research and monitoring

An active research and monitoring program has played a central role in the work to date. Ongoing research and monitoring will be critical to refining pollution mitigation options to maximise their effectiveness and minimise their costs. New evidence and knowledge can be incorporated into future versions of the Plan, and its implementation plans.

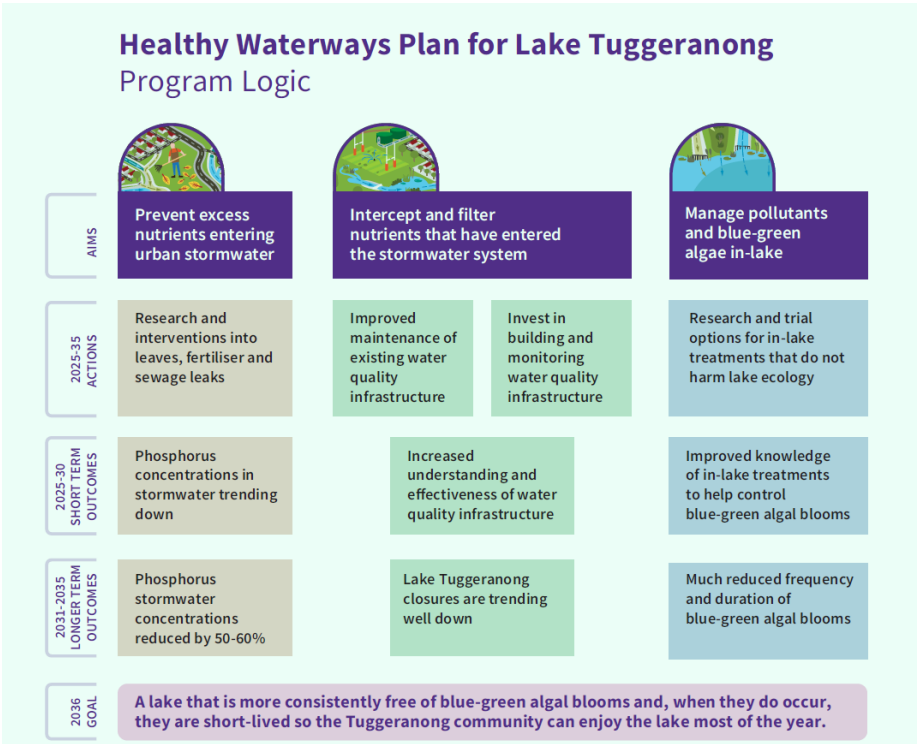
The highest research priorities are trials of promising options and investigations to better understand the fate of fertilisers applied to residents' blocks and to determine whether sewage (either through cross-connections or by other mechanisms) is a significant source of phosphorus in stormwater. It will be critical to continue to monitor the effectiveness of wetlands and other water quality assets, as well as other interventions.

Additional research will continue to refine knowledge and understanding of how to reduce phosphorus in the catchment. However, there is enough evidence already to identify priorities for restoration. Substantial improvements should occur in the lake within several years of the commencement of a material pollution mitigation program.

Next steps

The Government will create Version 1 of the Healthy Waterways Plan for Lake Tuggeranong based on this report, incorporating further inputs from First Nations people and feedback from the community. An implementation plan will then be developed to set out how the vision will be achieved over the next 10 years, including how it will be monitored and evaluated.

Healthy Waterways Plan for Lake Tuggeranong
Program Logic



Aerial view of Lake Tuggeranong. Source: MetroMap

Part 1 Context

- **The ACT Healthy Waterways Program**
- **Objective and scope of the report**
- **Vision**
- **Lake values**
- **Legislative and policy context for managing water quality in Lake Tuggeranong**
- **Lake Tuggeranong and its catchment**

The ACT Healthy Waterways Program

Addressing water quality in our urban lakes, and specifically the issue of blue-green algae, is a major challenge. The ACT Healthy Waterways Program (Healthy Waterways) was created to address the issue of declining water quality in ACT's rivers and urban lakes.

Stage 1 Healthy Waterways (2014–21) was a joint Australian Government and ACT Government investment, while the ACT Government is fully funding Stage 2 (2021 to present).

Over the last decade, Healthy Waterways has delivered a comprehensive suite of activities to help improve water quality and improve our understanding of the problem. It has built water quality assets (such as wetlands and raingardens); invested in research, monitoring and data analyses; built water modelling capability; and initiated community partnership programs to uplift catchment management practices.

Through this work, we have greatly improved our understanding about how ACT's urban catchments operate, the different sources of nutrient pollution that enter waterbodies and lead to algal blooms, the in-lake processes that promote algal blooms, and how the community wishes to participate in caring for waterways.

Of the urban lakes, Lake Tuggeranong has suffered the most chronically from water quality issues in recent years and has been the primary focus of investigative efforts to date. This report will underpin a *Healthy Waterways Plan for Lake Tuggeranong* (the Plan; Figure 1), which is the first of four Healthy Waterways plans for urban waterways.

Objective and scope of the report

The objectives of this report are to:

1. determine whether it is possible to achieve a substantial reduction in the incidence of algal blooms in Lake Tuggeranong through better catchment and waterway management
2. evaluate various options for mitigating stormwater pollution that drives algal blooms.

The Government will finalise the report as a *Healthy Waterways Plan for Lake Tuggeranong* once the community has provided feedback on the options (Figure 1). Subsequently, it will consider what level of funding will be investigated for the Plan to be implemented. Any funded restoration activities will be monitored and evaluated, and further research and stakeholder engagement will be conducted. The Government will periodically update the Plan as new knowledge comes to hand to ensure the plan achieves maximum value for the community at least cost.

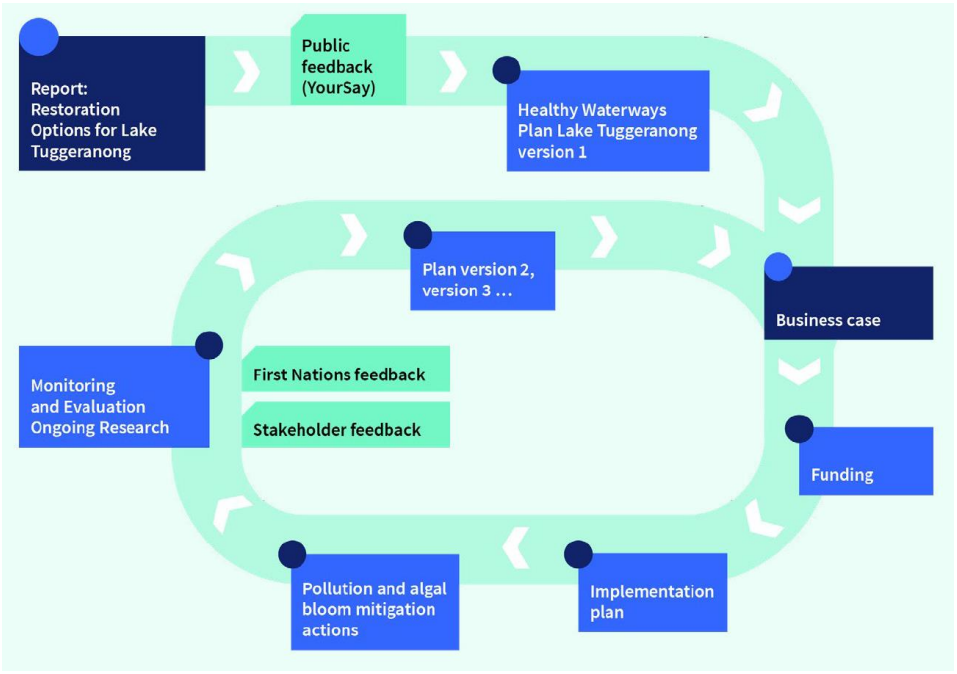


Figure 1. Role of Restoration Options for Lake Tuggeranong *in the adaptive management cycle for mitigating algal blooms in the lake.*

This report and the Plan prioritise focussing on algal blooms over other water quality issues because the ACT Government believes they are the highest priority for the Tuggeranong community (for example, TCC, 2024, Draft). Reducing the incidence of blue-green algal blooms in Lake Tuggeranong should improve its amenity and recreational values for residents and reduce health risks.

Vision

This report and the subsequent Plan address an ACT Government commitment for the 11th Assembly to *Develop and deliver a 10-year plan for a healthier Lake Tuggeranong*.

> The 10-year vision is:
> *By 2035, Lake Tuggeranong is more consistently free of blue-green algal blooms and, when they do occur, they are short-lived so the Tuggeranong community can enjoy the lake for most of the year.*

We need a 10-year time frame because new infrastructure assets will take time to build and become fully functional, and to allow enough time to assess the effectiveness of interventions while considering the background influence of year-to-year climate variability. Nevertheless, fulsome implementation of the Plan should lead to substantial improvements in water quality within several years.

Aquatic ecosystems in the ACT are highly valued by Traditional Custodians and the broader community as living systems that embody the interconnectedness of all life. Achieving this 10-year vision will support Traditional Custodian responsibilities to care for Country for future generations, as practiced for tens of thousands of years. This reflects Traditional Custodian understanding of water as an interconnected part of Country.

Lake values

Lake Tuggeranong provides multiple social, economic and environmental values for the ACT and region community. However, the 2022 State of the Lakes and Waterways report highlights that there are tensions between the competing values of urban lakes and waterways—for example the amenity of Lake Tuggeranong versus its role as a pollution trap—and widely differing expectations of urban water management (OCSE, 2022).

Mitigating downstream pollution

Canberra's lakes reduce downstream pollution by acting as sediment and pollution filters. NCEconomics (2023) estimated the market value of this function, known as 'avoided abatement cost', which describes how much it would cost to provide the equivalent pollution abatement if the lakes were not serving that function. They estimated the value of Canberra's urban lakes as pollution filters using a hypothetical comparison of water quality outcomes 'with' and 'without' the lake, where water quality upstream of the lake was used as a proxy for water quality 'without' the lake. The used total nitrogen as the water quality indicator because pollution abatement assets can reduce multiple pollutants at the same time, so only the highest-cost pollutant for each lake was used, to avoid the risk of double counting. The abatement costs were based on the cost of creating equivalent abatement capacity by building water quality assets. The cost of water quality assets was derived from construction costs in the ACT in the six years from 2017 to 2023.

The study estimated the net present value associated with Lake Tuggeranong's pollution abatement value is $133–144 million over 30 years. As discussed in Part 6, water quality assets are not the most cost-effective option for mitigating phosphorus pollution, so this is likely an overestimate of Lake Tuggeranong's pollution abatement value.

However, Lake Tuggeranong is not always effective as a pollution filter. The 2022 State of the Environment Report concludes, 'Lake Tuggeranong does not appear to be consistently mitigating the effects of urbanisation for the downstream waters with periods of higher phosphorus and nitrogen concentrations within and downstream of the lake compared to upstream of the lake'.

Providing opportunities for recreation and amenity

Canberra's urban lakes and their catchments provide important social values for residents. Access to blue spaces also contributes to improving people's physical, mental and spiritual wellbeing (UK Environment Agency, 2020; Dushkova et al., 2021; Lal and Akhikari, 2024). It follows that when algal blooms require the government to close the lake for long periods, there may be negative consequences for people's health and wellbeing.

The high value that Canberra residents place in their waterways is reflected in several surveys and community engagements undertaken from 2016 to 2023:

- A 2016 survey of more than 7000 people on Canberra's urban lake use found that the activity most often rated as 'highly important' was walking with other people, followed by picnics/barbeques, cycling and using playground areas (Schirmer & Mylek, 2016).
- In the findings of a 2018 ACT 'Better Suburbs' community survey, the citizen forum's first recommendation (out of 14) was to increase funding for lakes, ponds, wetlands, stormwater and water quality. This was ranked as more important for community members than issues such as street trees, roads, footpaths and public libraries (ACT Government, 2018).
- In community engagements as part of developing the Tuggeranong District Strategy, the Tuggeranong community said they value the lake for a range of recreational activities throughout the year, including walking, cycling, swimming, fishing and windsurfing (ACT Government, 2023b).
- A report commissioned by the ACT Government in 2023 explored residents' willingness to pay for environmental amenity and recreational use of Canberra's lakes (NCEconomics, 2023). The report found that the total annual non-market economic value of the lakes based on pollution control and amenity was approximately $159 million a year for Lake Tuggeranong, with the economic value from benefits to the community significantly outweighing the benefits attributable to water quality management (pollution abatement) provided by the lakes (Figure 2). (The much lower value of Lake Tuggeranong for pollution abatement in Figure 2 compared with its net present value is because Figure 2 reports annualised data whereas net present value is assessed for a 30-year period.)
- The same report indicated they were prepared to pay up to $70/per person/quarter (or $280/per person/year) to greatly improve the environmental (visual and smell) amenity of Lake Tuggeranong (NCEconomics, 2023). Across all lakes, the survey found that most lake users are infrequent, casual users who draw more value from lake amenity and lakeside facilities than from primary and secondary contact activities like swimming and boating. This finding is also consistent with findings from the earlier survey of Schirmer & Mylek (2016).

Environmental values

There is limited information on the ecological values of the lake. The Waterwatch Catchment Health Indicator Program (CHIP) 2023 report notes the lake has poor riparian condition with little native vegetation, but Eastern Long-necked Turtles, water dragons and occasionally Rakali (Australian native water rats) are present in the wetlands at the southern end of the lake (Upper Murrumbidgee Waterwatch, 2023).

The 2022 State of the Lakes Report found that the aquatic health of the lake supported ecological values to a 'fair' degree, noting limited information to determine a trend. This conclusion was based on the CHIP assessments and because water quality and ecosystem health of the lake are sufficient for the survival of stocked native fish (OCSE, 2022). Murray Cod and Golden Perch are stocked, primarily to support recreational fishing, it also to improve biodiversity and help balance the fish composition by adding native predators to the system. There are a lot of carp in the lake; surveys in 2015 and 2018 showed carp comprised around 90% of all biomass caught. This decreased to 60% in 2024 due to increased stocking of native fish (ACT Government, unpublished data, 2025).

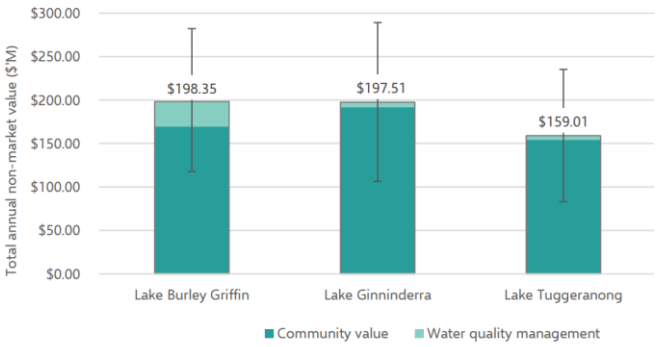


Figure 2. Total annual non-market value from ACT urban lakes. The community value is based on surveyed residents' willingness to pay for good water quality within the lakes through increases in rates. The water quality management value is based on the avoided cost of building water quality assets that provide the same level of treatment as the lake. Source: NCEconomics (2023).

Cultural values

Cultural values mapping can help to identify what First Nations cultural values and uses are associated with the lake, its tributaries and catchment.

An initial Ngunnawal Aboriginal Waterway Assessment (AWA) was conducted that assessed the health of Country and the waterways in the Tuggeranong catchment from a cultural perspective. The Assessment stressed the importance of:

- recognising Ngunnawal people as a part of the solution to restoring the health of Lake Tuggeranong
- reintroducing and respecting cultural practice in catchment management such as cultural burning and cultivation of pointer and keeping trees
- establishing Ngunnawal rangers
- continuing to conduct AWAs
- introducing more native plants to the creek and surrounding riparian and dry landscapes, including natives of cultural significance such as reeds for weaving
- restoring key features such as naturalising concrete drains
- creating a fully connected cultural way from the headwaters of Tuggeranong Creek to its confluence with the Murrumbidgee River
- avoiding pollution, including from blue-green algae, of the Tuggeranong Creek below Lake Tuggeranong
- considering river health and Country health as intertwined
- exploring opportunities for an entitlement to water for cultural purposes.

Further engagement should occur with Traditional Custodians as part of implementation planning to guide an integrated design approach that supports and enhances place-based management actions.

Lake Tuggeranong looking north towards Mount Taylor (photo: Jennifer Smits)

Legislative and policy context for managing water quality in Lake Tuggeranong

Lake Tuggeranong's management is prescribed by the *Planning Act 2023 (ACT),* which prioritises management objectives for all public land (including waterways) in the following order:

- Prevent and control floods by providing a reservoir to receive flows.
- Prevent and control pollution of waterways.
- Provide for public use for recreation.
- Provide habitat for fauna and flora (Schedule 3 [Part 3.2]).

Since there is little urban infrastructure downstream of Lake Tuggeranong to protect from floods, the primary management objective for Lake Tuggeranong under the Planning Act is to prevent and control pollution.

The Plan aligns with and supports the implementation of other ACT legislative and policy commitments on water quality, specifically the following:

- The *Lakes Act 1976,* administered by the Environment Protection Authority (EPA), which provides for the administration, control and use of urban lakes in Canberra (other than Lake Burley Griffin).
- The ACT Water Strategy 2024–2044 Striking the Balance sets a 20-year vision for ACT water management as: *'A community working together, managing water wisely to support a vibrant, sustainable and thriving region'.*
  Outcome 1 of the Strategy—Healthy Catchments and Waterbodies—aims to achieve 'Well managed, functioning catchments that provide sufficient clean water for the environment and human consumption, support healthy waterbodies, and contribute to liveability of the ACT community'.

- Focus on improved water quality standards to support identified environmental values and permitted uses for Lake Tuggeranong. Environmental values and permitted uses are defined through the Water Use and Catchment General Code (the Code), a subordinate instrument of the *Water Resources Act 2007* (ACT). Under the Code, Lake Tuggeranong and its catchment is defined as drainage and open space with the following environmental values and permitted uses of:
    - discharge of stormwater
    - irrigation water supply
    - waterscape view
    - aquatic habitat (lowland streams, urban lakes and ponds, urban wetland)
    - water-based recreation (boating).
- Water quality standards are set through the Environment Protection Regulation 2005 (ACT) Schedule 4, a subordinate instrument under the *Environment Protection Act 1997* (ACT), and support the policies, management objectives and values of the Code. Access Canberra (EPA) ensures compliance with the Environment Protection Regulation, including s44 that 'a person must not place, or permit to be placed, a pollutant in a waterway if the pollutant is likely to cause environmental harm.'
- The ACT and Region Catchment Strategy 2016–2046 establishes a 30-year vision to guide priority actions for a healthy Upper Murrumbidgee River region (upstream of Burrinjuck Dam to Tantangara Dam in NSW). Developed in partnership with the Australian Government, ACT Government, NSW Government, local councils, Icon Water and the community, it is currently undergoing a 5-yearly review.
- The 2002 Legislative Assembly committed to manage downstream water quality through an agreed motion that the water leaving the ACT via the Murrumbidgee River should be of no less quality than the water flowing into the ACT (ACT Legislative Assembly motion 5 June 2002 9.1[b]).
- The Canberra Urban Lakes and Ponds Land Management Plan's vision is to: *enrich local communities through the aesthetic, recreational, sporting, tourism, cultural and ecological values of lakes and ponds, and to provide opportunities for people to be involved in their use, care and management*. Under this plan, 'recreation' and 'visual landscape' are listed as Lake Tuggeranong's highest values (ACT Government, 2022b).
- The ACT's Water Resource Plan, developed under the Murray–Darling Basin Plan, contains a Water Quality Management Plan that sets locally relevant water quality targets.

None of these legislative and policy commitments consider whether and how to reduce the problem of blue-green algal blooms in Lake Tuggeranong, but they do underpin this report, which fills that gap.

Management of the ACT's lakes and ponds represents a collaborative effort across government, the private sector and the community (residents). ACT Government agencies and other organisations with responsibilities include:

- City and Environment Directorate
    - delivers the Healthy Waterways Program, undertakes water science, monitoring and modelling, implements the ACT Aquatic and Riparian Strategy;
    - implements Murray-Darling Basin commitments;
    - undertakes planning to include water sensitive urban design;
    - owns, manages, maintains the stormwater system and water sensitive urban design assets;

- manages urban open spaces, water quality services (dredging, street sweeping, GPT cleaning) recreation services on lakes and ponds, and dam safety;
- includes the Environment Protection Authority – the statutory decision maker under the *Water Resources Act 2007* and *Environment Protection Act 1997,* administers Environment Protection Regulations on environment, water quality and waterway health.

- Health and Community Services Directorate– monitors water quality of recreational water sites.
- ACT Emergency Services Agency – undertakes strategic and emergency flood risk management.
- Icon Water – owns, operates, maintains drinking water supply and wastewater system, undertakes long-term water resource planning.
- National Capital Authority – manages Lake Burley Griffin's water quality and waterway health.

Lake Tuggeranong and its catchment

Three major tributaries deliver inflows to Lake Tuggeranong—Kambah and Village creeks in the north (draining a fully urban area) and Tuggeranong Creek in the south (draining urban and rural areas)—as do several minor drains (Figure 3). Tuggeranong Creek runs through a series of settling ponds to improve water quality—Isabella Pond then Lake Tuggeranong wetlands—before discharging into Lake Tuggeranong (Figure 3). Key lake statistics are shown in Table 1 and Figure 4.

Geographical setting and early history

Before it was developed, the Tuggeranong Creek catchment featured hills and valleys with a large, shallow gravel aquifer with 1.5 times the current lake's volume. Tuggeranong Creek would have had a hydrology consistent with a 'chain-of-ponds' system (Lawrence, 2012). Chain-of-ponds systems usually occur in shallow, alluvial valleys where a river doesn't carry flow under baseflow conditions; instead of a continuous channel the river forms a series of irregularly spaced ponds (Mould and Fryirs, 2016). The other tributaries may originally also have been damp valleys, chains of ponds or small creeks.

There is evidence to suggest Ngunnawal people have occupied the Tuggeranong Valley for more than 20,000 years (Flood et al. 1987). The name 'Tuggeranong' comes from a Ngunnawal word for 'cold place' or 'cold plains'. Tuggeranong Creek would have provided an important source of water. Important cultural sites in the valley include scarred trees found at Lanyon (canoe tree) and the Wanniassa–Kambah area (ACT Heritage Council, 2024). Axe-grinding grooves have been found in a sandstone outcrop in what is now the suburb of Theodore (Flood, 1996). Tuggeranong Creek remains a culturally and spiritually important part of country for Ngunnawal people today, and undertaking further cultural values mapping would help provide us with a better understanding of this.

Europeans began grazing the valley with sheep and cattle in the late 1820s and homesteads were established close to watercourses, including Tuggeranong Creek. Lanyon Station was established in 1835 and the Tuggeranong and Lanyon Homesteads, which remain today, are reminders of this period.

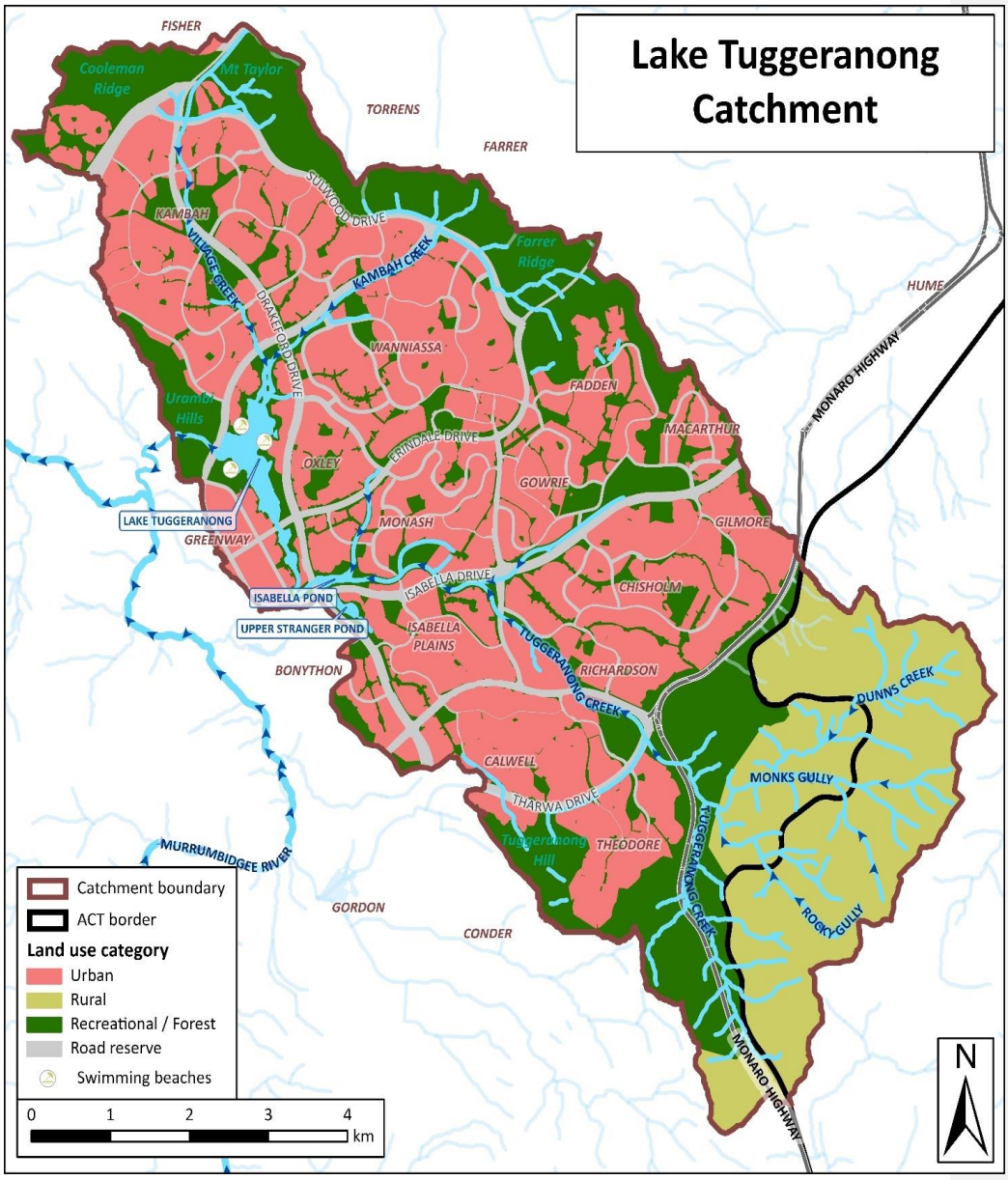


Figure 3. Lake Tuggeranong catchment showing its tributaries. The lake discharges into a short section of Tuggeranong Creek via an outflow channel and weir at the west corner of the lake. This creek then flows into the Murrumbidgee River.

Table 1. Lake characteristics and Tuggeranong climate. Source: (GHD, 2024) and www.bom.gov.au

Lake characteristic	
Size	**57 hectares**
Volume	**1790 megalitres (at normal operation)**
Average depth	**2.9 metres**
Maximum depth	**12.2 metres**
Average residence time of water	**58 days**
Average annual inflows	**9000 megalitres**
Minimum inflows (dry year)	**3000 megalitres**
Maximum inflows (wet year)	**18000 megalitres**
Tuggeranong climate	
Summer mean maximum temperature	**28.1 ^{0}Celcius**
Summer mean minimum temperature	**13.6 ^{0}Celcius**
Winter mean maximum temperature	**14.4 ^{0}Celcius**
Winter mean minimum temperature	**0.7 ^{0}Celcius**

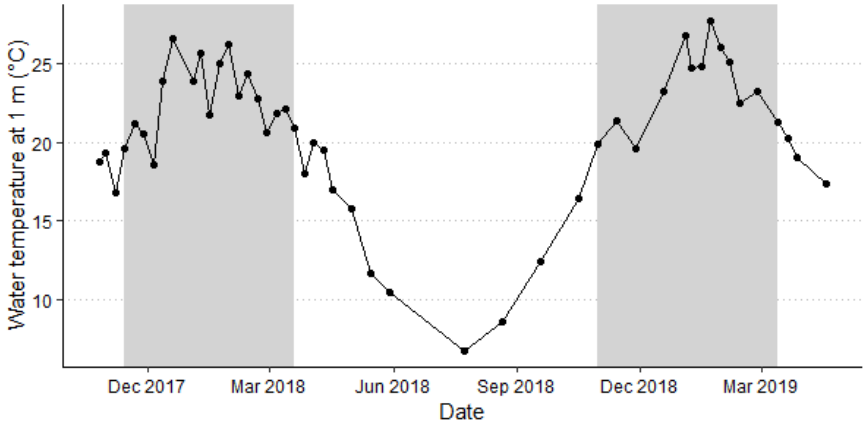


Figure 4. Surface water temperature in Lake Tuggeranong: Mean water temperature at a depth of 1 metre in the central basin of the lake. The grey rectangles that overlay the plot indicate the period from the first detected stratification to the final breakdown of stratification in the lake for the year. (Source: Figure 4-2 in Ubrihien et al., 2019, p.77).

An urbanised catchment—a new lake to filter sediment and concrete drains to channel flows

Tuggeranong was earmarked to be the third town centre of Canberra and was rapidly developed into suburbs throughout the 1970s and 1980s. Much of the shallow aquifer was drained using agricultural drains, stormwater pipes and concreting of the channel bed inset into the aquifer (Lawrence, 2012). To manage the flood impacts of urban runoff, most of the catchment's tributaries have been modified to become a constructed stormwater system of concreted open channels and underground pipes. Lake

Tuggeranong was built in 1987 by damming the Tuggeranong Creek at Athllon Drive. While some rural land still exists within the Tuggeranong catchment, it now has a built-up area of more than 50% (Table 2).

Urbanisation changes flow regimes by increasing the impervious surface area (Walsh et al., 2012). Dey et al. (2024) estimated that runoff is four times higher in the Lake Tuggeranong catchment now than when it was a natural catchment. This is because roofs, roads, buildings and concrete are water-resistant materials that prevent water from being absorbed into the landscape. This leads to high surface water runoff that makes its way to the stormwater system (Ladson et al., 2006), carrying pollutants with it.

Table 2. Land use in the Tuggeranong catchment (Dey et al. 2024).

Built-up area		Green space area	
Urban	**41.2%**	**Rural land**	**28.3%**
Roads/transport	**8.9%**	**Urban open space**	**10.2%**
Commercial land use	**1.8%**	**Natural bushland**	**9.5%**
Approx total	**52%**	**Approx total**	**48%**

Part 2 Water quality problems in Lake Tuggeranong

- **Blue-green algae**
- **Faecal indicator bacteria**

Lake Tuggeranong currently experiences frequent blue-green algal blooms and periods of elevated faecal bacteria levels. Other water quality issues in the lake or its tributaries include high turbidity and industrial pollution events; for example, from paint (Upper Murrumbidgee Waterwatch, 2022).

This report and the subsequent Healthy Waterways Plan for the lake focus primarily on addressing algal blooms over other water quality issues. This is because of the higher potential health risk associated with blue-green algal blooms, the fact they contribute to a large proportion of lake closures, and the significant visual and odour impact on the community during severe blooms, such as reported in TCC (in draft).

Blue-green algae

Blue-green algae (Cyanobacteria) are a group of bacteria present in virtually all aquatic environments worldwide. Blue-green algae are not plants but are photosynthetic bacteria, reproducing rapidly when given sunlight and warm, nutrient-rich conditions (Joehnk et al., 2008). They are buoyant, forming surface scums known as a blue-green algal bloom. When this happens, they block the light that would otherwise be available for favourable plant growth, discolour the water and may release a range of toxins. Such blooms are a persistent problem in Lake Tuggeranong, especially in summer. Algal blooms reduce visual amenity, release foul odours, pose a health hazard to residents and visitors and require the ACT Government to close the lake to recreational use.

Blue-green algae and human health

Some types of blue-green algae produce toxins (cyanotoxins) that can be harmful for humans, domestic animals and livestock that drink or make contact with the water, and for fish and other organisms living in the water.

There is increasing research and community interest in Australia and overseas into potential associations between cyanobacteria and neuro-degenerative diseases in humans (as noted, for example, by NSW Health, 2023). For example, studies have found an increased incidence of motor neurone disease in people living near waterbodies with blue-green algal blooms (Cox et al., 2003; Caller et al., 2009; Andrew et al., 2017; ABC Online, 2023; Torbick et al., 2018), although most of these studies could not confirm whether direct exposure to cyanobacteria had occurred.

The link between exposure to blue-green algae through primary or secondary contact and neuro-degenerative diseases has not been proven, except where foods have been grown in the presence of blue-green algae (Cox et al. 2003). Clusters of residents with motor neurone disease might be caused by a myriad of factors unrelated to blue-green algae blooms. However, researchers have yet to fully evaluate all plausible cause–effect mechanisms related to blue-green algae blooms and there is an argument for adopting the precautionary principle to mitigate potential risks to human health (Dunlop et al., 2021; Cox, 2021). This is particularly important while investigating airborne exposure pathways such as chronic exposure to aerosolised cyanotoxins downwind of affected waterbodies (Sutherland et al., 2021; Schaefer et al., 2020; Plaas & Paerl, 2021).

Lake Tuggeranong experienced a significant blue-green algae bloom over the summer of 2019/20 (photo: Alica Tschierschke)

Blue-green algae monitoring and lake closures

The Environment Protection Authority (EPA) monitors five sites in Lake Tuggeranong during the recreational season, which runs from October to April. The lake is closed to recreational use if either blue-green algae or faecal bacteria concentrations exceed the levels specified in the ACT Guidelines for Recreational Water Quality. Data analysed from 2015 to 2024 shows frequent closures throughout the recreational season with at least one swimming beach closed for more than 50% of the time for seven of those nine years (Figure 5).

In the 2022–23 season, EPA monitoring showed that all three swimming beaches were closed for almost the entire recreational season. In addition, blue-green algal blooms kept the lake closed to primary contact recreation from mid-January 2023 through to the beginning of June 2023, well beyond the recreational season.

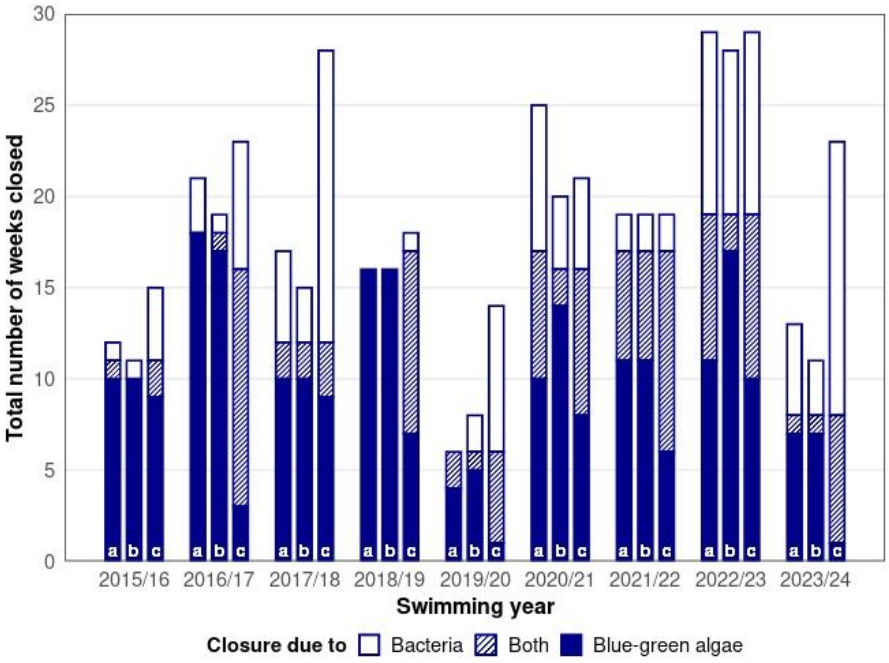


Figure 5. Number of weeks of the swimming season (30 weeks from Oct–April) that Lake Tuggeranong was closed to swimming at one or more beaches due to blue-green algae or bacteria between 2015 and 2024. Column a: Ngadyung Beach, Column b: Nguru Beach, Column c: Tuggeranong Town Beach

Information about how water quality in Lake Tuggeranong is monitored, and current alerts and closures, is published on the ACT City Services website www.cityservices.act.gov.au.

Faecal indicator bacteria

As Figure 5 shows, lake closures can also be due to the presence of faecal indicator bacteria, with Tuggeranong Town Beach showing a higher incidence of closures due to this cause.

ACT Health routinely tests ACT lakes for faecal contamination using the faecal indicator bacteria enterococci. These are a group of bacteria found in the intestines of humans and animals; their presence in water may indicate domestic sewage leaks or contamination from diffuse sources of human and animal waste. Water managers use enterococci as the standard faecal indicator bacteria to test water quality in recreational waters in Australia because they are well understood, easy to detect and their presence reliably predicts health risks associated with exposure to waterborne bacterial pathogens.

Monitoring work using Microbial Source Tracking is currently underway to understand the extent the faecal matter is coming from human or animal sources. Findings from this work will inform future iterations of the Plan. In the meantime, many of the interventions proposed to reduce algal blooms will also remove bacteria and other pollutants, such as excess carbon, nitrogen and total dissolved solids, that are potentially causing issues in the catchment.

Part 3: The cause of algal blooms

- **Drivers of algal blooms**
- **Supply of phosphorus: catchment versus lake sediments**
- **Catchment sources of phosphorus**

Drivers of algal blooms

The prevalence of blue-green algae is linked to the trophic state of a water body. Trophic state is a description of the biological productivity of a water body and depends on factors such as the concentration of nutrients used by plants (and blue-green algae) such as phosphorus and nitrogen (South Dakota State University Extension, 2022).

Water bodies in an oligotrophic state have very low nutrient concentrations and tend to have very clear water with little plant or algal growth and high oxygen concentrations that depress the release of algal nutrients stored in lake-bottom sediments. Hence, oligotrophic lakes are not prone to algal blooms. Water bodies in a mesotrophic state have a moderate amount of nutrients, moderately clear water, some algal blooms in late summer and oxygen depletion at bottom of lake as biomass decomposes. Most of the time, the water quality is within an acceptable limit to provide recreation, amenity and ecological benefits. Finally, water bodies in a eutrophic state are nutrient rich, with highly productive plant growth and high turbidity. They are seasonally deficient in oxygen, which may lead to fish kills. Eutrophic lakes may experience regular algal blooms.

When a waterway is in a eutrophic state, nutrient concentrations are so high that blue-green algae blooms are likely to occur whenever the conditions are stable (low flow), the water is warm enough and there is enough light penetrating through the water column (Paerl, 1988). These have been the conditions in Lake Tuggeranong for more than a decade, with blooms occurring every summer.

Nutrient overload in Lake Tuggeranong

It is widely accepted that phosphorus is the main nutrient that drives algal blooms in freshwater systems; without it, algal growth is severely limited (Carvalho et al., 2013), including in Lake Tuggeranong (Ubrihien et al. 2019). While nitrogen is also essential for algal growth, its absence in lake water does not limit algal growth in the same way as phosphorus because blue-green algae can source nitrogen from the atmosphere (a process called nitrogen fixing) as well as from the water. Therefore, to reduce the incidence and severity of algal blooms, we need to reduce the availability of phosphorus in the system. However, most management options to reduce phosphorus in stormwater will also reduce nitrogen.

To reduce the phosphorus available to blue-green algae in the lake, and therefore the risk of severe algal blooms, we need to know where the phosphorus is coming from; whether it's mainly coming from the Tuggeranong catchment and reaching the lake via stormwater inflows, or if it is mainly coming from phosphorus already trapped within the lake bottom sediments (Lawrence et al. 2000; e.g. Nikolai and Dzialowski, 2014).

Phosphorus is transported to the lake in stormwater, either in a dissolved or particulate form. Particulate forms are small pieces of plant matter containing phosphorus or phosphorus bound to sediments. Sediment-bound phosphorus is often a result of erosion in the catchment or is blown into drains as dust and dirt. In its dissolved forms, phosphorus, especially phosphate, is more readily available for use by blue-

green algae (bioavailable; Lawrence et al. 2000), making it more immediately problematic in causing algal blooms.

Supply of phosphorus: catchment versus lake sediments

Much of the particulate phosphorus that is washed by storms into Lake Tuggeranong settles on the bottom of the lake and creates a nutrient-rich sediment layer. This creates an internal supply of phosphorus in the lake that can be released in a dissolved form later to become bioavailable through in-lake processes (Box 1).

Research by the University of Canberra (Ubrihien et al., 2019) found that the concentration of phosphorus observed in the surface water of Lake Tuggeranong was more than three times that required to support an algal bloom, with further significant amounts detected in sediments at the bottom of the lake. The internal supply of phosphorus—released from lake-bottom sediments—was enough to drive an algal bloom. However, the research found that the external supply of phosphorus to the lake from its catchment was five times the internal supply of phosphorus from lake sediments.

These findings suggest that internal supply of phosphorus is not driving most algal blooms in Lake Tuggeranong. Therefore, to mitigate blooms, water managers need to address catchment sources of phosphorus pollution before dealing with sources within Lake Tuggeranong.

Catchment sources of phosphorus

There are many potential sources of nutrients and other pollutants from urban catchments (as shown, for example, by Muller et al. 2020). Recent research and water quality monitoring in the Tuggeranong catchment has found that:

- phosphorus is mainly coming from urban, not rural, areas (Ubrihien et al., 2020; Upper Murrumbidgee Waterwatch, 2023)
- phosphorus is coming from many small sources across the whole catchment (diffuse sources), rather than from one or two large, concentrated locations (point-source) (Ubrihien et al. 2019)
- around 50% of the catchment-based phosphorus is in dissolved, bioavailable forms (Ubrihien et al., 2019), meaning it is available for uptake by blue-green algae
- leaves, grass clippings, fertiliser products (including composts and manures), soil and sewage are all likely contributing to catchment-based phosphorus (Ubrihien et al., 2019; Concepts of Change, 2023).

Soil

Soil can contain phosphorus both in its crystalline structure and adsorbed to soil particles. Sediments can release the adsorbed portion of phosphorus to water, after which algae can take it up. Because this is a slow process, most of the adsorbed phosphorus is not immediately bioavailable. However, sediments may release phosphorus over time once they are deposited in a lake.

Phosphorus adsorbed to clays suspended in the water column can take hours to weeks or longer to be released into water and available for uptake by algae.

Box 1. Why did dry weather in 2019–2020 limit algal blooms?

The Tuggeranong catchment experienced a dry period from September 2019 to January 2020, with only 6 mm of rain falling in the catchment. In Lake Tuggeranong, no blooms occurred and there were no lake closures due to blue-green algae during that time.

Dry conditions impact the lake's susceptibility to algal blooms by impacting in-lake processes. During the warmer months, Lake Tuggeranong experiences thermal stratification. This is where a stable zone of cooler water forms at depth in the lake where daylight does not penetrate and a warmer, light-filled, less-dense layer of water sits on top. In this top layer the light allows for photosynthesis to occur and bacteria, algae and other micro-organisms consume the available nutrients, most of which are washed in from the catchment. During dry periods, these top-layer nutrients are not replenished as they are consumed, which prevents blue-green algae from blooming.

Catchment phosphorus can also end up in the cool lower layer, with much of it bound to sediment on the lake floor where it's not bioavailable. Carbon also gets washed into the lake from the catchment as organic matter such as leaves. As bottom-dwelling bacteria feed on the carbon, they use up oxygen in the water; if the lake is stratified for a long time, this process creates an oxygen-depleted (anoxic) environment. Under anoxic conditions, phosphorus can be released from the sediment to become bioavailable. The released, bioavailable phosphorus can be brought to the top layer by diffusion or by mixing of bottom and surface waters as stratification later weakens or breaks down with winds, cool weather or rainfall.

In autumn in Lake Tuggeranong, the top layer of water cools and eventually sinks, forcing the bottom water, with its bioavailable phosphorus, to the surface. This is known as turnover and can cause a late season blue-green algal bloom. These are often of a shorter duration and less severe than summer blooms.

Blue-green algae can also access nutrients in bottom waters by modifying their buoyancy to move up and down through the water column.

University of Canberra researchers monitored phosphorus concentrations in the lake over the 2019/20 dry period and hypothesised that blooms didn't occur during this time because low baseflows meant there was a limited supply of nutrients in the top layer of the lake (Ubrihien et al., 2020). Their data also suggested that lack of carbon inputs may have led to reduced bacterial activity in the bottom layer, meaning less oxygen was consumed and the phosphorus remained bound to the sediments rather than becoming bioavailable.

One implication of this is that removing sources of phosphorus *and* carbon in the catchment may have a greater combined impact on reducing the incidence of algal blooms. The influence of dry vs wet weather conditions is also a key part of understanding year-to-year variability in the number, duration and intensity of blue-green algal blooms in Lake Tuggeranong.

Development sites

Tuggeranong District's population is predicted to be stable between 2022 and 2060, but there is still a potential future housing demand of 1100 dwellings by 2050 in the district forecast (ACT Government, 2022b, 2023b). While there are no greenfield suburbs planned, there are plans to redevelop existing areas through infill, and smaller-scale construction projects like knock-down rebuilds or major home renovations will also occur.

Development sites might contribute phosphorus to the stormwater system as phosphorus bound to the sediments in drainage or from roads that construction vehicles track mud onto. The University of Canberra examined the overall effect of urban development sites on the stormwater system in Lake Tuggeranong catchments in 2024 (Ubrihien et al., 2024b). They found that during storms, stormwater concentrations of total suspended solids were significantly higher downstream of development sites compared to upstream. However, levels of total and dissolved phosphorus did not vary significantly between stormwater sampled above and below development sites. The sediments from development sites are likely to be subsurface soils and thus low in phosphorus.

Leaf litter and grass

Phosphorus from plant materials can make up a substantial portion of the total phosphorus inputs in an urban catchment (Duan et al., 2014; Janke et al. 2017; Selbig, 2016; Muller et al. 2020). Plant materials have different amounts of phosphorus depending on the plant species and part of the plant (blossoms, fruits or leaves; Hill, et al., 2022).

Leaf litter (leaves, sticks, nuts, flowers) and grass clippings release nutrients as they decompose or are wet. This can happen quickly; research in the Tuggeranong catchment by the University of Canberra suggests that leaves will leach out most of their phosphorus within two days of either continuous or periodic inundation (Ubrihien et al., 2024a). In an urban environment with lots of impervious surfaces, leached, dissolved phosphorus cannot soak into the soil where soil particles could absorb it, or vegetation take it up. Instead, it enters the stormwater system where concrete channels and pipes convey it rapidly to lakes and waterways.

While much of Canberra is known for its deciduous street trees, nearly 80% of street trees in the Tuggeranong catchment are eucalypts (ACT Government, 2022a). From December 2022 to November 2023 the University of Canberra investigated the potential contribution of street trees' leaves to nutrients in the Tuggeranong catchment (Ubrihien et al. 2024a). They measured the deposition rate of leaves for the four most common eucalypt species onto impervious surfaces to determine their potential nutrient leaching rates, and then extrapolated this across the catchment by using estimates of tree canopy hanging over impervious surfaces. They found:

- the amount of leaf fall from these species was greatest in summer
- the phosphorus leached from leaves differed greatly between eucalypt species, with *Eucalyptus sideroxylon* leaching the most phosphorus
- the annual supply to Lake Tuggeranong of dissolved nitrogen, phosphorus and organic carbon contributed by leaves across the catchment as 25, 43 and 6,748 kg per year, respectively. They note these are probably underestimates because they only capture litter that falls directly from the overhanging canopy, not any that is blown or washed onto roads.

The phosphorus content of *E. sideroxylon* leaves as measured here is comparable to the average phosphorus content of leaves from a variety of deciduous trees measured in northern hemisphere studies

(Duan et al. 2014; Hill et al. 2022). The average phosphorus content of leaves from all the eucalypt species studied in the Tuggeranong catchment was generally slightly lower than the average for deciduous leaves.

In the same study the University of Canberra also measured grass clippings deposition (Ubrihien et al. 2024a). It found:

- nutrient deposition from grass clippings varies between seasons (with higher releases in summer) and between different mowing events
- an average 'mowing event' releases 33–76 mg of phosphorus for each square metre of impervious surface next to a mown area. The average varied depending on the season and whether clippings were continuously or intermittently soaked during the experiments.

Booksmythe et al. (2024) extrapolated these estimates to all the road surface within two metres of mown open space in the Lake Tuggeranong catchment, multiplied by the around 11 mowing events per year undertaken by ACT City Services, and found that this equates to clippings contributing between 85–200 kg of phosphorus per year to the lake.

Together, according to these estimates, leaves and grass contribute around 130–240 kg phosphorus per year on average to Lake Tuggeranong.

Urban open space mowing

ACT City Services manage the mowing of all urban open spaces in accordance with Canberra's Lakes and Ponds Land Management Plan and the complementary Urban Open Space Land Management Plan. Together, these plans require that:

- mowing programs aim to improve the ACT's water quality outcomes
- verge managers remove cut vegetation from guttering
- mowing cannot occur within five metres of waterbodies
- verge managers seek the Conservator of Flora and Fauna's advice on mowing areas next to certain waterbodies including Lake Tuggeranong District Park (south) and Isabella Ponds grassland.
- However, some cut vegetation will still end up blowing into gutters. The government is exploring ways to minimise this impact.

Fertiliser

Some residents and businesses use fertilisers to enrich soils with nutrients important for plant growth and health, including phosphorus, nitrogen and potassium. They fertilise residential lawns and gardens as well as public and private green spaces like sports fields, golf courses and gardens. Fertilisers can be a major source of phosphorus pollution of stormwater (Muller at al. 2020).

Fertiliser products come in different forms (manure, compost, chemical/synthetic) and have different release rates. The type of fertiliser used, how much is applied and when it is applied determine how well the plants can take it up, and whether it will stay in (or on) the soil or be transported out of the lawn, turf or garden bed and into waterways.

Nutrients can end up being 'exported' from residences to waterways either in dissolved or particulate form if too much fertiliser is applied (more than can be taken up by soils and plants), it is applied just before rain, or it is applied to soils that don't absorb water well.

Household fertiliser use

A Healthy Waterways funded survey in 2023 heard from 400 Canberra residents about the type and quantity of fertiliser they use (Concepts of Change, 2023). The findings of this survey were that:

- households use an average 84 kg of garden nutrient boosters (fertilisers, manures, compost) annually, which equates to 0.59 kg of phosphorus per household
- 6% of households use a paid gardening service and these accounted for 0.11 kg of annual phosphorus use by households, making a total of 0.70 kg phosphorus applied per household
- around half of Canberra residents use no fertiliser at all, with most of the fertiliser applied by the top 20% of users
- by volume, compost and manure are the most used fertiliser.

There are 21,000 low to medium density residential, detached and semi-detached dwellings with gardens in Tuggeranong (Booksmythe et al. 2024). Survey data on the amount of fertiliser applied by Canberra householders to their blocks combined with data from a literature review on the proportion of phosphorus that leaks into stormwater from different fertilisers (Booksmythe et al. 2024) yields a wide-ranging estimate of around 90–1,200 kg of phosphorus per year entering stormwater from fertilisers applied by householders, with an intermediate estimate of around 550 kg per year. The wide range is because of significant uncertainty in the export rates for phosphorus in fertilisers applied by residents or their gardeners.

Sports field fertiliser use

The Tuggeranong catchment includes approximately 70 hectares of managed sports grounds. Most of these are public grounds managed by ACT City Services Sport and Recreation, with about 7 hectares being privately managed.

The University of Canberra's research in the Tuggeranong catchment found that water samples taken near sports fields had slightly elevated phosphorus concentrations (total and dissolved) (Ubrihien et al., 2020). While they still represent a relatively small component of overall catchment phosphorus, they warrant further investigation.

More work is needed to understand the nutrient transport pathways around sports fields**.** Soil moisture testing and on-ground observations of public sports fields don't indicate high volumes of surface water runoff, so it's possible the elevated concentrations detected represent historical fertiliser use (going back decades) that is leaching out through the system at a subsurface level.

In general, both public and private sports field managers practice careful application of fertiliser as it represents a significant input cost. In 2022 several private sports field managers were surveyed about their fertiliser application practices (Edmonson, 2022). The survey found that private managers had a detailed knowledge of turf nutrient requirements and, as fertiliser is a major expense, were managing fertiliser application as efficiently and effectively as possible.

ACT City Services Sport and Recreation manage public sports fields in Tuggeranong using practices to improve irrigation efficiency and water retention, prevent surface water runoff and manage the chemical composition of the soil profile to improve nutrient uptake. These help prevent nutrients being exported from sports fields in runoff.

Installing additional bioretention swales between a sports field and the stormwater channel would help intercept and filter any nutrients exported from the sports fields.

Leaky sewerage pipes

Leaking sewers can be a major contributor to water quality issues in urban areas, causing increased nutrients, suspended solids and microbial pollutants to enter waterways. Sewers can become defective and leak from structural problems (broken joints, cracks, fractures and holes), operational problems (root intrusion, sediment accumulation and grease build up) and hydraulic capacity failures (Nguyen & Venohr, 2021). As holes are drilled in urban catchments for a variety of purposes, pipes can be damaged and leak into the stormwater system.

Healthy Waterways has commissioned a study to help characterise how large a problem sewage leaks might be, noting that they might affect not only nutrient concentrations but levels of faecal pollution, which can also result in lake closures. Results will be delivered in 2025 and will be incorporated into later versions of the Plan.

Part 4: The target – how much phosphorus to mitigate?

- **Form of phosphorus**
- **Water quality modelling approach**
- **Inputs of phosphorus from the catchment**
- **Current and target supply of phosphorus to the lake**
- **Reconciling some estimates based on research and modelling**

Form of phosphorus

The models and other analyses presented below predict total phosphorus or its effects. There are not enough data to inform what proportion of the particulate fraction of phosphorus in Tuggeranong stormwater is bioavailable, so total phosphorus is used to predict algal responses—and total phosphorus data used in model calibrations—rather than dissolved or bioavailable phosphorus. So, even though algae actually take up dissolved phosphate, in these analyses, 'phosphorus' refers to total phosphorus.

Water quality modelling approach

Dey et al. (2024) developed two coupled water quality models to help estimate how much the supply of phosphorus from the catchment to the lake needs to drop to substantially decrease the incidence of algal blooms in the lake.

The first model is a catchment model that predicts how much water and phosphorus will reach Lake Tuggeranong and how this changes with daily variations in rainfall. The researchers initially used pollution generation rates from different types of land use, derived from the scientific literature, which they then calibrated with observations of water quality and flow in storm events that came from research by the University of Canberra (Ubrihien at al. 2019, 2020).

The second model is a simple in-lake model that predicts how phosphorus concentrations in the lake will change in response to varying runoff and inflow of phosphorus, and then the amount of algae that will grow in response to this. Kahn and Dey (2024) predicted the algal response indirectly using chlorophyll *a* concentration. Chlorophyll *a* is a pigment in many plants and algae that helps them absorb light and is used to assess the amount of algae (ANZECC and ARMCANZ, 2000). They then assigned predicted concentrations of chlorophyll *a* concentration to trophic states: Oligotrophic <5 µg/L, Mesotrophic <15 µg/L, and Eutrophic >15 µg/L.

Inputs of phosphorus from the catchment

The water quality modelling has shown that that the stormwater flowing off the catchment carries very high levels of phosphorus, with an average annual supply to the lake of 1,656 kg phosphorus/yr (Dey et al., 2024; Table 3). This is greater than the annual estimate of 500 kg estimated by Ubrihien, et al. (2019), which was based on data collected in a dry period, with reduced inflows from the catchment.

Table 3. Modelled annual total phosphorus (TP) supply to Lake Tuggeranong (kg/yr) generated for each combination of functional land use and surface type imperviousness: road, hardstand, roof and pervious (from Appendix 5 in Dey et al., 2024).

FUNCTIONAL LAND USE	Road TP (kg/yr)	Hardstand TP (kg/yr)	Roof TP (kg/yr)	Pervious TP (kg/yr)	Total TP (kg/yr)
Suburban	322	169	314	140	945
Commercial	17	45	30	16	108
Open space	243	76	5	88	412
Rural	0	0	1	132	133
Sports field	0	0	0	58	58
Total annual supply (kg/yr)	582	290	350	434	1,656

Based on research data (Ubrihien et al., 2019, 2020), about 50% of this input is in a dissolved form, with most of it ready for uptake by algae. Dey et al. (2024) predict that the seven constructed wetlands built in Stage 1 of Healthy Waterways have reduced the amount of phosphorus entering the lake annually by 214 kg, or 13%, from 1,656 kg to 1,442 kg.

Current and target supply of phosphorus to the lake

Current supply

Kahn and Dey (2024) used an in-lake algal response model to determine the phosphorus mitigation target (Figure 6). Under current flow and levels of phosphorus supply (Figure 6, 'No P reduction'), their modelling clearly indicates that Lake Tuggeranong will remain in a eutrophic state, with chlorophyll *a* concentrations over 15 μg/L, even in years with relatively little rainfall when smaller amounts of nutrient are transported to the lake. This fits with observations of consistently high levels of phosphorus and frequent blue-green algal blooms in the lake in recent years. It also supports the findings of a 1982 hydrological study of the catchment, which predicted that based on nutrient levels at the time, the lake would exist in a eutrophic state for most of the time (Beer et al., 1982).

A suitable and realistic chlorophyll *a* concentration target range to aim for in Lake Tuggeranong, correlating to a mesotrophic state, is in the range of 5–15μg/L. This target range is based on the following considerations:

- The model predicts that in a predevelopment scenario (when the area was entirely native bushland), Lake Tuggeranong would typically have been in a mesotrophic state, with a chlorophyll *a* concentration in the range of 0–18 μg/L (Figure 6: 'Predevelopment') (Dey et al., 2024).
- The ANZECC guidelines specify a range of 5–15 μg/L for mesotrophic conditions (see Table 8.2.1 in ANZECC and ARMCANZ, 2000).
- In the nearby Googong Reservoir, a water supply with a reduced level of disturbance, chlorophyll *a* concentrations are typically in the range of 0–28 μg/L, with annual averages consistently in the range of 4–10 μg/L.

- The Australian Environment Council recommends that chlorophyll *a* concentrations in recreational waterbodies be kept below 20 μg/L for recreational lakes and 5 μg/L for water supply reservoirs (AEC, 1987). In the ACT, the Environment Protection Regulation sets a more stringent target of less than 10 μg/L for contact-based activities (noting that direct observations of algal counts rather than chlorophyll *a* concentrations are used to determine when to close lakes in the ACT).

Target supply to mitigate algal blooms

Kahn and Dey (2024) predict that a mesotrophic state can be achieved in Lake Tuggeranong for most the time if the average annual phosphorus supply to the lake is reduced by 700 kg, having already accounted for the effect of the seven constructed wetlands built in Stage 1 of Healthy Waterways (Figure 6). They did not adopt a higher target because the further reduction in phosphorus would not significantly reduce algal blooms but would cost a lot more to achieve.

A target of 700 kg represents 49% of the total supply of phosphorus to the lake from the catchment.

Note that these targets are indicative only, developed for the purpose of communicating the benefits of different management scenarios. While the 700 kg target is based on annual averages, the required reductions will be higher in very wet years and lower in dry years.

How will the lake behave if the target phosphorus reduction is achieved?

With a 700 kg annual reduction in phosphorus, modelling by Kahn and Dey (2024) suggests the lake will be in a mesotrophic state—or better, in an oligotrophic state—in approximately 75% of years (3 out of 4 years; Figure 6). Under these conditions, some blue-green algae would be present, but the likelihood of problem blooms would be lower than now, and the lake should mainly be in a condition suitable for contact-based activities. Closures may still occur due to elevated levels of faecal indicator bacteria.

The modelling also reveals there will likely always be considerable variation in the concentration of phosphorus in Lake Tuggeranong over time, driven by variation in climatic conditions. Specifically, in very wet years the significant amount of phosphorus coming off the catchment will likely overwhelm any attempts to reduce nutrient levels in the lake, leading to eutrophic conditions.

For example, with a target 700 kg annual reduction in phosphorus, the modelling predicts that in about 25% of years (the wettest years) the lake will still be in a eutrophic state, with sufficient nutrients to promote algal blooms. However, wet years also tend to be relatively cooler, which would reduce the likelihood of severe blooms. Some algae would also flush from the lake in wet years.

Conversely, in relatively dry years, any phosphorus removed from the system represents a relatively larger proportion of the total supply reaching the lake. So, for a target 700 kg annual reduction in phosphorus, modelling by Kahn and Dey (2024) suggests about 25% of years (the driest years) will experience oligotrophic conditions in the lake, with very low concentrations of nutrients, relatively clear water and very little risk of algal blooms occurring.

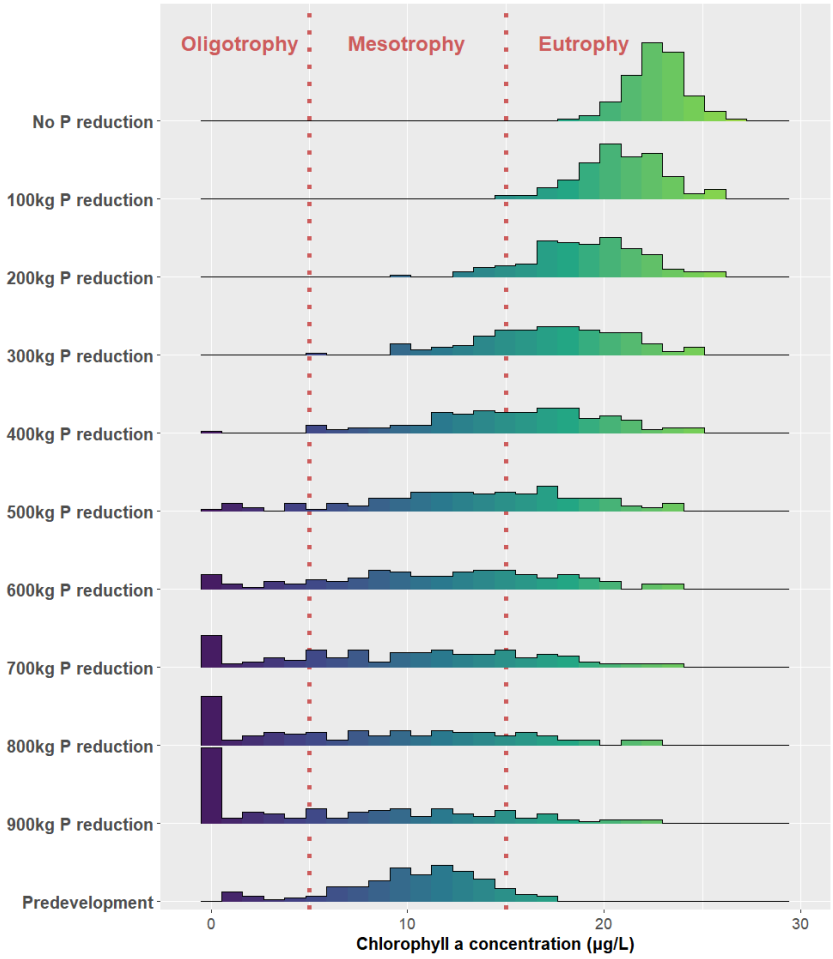


Figure 6. Modelled distribution of predicted chlorophyll a concentrations (an indicator of trophic state) in Lake Tuggeranong under varying supply of phosphorus (P). The top row 'No P reduction' shows the lake in its current, eutrophic state. The bottom, 'Predevelopment' row shows the predicted chlorophyll a concentrations if there were no urban development upstream of the lake, indicating that it would have been in a mesotrophic state in most years, but still occasionally have reached a eutrophic state, supporting algal blooms.

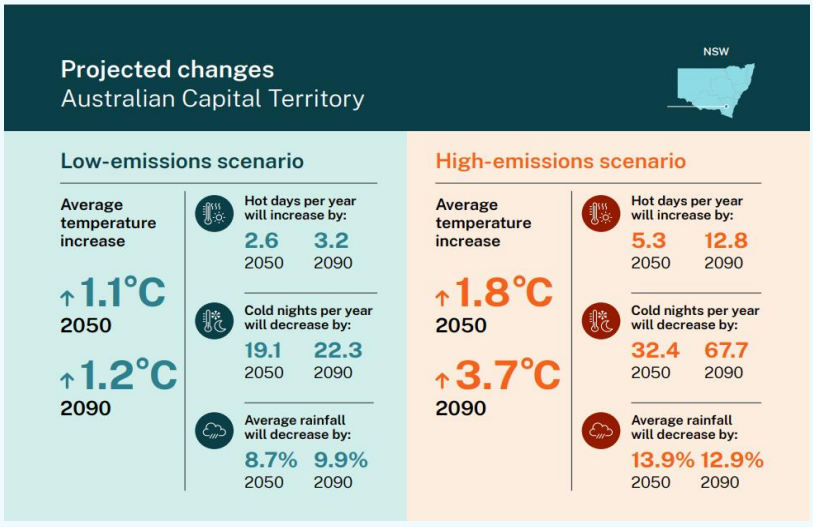
Box 2. How will climate change affect nutrient dynamics and algal blooms?

In the future, the ACT will experience hotter average temperatures, more hot days per year and decreased average rainfall, particularly in spring (NSW Department of Climate Change, the Environment and Water, 2024). Across Australia, including the ACT, extreme rainfall events (storms) will become more intense. The Australian Rainfall and Runoff Guidelines projectpredict the biggest increases forwill be in very short storms. For example, under scenario SSP3-7.0, storms of under one hour will increase in intensity by 18% by 2030, and by 29% by 2050 (Wasko et al., 2024). More intense localised storms may increase the frequency of 1% Annual Exceedance Probability (AEP) (in layman's terms, 1 in 100 year storms) flooding events in the ACT. The ACT Government's ACTMapi website shows the extent of riverine flooding that would be expected during a 1% AEP flood event.

These changes to temperature, rainfall averages and storm intensity will likely impact nutrient dynamics in the Tuggeranong catchment, for example:

- higher storm intensity will impact streamflow and the way that nutrients are mobilised in, and transported through, the catchment
- hotter temperatures will affect when eucalypt species drop their leaves, how much they drop and the phosphorus content of the leaves
- higher water temperatures will affect in-lake processes like thermal stratification and turnover.

These effects are anticipated but have not yet been studied or quantified in the Lake Tuggeranong context. However, a response framework developed for Victoria's waterbodies argues that climate change will exacerbate blue-green algal blooms through factors including increased temperatures, stronger stratification, increased nutrient levels due to extreme wet/dry periods, longer residence times of water in water bodies and storm events (HydroNumerics, 2020).



Climate change projections for the ACT (NARCliM 2024)

Reconciling some estimates based on research and modelling

There are two notable instances where the predictions from catchment water quality modelling and results from catchment research are not fully aligned.

The first relates to the contribution that fertiliser applied on residential gardens makes to phosphorus levels in stormwater. The Lake Tuggeranong catchment water quality model predicts that only around 140 kg/year of phosphorus is generated from pervious suburban land use (Table 3). This is the land use category representing residential yards and gardens, which would include fertiliser use by residents or their gardeners and other sources of phosphorus from residential blocks. The model is based on published literature of phosphorus draining from household blocks and was calibrated to the observed data on phosphorus concentrations in runoff and waterways around the catchment.

In Part 3, the amount of phosphorus entering stormwater from residences, based on surveys of residents, is conservatively estimated at around 90–1,200 kg of phosphorus per year, with an intermediate estimate of around 550 kg per year. The model prediction of around 140 kg/year leakage is within, but at the very lower end, of the estimate of around 90–1,200 kg of phosphorus per year based on the surveys of residents. Since 140 kg/year is well below the middle estimate of 550 kg/year, the difference between the prediction based on modelling and the estimate based on research warrants further investigation.

The second instance where the catchment water quality model and research yield different results relates to the contribution of phosphorus due to leaves and grass. The effect of nutrients leaching from leaf and grass litter—and soils and other road detritus—on roads was assessed through the catchment model as 582 kg/year (Table 3). This is greater than the research estimate of around 130–240 kg/year based on leaf-fall patterns plus biomass of grass on road verges in Part 3 (Ubrihien et al., 2024a). However, there are reasons to believe that the estimates for leaf-fall biomass are underestimated (see Part 3). To date there have been no independent estimates for how much soil and non-leaf debris is on the roads and how much extra phosphorus this contains.

Further research is required to ensure fertilisers applied to household blocks are not making a larger contribution than suggested by the modelling, and to clarify the contribution of leaves and grass. However, both sources of phosphorus pollution are likely to be significant and are preventable so consideration needs to be given to reducing both sources of pollution.

Part 5: Options to mitigate phosphorus pollution

- Reduce the amount of phosphorus entering stormwater at the source
- Slow the flow and filter the stormwater
- Treat the water in-lake

Previous research and programs in the ACT and elsewhere have identified and trialled a range of potential phosphorus mitigation options. For this report, options were shortlisted based on the availability of data to support cost-effectiveness analyses. In some instances, cost-effectiveness data were based on local trials of options. The Healthy Waterways team has yet to evaluate some other very promising options, or variants of options, because of a lack of relevant data on which to base cost-effectiveness. These options will be evaluated as data on their cost-effectiveness becomes available through ongoing research and trials.

Conceptually, there are three stages in the 'journey of the stormwater' where phosphorus might be removed from the system or algae may be directly treated through various options (Table 4 and Figure 7). This section describes these stages.

Table 4. Pollution mitigation options to remove phosphorus in the 'journey of the stormwater'.

	Where to remove phosphorus/treat algae		Mechanism
1	**At the source/s**		Reduce the amount of phosphorus before it enters the stormwater system (phosphorus pollution prevention).
	1.1	Targeted street sweeping	Optimise street sweeping (for frequency, location and seasonality)
	1.2	Pollution prevention partnerships	Promote waterways-friendly gardening practices by working with community and business.
	1.3	Water sensitive urban design (WSUD)	Adopt suburb designs—or retrofit elements to existing suburbs—that minimise the impacts of urban development on the natural water cycle and better integrate suburbs into the natural landscape.
2	**In the stormwater system**		Use water sensitive urban design infrastructure to divert runoff in storms, allowing it to slow down, be filtered naturally by wetlands and/or to seep slowly back into the landscape.
	2.1	Infrastructure that reduces stormwater peaks	Retain stormwater in green belts, detain it in tanks and/or recycle it.
	2.2	Infrastructure that improves stormwater quality	Create various types of constructed wetlands.
	2.3	Maximised effectiveness of water quality infrastructure	Sequentially place constructed wetlands and other water quality/ quantity assets along drainage lines and waterways to reach end-of-system targets and maintain the infrastructure in good condition.
3	**In the lake**		Use anti-algal agents that either compete with algae or treat the algae once it grows to bloom proportions.
	3.1	Reduction of nutrient levels and/or competition with blue-green algae	Deploy materials or processes that remove nutrients from surface waters, where algae live, or promote natural competitors to algae.
	3.2	Direct treatment of algae	Apply algicides or physical mechanisms to destroy or remove algae.

Reduce the amount of phosphorus entering stormwater at the source

There are several ways to prevent waters from becoming polluted in the first place, rather than allowing them to become polluted and then treating the pollution or its effects within the stormwater system.

Targeted street sweeping

The ACT Government's street sweeping program removes leaves and debris from kerbs and gutters along Canberra's urban roads. Every street in Canberra receives at least two full sweeps each year, with additional local sweeps between April and September during the heavy period of leaf-fall (See: https://www.cityservices.act.gov.au/roads-and-paths/road-infrastructure-and-maintenance/street-sweeping).

One option is to increase the frequency of sweeps. As described in Part 4, leaf litter and grass clippings release nutrients quickly as they decompose or are wet. They lose most of their phosphorus within two days of either continuous or periodic inundation (Ubrihien et al., 2024a). The intent of increasing the frequency of street sweeping is therefore to remove leaf and grass litter from gutters before the phosphorus and other nutrients have had a chance to leach out of the litter. Other ways to optimise street sweeping regimes include concentrating sweeping during summer seasons or in locations with greater tree canopy near roads.

Pollution prevention partnerships

Canberra's residents affect waterway health in the way they manage leaves, grass and fertilisers on their blocks. Through Healthy Waterways, the ACT Government has been building expertise in supporting households to prevent stormwater pollution since 2016. It is working with the community to improve awareness and to support households to adopt practices that promote waterway health, like collecting leaves from the road verge.

Since the evidence began to point strongly to leaf litter in gutters and on paved surfaces as one of the top pollutants, programs have been developed and tested that target leaves directly.

From 2020–23, the government partnered with Griffith University and community stakeholders to test numerous interventions under the project title 'The Leaf Collective'. Three iterations of the program were run—two during autumn and one during summer. In all three campaigns householders reported an increase in the volume of leaf litter they collected from areas draining to stormwater. On average, they collected 20% more than the control groups collected. Attitudes towards the value of leaf litter also changed, with more people adding leaves to compost or using them to create leaf mould, and fewer people disposing of them inappropriately in their general waste bins.

From 2023–25, the government has delivered a smaller program. It features the most popular elements of the earlier pilots, such as the leaf-bag giveaway and leaf cages in schools and is gradually building in more offerings. Community stakeholders and individual community members consistently give positive feedback about these initiatives.

Our understanding of the impacts of fertiliser use on phosphorus pollution in stormwater is less advanced. The ACT Government piloted a 'Love the Lakes' program in May 2024 that aimed to reduce garden fertiliser use in households that use high amounts. Concepts of Change (2023) interviewed 600 households across Tuggeranong and coached householders (via telephone or in-person) about ways they could reduce fertiliser use. When the householders were contacted again in late 2024, they reported an average 36% decrease in fertiliser use during spring.

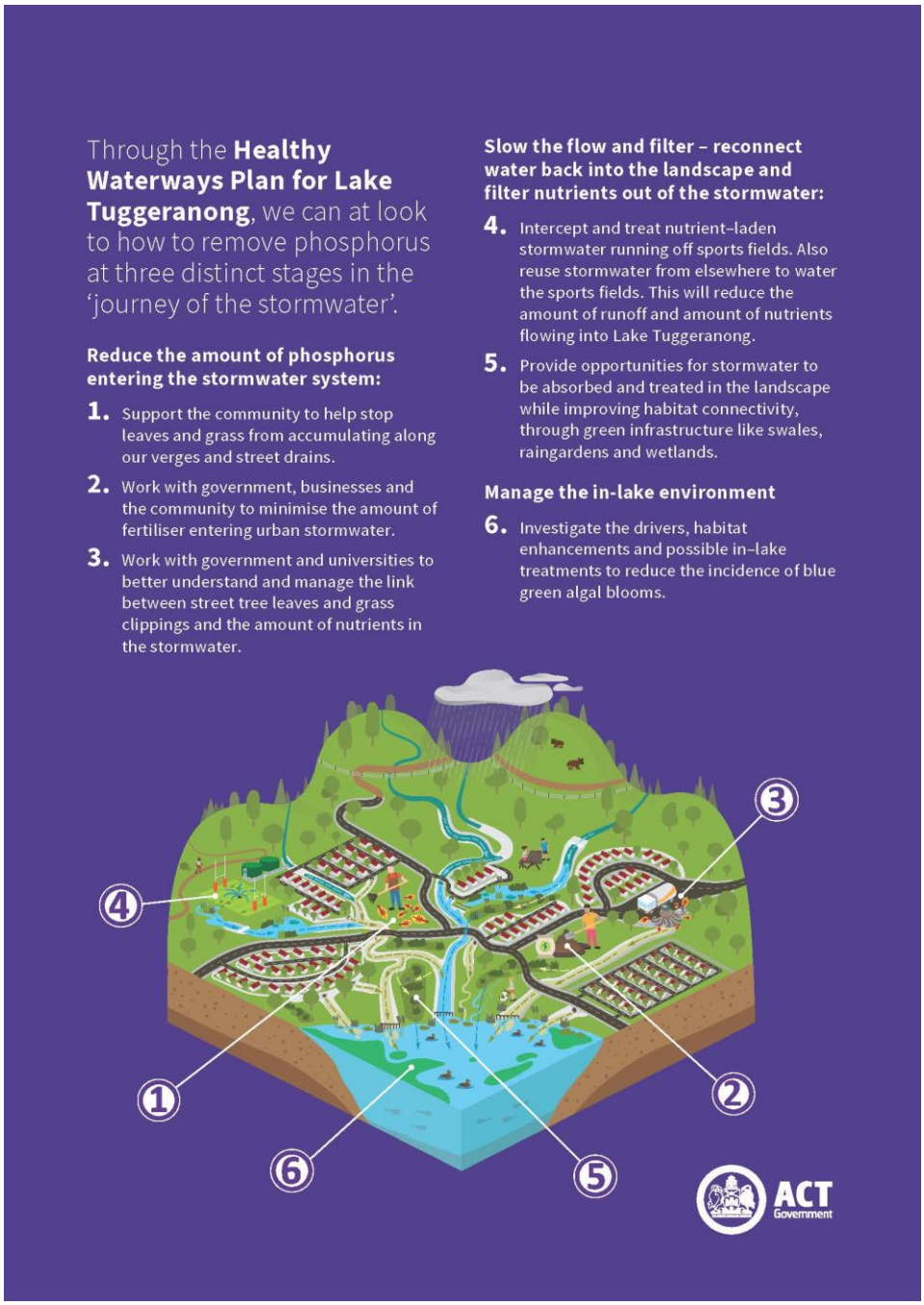


Figure 7. Conceptual model showing where phosphorus can be removed from its source to the lake.

Garden service providers were also contacted. They reported applying an average 1.78 kg of phosphorus per garden per year, which accounts for about 15% of the total amount of phosphorus applied across Canberra. Working with garden service providers offers another potential avenue to reduce fertiliser use.

Water Sensitive Urban Design

For many decades, town planning adopted engineering solutions aimed at flood mitigation that turned many ACT waterways into straight pipes and concrete drains. These engineered systems are very efficient at conducting stormwater, and the nutrients it carries, rapidly and directly out of urban landscapes to the natural waterways without opportunities for treatment by catchment soils and vegetation. Studies into urban runoff in storms suggest it has fewer adverse impacts on water quality in natural waterways if there is less direct flow from impervious surfaces, such as roads, to natural waterways (Ladson et al 2006, Walsh et al. 2022).

Water Sensitive Urban Design (WSUD) planning, landscaping and infrastructure promote infiltration of urban stormwater into the soil, increase water retention, reduce flow rates and filter out nutrients from stormwater in the catchment. Using WSUD helps reduce runoff and improve water quality before stormwater enters natural waterways such as Lake Tuggeranong (for example, see Ubrihien et al. 2020).

WSUD infrastructure has been a key feature of Healthy Waterways over its 10 years to date. The program has built 27 water quality assets, predominantly ponds, wetlands, rain gardens and channel restorations across urban Canberra since 2014.

In developing these assets, Healthy Waterways worked across government to ensure the asset designs were either approved against Municipal Infrastructure Standards (MIS) or Municipal Infrastructure Technical Standards (MITS) or are new and effective designs. The new designs allow for an expansion of the MIS and MITS standards, which means there are now more options in the infrastructure toolkit that water managers can use to improve stormwater quality.

Infrastructure that reconnects storm runoff with its catchment

WSUD infrastructure may target either reducing the amount of runoff in storms or improving stormwater quality or both. Features can be added to an urban area to retain water in the landscape or route small streams of stormwater back into green space, such as castellated kerbs and landscape contours (Table 5). This allows stormwater to soak back into natural catchment areas where it is mostly retained (for example, it evaporates or is taken up by plants) or is cleansed by surface vegetation and soils. At one end of the spectrum these features are capital works; for example, Healthy Waterways built some small runoff infrastructure assets such as castellated kerbs to reduce the volume of water in the stormwater system. At the other end of the spectrum, landcare groups can improve stormwater retention simply by roughening drainage lines (Alluvium, 2023). In the case of stormwater recycling, water is diverted from pipes, drains or WSUD infrastructure and usually treated before being used, sometimes to irrigate green space like sports fields and golf courses, and sometimes for other purposes, such as in construction.

Table 5. Types of runoff infrastructure built in the ACT.

Type of infrastructure	How it works
Castellated kerbs	Roadside drains have gaps in them where some of the stormwater is diverted into adjacent green space where the stormwater can be absorbed into the soil.
Landscape roughening	Small mounds are dug into slopes to temporarily capture runoff and allow it to sink into the soil (Alluvium, 2023).
Rainwater tanks	Hold water in the landscape using above or below ground storage tanks for rainwater usually sourced from roofs.
Detention tanks	Built underground to temporarily store stormwater sourced from drains and often used to irrigate sports fields.
Stormwater recycling	Stormwater is diverted to tanks before being cleaned and used instead of potable water; for example, to irrigate sports fields. It may be cleaned by a combination of constructed wetlands, groundwater aquifers, and/or a filtering unit in a shipping container.

Slow the flow and filter the stormwater

Infrastructure that reduces stormwater peaks

Tanks can be used to temporarily store stormwater before the water is either used (for example, to water resident's gardens) or released back into the stormwater system. The delayed release of stormwater reduces peak flows and allows downstream wetlands and ponds more time to process and treat a greater volume of the stormwater.

Infrastructure that improves stormwater quality

WSUD infrastructure is built with a primary function of treating pollutants and improving water quality. This infrastructure includes a variety of constructed wetlands, where plants and soil media filter nutrients and fine sediment particles from the stormwater. Different types of constructed wetlands are shown in Table 6. Constructed wetlands can also have several added benefits such as providing riparian (waters-edge) and aquatic habitat for wildlife within urban areas, reducing urban heat, enhancing values of importance to Traditional Custodians and contributing to urban amenity. The wetlands, ponds and raingardens built in the Healthy Waterways program are examples of WSUD infrastructure that target improving stormwater quality by removing pollutants.

In the Tuggeranong catchment, research by the University of Canberra has shown that most nutrients are mobilised and transported during big storm events where flow volumes are high (Ubrihien et al., 2020). In this situation, wetlands are only able to treat a small proportion of the nutrient-laden flows, with the remainder bypassing the wetlands. Part 6 further considers the implications of this.

Maximising the effectiveness of WSUD infrastructure

Treatment trains

The effectiveness of water quality assets can be maximised through careful design and sequential placement of different types of assets. A series of assets working in sequence to reduce and improve stormwater quality is known as a treatment train.

Box 3. Urban catchments create more runoff in storms

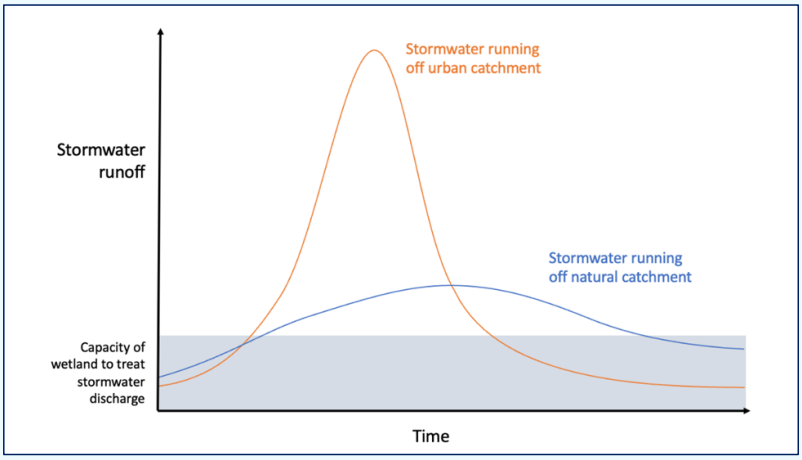
Phosphorus pollution in Lake Tuggeranong is, in large part, a result of urbanisation. Water that flows over the land surface is known as runoff, which in urban areas quickly enters the engineered stormwater system.

In a natural catchment, rain falls on trees and vegetation, which take energy out of the water and allow it to be absorbed into the soil and bedrock. When the ground is saturated, water will eventually start to run off, but at lower volumes and speeds than in an urbanised catchment. When the runoff ceases, water will be slowly released from the landscape, allowing waterways to flow at a gentler rate over a longer period.

The highly urbanised nature of the Lake Tuggeranong catchment means that much of the catchment is covered by roofs, buildings, roads, concrete paving and other surfaces that water can't soak into, known as impermeable surfaces (Codner et al., 1988). Rain therefore runs off impermeable surfaces. This runoff washes lots of phosphorus from these impermeable surfaces into the stormwater system, which is also highly impermeable, and on to Lake Tuggeranong. Models estimate that the volume of runoff from the Lake Tuggeranong catchment is three times higher than that of a natural catchment (Dey et al., 2024). Consequently, urban stormwater systems are very 'flashy' waterways, with water levels rising quickly after rainfall, and falling back to baseflow levels almost as quickly (see the hydrograph in the figure below).

Large amounts of runoff in an urban system make it difficult to treat the high levels of phosphorus in stormwater. A wetland only has the capacity to treat a limited amount of stormwater per hour, so the smaller the volume and longer the duration of flow from a storm event, the greater the proportion of stormwater that will be treated.

By reconnecting more runoff and stormwater back into the landscape, we can start to return the catchment to a more natural flow state. This would provide more opportunities for water to be absorbed into the landscape, and for wetlands and their plants to better capture phosphorus from the remaining stormwater and prevent it from reaching Lake Tuggeranong.



Idealised depiction of stormwater flow in an urban vs natural catchment and the capacity of a wetland to treat the stormwater. The grey area indicates the volume of water that a wetland can treat over a given period and shows the 'flashy' nature of stormwater coming off an urban catchment.

For example, placing runoff infrastructure such as castellated kerbs higher up in the catchment can divert water back onto grassy areas, which reduces the volume of phosphorus-laden stormwater running down the drains. Detention tanks, like rainwater tanks connected to roofs of houses, can capture stormwater peaks and either release some of the stormwater slowly after the storm has passed (for example, by using a specially designed 'leaky tank') or be used for watering gardens. Around playing fields, smaller swales and raingardens filter out coarse sediments and some nutrients from the stormwater before it flows downstream to bigger wetlands and ponds.

Using a treatment train in this way is particularly effective during big storm events by allowing bigger wetlands downstream to more effectively treat more of a storm event's runoff (and for longer) because flow volumes have been reduced upstream and the first pass through smaller filtering infrastructure that has already filtered some nutrients and sediments, reducing the pressure on the bigger downstream wetland.

Maintenance

When sediments do build up in a constructed wetland and the water plants absorb all the nutrients they can, the wetland needs to be maintained to retain its ability to clean the stormwater. This is an often-overlooked part of managing them for optimal effectiveness. Maintenance can include removing built-up sediments, which reduce the wetland's capacity to hold and filter stormwater and harvesting water plants regularly to remove the nutrients they contain from the system and prevent them from decaying back into the water.

Raingardens are renowned within the stormwater industry as particularly sensitive to poor maintenance. They can become completely dysfunctional if their inlets become blocked and their surface sediments clogged and overgrown with trees or weeds that disrupt their ability to function properly. Operational and maintenance requirements are a key design feature of WSUD infrastructure. The choice of assets and the level of maintenance funding need to be considered before committing to such projects.

Table 6. Types of constructed wetlands built in the ACT.

Type of infrastructure	How it works
Ponds	Stormwater is routed to one or more settling ponds fringed with emergent aquatic plants. The overflow is returned to the stormwater channel.
Traditional wetlands	Stormwater is diverted from channels and routed through a sequence of pools and shallower beds of emergent aquatic plants before being returned to the stormwater drain.
Raingardens	Stormwater floods the soil surface, which has dense growth of emergent aquatic plants, then percolates downwards through the soil and is collected in pipes and returned to the stormwater drain.
Bioretention swales	These smaller, vegetated drains operate in the same way as raingardens and are often targeted at point sources of pollution such as sports fields.
Subsurface wetlands	Stormwater is routed horizontally through gravel beds overlain by soils and emergent aquatic plants. Plant roots extend into the gravel beds. The overflow is returned to the stormwater drain. The aquatic plants remove dissolved nutrients, as in a hydroponic garden.
Channel re-naturalisations	Concrete stormwater open drains or channels are replaced with various combinations of pools, riffles, runs and beds of aquatic plants. In the process, the channels may be reconnected with surrounding floodplain sediments and aquifers.

Box 4. Examples of Water Sensitive Urban Design (WSUD) in Tuggeranong

WSUD infrastructure has been a key feature of Healthy Waterways. Twenty water quality assets, predominantly ponds, wetlands, rain gardens and channel restorations, were built in Healthy Waterways Stage 1. Seven of eight assets have been built in Stage 2, with the final asset slated to be built in 2025.

1. Bioretention swale at Kambah District Playing Fields

2. Pond at Kett St near the Kambah shops

3. Drain naturalisation at Tuggeranong Creek in Calwell – before

4. Drain naturalisation at Tuggeranong Creek in Calwell – after (but before plantings have grown)

Treat the polluted water in-lake

Alongside pollution reduction programs and infrastructure, in-lake treatments are a complementary management tool to further reduce nutrient levels in the system and curb blue-green algal blooms. Blue-green algal blooms are an issue across Australia and globally, affecting drinking water catchments, recreational water bodies and the agricultural industry. Governments, industry and the research community have invested heavily in trying to find solutions and a range of in-lake treatments have been developed (see Table 7).

Broadly, these in-lake treatments try to address blue-green algal bloom by either:

- reducing nutrient levels in a waterbody (adsorptive materials, lake water treated by a lakeside bioretention, biological competitors, water treatment plant) or
- treating the algae directly with chemicals such as algicides or through physical actions or with water treatment plant.

Trials of in-lake treatments—past and future

In 2019–2020 the ACT Government engaged the University of Canberra to conduct in-lake mesocosm experiments using Phoslock™ (adsorptive material), Diatomix™ (modifies the nutrient composition of the water to favour species that promote the growth of diatoms at the expense of blue-green algae) and peroxide (an algicide). The experiments found these methods to be ineffective at reducing established blue-green algal blooms in Lake Tuggeranong. However, the timing of their application, after a bloom was established, may have limited the effectiveness of at least the Phoslock and peroxide treatments. The experiment report suggests that Phoslock offers a promising way to limit internal phosphorus loading, provided catchment sources can be controlled first. It recommends further trials that apply treatments before the onset of a bloom (Ubrihien et al., 2019).

Two floating wetlands have been deployed; one in Lake Tuggeranong and the other outside the Tuggeranong catchment at Yerrabi Pond. The floating wetlands directly compete with algae for light and nutrients. They have yet to be evaluated for their performance.

A range of existing and emerging technologies and methods to treat phosphorus in the lake have been identified, including filtration, sedimentation, floatation, biological and chemical removal (GHD, 2024). This work pointed to potential opportunities to use a combination of bioretention basins and phosphorus adsorptive (chemically binding) material. For example, Poseidon Pellets™ are a patented product made of magnesium carbonate beads, which adsorb phosphorus and ammonia from water. They could be used in a variety of ways; a water-permeable bag containing the beads can be placed in stormwater or suspended in the surface waters of the lake or in a bioretention basin. Once the pellets become saturated with phosphorus they need to be replaced.

Other in-lake treatments may also be trialled in the future through the Healthy Waterways research program, but the immediate priority will be to reduce catchment sources of phosphorus.

Table 7. Different types of in-lake treatments. All have potential adverse environmental impacts and most are likely to have low effectiveness until pollution from the Lake Tuggeranong catchment is reduced. Only a small number of these treatments have been trialled in Canberra, where the focus has been on reducing pollution in the catchment.

Treatment type	How it works
	By reducing nutrient levels and/or competing with blue-green algae
Adsorptive materials	Materials deployed to the lake bind phosphorus strongly, removing dissolved forms from water so the phosphorus is not available for uptake by blue-green algae.
Bubblers	Bubblers increase levels of dissolved oxygen in the water column, which encourages the formation of iron and manganese precipitates that bind dissolved phosphorus. The precipitates then sink and are stored in the lake sediments.
Bioretention	Water from the lake is circulated through raingardens at the edges of the lake, which partially filter the phosphorus by binding it to soil media and incorporating it into plant biomass.
Biological competitors	Competitors promote the growth of water plants or beneficial algae or bacteria that compete with blue-green algae, suppressing their growth.
	By treating algae directly, either in-lake or with water treatment plant
Algicides	Chemical agents aim to selectively kill algae.
Physical	Physical methods either physically break up blue-green algal cells or force them to the surface of the lake where they can be removed by skimming.

Conclusion for in-lake treatments

Unfortunately, there is no treatment that is effective in all contexts or that does not adversely affect the aquatic environment. Since in-lake treatments are unlikely to ever be effective enough to curb nutrient levels that fuel algal blooms, and the excessive use of algicides would present a heightened risk of impacts to non-target organisms, they do not represent a sustainable, stand-alone solution. However, water managers may need to use them both as an interim measure over the next decade, while we work to mitigate the sources of catchment loads, and then as a periodic solution when algal blooms arise despite best efforts to prevent them.

Part 6: Benefits and cost-effectiveness of options

- **Selection of options for analysis**
- **Benefits and cost-effectiveness of options**
- **Can we reach the phosphorus reduction target?**

Selection of options for analysis

Booksmythe et al. (2024) analysed a subset of options for mitigating phosphorus pollution for their potential to contribute to solving the algal bloom problem in Lake Tuggeranong (Table 8). They only analysed options or variants of options if their costs and effectiveness could be well characterised based on local trials or scientific literature. Of the nine selected options to remove phosphorus, five prevent phosphorus entering the stormwater system and four treat it once it's in the system.

Commented [JM2]: Ten? (There are ten options in following tables and figures)

They did not select any options for directly treating algae in-lake and selected only one in-lake treatment for reducing nutrient levels and/or competing with blue-green algae (floating wetlands). This is because the initial focus is to mitigate the phosphorus pollution that is driving algal blooms. Other in-lake options will be considered in future once their costs and benefits (and risks) are better understood and phosphorus pollution to Lake Tuggeranong has been reduced.

Benefits and cost-effectiveness of options

Method for determining cost-effectiveness

Booksmythe et al. (2024) defined four investment levels for each pollution mitigation option (Table 8). For example, for the option 'increased street sweeping', the investment levels were 12, 24, 36 and 48 sweeps a year.

They then derived data for costs and effectiveness (in terms of phosphorus reduction) of the investment levels from the scientific literature and the results of local trials. They estimated the benefits (kg phosphorus removed), costs (Net Present Value or 'NPV' over a 30-year period) and cost-effectiveness ($/kg phosphorus removed) of all investment levels. Cost-effectiveness represents the cost/effectiveness ratio of each investment level and was calculated as marginal annual benefit (kg phosphorus removed/year) / marginal annual cost (NPV to implement over 30 years divided by 30). The ongoing operation and maintenance costs were discounted by 7% per annum after the first year.

The researchers used a 30-year timeframe to calculate total costs because it allows for the comparison of options with very different cost schedules. For example, some options have large upfront costs, but low ongoing costs (for example, castellated kerbs) and some options have lower upfront costs, but higher ongoing costs (for example, street sweeping).

Results

Table 9 and Figures 8 and 9 present the annual load of phosphorus removed (the benefit or effectiveness of an option), the 30-year cost and the cost-effectiveness of each option's four levels of investment to mitigate phosphorus pollution. Note that the 30-year cost in Table 9 is the total cost of this option/investment level and any previous investment levels of the option.

It is clear from these data that street sweeping and adding extra water quality assets are the most effective options for reaching the 700 kg target, with the rest of the options bunched below these two in their effectiveness.

Table 8. Options considered in this report to reduce phosphorus pollution of stormwater (Booksmythe et al., 2024).

Option	Description
Street sweeping	Increase the amount of street sweeping in the catchment to remove more organic material from the roads, preventing it from leaching phosphorus into the stormwater drains. The implementation level reflects sweeping frequencies of 12 to 48 sweeps per year. Other ways to optimise street sweeping regimes have yet to be evaluated.
Fertiliser management	Identify and target the relatively small number of households that use excessive amounts of fertiliser to help them use either low-phosphorus fertiliser or no fertiliser at all. The implementation level reflects the reach of the program.
Open space mowing	Reduce the amount of grass clippings from municipal mowing that end up on the road, preventing them from leaching phosphorus into the stormwater drains. The implementation level reflects different management approaches, from having designated street sweeping trucks follow immediately after mowing events to towing electric blowers behind mowers to divert clippings away from the road.
Rainwater tanks	Capture stormwater from roofs for reuse on residential blocks. This may aid in removing some phosphorus in the system as well helping to reduce urban runoff. The implementation level reflects the number of houses that would have a tank installed.
Stormwater recycling	Divert and filter stormwater to storage tanks at sports fields for use in irrigating the fields. The implementation level reflects the number of sports field sites at which water managers would install this infrastructure.
Castellated kerbs	Retrofit outlets into road kerbs to divert some of the stormwater to open green space and allow it to filter into the ground. The implementation level reflects the number of outlets installed (water managers are limited by availability of suitable places in the Tuggeranong catchment; that is, areas adjacent to green space).
New water quality infrastructure—sports fields	Build swales around sports fields to potentially capture any phosphorus leaching out from fertiliser. Sports field managers currently appear to be fertilising optimally and the leaching may be more a legacy issue. The investment level reflects the number of sports field sites at which water managers would install this infrastructure.
New water quality infrastructure	Construct more wetlands at suitable locations in the catchment to treat phosphorus in the stormwater. The implementation level reflects the number of wetlands constructed, ranging from the two most effective builds to the ten most effective builds
Maintenance of existing water quality infrastructure	Ensure maintenance (such as dredging out built-up sediment and harvesting plants) of existing WSUD infrastructure in the Lake Tuggeranong catchment to maximise its performance and capture the largest amount of nutrients possible. The implementation level reflects the number of assets maintained.
Floating wetlands	Install more floating wetlands on Lake Tuggeranong to draw phosphorus out of the lake water. The implementation level reflects the number and size of wetlands installed.

Table 9. Summary of phosphorus (P) removal performance, total 30-year cost and cost-effectiveness for four levels of investment for each of ten pollution mitigation options assessed independently (Booksmythe et al., 2024). 30-year total lifecycle cost is the estimated cost of implementing and operating a mitigation option over 30 years, with annual operation and maintenance costs discounted by 7% per annum after the first year.

P mitigation option and level	Unit	P removed (kg/year)	30-year cost ($)	Cost-effectiveness ($/kg P)
Install additional WSUD 1	Build 2 new WSUD assets	106.21	$22,507,500	$7,064
Install additional WSUD 2	Build 5 new WSUD assets	169.67	$48,369,492	$9,502
Install additional WSUD 3	Build 8 new WSUD assets	226.22	$73,862,467	$10,884
Install additional WSUD 4	Build 10 new WSUD assets	240.46	$84,519,403	$11,716
Maintenance of existing WSUD 1	Enhanced maintenance of 2 assets	35.84	$10,177,128	$9,465
Maintenance of existing WSUD 2	Enhanced maintenance of 3 assets	61.78	$19,086,579	$10,298
Maintenance of existing WSUD 3	Enhanced maintenance of 4 assets	79.93	$26,352,433	$10,990
Maintenance of existing WSUD 4	Enhanced maintenance of 5 assets	88.02	$30,352,433	$11,495
Increase street sweeping 1	12 street sweeps per year	203.70	$7,030,414	$1,150
Increase street sweeping 2	24 street sweeps per year	320.10	$14,060,827	$1,464
Increase street sweeping 3	36 street sweeps per year	372.50	$21,091,242	$1,887
Increase street sweeping 4	48 street sweeps per year	395.80	$28,121,656	$2,369
Manage grass clippings 1	Blow clippings into verge, low P removal estimate	16.40	$2,018,874	$4,103
Manage grass clippings 2	Blow clippings into verge, high P removal estimate	26.10	$2,018,874	$2,578
Manage grass clippings 3	Sweep clippings in verge, low P removal estimate	32.70	$1,521,462	$1,551
Manage grass clippings 4	Sweep clippings in verge, high P removal estimate	52.30	$1,565,956	$998
Sports field fertilizer management 1	Protect 25% of sports fields with bioretention swales	14.93	$4,204,451	$9,387
Sports field fertilizer management 2	Protect 50% of sports fields with bioretention swales	29.85	$11,817,327	$13,196
Sports field fertilizer management 3	Protect 75% of sports fields with bioretention swales	44.78	$19,430,204	$14,463
Sports field fertilizer management 4	Protect 100% of sports fields with bioretention swales	59.70	$31,445,222	$17,557
Household fertilizer management 1	Low P target (assume cost is $10,000/kg P/year)	20.00	$6,000,000	$10,000
Household fertilizer management 2	Medium P target (assume cost is $10,000/kg P/year)	32.67	$9,800,000	$10,000
Household fertilizer management 3	High target (assume cost is $10,000/kg P/year)	45.33	$13,600,000	$10,000
Household fertilizer management 4	Very high target (assume cost is $10,000/kg P/year)	58.00	$17,400,000	$10,000
Install castellated kerbs 1	Install 1 kerb outlet for every 4 sumps (or 453 outlets)	15.56	$4,532,500	$9,708
Install castellated kerbs 2	Install 1 kerb outlets for every 3 sumps (or 604 outlets)	20.75	$5,990,823	$9,624
Install castellated kerbs 3	Install 1 kerb outlets for every 2 sumps (or 906 outlets)	31.13	$8,539,901	$9,146
Install castellated kerbs 4	Install a kerb outlet for every sump (or 1813 outlets)	62.25	$14,349,291	$7,684
Install floating wetlands 1	Deploy 1000 m^2 of wetland	3.00	$1,226,000	$13,622
Install floating wetlands 2	Deploy 2000 m^2 of wetland	6.00	$2,452,000	$13,622
Install floating wetlands 3	Deploy 3000 m^2 of wetland	9.00	$3,678,000	$13,622
Install floating wetlands 4	Deploy 1000 m^2 of wetland	12.00	$4,904,000	$13,622
Stormwater recycling for irrigation 1	Build best 2	8.81	$2,673,863	$10,115
Stormwater recycling for irrigation 2	Build best 4	15.12	$4,588,909	$10,115
Stormwater recycling for irrigation 3	Build best 6	19.19	$7,339,284	$12,748
Stormwater recycling for irrigation 4	Build best 8	21.78	$10,816,870	$16,558
Household rainwater tanks 1	2,500 new households to install water tanks	15.00	$12,500,000	$27,778
Household rainwater tanks 2	2,500 new households to install water tanks	30.00	$25,000,000	$27,778
Household rainwater tanks 3	2,500 new households to install water tanks	45.00	$37,500,000	$27,778
Household rainwater tanks 4	2,500 new households to install water tanks	60.00	$50,000,000	$27,778

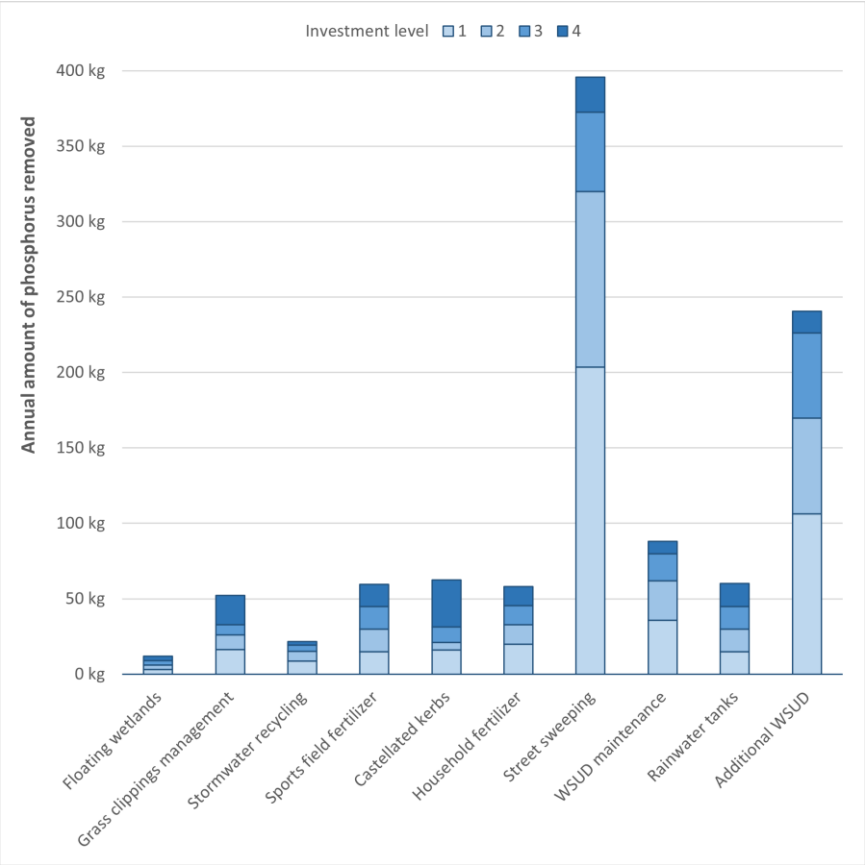


Figure 8. Benefit (or effectiveness) of different levels of investment in pollution mitigation options, from Table 9. Each stacked histogram represents the incremental benefit of the four levels of investment in each option.

An important conclusion of this work is that options to prevent waters from becoming polluted in the first place—street sweeping and ensuring grass clippings from road verges do not enter drains—are more cost-effective than all other options, most notably, the construction of water quality assets. Thus, the most cost-effective way to improve water quality is to prevent waters from becoming polluted rather than relying on water treatment to achieve clean water.

Implications

Several key findings emerge from these results:

- There are no silver bullets; no pollution mitigation option has the potential to reach the 700 kg/year phosphorus mitigation target on its own. Managers will need to implement multiple options to reduce phosphorus pollution to a substantial extent and thus restrict the incidence of algal blooms.

Figure 8. Benefit (or effectiveness) of different levels of investment in pollution mitigation options, from Table 9. Each stacked histogram represents the incremental benefit of the four levels of investment in each option

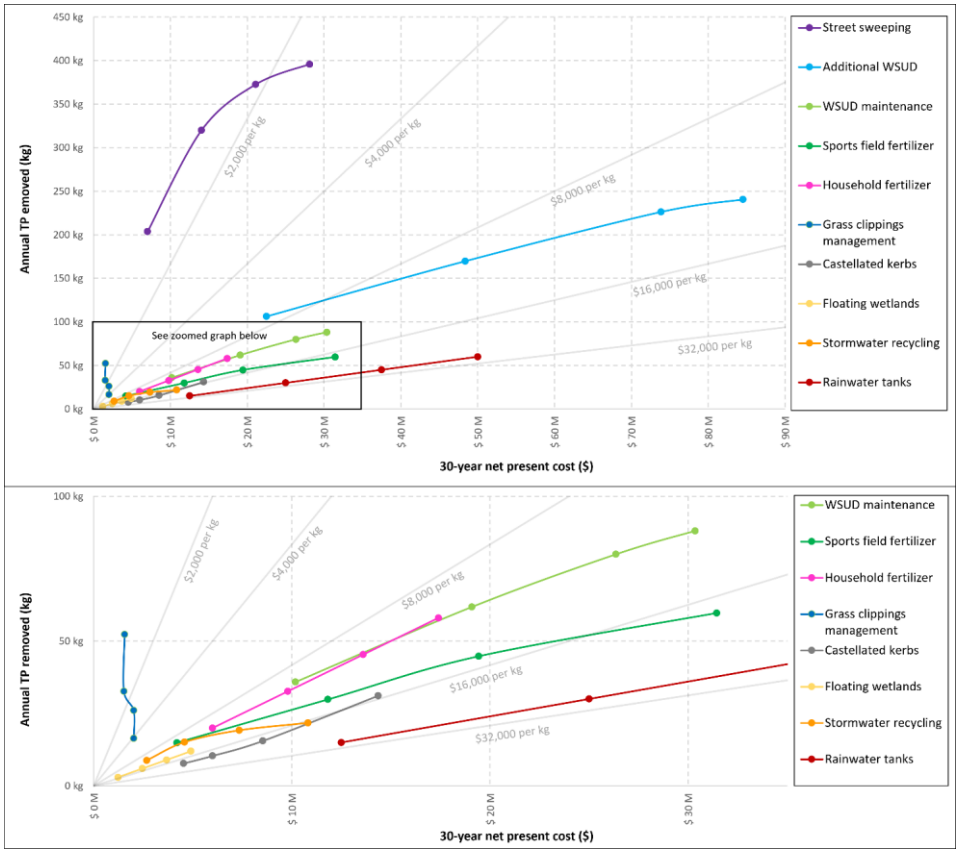


Figure 9. Annual total phosphorus load removed and 30-year lifecycle cost of each incremental investment level for the 10 assessed options for mitigating phosphorus pollution (Booksmythe et al., 2024). Coloured lines connect the four estimates for each option. Grey lines are a guide indicating the cost-effectiveness (cost per kg phosphorus removed) of the estimates. The top panel shows all estimates; the bottom panel shows a zoomed in view of the estimates within the inset box.

- Street sweeping is the most cost-effective option in both scenarios and removes the largest amount of phosphorus (as also indicated in Figures 8 and 9).
- Large water quality assets placed low down in catchments are necessary to treat unavoidable pollution but are not sufficient on their own to achieve the target reduction in phosphorus pollution of stormwater. Managers will need to implement options that prevent stormwater from getting polluted in the first place to substantially reduce the incidence of blue-green algal blooms in Lake Tuggeranong.

Box 5. Street sweeping pilot

Based on the research findings that leaves contribute to stormwater pollution (see Part 3), a pilot street sweeping program was conducted over the summer of 2023/24 to better understand how much the leaves and other organic matter from streets contribute to the amount of nutrients in urban stormwater, and to begin to understand the efficacy of increasing the frequency of street sweeping as an option to mitigate pollution.

Over three months, two sub-catchments in the Lake Tuggeranong catchment were swept every fortnight and two sub-catchments were left unswept. Stormwater samples were collected during storm events to see if the fortnightly-swept catchments showed a reduction in nutrient concentrations. Samples of the material swept off the roads by the trucks were also taken to a lab for analysis.

The results indicate that leaves and other organic material on the roads are contributing significant amounts of phosphorus to stormwater in the catchment. Analysis of the material collected by street sweeping trucks (which included leaves, soil, grass clippings, gravel and road material) estimated that 39.2 kg of phosphorus was removed from the roads in the swept sub-catchments during the experiment. Scaled up to the Tuggeranong catchment, this pilot suggests that a fortnightly program of street sweeping could intercept around 300 kg a year of phosphorus, which is more than 40% of the target of 700 kg/year.

Analysis of the stormwater samples showed a modest decrease in phosphorus concentrations in stormwater from the swept sub-catchments over time, compared to the unswept sub-catchments. As there are many other factors that can influence nutrient concentrations in stormwater, the project was repeated in the summer of 2024/25 to strengthen our understanding of how much leaves contribute to phosphorus in the stormwater. Analysis of this second trial is underway.

The street sweeper used in the pilot program.

Can we reach the phosphorus reduction target?

The analyses of the effectiveness of individual pollution mitigation suggest that the ACT Government can succeed in curbing algal blooms in the lake if it implements a program to reduce phosphorus pollution. However, in practice, water managers will implement various pollution mitigation options concurrently, and this will affect their combined performance. This decrease arises because some pollution mitigation options partially offset the beneficial effects of others. For example, having a dedicated street sweeper follow mowers of road verges would diminish some of the effect of sweeping suburbs 36–48 times a year.

Dey et al. (2024) used the catchment water quality model to model this interactive effect. Their modelling indicates that the interactive effect reduces the total phosphorus removed by 25% and 34% for two different combinations of pollution mitigation options implemented concurrently, or ca. 30%. However, there are good reasons to argue that the 700 kg/year pollution reduction target can still be met.

Firstly, the management options to mitigate pollution are currently conceived in a simple way. Refinement of the options, both during implementation planning and in models, should both decrease their cost and increase their effectiveness. For example, street sweeping in winter, when cold temperatures limit algal growth, may have little impact on lake closures. Eliminating winter street sweeping will reduce costs. Targeting sweeping efforts in suburbs with a high density of street trees, and adding a complementary community program for collecting leaves, may intercept a greater amount of pollution from leaves and grass on verges, reducing the nutrient pollution from these sources beyond that predicted by Dey et al. (2024) for the most intense investment level of this option in the model. There are many nuances to the design of community partnerships and the design and siting of water quality assets that could increase their effectiveness above the average value used in the modelling.

Secondly, several promising pollution mitigation options have yet to be explored that may help to meet the phosphorus mitigation target. Apart from floating wetlands, in-lake treatments have not been included in the modelled options, and these could contribute to further phosphorus reduction. For example, new products are emerging that draw and capture phosphorus out of stormwater, both in the catchment and in the lake itself. One potential intervention that has shown promising results in trials overseas is Poseidon Pellets™. These pellets consist of porous granules that adsorb dissolved phosphorus from water. They promise a high rate of phosphorus adsorption at a relatively low cost but remain untested locally.

The uncertainty about the extent that fertilisers applied to residents' gardens contribute to stormwater pollution (Part 4) does not preclude taking action now. If it turns out from further research that the fraction of phosphorus attributed to fertiliser use is more than is currently estimated, and the fraction due to leaves and grass is less, there would be a shift in emphasis from options that target leaves to ones that target fertilisers. The same is true if sewer leaks turn out to be an important source of phosphorus; the leaks would need to be fixed but it would still be necessary to deal with leaves, grass and fertilisers.

The main cautionary note is about how quickly algae in Lake Tuggeranong will respond to reduced supplies of phosphorus from the catchment. Algal blooms may persist if the phosphorus in the sediments is able to sustain the blooms. This may mean it takes longer than the goal of a decade to fix the algal bloom problem. The long-term research focus should include investigations into in-lake treatments that reduce the supply of phosphorus from the sediments or compete with algae for phosphorus, such as Poseidon Pellets™.

Key conclusions can be drawn from the analyses in this report:

- There is sufficient knowledge to have confidence that a suite of actions can lead to a substantial reduction in the frequency of blue-green algal blooms in Lake Tuggeranong. Inflows of phosphorus pollution can be reduced by up to 700 kg/year within ten years, but whether this would significantly reduce algal blooms in the same time frame may depend on the development of in-lake treatments to deal with phosphorus stored in lake sediments.
- Algal blooms probably cannot be prevented from forming altogether. The analyses carried out for this report suggest the best that can be achieved is for algal blooms to be prevented in three out of four years on average.
- This means that the ACT Government may need to consider developing ways to treat algal blooms as they arise in the years where pollution levels may permit their formation. These may range from the promotion of algal competitors to the use of algicides (see Part 5).

Part 7: The path forward

- **Research agenda**
- **Suggested priorities for restoration**
- **Next steps to finalise the Plan**

The research findings and modelling work presented in this report provide confidence that the ACT Government can make real progress in addressing the problem of algal blooms in Lake Tuggeranong. The target level of phosphorus reduction is achievable, and this would reduce the impacts of blue-green algal blooms. Figure 10 shows a high-level plan for how this could be achieved, from which funding for implementation can be considered.

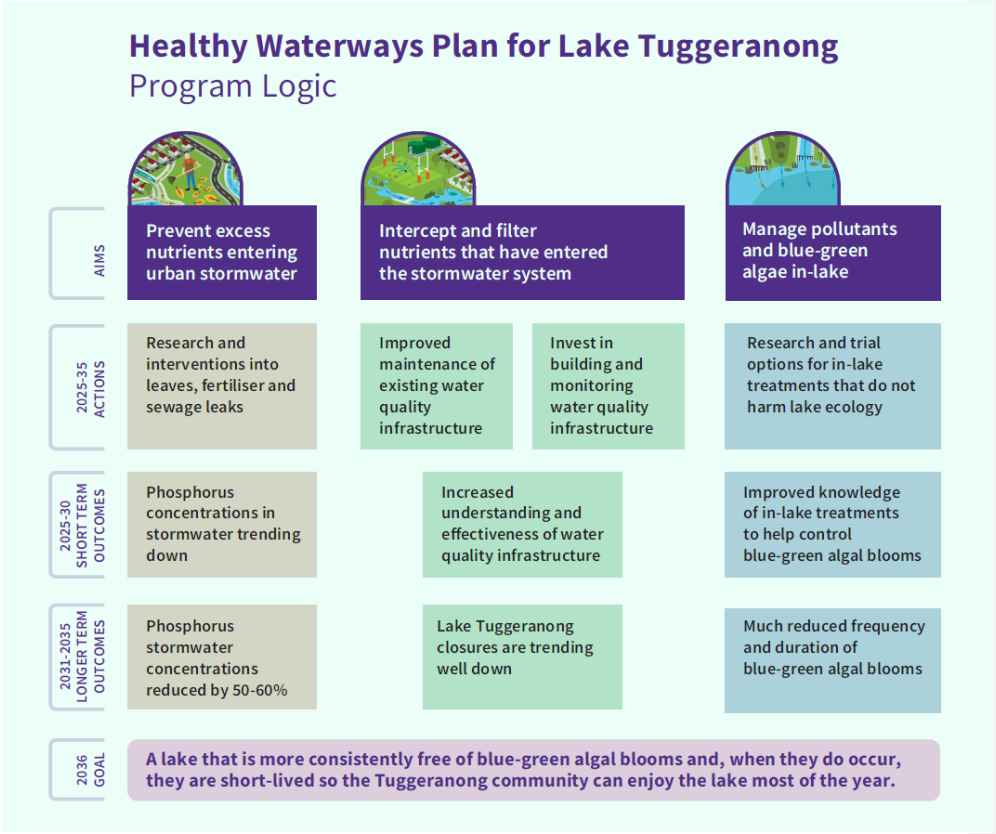


Figure 10. Draft program logic to guide more detailed implementation plan.

Research agenda

Ongoing research and monitoring is critical to refining options to mitigate pollution, to maximise their effectiveness and minimise their costs. The ACT is one of only a small number of jurisdictions in the world actively monitoring constructed wetlands. This is important for testing how well wetland assets perform against design model expectations (including as stormwater entering them becomes cleaner over time) and for informing how the assets are operated and maintained.

The highest priorities for research are to:

- trial promising pollution mitigation options
- investigate; to better understand, the fate of fertilisers applied to residents' blocks
- determine whether sewer cross-connections are a significant source of phosphorus in stormwater.

Table 14 describes the Healthy Waterways research program up to the summer of 2025/26.

Refinement of various management options is also a priority but will occur as a matter of normal business in the implementation phase of a future Healthy Waterways plan for the lake.

Suggested priorities for restoration

Additional research will continue to refine knowledge and understanding of how to reduce phosphorus in the Lake Tuggeranong catchment, but there is enough evidence already to investigate funding for several priority actions.

Expand street sweeping program to be more often and seasonally optimised

Research by the University of Canberra (Ubrihien et al., 2019) plus the street sweeping pilot by the University of Canberra, Healthy Waterways and City Services demonstrated that leaves contribute a significant amount of phosphorus to catchment loads in the Tuggeranong catchment. Modelling by Booksmythe et al. (2024) indicates that an expanded street sweeping program would remove a significant amount of phosphorus from the catchment. If, for example, streets were to be swept 36 times a year, this would remove up to 316 kg/year or 53% of the target phosphorus reduction amount of 700 kg/year and cost up to around $1.4 million annually (Table 10, noting that the cost of investment level 3 has been annualised).

The Healthy Waterways team and ACT City Services ran a street sweeping pilot again in the summer of 2024/2025 to strengthen findings and inform how best to optimise a future street sweeping program to capture seasonal leaf fall.

New community pollution prevention programs

A successful community pollution prevention program that encourages communities to collect leaves and reduce fertiliser use will complement increased street sweeping by reducing the volume of leaves that make it onto roads. This will reduce the green waste going to landfill and disposal costs since, at present, all waste from streetsweeper trucks is deemed contaminated waste and goes to landfill.

The Leaf Collective and Love the Lakes pilot programs received positive feedback from the community and provide valuable insights into how to engage the community to change their practices around fertiliser use

and leaves. In late 2024 a new program that builds upon the successes of the pilots was rolled out as the Waterways Friendly Gardening program.

Build new WSUD infrastructure

WSUD infrastructure cannot solve the problem of blue-green algal blooms on its own and is relatively costly to build and maintain (Table 10). However, there is value in building some additional water quality assets in the Tuggeranong catchment because there will always be some unavoidable pollution of stormwater, which these assets will help to intercept before the pollution reaches the lake. Constructed wetlands also provide other benefits to the community including habitat for native plants and animals, urban cooling (Tapsuwan et al., 2024), public amenity (NC Economics, 2023) and cultural value.

As with all existing suburbs, space constraints and underground services limit the locations where new water quality assets can be built. However, Healthy Waterways feasibility studies have identified several potential locations that could be investigated further.

Table 14. Healthy Waterways forward research agenda to 2026 for Lake Tuggeranong.

Area of research	Description	Estimated start date
Investigate potential leaks from sewerage—caffeine tracking study	Use caffeine in stormwater samples from across the catchment as an indicator of sewerage ingress.	Underway
Performance of constructed wetlands	Monitor the performance of four Stage 1 assets: two wetlands and two raingardens.	Underway
Street material content analysis	As part of the street sweeping project, run a study to understand what proportion of road matter phosphorus comes from non-leaf matter sources (e.g. from car tyres).	Summer 2024/ 2025
Maintenance of channel naturalisations	Develop methods to remove sediments accumulated in plant beds without destroying the plants.	Mid 2025
Investigate potential leaks from sewerage—Microbial Source Tracking	Test and compare the location, quantity and type of faecal matter (animal or human) found in different catchments after rain events, including Lake Tuggeranong.	Mid 2025
Investigate contribution of leaves on roofs to nutrient loads in stormwater	Examine how much leaves that fall on roofs are contributing to stormwater pollution given roofs are the biggest impervious area in the ACT.	Mid 2025
Circular economy—enhancing cost effectiveness of bioretention	Investigate income-generating potential from harvesting of vegetation from stormwater treatment ponds, floating wetlands etc., including when it's combined with swept material being used for biochar feedstock.	Mid 2025
Trial of Poseidon Pellets™	Run small-scale laboratory and field trials to test viability of Poseidon Pellets in the Lake Tuggeranong context.	Spring/Summer 2025/2026
Phosphorus content in leaves and soil	Investigate whether urban street trees of Tuggeranong shed unusually high levels of phosphorus in their leaves and where they access phosphorus from (soil or other sources such as the sewerage network).	Spring/Summer 2025/2026
Fertiliser leaching rates	Investigate runoff from residential blocks or gardens to estimate export rates of nutrients from fertiliser.	Spring/Summer 2025/2026
Maintenance of constructed wetlands	Develop approaches to harvesting macrophytes to increase the export of nutrients from wetlands and stimulate further uptake of nutrients.	Spring/Summer 2025/2026

Improve maintenance of existing water quality assets

The ongoing performance of all water quality assets relies on good operation and maintenance practices. Modelling by Booksmythe et al. (2024) indicates that improving the maintenance of existing Stage 1 and 2 water quality assets would deliver substantial phosphorus reduction benefits (Table 10). The Healthy Waterways and ACT City Services teams are exploring several ideas for facilitating the operation and maintenance of water quality assets to improve their performance.

Next steps to finalise the Plan

The Government will create Version 1 of the Healthy Waterways Plan for Lake Tuggeranong based on this report, incorporating further inputs from First Nations people and feedback from the community. An implementation plan will then be developed and funded to set out how the vision will be achieved over the next 10 years, including how it will be monitored and evaluated.

Glossary

Term	As defined in the Plan
Adsorption, adsorbed	The adhesion of a substance (e.g. charged phosphorus ions) to a surface (such as charged clay particles in soil or Poseidon Pellets™).
Bacterial pathogen	Bacteria that can lead to illness.
Baseflow	Streamflow continues between rain events.
Bioavailable	(for plant nutrient–algae relationship) Plant nutrients that are in a form that can be absorbed and used by algae to support growth and metabolism.
Bioretention	Infrastructure (for example, swales or raingardens) comprised of soil, plants and microbes to treat and filter stormwater. Stormwater is spread through the surface of the infrastructure, percolates vertically and is collected in outlet pipes at the base of the asset, leaving behind filtered pollutants.
Bioretention basin	Landscaped depression to manage and treat runoff. See 'Bioretention'
Bioretention swale	Type of bioretention system using linear, vegetated drains in a landscape to capture and filter runoff.
Blue-green algae	A group of photosynthesising, algae-like bacteria that live in freshwater, estuarine and marine environments. Also known as cyanobacteria.
Calibrate, calibration (models)	Adjusting water quality models so they provide a good description of the water quality in Tuggeranong's waterways. This is achieved by comparing model predictions with actual measurements of water quality in the stormwater system and making adjustments to the model to minimise its differences with the observed data.
Catchment	Area of land where precipitation collects and drains to a common outlet (for example, a river or waterbody). May also be known as a drainage basin.
Chlorophyll *a*	A pigment in many plants and algae that helps them absorb light energy and convert it to chemical energy in a process called photosynthesis. Chlorophyll *a* is often used as a proxy to assess algae biomass as it is easier to measure than biomass.
Constructed wetlands	Both a general term for water quality assets comprised of soil, plants and microbes to treat and filter urban runoff, and a reference to a specific type of asset where stormwater that is diverted to the wetland flows laterally to an outlet at its downstream end (as compared to 'bioretention'; see definition above).
Cyanobacteria	See blue-green algae.
Diffuse source	A non-point source, where pollutants are generated from many sources across the catchment.
Deposition rate	(for leaves) The volume of leaves that fall from trees for a given area/time.
Enterococci	Bacteria commonly found in the intestines of humans and animals, used to indicate faecal pollution in waterbodies.
Eutrophic	Water bodies in a eutrophic state are nutrient rich, with highly productive plant growth and high turbidity. They are seasonally deficient in oxygen, which may lead to fish kills. Eutrophic lakes may experience regular algal blooms.
Export rate	% of nutrient (in this case phosphorus) in applied fertilisers lost to runoff.
Hydrograph	A way to display the flow of water over time.
Impervious surface	Water-resistant surface that is a partial or total barrier to water, such as concrete, roofs, roads.
Management scenarios	Packages of phosphorus pollution mitigation options that together are intended to achieve a desirable water quality outcome.
Mesocosm	Enclosure set up in the lake to study aquatic responses under controlled conditions.
Mesotrophic	Water bodies in a mesotrophic state have a moderate amount of nutrients, moderately clear water, some algal blooms in late summer and oxygen depletion at

Term	As defined in the Plan
	bottom of lake as biomass decomposes. If they do experience algal blooms, it is typically in late summer.
Microbial Source Tracking	Method to identify the sources of faecal contamination in water bodies; that is, whether it comes from humans or animals (domestic pets, wildlife, livestock).
Net Present Value (NPV)	The difference between the present value of cash inflows and outflows over time.
Nitrogen	Key nutrient essential for the growth of aquatic plants and algae. Excess nitrogen can lead to nutrient pollution which can cause algal blooms.
Nutrient load	Refers to the amount of nutrients entering a waterbody in a given time period; for example, kg phosphorus entering Lake Tuggeranong per year.
Oligotrophic	Water bodies in an oligotrophic state have very low nutrient concentrations and tend to have very clear water with little plant or algal growth. High oxygen concentrations depress the release of algal nutrients stored in lake-bottom sediments. Hence, oligotrophic lakes are not prone to algal blooms.
Phosphorus	Key nutrient essential for the growth of aquatic plants and algae. Excess phosphorus can lead to nutrient pollution which can cause algal blooms. Can be either particulate (sediment-bound) or present in dissolved forms. Total phosphorus (TP) is the sum of all forms of phosphorus present in a sample. In this report, phosphorus refers to total phosphorus unless otherwise stated and these terms are used interchangeably.
Phytoplankton	Photosynthesising microscopic organisms that live suspended in water. Blue-green algae/cyanobacteria are a type of phytoplankton.
Point-source	Where pollutants are generated from specific sources in the catchment such as nutrients from a sewage treatment plant outlet.
Pollutant, Pollution (of water)	A substance (like phosphorus) that is present at levels that can cause harm to life. Phosphorus is not directly harmful but is a pollutant at high concentrations or supply because it promotes the growth of harmful algae.
Pollution mitigation options	Individual approaches to reducing the level of phosphorus in stormwater such as increasing the frequency of street sweeping or building water quality assets.
Raingarden	A water quality asset using bioretention technology in a shallow, landscaped depression to capture and filter urban runoff.
Runoff	Water that flows over the surface of the ground when it cannot sink into the ground.
Runoff infrastructure	Infrastructure or landscaping that holds, redirects and/or slows runoff to allow it to sink into the landscape.
Sediments	In this context, sediments are bits of soil and organic matter eroded from the catchment into stormwater and lake water. Sediments may become deposited in the bottom of lakes.
Stormwater	Water generated through rain that has made its way into the stormwater system.
Stormwater runoff	Rain that isn't absorbed into the ground and flows over the landscape.
Stormwater system	Concrete channels and pipes designed to direct stormwater away from built up areas to reduce flood risk.
Stratification	Formation of distinct thermal layers in the water column, which affect the distribution of oxygen and nutrients within the lake.
Suspended solids	Small particles that remain suspended in water, affecting water quality and aquatic life by reducing light penetration and temperature.
Total dissolved solids	The inorganic and organic substances dissolved in water. They are used as an indicator of water quality.
Treatment train	Water quality infrastructure working in sequence to remove pollutants and manage water flow to a target level.

Term	As defined in the Plan
Trophic state	Describes the biological productivity of a water body and depends on factors such as the concentration of nutrients like phosphorus and nitrogen (see oligotrophic, mesotrophic, eutrophic).
Turnover	Seasonal process where water layers mix resulting in the redistribution of oxygen and nutrients throughout the lake.
Water Sensitive Urban Design (WSUD)	WSUD seeks to minimise impacts of urban development on the natural water cycle by integrating developments with a site's natural features and promoting the integration of stormwater, water supply and sewage management.
Water quality assets	Infrastructure solutions that aim to filter water of pollutants, such as constructed wetlands, raingardens and ponds. Water quality assets are also commonly referred to as 'WSUD infrastructure'.

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Attachment G

ACT Government

Lake Tuggeranong Catchment Model

Technical Report: Configuration and Calibration of the Water Quantity and Quality Model

Water Information Services, ACT Office of Water

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Environment, Planning and Sustainable Development Directorate

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ACT Government Disclaimer

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Executive Summary

Lake Tuggeranong is a small (57 ha) urban lake in southern Canberra. Lake Tuggeranong was constructed in the late 1980s on Tuggeranong Creek, a 66 km^2 catchment that is predominantly (62%) urbanised. In recent decades, Lake Tuggeranong has been plagued by poor water quality. Since 2017, there has been a concerted effort to improve water quality in the lake through the construction of Water Sensitive Urban Design (WSUD) infrastructure throughout the catchment, and a major research program to understand the causes of poor water quality, and sources of pollutants entering the lake. This work has been undertaken as part of the ACT Healthy Waterways program.

The ACT Government has commited to developing Healthy Waterways Plans for priority catchments in the ACT. The draft Lake Tuggeranong plan aims to provide a suite of potential management options to Government to further improve water quality in Lake Tuggeranong. To acheive this, modelling and analyses have been undertaken to examine a broad range of management scenarios and identify cost-effective options to improve water quality in Lake Tuggeranong. To support these analyses, a catchment model was developed in the eWater model platform Source to support the testing of water quality management scenarios, and rank these scenarios based on cost-effectiveness.

This report presents an overview of the development, calibration and outputs of the Lake Tuggeranong catchment model. The underlying rainfall-runoff model chosen for this task was a Sacremento daily timestep model, implemented in Source. Fine-scale delineation of subcatchments, land use and imperviousness, flow regulation infrastructure and WSUD infrastructure were included in the model, to provide a complete, current assessment of the Lake Tuggeranong catchment. A total of 75 subcatchments were delineated to key infrastructure within the catchment, existing monitoring locations, and other features of interest. LIDAR data captured in 2020 was used to quantify surface imperviousness within subcatchments, facilitating an explicit representation of imperviousness in the model.

A comprehensive compilation of water quality data and streamflow data collected in the catchment from 2014 to the present was used to calibrate the Source model. The initial flow calibration is rated as suitable for estimating long-term catchment mean annual flow and long-term mean annual pollutant loads. The water quality model is parameterised against observed end-of-catchment median event concentrations of total phosphorus, total nitrogen, and total suspended solids, in the absence of load-based water quality data. The model estimates pollutant loads generated in the catchment based on land use and imperviousness data.

The parameterised model was used to simulate daily flows and pollutant loads generated in the Lake Tuggeranong catchment between 1889 and 2023, the period for which observed rainfall and climate data was available. Under current catchment land use and management conditions, the modelled average annual inflow to Lake Tuggeranong is 8.8 GL/year. The modelled mean annual loads of pollutants entering Lake Tuggeranong are 1,442 kg/year total phosphorus, 11,894 kg/year total nitrogen, and 397,064 kg/year total suspended solids.

The results provide a robust foundation for future catchment management plans and strategies.

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1. Introduction

Lake Tuggeranong is a small (57 ha) urban lake in southern Canberra. The lake was constructed in the late 1980s on Tuggeranong Creek, a 66 km^2 catchment that is predominantly (62%) urbanised. In recent decades, Lake Tuggeranong has been plagued by poor water quality, with high loads of nutrients (phosphorus and nitrogen) and sediments entering the lake. Since 2017, there has been a concerted effort to improve water quality in the lake through the construction of Water Sensitive Urban Design (WSUD) infrastructure such as wetlands, swales and raingardens throughout the catchment, and a major research program to understand the causes of poor water quality, and sources of pollutants. This work has been undertaken as part of the ACT Healthy Waterways program.

The ACT Government has commited to developing Healthy Waterways Plans for priority catchments in the ACT. The Lake Tuggeranong draft plan aims to provide a suite of potential management options to Government to further improve water quality in Lake Tuggeranong. To acheive this, modelling and analyses have been undertaken to examine a broad range of management scenarios and identify cost-effective options to improve water quality in Lake Tuggeranong. To support these analyses, a catchment model was developed in the eWater model platform Source (Argent, et al., 2005) to support the testing of water quality management scenarios, and rank these scenarios based on cost-effectiveness.

This report documents the development of a new, daily timestep water quantity and quality model for the Lake Tuggeranong catchment. The purpose of the model is to simulate long-term mean annual flows and associated pollutant loads entering Lake Tuggeranong, to inform and support catchment improvement studies and associated management strategies.

The model builds upon and extends previous models describing the Lake Tuggeranong catchment by:

- Including long-term, gap-filled climate data to extend the time period over which simulated results are available (1889-2023);
- Incorporating and combining up-to-date spatial data on land use and land surface imperviousness in the catchment;
- Undertaking hydrological model calibration;
- Adopting a model structure delineated to
    - water quality monitoring points to facilitate water quality model parameterisation;
    - existing and potential water quality improvement infrastructure (i.e., WSUD infrastructure) to facilitate estimation of pollutant load reduction from this infrastructure.

1.1 Overview of previous modelling and monitoring studies in the catchment

The model presented in this report builds on several published and unpublished modelling and monitoring studies undertaken in the Lake Tuggeranong catchment to describe flows and water quality in Lake Tuggeranong. These studies are reviewed briefly below, highlighting how the data has been used to inform the current study.

1.1.1 Modelling studies

Lake Tuggeranong catchment MUSIC 6 model, GHD (2015)

To inform the early stages of the Basin Priority Project, GHD developed a model of the Lake Tuggeranong catchment using the software MUSIC (Model for Urban Stormwater Improvement Conceptualisation) to aid in identifying sources of pollutant loads entering Lake Tuggeranong (GHD, 2015). The Lake Tuggeranong catchment was delineated based on contour information and the ACT stormwater network. Existing WSUD infrastructure in the catchment at the time comprised only gross pollutant traps (GPTs) with or without sedimentation basins, as well as Lake Tuggeranong, Isabella Pond, and Upper Stranger Pond. These assets were each represented as GPT, sedimentation basin, or wetland nodes in the MUSIC model. Land use classification in the model was based on ACT Government land zoning data aggregated to six broad categories, and imperviousness was based on values for each land use category from the published literature. Likewise, water quality parameters (event mean concentration, EMC, and dry weather concentration, DWC, of pollutants) were taken from the literature, rather than derived from existing data in the Lake Tuggeranong catchment.

The MUSIC model simulated flows and pollutant loads in the catchment under rainfall and evaporation conditions for the 10-year period from 1968-1977. It predicted an annual flow volume of 20,600 ML in the Lake Tuggeranong catchment, with an annual average of 2.7 tonnes TP, 31.5 tonnes N, and 2230 tonnes TSS generated given the existing WSUD infrastructure in the catchment at the time.

Lake Tuggeranong catchment MUSIC X model, eWater Ltd (2022)

eWater developed another MUSIC model of the Lake Tuggeranong catchment to assess the potential pollutant load reductions associated with WSUD assets that were constructed up to June 2019 as part of the ACT Healthy Waterways project (eWater Ltd, 2022). The Lake Tuggeranong catchment was delineated to 11 subcatchments, 7 of which drained through WSUD assets. The model operated on a 6-minute time step for the period 2010-2015. Published or MUSIC default values for hydrology and water quality parameters were applied to the model, which adopted a land use -based stochastic EMC/DWC approach to water quality modelling.

Land use was derived from 0.5m LIDAR coverage mapping impervious surfaces in the catchment and was divided into 6 classes (roof, road, hardstand, pervious, bushland, and rural). WSUD assets were incorporated in the model by importing and combining the 7 existing MUSIC models representing the detailed design configurations of each asset. Design configurations are expected to differ slightly from works-as-executed configurations.

The MUSIC model predicted an annual flow volume of 14,284 ML, with an annual average of 4.8 tonnes P, 39.8 tonnes N, and 2320 tonnes TSS generated in the Lake Tuggeranong catchment. However, the model was uncalibrated and over the period 2010-2015 overestimated flows by 57.2%, compared to observed data from the gauge immediately downstream of Lake Tuggeranong (Tuggeranong Creek upstream of Sewer Crossing, gauge 410779). The model is therefore also likely to overestimate pollutant loads in the catchment. However, the percentage removal of pollutants associated with each WSUD asset may be used as a starting point in the current modelling study to represent the treatment performance of existing assets.

Upper Murrumbidgee catchment Source models, Alluvium (2017) and eWater Ltd (2019)

Alluvium (Alluvium, 2017) developed an Upper Murrumbidgee catchment model in Source with the best available data and methods as a part of a project to meet requirements for the Murray-Darlin Basin Plan and the ACT Water Resource Plan. Alluvium's model delineated the Upper Murrumbidgee catchment into 440 subcatchments, using a 20 m digital elevation model (DEM), water management and hydrological boundaries, and stream gauging locations. Current ACT and NSW land use classifications, consistent with the Australian Land Use Mapping (ALUM) codes, were combined into 20 functional units for use in the model. The model used climate data from 1980-2016 and a combination of SIMHYD and GR4J rainfall-runoff models, assigned to urban and agricultural subcatchments, respectively. Observed discharge and water quality data from storages (dams and lakes) and sewage treatment plants (STPs) were used to parameterise the model. The model calibration was moderate for most of the gauges, with missing data at both hydrology and water quality monitoring gauges constituting a major limitation of the model. Moreover, due to the large number of subcatchments, model performance was very slow.

Alluvium's Source catchment model did not estimate flows and pollutant loads entering Lake Tuggeranong, instead providing estimates for the outlet of the Lake Tuggeranong catchment, including the effect of the lake itself on these parameters. The model predicted an annual flow volume of 5,868 ML for the outflow from the Lake Tuggeranong catchment, with an annual average load of 0.29 tonnes P, 5.63 tonnes N and 128.9 tonnes TSS.

In 2019, eWater identified a number of potential improvements to Alluvium's Upper Murrumbidgee catchment model and rebuilt the model (eWater Ltd, 2019). Their updated catchment model defined fewer subcatchments outside the ACT, delineating a total of 163 subcatchments, to improve model performance. eWater's model retained the climate data, land use and functional unit classifications used in Alluvium's model, but used the LASCAM rainfall-runoff model across all subcatchments to enable assessment of the hydrological impacts of land use change. The updated catchment model also incorporated Canberra's water supply, with storages configured to operate, albeit without implementation of operating rules.

Water quality parameters (EMC and DWC) in this model used values taken from the literature, rather than being fitted to observed data. While flow parameters were calibrated to observed data from 32 gauges across the Upper Murrumbidgee catchment, the model did not calibrate end-of-catchment values for the Lake Tuggeranong catchment to the downstream gauge Tuggeranong Creek at Sewer Crossing (410779). Therefore this model configuration cannot provide reliable estimates of the total flow and loads generated from the Lake Tuggeranong catchment.

1.1.2 Monitoring studies

University of Canberra Lake Tuggeranong research project, Stage 3 report (2020)

The University of Canberra's Lake Tuggeranong research project has demonstrated the importance of external sources of nutrients to water quality in Lake Tuggeranong. Stage 3 of the Lake Tuggeranong research project analysed the nutrient contribution from different subcatchments, in order to understand the relative influence of different land uses on nutrient inputs to the lake (Ubrihien, et al., 2020). Water sampling during rainfall events was undertaken in the Kambah Creek and Village Creek subcatchments over two years (2018 – 2020), with more than 2000 grab samples collected and analysed. The monthly total

phosphorus (TP), total nitrogen (TN) and total suspended solids (TSS) loads to Lake Tuggeranong were calculated for each subcatchment.

It was found that event discharge and loads of TP, TN, and TSS were much greater than those from baseflow. Event samples from urban areas of the subcatchments had high concentrations of nutrients with an unexpectedly high proportion in dissolved form. This study was constrained by extremely dry weather conditions over the spring and summer of 2019-20, which limited opportunities to collect event samples in a season of key interest. The movement of water and associated nutrients measured during these extreme conditions are unlikely to be representative of wetter years. Additionally, the lack of streamflow gauging at water quality sampling sites made it difficult to accurately estimate the nutrient loads entering the lake. Flow-weighted mean concentrations of nutrients from event samples were essential to calculate the load.

Despite these limitations, Stage 3 of the Lake Tuggeranong research project provides a significant water quality dataset including manual grab-sampling as well as data from 6 autosamplers at fixed locations on inflows to Lake Tuggeranong. The median measured concentrations of TP, TN and TSS from this work have been used in the parameterisation of our water quality model.

ACT Government water quality data

Several water quality monitoring programs supported or contracted by the ACT Government have measured pollutant (nutrient and sediment) concentrations at sampling sites across ACT waterways, including in the Lake Tuggeranong catchment. These have been collated into a single dataset and used in the parameterisation of our water quality model.

Waterwatch

This dataset includes water quality samples collected from eight different sampling sites in the Lake Tuggeranong catchment from 2017 to the present. The water quality parameters recorded include concentrations of TP and nitrates. Waterwatch data are publicly accessible at https://biocollect.ala.org.au/actwaterwatch. Following review and a focus on event flow water quality samples for model configuration, Waterwatch data were not used in the parameterisation of our water quality model.

Land Use Monitoring program (LUM)

Water quality data was collected from a single site in the Lake Tuggeranong catchment over 2018 and 2019. The water quality parameters recorded include concentrations of TP, TN and TSS.

Basin Plan Phase 1 (BPP1)

Under this program grab-samples were collected from 20 sampling sites in the Lake Tuggeranong catchment and analysed for water quality parameters including concentrations of TP, TN, and TSS.

ACT Lakes and Rivers water quality monitoring program

The ACT Lakes and Rivers water quality monitoring program has maintained two grab-sampling locations on Lake Tuggeranong. While these data were not used explicitly in the Source model calibration, they are

relevant to the in-lake modelling described in the supplement to this report, *Predicting phosphorus concentration and trophic state of Lake Tuggeranong* (Kahn & Dey, 2024).

1.2 Key gaps addressed by this study

The brief review above highlights the considerable amount of new water quality data that is now available for the Lake Tuggeranong catchment, including some event-based concentration data. The new data can be used to refine model water quality parameters that were previously based on values derived from the published literature. The modelling studies described above are limited in their utility as catchment models in the current planning context, as they either did not have the tools or resources available to calibrate model hydrology or were calibrated over a spatial resolution too coarse to investigate detailed catchment management strategies. Additionally, these previous studies simulated results over relatively short timeframes (6 – 36 years).

This study therefore aims to address these gaps by:

1. Preparing a high spatial resolution catchment model that uses a long-term historical climate observations dataset to simulate results over the 133-year period 1889-2023.
2. Calibrating the catchment model to ensure that end-of-catchment observed flows match modelled flows over the long term, so that the model accurately represents long-term water yield.
3. Using available event-based and baseflow water quality data to parameterise land use -based water quality models and derive new estimates of mean annual pollutant loads to Lake Tuggeranong.

Section 2 of this report collates and summarises the input data used to build and parameterise the model including terrain models, land use, water quality assets, hydrological and water quality data. Section 3 describes the model construction and parameterisation procedures and associated results and limitations. Section 4 presents the results of long-term flow and load estimates for the catchment under the current conditions including spatial results and estimated loads to Lake Tuggeranong. Section 5 presents the predevelopment and current scenario analysis of the catchment. Section 6 provides the conclusions and recommendations for next steps to improve model performance through additional data collection or by upgrading the model techniques.

2. Model input data

The Source modelling framework allows the simulation of catchment hydrology and pollutant generation in response to rainfall and climatic processes, catchment characteristics, land use and imperviousness, and waterway management. This requires the input of data describing each of these elements, enabling the catchment to be represented as a connected patchwork of areas for which the conversion of rainfall to runoff, the generation of pollutants, and the flow of surface waters between areas, can be calculated. Dividing the catchment into subcatchments for which flow and water quality data are available allows finer-scale calibration of the model to observed data in the catchment.

This section describes the input data sets used for model creation and parameterisation including:

- Subcatchment delineation;
- Land use classification and imperviousness;
- Water quality data;
- Climate data;
- Lake configuration;
- Streamflow and storage level data;
- WSUD asset configuration.

2.1 Subcatchment delineation

The Lake Tuggeranong catchment is approximately 6,600 hectares and is mostly (62%) urbanised. The southeastern part of the catchment is rural and extends across the ACT border into NSW. Catchment development began in the 1980s (Beer, Young, Humphries, & Burgess, 1982) and continued into the early 1990s. The Lake Tuggeranong catchment is the smallest Water Management Area in the ACT, and also encompasses a small component of the Upper Murrumbidgee water management area due to diversion of the upper Stranger Pond catchment to Lake Tuggeranong at Isabella Pond.

Because the subcatchments delineated to WSUD assets for the eWater (2022) study contained some discrepancies with the ACT Government stormwater network map, a new subcatchment map was created using a pit-filled, 1 m DEM based on high-resolution LIDAR data (ACT Government, 2016) and the ACT Government stormwater network map. Subcatchments within the Lake Tuggeranong catchment were delineated to:

- known water quality monitoring locations;
- known streamflow monitoring locations;
- existing WSUD assets;
- ponds and storages.

This resulted in 75 subcatchments, shown in Figure 1. When identifying water quality monitoring sites for catchment delineation, University of Canberra water quality monitoring sites based on the stormwater network were prioritised.

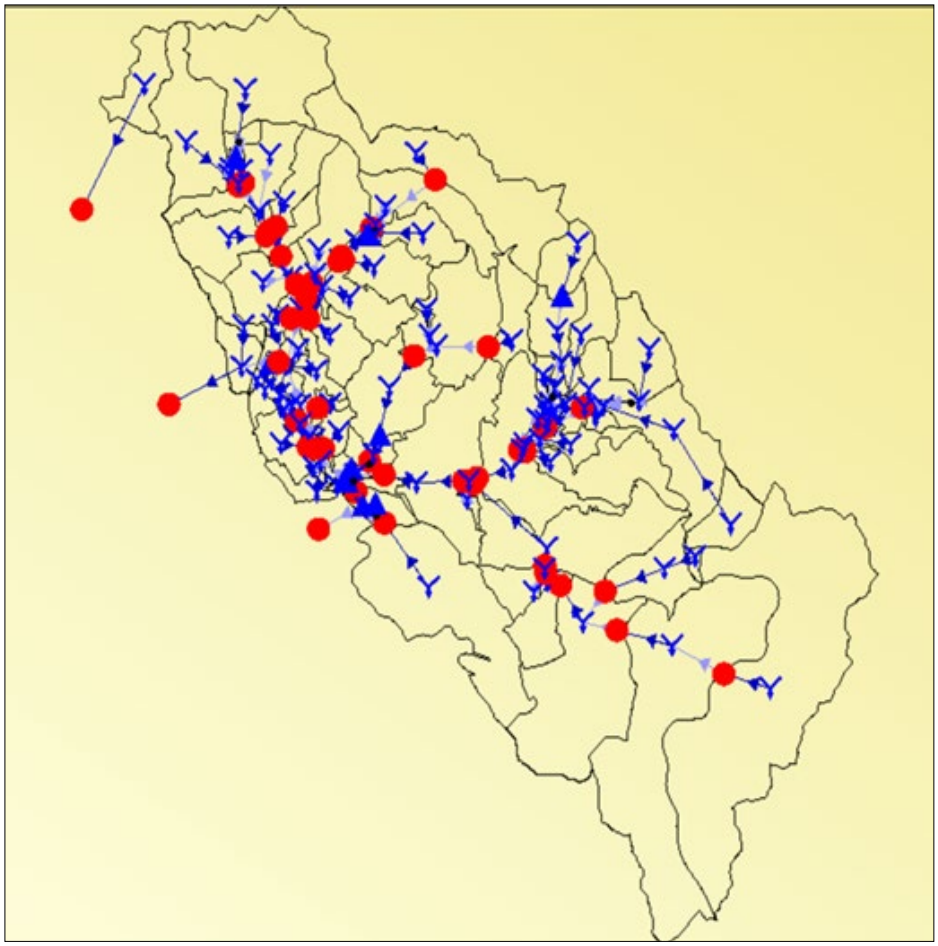

Figure 1. Screenshot of the Source model-generated Lake Tuggeranong subcatchment map, showing nodes defined by flow and water quality monitoring locations (large red points) and WSUD infrastructure (large blue triangles). Blue 'Y' symbols represent flow and pollutant generation within subcatchments and small blue arrows indicate the direction of flow.

2.2 Land use classification and imperviousness

Land use classification for the Lake Tuggeranong catchment model aims to represent a wide range of land uses that could be subject to different structural and non-structural catchment management actions, such as suburban street sweeping, construction of additional WSUD assets, or education around private household fertilizer use. To this end, broad land use classifications adopted for previous modelling studies (eWater Ltd, 2022) were disaggregated to a more granular set of classifications based on ACT Government land zoning. These were combined with data on land surface imperviousness to derive land use for the Lake Tuggeranong catchment model as follows:

1. Aerometrix (2020) LIDAR data at 0.5m pixel resolution was trimmed to the Lake Tuggeranong catchment, mapping 5 land surface imperviousness classes:
    - Impermeable ground level (i.e., roads and hardstand)
    - Impermeable above ground level (i.e., roofs)
    - Permeable ground level (i.e., pervious, unpaved ground)
    - Permeable above ground level (i.e., tree canopy)

- Water

2. The LIDAR data was converted to shapefile and intersected with the 2023 ACT Government land zoning GIS layer trimmed to the Lake Tuggeranong catchment, consisting of 17 land use zones consistent with ALUM codes:
   - Business zone
   - Community Facilities
   - Core zone
   - Leisure and accommodation
   - Local centre
   - Services
   - Services zone
   - Medium density residential
   - Suburban
   - Suburban core
   - Transport
   - Urban open space
   - Restricted access recreation zone
   - Hills ridges and buffer areas
   - Designated
   - River corridor
   - Rural

   The entire NSW portion of the catchment was classed as 'Rural' land use.
3. This cross-classified land use layer was intersected with the ACT Government road edges GIS layer, to identify road area within each land use zone. Areas classified as impermeable ground level that fell outside of the roads boundary were deemed hardstand, and areas classified as permeable above ground level that fell within the roads boundary (i.e. where trees overhung road) were reclassified as road (impermeable ground level). This approach yields a more precise classification of road area than the approach of eWater (eWater Ltd, 2022), where road centrelines buffered by 5m were used to estimate the area of impermeable road surface within the transport classification of the land zoning map, which includes the entire road corridor consisting of largely permeable open space.
4. Finally, visual inspection of aerial imagery was used to identify and manually delineate irrigated sports fields based on their "greenness" relative to nearby open spaces, and assign them a specific land use classification.
5. The land use and imperviousness layer was converted to a 0.5m grid, which was intersected with the Lake Tuggeranong subcatchment map to obtain the area of each land use - imperviousness combination within each subcatchment.
6. The detailed land use types were grouped into six major functional units for incorporation into the Source catchment model: suburban, commercial, open space, rural, bushland and sports field, each containing imperviousness classifications of road, hardstand, roof, permeable ground level, permeable above ground level, and water. The final land use and imperviousness classification schedule, and the area associated with each land use functional unit in the model domain is provided in Appendix C.

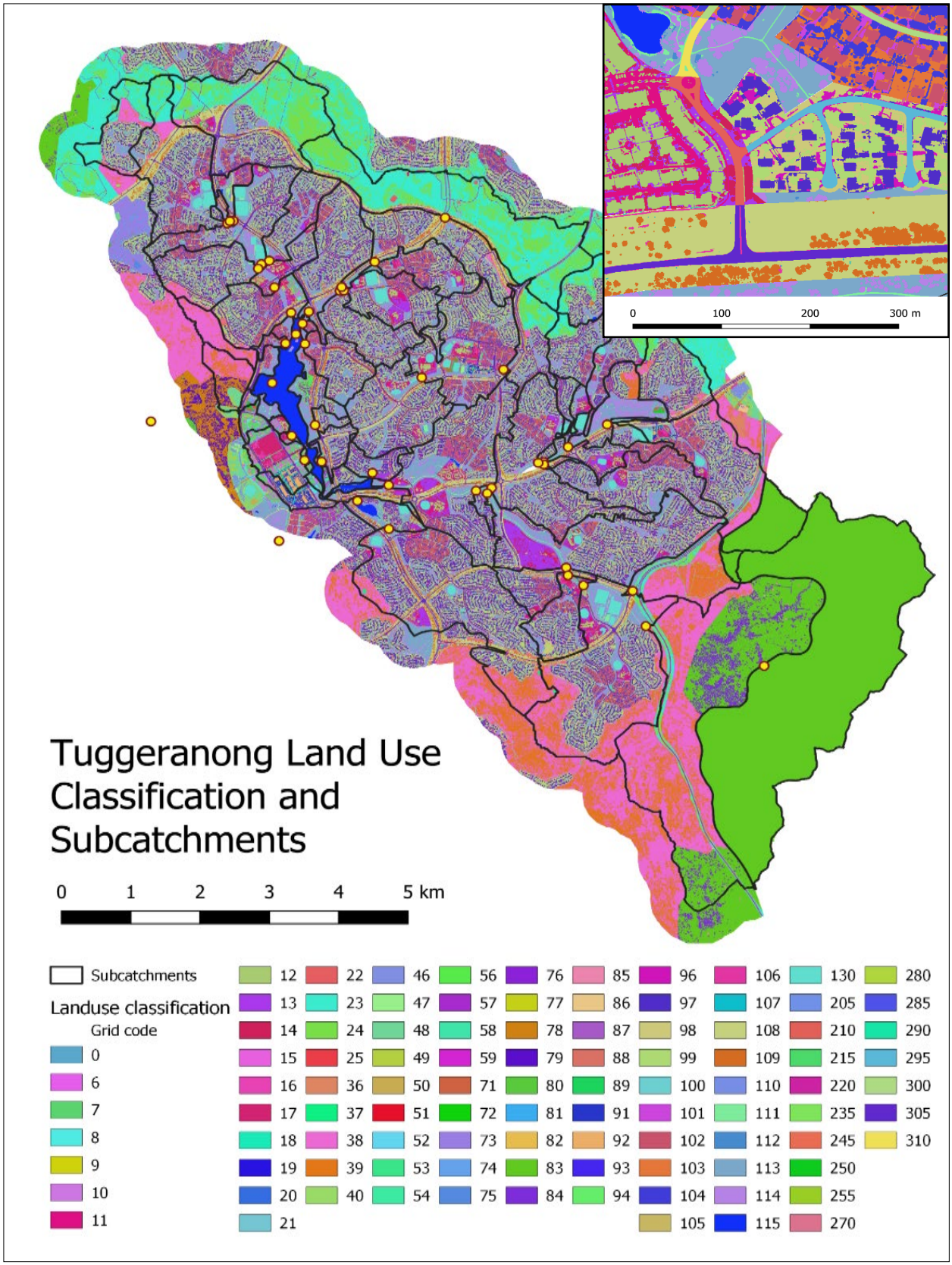

Figure 2. Land use map of the Lake Tuggeranong catchment with colours representing the unique code for each land use - imperviousness combination. Yellow dots indicate water quality or streamflow monitoring locations. **Inset:** close-up detail of a section of the map showing roads, rooftops and open space.

2.3 Water quality data

Water quality data from within the Lake Tuggeranong catchment was collected by a range of programs between 2014 and 2021 (Table 1). Some of the programs entailed event-based monitoring of specific land uses whilst others were focussed on grab sampling from many sites throughout the catchment to try and understand spatial variation of water quality and how it may relate to land use.

Table 1. The number of water quality samples collected across five monitoring programs and analysed for 3 pollutants used in model calibration. TP, total phosphorus; TN, total nitrogen; TSS, total suspended solids.

Monitoring program	Years active	Number of sites	TP	TN	TSS
Basin Plan Phase 1 (event sampling)	2014-2015	19	93	93	93
ACT Government Land Use Monitoring program (event sampling)	2018-2019	1	93	93	93
Lake Tuggeranong Research Project (event sampling)	2017-2018	7	1385	1376	1071
University of Canberra (grab sampling)	2018-2020	29	315	315	316
Upper Murrumbidgee Waterwatch (grab sampling)	2014-2021	8	585		
Total			2471	1877	1573

Table 1 shows there is a large amount of historical water quality data potentially available for use. However, no study in the catchment has converted the measured pollutant concentrations to loads, which requires simultaneously monitoring of flows in order to calculate flow-weighted mean concentrations.

Catchment models typically adopt a land use based EMC/DWC approach to estimate mean annual pollutant load, with model calibration achieved by matching observed loads to modelled loads. As no observed load data is currently available, we adopted the following model parameterisation approach:

1. All pollutant concentration data from the available water quality studies was compiled into a single data frame. For days where multiple samples were collected from a site, the mean of these samples was calculated as an approximation of the mean concentration occurring on that day.
2. Modelled daily flows and modelled pollutant concentrations were compiled into a single data frame and the event flow threshold, defined as the flow threshold that is exceeded in the top 10% of all modelled flow days, was identified.
3. For each day that observed pollutant concentration data was available, we retrieved the modelled flow and associated modelled concentration for the pollutant and monitoring site in question. We split this date-matched data between event and baseflow conditions and calculated the medians of the observed and modelled data for each site.

The median observed pollutant concentration value was compared to the median modelled pollutant concentration value for sites at the six major lake inlet points and a scaling factor estimated to scale the EMC values for that pollutant. The scaling factor was applied across all land uses for that pollutant.

Parameterisation steps 1-3 above were then re-run to test the model fit. This model parameterisation approach preserves the typical difference between land use-based EMC/DWC combinations whilst date-matching median observed lake inflow concentrations to the median modelled concentrations.

Figure 3 provides example plots and data for the monitoring point at the Village Creek inlet to Lake Tuggeranong. Modelled median event-based concentrations of TP exceed observed concentrations, however across all observed data (event and baseflow), median modelled concentrations match observations (n = 275). The time series of modelled concentrations can never attain the variability of observations due to the fixed nature of the EMC/DWC modelling method.

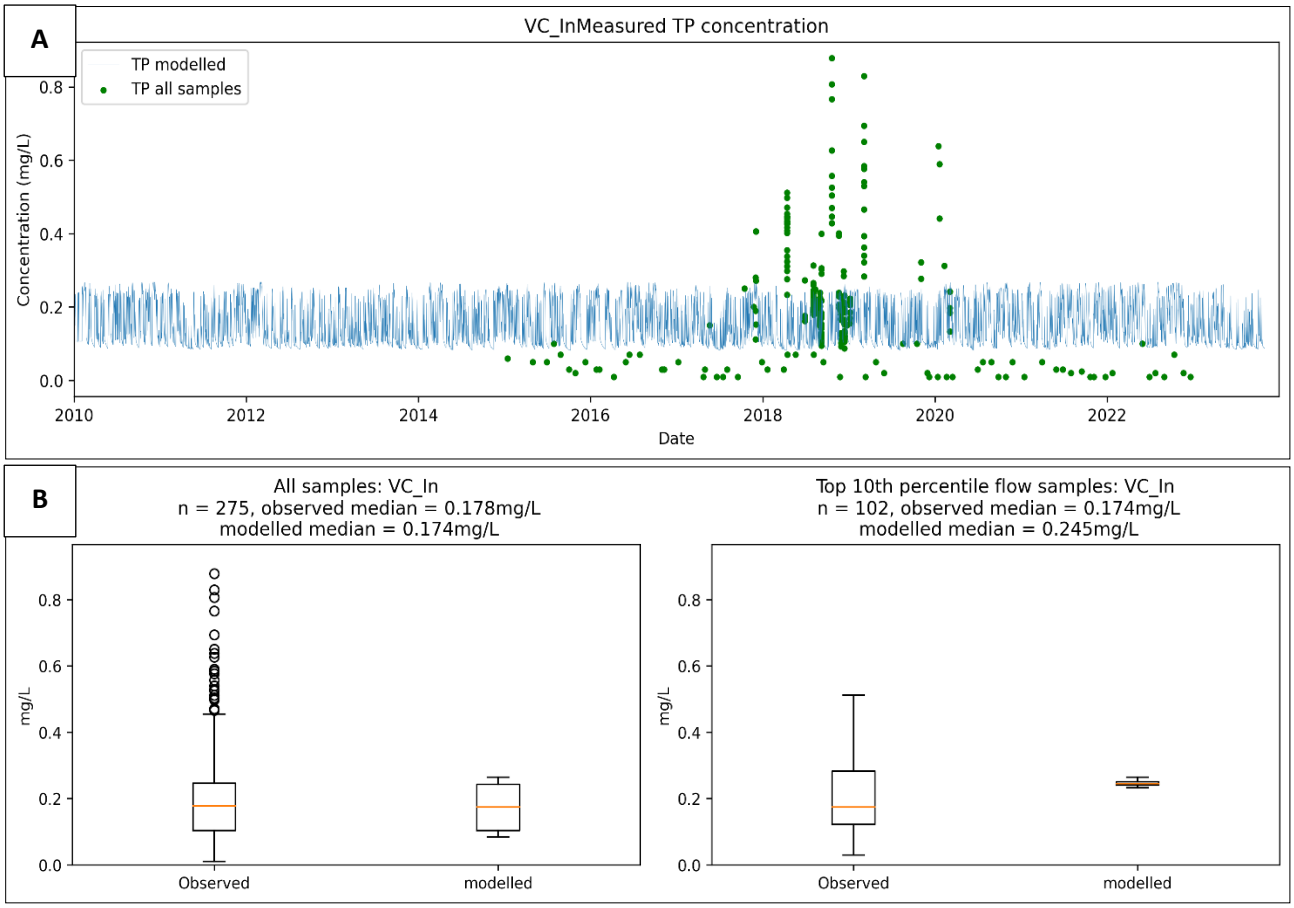

Figure 3. Example of the comparison of observed vs. modelled pollutant concentration data for a single water quality monitoring point. A) Time series of modelled total phosphorus (TP) concentrations (blue line) and date-matched observed median TP concentrations (green points) for the monitoring point at the Village Creek inlet to Lake Tuggeranong. B) Boxplots showing the distributions of modelled and observed median TP concentrations for all samples (left panel) and samples from the top 10th percentile of flow events (right panel) for the monitoring point at the Village Creek inlet to Lake Tuggeranong.

2.4 Climate data

Several climatological stations located within the Lake Tuggeranong catchment could provide data for sub-daily rainfall-runoff modelling. However, to meet the aims of the current model a long-term daily rainfall record without gaps is required. We therefore used patched daily data from the Tuggeranong (Isabella Plains) climatological station (Bureau of Meteorology station number 070339). This station is located within

the Lake Tuggeranong catchment (Figure 4) and has been open since May 1996 - present with 99% completeness of the data record. For this post-1996 period we were able to provide complete observed climate data to the model. To cover the entire period 1889-2023, we used patched data for the pre-1996 period from the SILO (Scientific Information for Land Owners) patch point dataset for this station (https://www.longpaddock.qld.gov.au/silo/).

The following climate variable time series associated with this site were used for catchment modelling:

- Rainfall (mm/d) for rainfall-runoff modelling and water body water balance modelling;
- Morton's wet-environment areal evapotranspiration over land (mm/d) for rainfall-runoff modelling (MWet);
- Morton's shallow lake evaporation (mm/d) for water body water balance modelling (MLake);
- Maximum and minimum temperature for experimental stormwater and lake temperature modelling (Tmax and Tmin) ;
- Evapotranspiration (mm/d) of short crop for irrigation modelling.

2.5 Lake Tuggeranong storage configuration

Lake Tuggeranong is modelled as a completely mixed storage, taking inflows from the whole catchment and releasing flows according to the stage (water level) -discharge relationship of its outflow point at Lake Tuggeranong weir. The lake is also subject to daily rainfall and daily evaporation (MLake), modelled using the SILO daily time-series for the Tuggeranong (Isabella Plains) climatological station (station ID 070339). As Lake Tuggeranong does not have any water supply requirements, no water use is modelled for this storage.

To configure the Lake Tuggeranong storage node, a rating curve was derived from the bathymetry data and imported into the model. This was calculated from the observed water level measured at the Lake Tuggeranong weir (gauge 410784), using the level-volume-area (LVA) relationship for Lake Tuggeranong obtained from bathymetry data collected in 2015 by Steger and Associates Registered Land Surveyors under the Basin Priority Project (data provided in Appendix A).

The lake outlet was configured as an ungated spillway, using the stage-discharge rating table for the Lake Tuggeranong weir (gauge 410784) supplied by ALS Hydrographics via their HYDSTRA database. The stage-discharge data is provided in Appendix B.

2.6 Streamflow and storage level data

2.6.1 Gauge 410779: Tuggeranong Creek upstream of Sewer Crossing

The key streamflow data available for this catchment comes from the gauge at Tuggeranong Creek upstream of Sewer Crossing (gauge 410779; Figure 4) which is located a short distance below the Lake Tuggeranong outflow. Recorded streamflow data is available from 1986 and the gauge remains current. Gauge records show that the maximum recorded flow rate is approximately 200 cumecs, while the maximum rated flow is 108 cumecs or approximately 50% of the maximum recorded flow. Flows greater than 100 cumecs have occurred approximately 6 times since 1990. 216 gaugings (validating measurements) have been undertaken at the site since 1986, with the highest flows being gauged within the first few years of site establishment. Since 2000, the maximum gauged flow has been approximately 6.5 cumecs.

Consequently, higher recorded flows have higher associated uncertainty. However, the gauging record shows a stable relationship with little scatter, with gaugings covering the majority of observed flows at the site, indicating a reliable stage-discharge curve. The site is therefore rated as suitable for model calibration.

2.6.2 Additional short-term streamflow monitoring sites

Additional streamflow records collected by the ACT government for various short-term studies are included in the model:

- 410650 Upper Stranger Pond (1990-1990) Inflow to the pond at GPT
- 410651 Upper Stranger Pond (2017-2018) Outflow from Upper Stranger Pond
- ES1701 Tuggeranong Channel @ Clive Steele (2017-2018)
- ES1702 Monash Channel @ Charleston (2017-2018)

As validation gaugings are generally unavailable for these short-term monitoring sites, they are used for indicative comparison purposes rather than model calibration.

2.7 Water Sensitive Urban Design assets

Geographic location and pollutant reduction performance data were available for eight existing WSUD assets in the Lake Tuggeranong catchment, built under Stage 1 of the ACT Healthy Waterways program. eWater (eWater Ltd, 2022) modelled the flow and water quality performance of these assets using MUSIC (Table 2). Each of these eight WSUD assets is represented in the current Lake Tuggeranong catchment model as a splitter node that diverts flow to the asset, and a storage node that applies a water quality decay function, representing the percentage reduction in pollutant loads (TP, TN, and TSS) achieved by the asset. Splitter nodes are configured with a maximum flow rate that is diverted into the asset, and any flow above this bypasses the asset, based on the MUSIC modelled high-flow bypass threshold. Storage nodes are configured based on asset design information from their respective preliminary sketch plan (PSP) or design acceptance reports, and their pollutant load decay rate was initially set to match the MUSIC modelled percent reduction rate with a default half-life of 1 day. Field observations indicated that some assets are not currently performing to their full capacity, and the pollutant load decay rates were adjusted to reflect the reduced performance of these assets (Table 2).

Table 2. Adjusted efficiencies (% reduction) of water quality parameters for eight Healthy Waterways Stage 1 WSUD assets, matching the current observed working condition of assets. These values were implemented in the Lake Tuggeranong catchment model. Values in parentheses are the predicted efficiencies from MUSIC models in the technical reports for each asset *(eWater Ltd, 2022)*.

Asset	% Flow bypassed	% TP reduction	% TN reduction	% TSS reduction
TG008	41	27 (54)	25 (51)	41 (82)
TG010	28	54 (78)	51 (74)	66 (95)
TG011N	75	39 (66)	31 (53)	45 (75)
TG011S	75	39 (66)	31 (53)	45 (75)
TG012	29	20 (20)	9 (9)	24 (24)
TG017	52	60 (60)	47 (47)	65 (65)
TG029	49	10 (51)	9 (47)	14 (74)
TG030	66	28 (28)	15 (15)	32 (32)

3. Model build and parameterisation

3.1 Hydrology

3.1.1 Lake Tuggeranong catchment model build

A single catchment model representing the Lake Tuggeranong catchment was developed in Source version 5.3 (https://ewater.org.au/ewater-solutions/tools/source/). The model operated on a daily timestep using long-term, gap-filled climate observations from 01/01/1889 to 30/10/2023. Using a 1 m pit-filled DEM and the ACT Government stormwater network, the catchment was delineated into subcatchments based on flow gauging and water quality monitoring sites as well as WSUD asset locations. A node link network of the catchment model was established. Land use classifications and land surface imperviousness data were combined to define functional units implemented in the model.

The gauge downstream of Lake Tuggeranong (Tuggeranong Creek upstream of Sewer Crossing, gauge 410779) was identified as the node for flow calibration. For hydrologic parameterisation for this gauge, daily timestep streamflow data from 06/02/1986 to 30/10/2023 was input to the catchment model. The internal calibration tool using the objective functions square root daily, exceedance, and bias, was implemented to achieve a suitable fit between modelled and measured data. The daily Nash-Sutcliffe efficiency (NSE) coefficient (Nash & Sutcliffe, 1970) was used as the model performance criterion.

3.1.2 Model calibration

SIMHYD and Sacramento rainfall-runoff models were tested for their suitability for model calibration. The initial flow calibration was conducted for the Lake Tuggeranong catchment before delineation into subcatchments, for the period 01/01/1996 to 30/10/2023, with a warm-up period of 10 years (1986-1995). The permanent impervious fraction of the catchment (pctim) for roads, roofs and hardstand was set to 90% impervious in the Sacramento model as these land uses generate more runoff than permeable surfaces. The objective functions used in the calibration were square root daily, exceedance, and bias. Shuffled Complex Evolution (SCE) followed by Rosenbrock were chosen for optimisation, with 5 iterations and a population number of 500. The Sacramento rainfall-runoff model performed better than the SIMHYD model, providing a better fit with the recorded flow data (Table 3).

Table 3. Model performance statistics for the Sacramento and SIMHYD rainfall-runoff models.

Rainfall-runoff model	Daily Nash-Sutcliffe coefficient	% Volume bias
Sacramento	0.803	-0.85
SIMHYD	0.744	0.001

The initial calibration results confirmed the selection of the Sacramento rainfall-runoff model for the Lake Tuggeranong catchment. The calibrated hydrologic parameters for this model are provided in Table 4.

Table 4. Calibrated hydrologic parameters for the Lake Tuggeranong catchment model using a Sacramento rainfall-runoff model.

Parameter	Suburban	Open space	Commercial	Rural	Bushland	Sports field
Soil moisture store (Lztwm) (mm)	75	75	75	75	75	75
Soil moisture store (Lzfsm) (mm)	15	15	15	15	15	15
Soil moisture store (Lzfpm) (mm)	267.5	267.5	267.5	267.5	267.5	267.5
Rate of lateral outflows (Lzsk)	0.03	0.03	0.03	0.03	0.03	0.03
Rate of lateral outflows (Lzpk)	0.003	0.003	0.003	0.003	0.003	0.003
Rserv	0.346	0.346	0.346	0.346	0.346	0.346
Losses (Side)	0	0	0	0	0	0
Time delay in runoff (UH1)	0.88	0.88	0.88	0.88	0.88	0.88
Time delay in runoff (UH2)	0	0	0	0	0	0
Time delay in runoff (UH3)	0	0	0	0	0	0
Time delay in runoff (UH4)	0.0109	0.0109	0.0109	0.0109	0.0109	0.0109
Time delay in runoff (UH5)	0.03	0.03	0.03	0.03	0.03	0.03
Soil moisture store (Uztwm) (mm)	75.44	75.44	75.44	75.44	75.44	75.44
Soil moisture store (Uzfwm) (mm)	75	75	75	75	75	75
Rate of lateral outflows (Uzk)	0.5	0.5	0.5	0.5	0.5	0.5
Water percolation (Zperc)	153.46	153.46	153.46	153.46	153.46	153.46
Water percolation (Rexp)	3.02	3.02	3.02	3.02	3.02	3.02

Parameter	Suburban	Open space	Commercial	Rural	Bushland	Sports field
Impervious runoff (Pctim)	0.5	0.5	0.5	0.5	0.5	0.5
Losses (Sarva)	0	0	0	0	0	0
Losses (Ssout) (mm)	0	0	0	0	0	0
Impervious runoff (Adimp)	0.30	0.30	0.30	0.30	0.30	0.30
Water percolation (Pfree)	0.19	0.19	0.19	0.19	0.19	0.19

Table 4 continued. See caption previous page.

3.1.3 Model verification

To verify the modelled flow generation of the Lake Tuggeranong catchment, a comparison was made with the Jerrabomberra catchment, which has similar geographic features and location.

A model of the Jerrabomberra catchment was set up in Source using the climate variables daily rainfall and Morton's wet-environment areal evapotranspiration over land (MWet). The rainfall data was obtained from SILO, using station ID 70066 for the NSW portion of the catchment, and station 70249 for the ACT portion. The MWet data was obtained from SILO station ID 70072. The gauged flow data used for calibrating this catchment came from Jerrabomberra at Hindmarsh (gauge 410790), obtained from ALS Pty Ltd. The model was calibrated using a Sacramento rainfall-runoff model, and the objective functions square root daily, exceedance, and bias. SCE followed by Rosenbrock were chosen for optimisation, with 5 iterations and a population number of 500. The calibration was a moderate fit with a daily Nash-Sutcliffe coefficient of 0.59 and volume bias of 0%.

The runoff coefficients of both the Lake Tuggeranong and Jerrabomberra catchments were calculated to compare their performance under predevelopment conditions, represented by 100% bushland land use. The runoff coefficient of the Lake Tuggeranong catchment was approximately 7%, and that of the Jerrabomberra catchment was approximately 8.5%. The two catchments performed similarly under pre-development conditions, verifying the flow generation of the Lake Tuggeranong catchment model.

3.1.4 Model uncertainty estimation

At this stage, model uncertainty estimation has not been undertaken.

3.1.5 Flow routing calibration

Due to the small catchment size and largely urban land use, flow routing was not undertaken in any reach in the Lake Tuggeranong catchment model.

3.1.6 Lake water balance

The lake water balance accounted for all inflows, outflows, rainfall, and evaporation from the lake.

3.2 Water quality

Source catchment models are best suited to estimating long-term mean annual catchment pollutant loads rather than daily concentrations. Ideally, empirical measurements of EMC and DWC from different land uses would be used to parameterise the model. However, as described in section 2.3, water quality data from the Lake Tuggeranong catchment has not been collected concurrently with quantitative flow data, precluding the calculation of EMC. As a result of these data limitations, and noting that long-term inflows and pollutant load into the lake are a key predictive output of the model, a simple approach was adopted to adjust land use -based model water quality parameters using available monitoring data:

1. For each water quality monitoring site, daily median event flow concentrations for each pollutant were calculated for all available dates, as described in section 2.3.
2. A baseline simulation run of the model was performed using EMC and DWC values adapted from the literature (Fletcher, Duncan, Poelsma, & Lloyd, 2004), (Witt, Mainwright, & Weber, 2015), (Melbourne Water, 2024), (Blacktown City Council, 2020), and the modelled daily flows and predicted pollutant concentrations for all monitoring sites were extracted.
3. Baseline modelled pollutant concentrations were date-matched with observed median flows and concentrations to allow for later flow stratification (if appropriate) and to account for sample population representativeness (dry periods or wet periods).
4. Median observed and modelled pollutant concentrations for six major lake inflow sites were then calculated, and used to estimate scaling factors to adjust the literature-derived EMC values for majority land uses (roads, roofs, hardstand, and pervious areas of suburban, commercial, and open space land use categories). Where data allowed, inflow-specific scaling factors were applied.
5. The model was re-run using the scaled EMC values (Appendix D), and modelled median concentrations were once again compared against observed median concentrations.
6. When median modelled and observed values were in agreement, the model parameters were checked against literature values to ensure that the model estimate remained in the anticipated range.

4. Results

4.1 Flow calibration

A hydrograph time series for flows in the Lake Tuggeranong catchment over the model calibration period, 1996-2023, is presented in Figure 4. The hydrograph demonstrates good agreement between the timing and magnitude of modelled and observed flows, which are highly correlated with a daily Nash-Sutcliffe coefficient of 0.88 indicating a very good fit (Moriasi, et al., 2007). There is acceptable peak flow matching with an overall low bias, suggesting the model is reliable in simulating high flow events (Table 5). This strong performance across flow magnitudes confirms the robustness of the model calibration and its suitability for simulating the hydrology of the Lake Tuggeranong catchment.

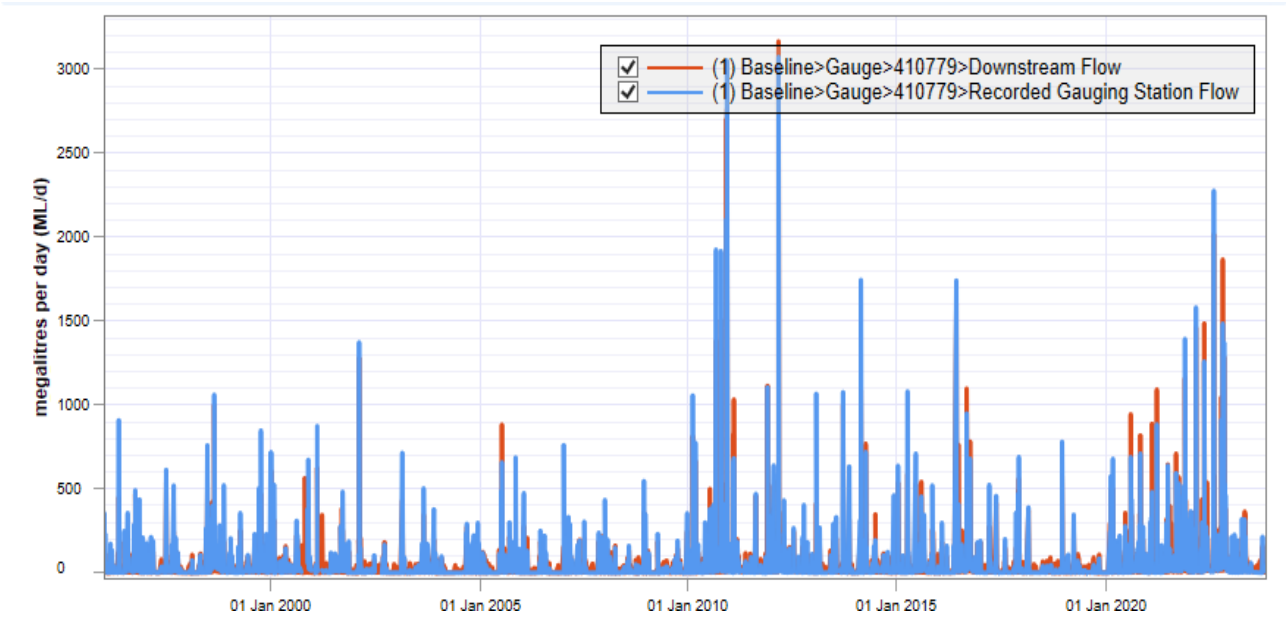

Figure 4. Modelled (red) and observed (blue) flows (daily discharge, ML/d) for Tuggeranong Creek upstream of Sewer Crossing (gauge 410779).

Table 5. Flow calibration model performance statistics for Tuggeranong Creek upstream of Sewer Crossing (gauge 410779).

Performance criterion	
Daily Nash-Sutcliffe Efficiency coefficient	0.88
Monthly Nash-Sutcliffe Efficiency coefficient	0.92
% Volume bias	-0.25

Figure 5 depicts the cumulative flow curve over the calibration period, demonstrating good agreement between modelled and observed flow over the entire period. This agreement indicates that the model accurately captures the total volume of water passing through the catchment, validating its performance in representing the overall hydrological processes.

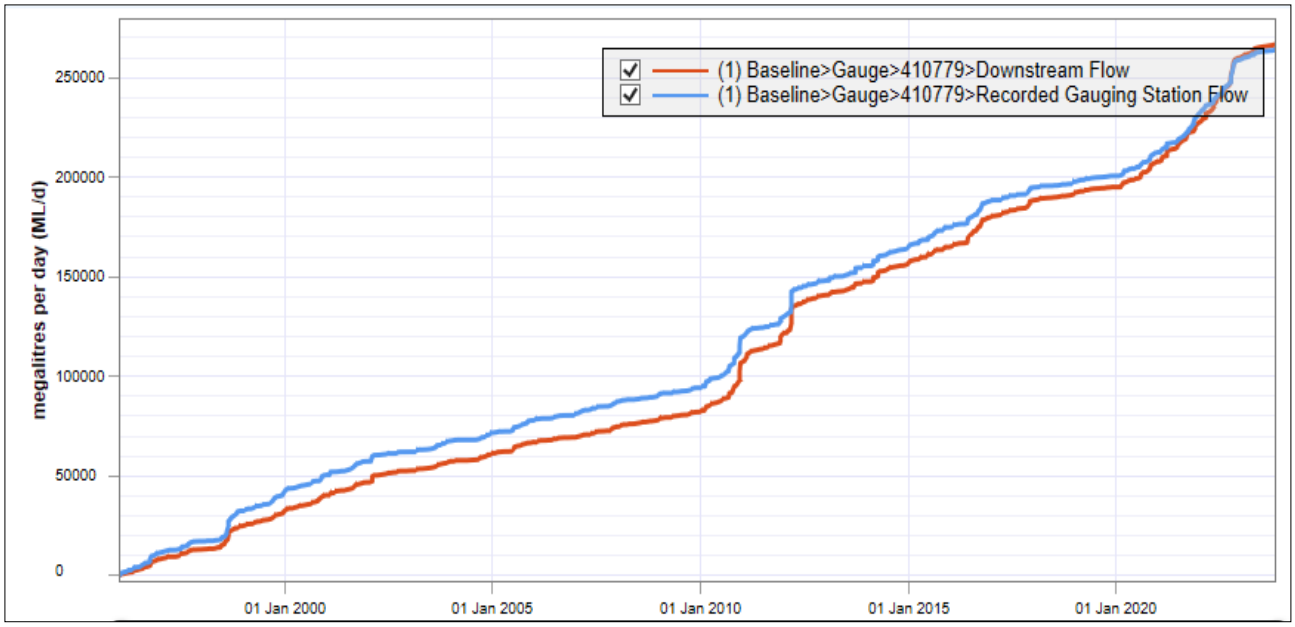

Figure 5. Modelled (red) and observed (blue) cumulative flow for Tuggeranong Creek upstream of Sewer Crossing (gauge 410779), 1996-2023.

Figure 6 illustrates the flow duration curve for flows in the calibration period, showing generally good agreement between modelled and observed flow across most flow conditions. However, discrepancies are noted particularly at low flows. This suggests that while the model performs well overall, there may be areas where the representation of low-flow conditions could be further refined or calibrated.

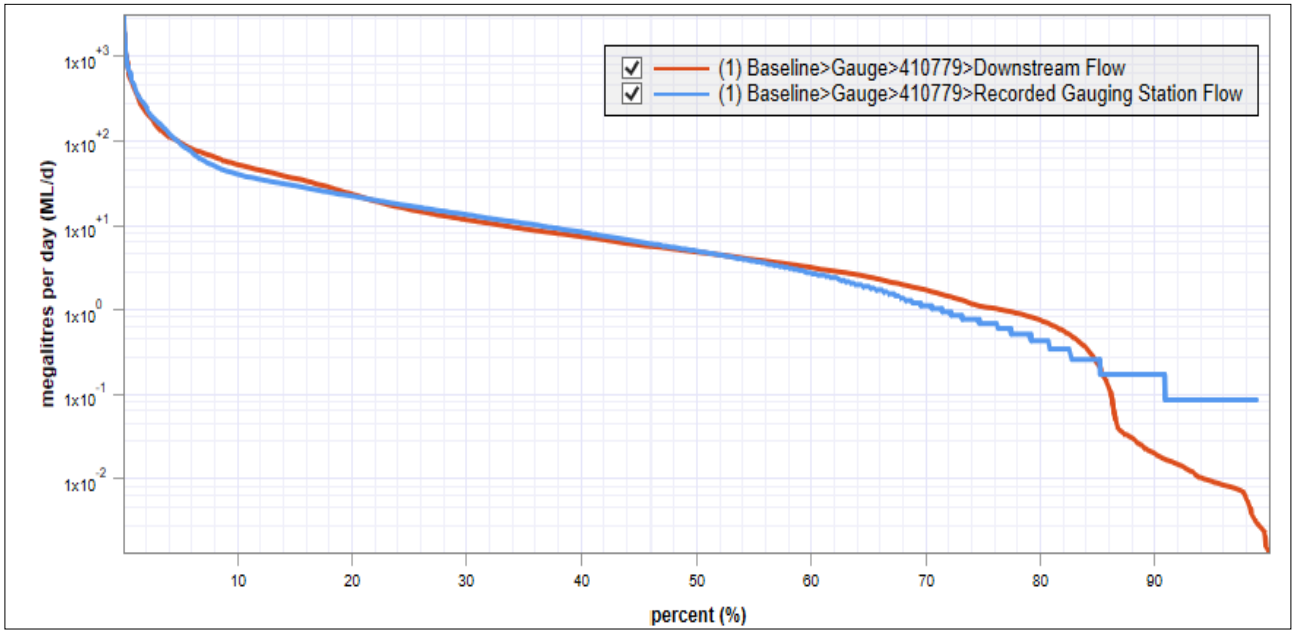

Figure 6. Modelled (red) and observed (blue) flow exceedance curve for Tuggeranong Creek upstream of Sewer Crossing (gauge 410779), 1996-2023.

Figure 7 presents the residual mass curves for observed and modelled flows over the calibration period. The difference between the curves indicates the cumulative difference between observed and modelled flows over time. Ideally, this difference should hover around zero, indicating minimal bias or systematic error in the model.

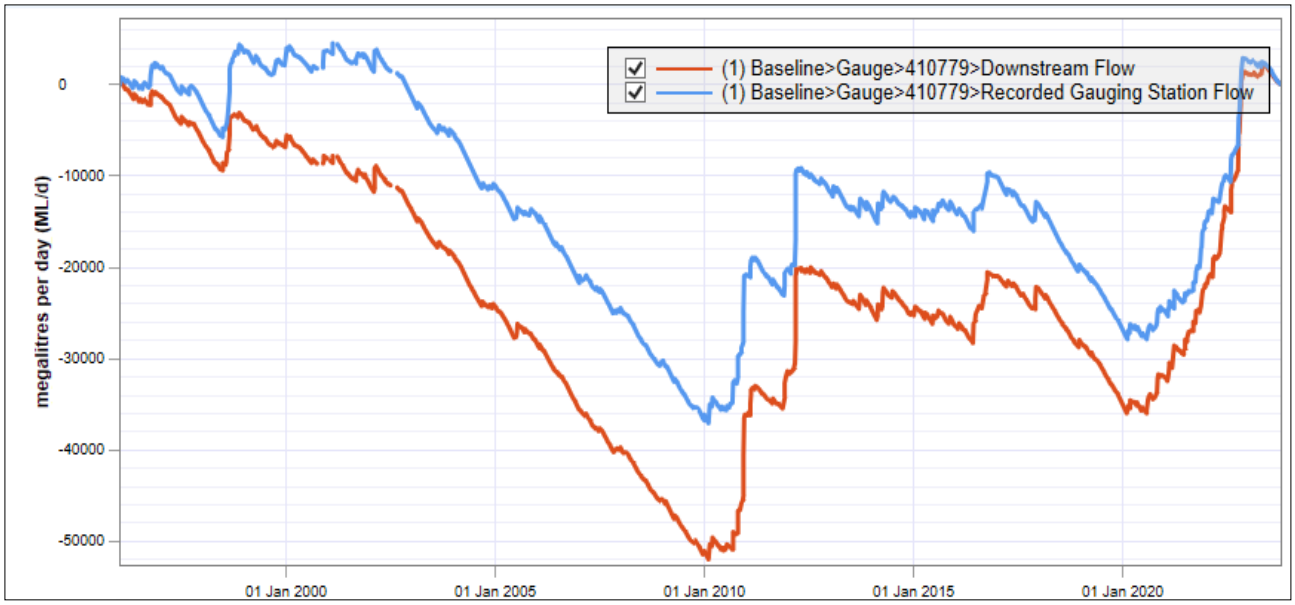

Figure 7. Modelled (red) and observed (blue) residual mass for Tuggeranong Creek upstream of Sewer Crossing (gauge 410779), 1996-2023.

The above plots collectively provide a comprehensive evaluation of the model's performance in simulating hydrological processes in the Lake Tuggeranong catchment, capturing overall flow patterns.

4.2 Water quality calibration

Figure 8 illustrates the comparisons between the median observed and modelled concentrations of TP, TN, and TSS for 34 sites across the Lake Tuggeranong catchment where water quality monitoring was undertaken. These comparisons provide a visual representation of the model's performance in simulating water quality across the catchment. At well-sampled sites, there is generally good agreement between the observed and modelled concentrations. Discrepancies at other sites are primarily due to insufficient sample numbers (Figure 9). Higher median TP concentrations are noted for sites in the Village Creek, Kambah Creek, and Wanniassa subcatchments (site codes beginning with VC, KC, WS respectively) compared to other areas within the Lake Tuggeranong catchment.

As there were multiple sampling locations across the catchment the mean of site medians can provide a robust central tendency measure. The mean of the median modelled concentration for TP is 0.17 mg/L, for TN is 1.33 mg/L, and for TSS is 49.7 mg/L.

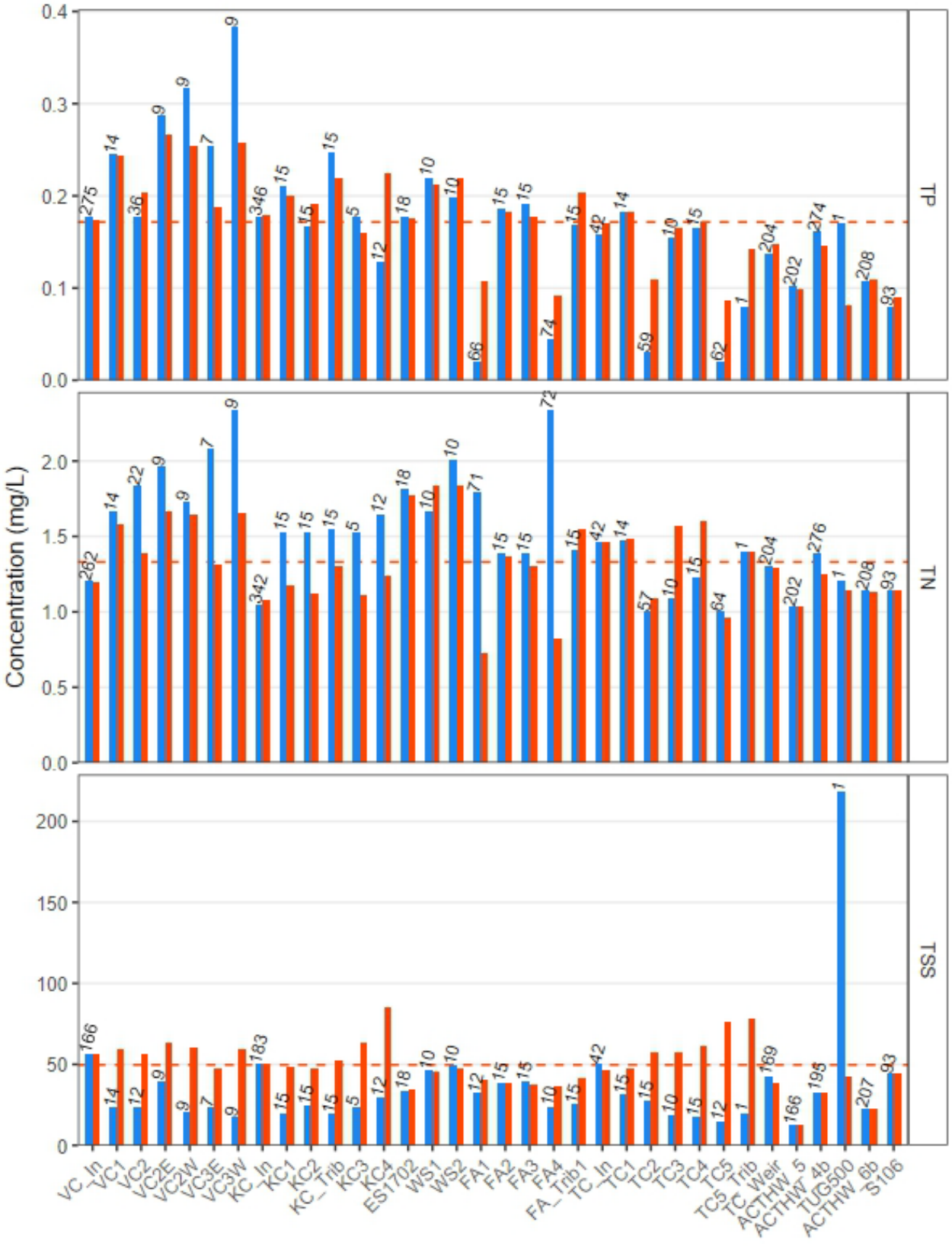

Figure 8. Observed (blue) and modelled (red) median concentrations of total phosphorus (TP; top panel), total nitrogen (TN; middle panel), and total suspended solids (TSS; bottom panel) for each water quality monitoring site in the Lake Tuggeranong catchment. Blue bars are labelled with the number of samples per site analysed for each parameter. The red dashed lines indicate the means of the median modelled concentrations of each pollutant (see text).

Figure 9 illustrates the deviations of modelled from observed site median concentrations for the three water quality parameters, as a function of the number of samples at the monitoring site. A value of zero indicates no bias in the model estimates for that site (i.e. no consistent over- or under-estimation of concentrations, compared to observed values). For all three parameters, deviations decline sharply with increasing sample size. The median deviation for TP is close to zero with a narrow interquartile range, indicating low overall bias. TN deviations are more spread out, with a slight overall positive bias indicated by the median just above zero. TSS deviations have a narrow interquartile range, with a median deviation below zero indicating an overall negative bias, and a notable positive outlier. As for TP and TN, the vast majority of substantial deviations for TSS occur for sites with very low sample sizes.

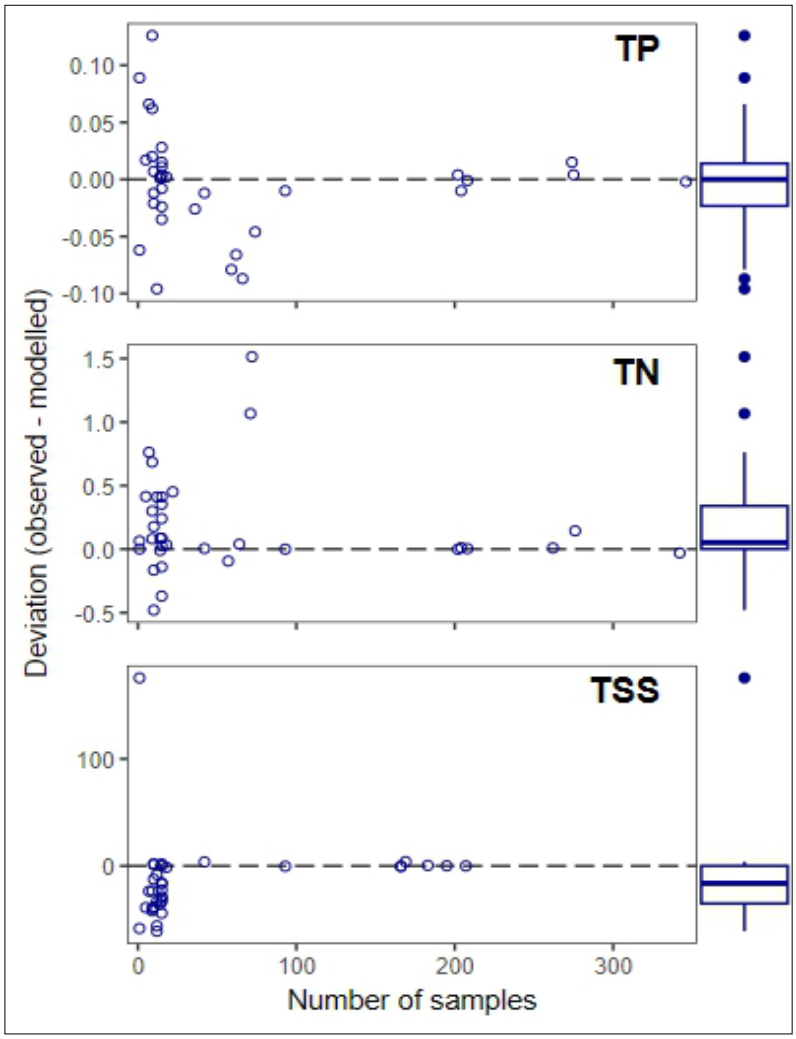

Figure 9. Scatter plots showing the deviation of modelled from observed median concentrations of total phosphorus (TP), total nitrogen (TN), and total suspended solids (TSS) as a function of sample size at 34 water quality monitoring sites in the Lake Tuggeranong catchment. The dashed grey line at zero indicates no bias in the model estimates for a given site. Box-and-whisker plots illustrate the spread of deviations.

4.3 Catchment modelling results

The calibrated catchment model was simulated over the climate period January 1889 – October 2023, and summaries of the total flow and pollutant loads were calculated for each complete year (1889-2022). Under current catchment land use and management conditions, the modelled mean annual inflow to Lake

Tuggeranong was 8.8 GL/year. The modelled mean annual loads of pollutants entering Lake Tuggeranong were 1,442 kg/year total phosphorus, 11,894 kg/year total nitrogen, and 397,064 kg/year total suspended solids.

Figure 10 presents a series of heat maps illustrating the modelled mean annual loads of TP, TN and TSS generated in different subcatchments of the Lake Tuggeranong catchment, with darker shading indicating a higher load. The pollutant load generated depends on the land uses within each subcatchment. The highest mean subcatchment TSS loads fall between 160 – 180 kg/ha/yr. The highest TN loads are between 3.5 – 4 kg/ha/yr, and the highest TP loads are between 0.6 – 0.7 kg/ha/yr. For all three pollutants, higher load generation occurs in more urbanised catchments. This broad visual representation can help in identifying the areas requiring critical attention to improve water quality in the catchment.

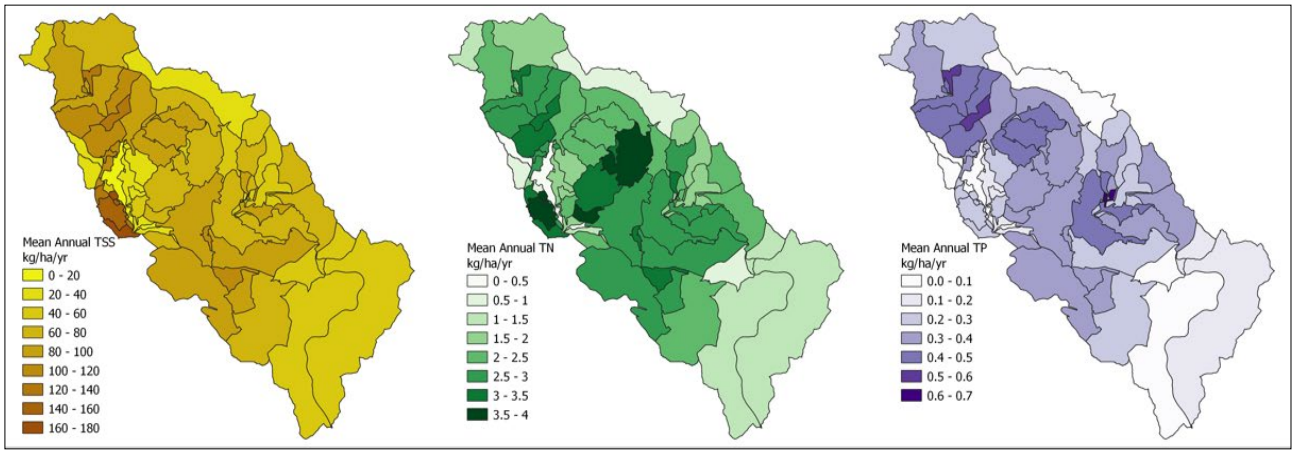

Figure 10. Heat maps of the Lake Tuggeranong catchment for mean annual loads of total suspended solids (TSS, left), total nitrogen (TN, centre) and total phosphorus (TP, right) generated in each subcatchment. Darker shading indicates higher mean annual concentrations.

Figures 11-13 show time-series of modelled daily inflows, pollutant concentrations, and pollutant loads entering Lake Tuggeranong in 2016, a year with a good spread of wet and dry periods. High flow events, likely driven by rainfall, lead to increased runoff, which carries higher concentrations and loads of phosphorus, nitrogen, and suspended solids into the lake. In 2016, the model estimates that the largest flow event saw over 1600 ML enter Lake Tuggeranong in a single day, representing 10% of the total annual inflow that year. This event carried loads of approximately 300 kg TP, 2,500 kg N, and 75,000 kg TSS to the lake, representing 12-13% of the total annual load of each pollutant entering Lake Tuggeranong in 2016. This pattern highlights the impact of storm events on water quality and the importance of managing runoff from the catchment to the lake.

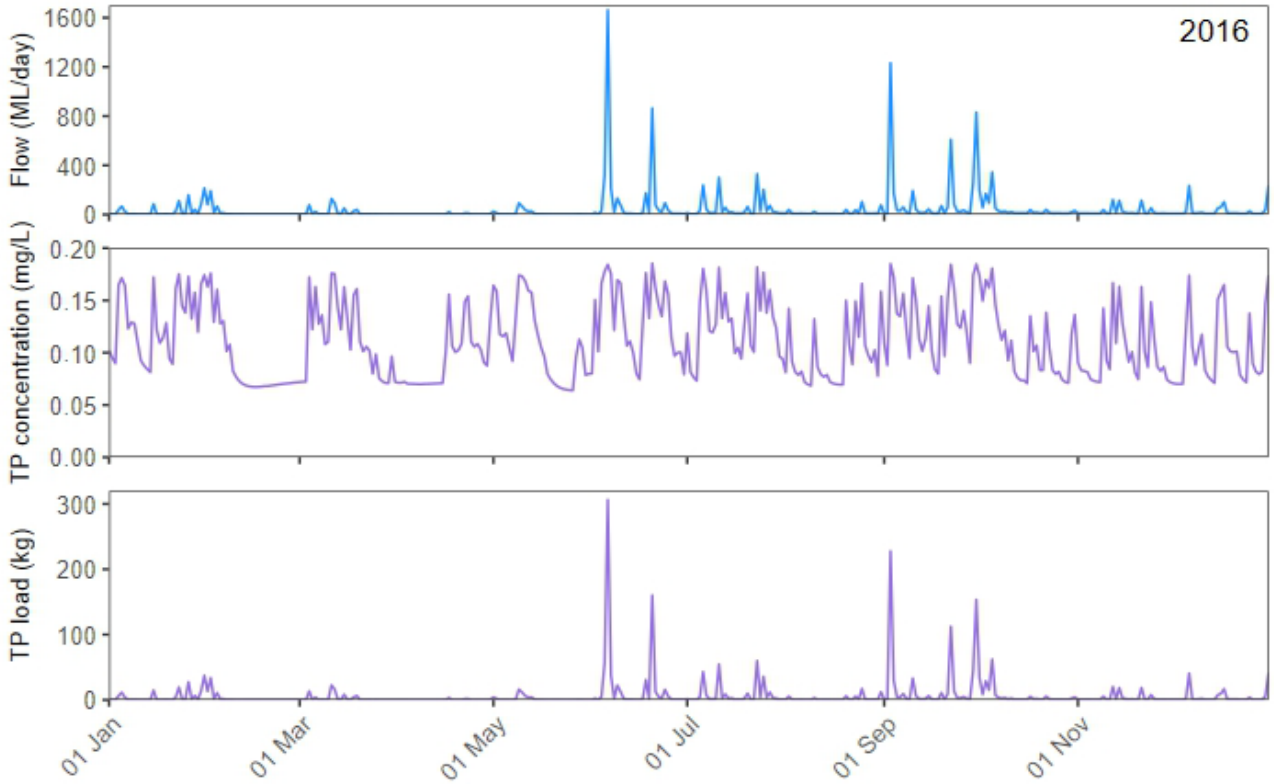

Figure 11. Modelled daily flow and total phosphorus (TP) concentration and load entering Lake Tuggeranong, 2016.

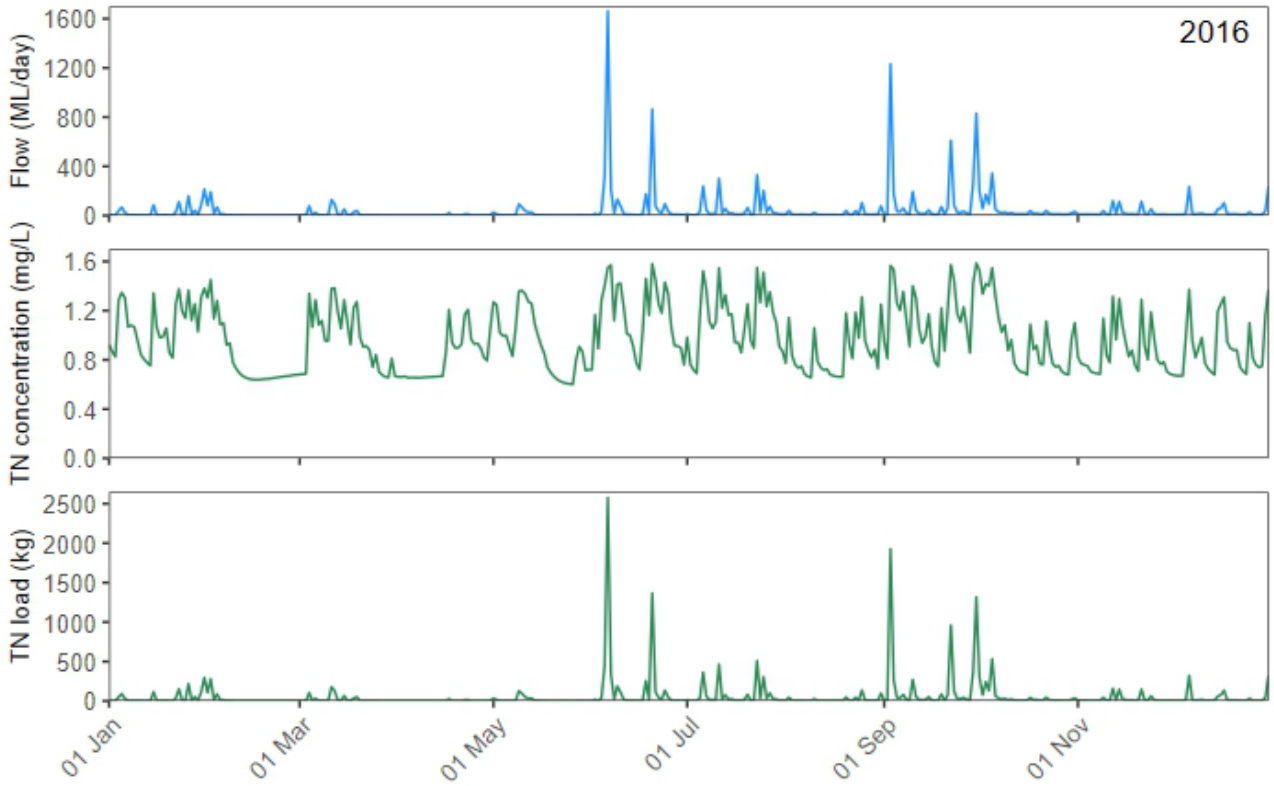

Figure 12. Modelled daily flow and total nitrogen (TN) concentration and load entering Lake Tuggeranong, 2016.

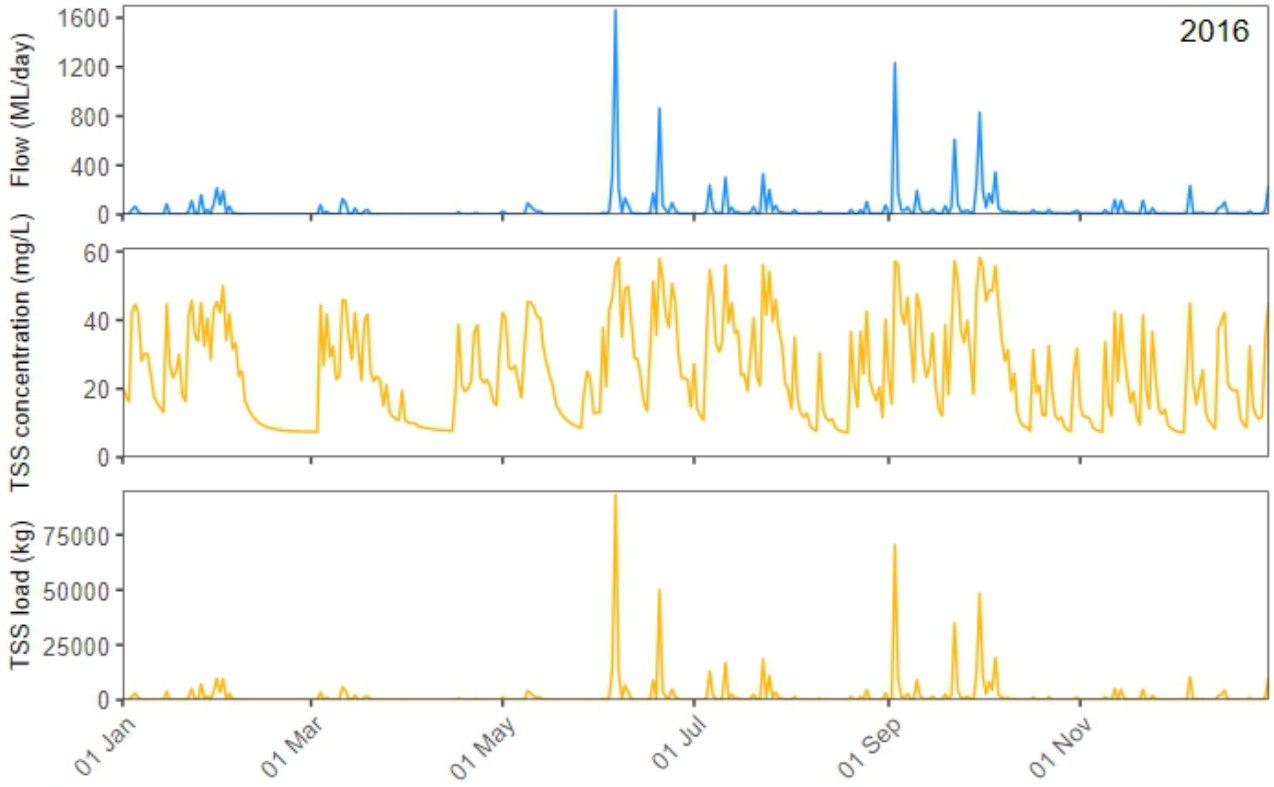

Figure 13. Modelled daily flow and total suspended solids (TSS) concentration and load entering Lake Tuggeranong, 2016.

Figure 14 shows the relationships between daily inflows, concentrations, and loads in 2016 for TP; TN and TSS showed the same patterns in the shape of these relationships.

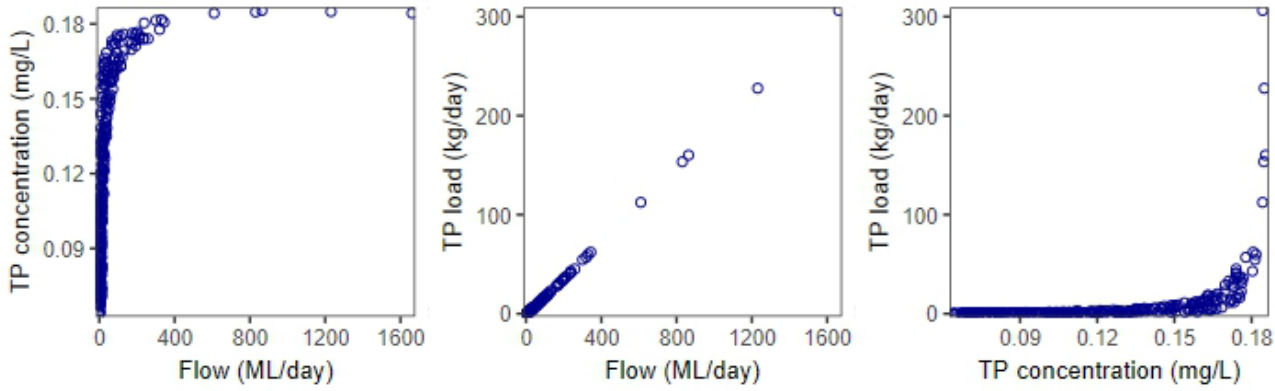

Figure 14. Relationships between the daily inflows and concentrations and loads of total phosphorus (TP) entering Lake Tuggeranong in 2016. The same relationships were seen for total nitrogen and total suspended solids.

4.4 Scenario analysis

4.4.1 Current and predevelopment scenarios

To understand the impact of changes to land use and urban development on the hydrology and water quality of the Lake Tuggeranong catchment, two contrasting land use scenarios were simulated using the

calibrated catchment model. The first, 'current' scenario was the model of current land use and infrastructure conditions described in Section 4.3. Under the current scenario the modelled mean annual inflow to Lake Tuggeranong was approximately 8.8 GL, and the modelled mean annual pollutant loads were 1,442 kg TP, 11,894 kg TN, and 397,064 kg TSS. Figure 15 presents the long-term modelled annual inflow and pollutant loads entering Lake Tuggeranong under the current scenario, for the period 1889-2022.

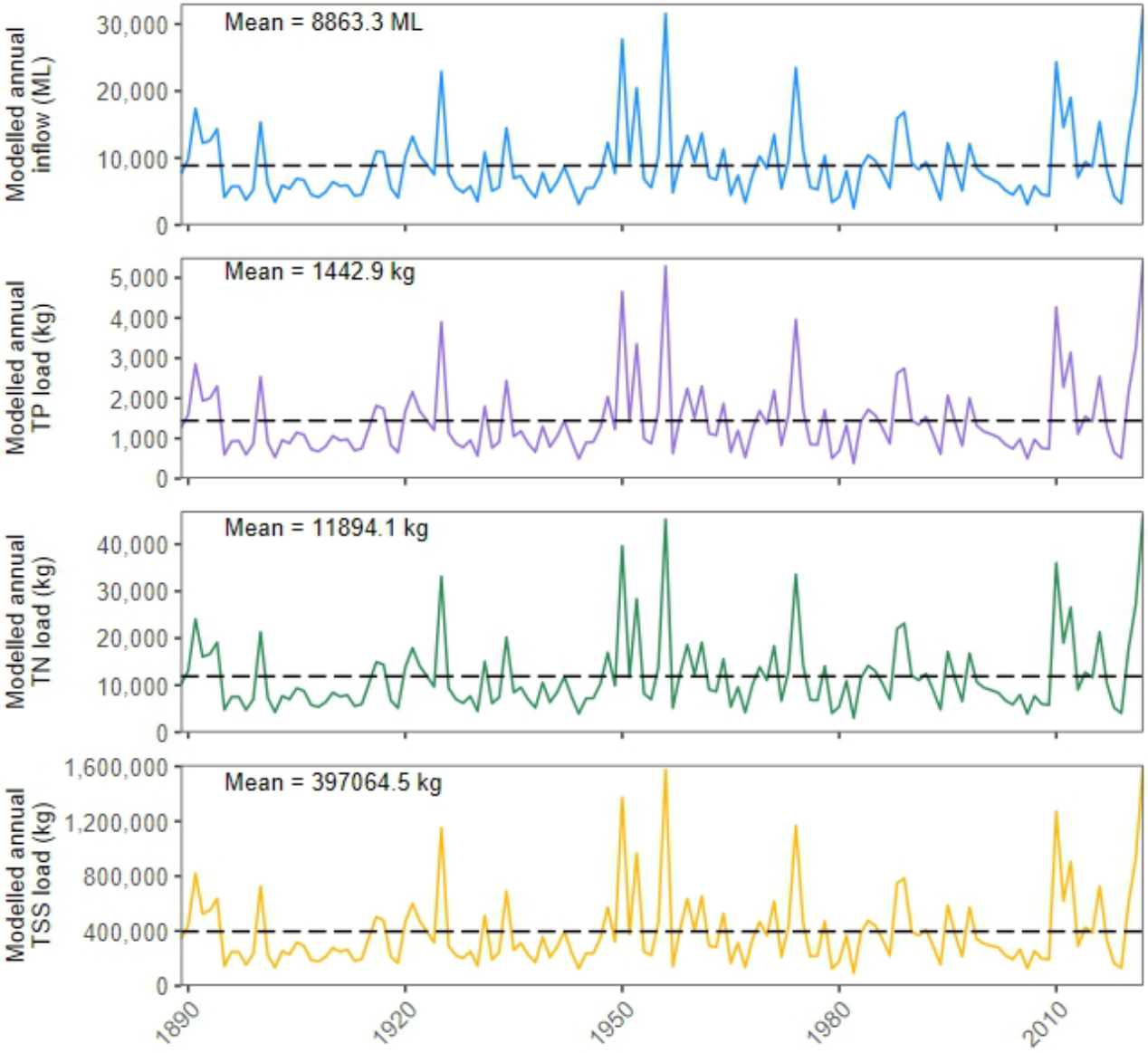

Figure 15. Long-term modelled annual inflows and annual loads of total phosphorus (TP), total nitrogen (TN), and total suspended solids (TSS) entering Lake Tuggeranong under current catchment conditions, for the period 1889 – 2022.

We compared this current scenario to a 'predevelopment' scenario, where all infrastructure (apart from Lake Tuggeranong itself) and developed land uses were removed from the model. Land use for all subcatchments was configured to be entirely bushland, to allow estimation of the runoff and pollutant generation under natural conditions. The results of the predevelopment scenario for the Lake Tuggeranong catchment were validated using the adjacent Jerrabomberra catchment, which has similar geographic conditions, for comparison (see Section 3.1.2). Figure 16 presents the long-term modelled annual inflow and pollutant loads entering Lake Tuggeranong under the predevelopment scenario, for the period 1889-

2022. The mean long-term annual inflow to the lake under predevelopment conditions was approximately 3,268 ML, and the modelled mean annual pollutant loads were 325 kg TP, 2470 kg TN, and 99,673 kg TSS.

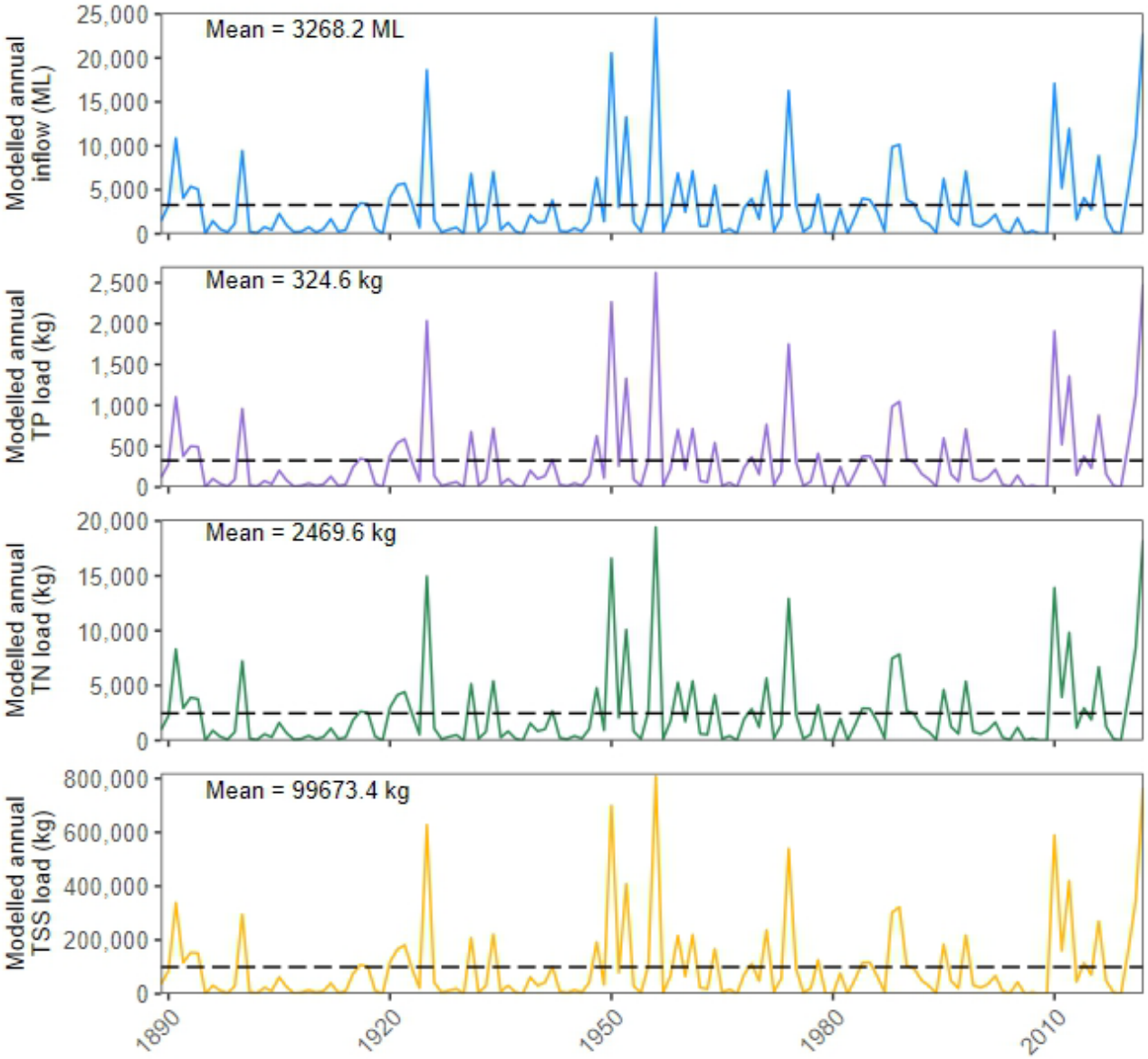

Figure 16. Long-term modelled annual inflows and annual loads of total phosphorus (TP), total nitrogen (TN), and total suspended solids (TSS) entering Lake Tuggeranong under predevelopment catchment conditions, for the period 1889 – 2022.

Table 6 and Figure 17 present comparisons of summary statistics for modelled annual inflows and pollutant loads generated under the current and predevelopment scenarios, for the period 1889-2022. On average, annual inflows to Lake Tuggeranong under predevelopment conditions were 25.5% of annual inflows under current conditions. The reduction in annual inflows, as well as reduced pollution generation modelled from the undeveloped catchment, meant that annual pollutant loads entering Lake Tuggeranong under predevelopment conditions were on average approximately 15% of annual pollutant loads under current conditions.

Table 6. Summary statistics describing modelled annual inflow volumes and loads of total phosphorus (TP), total nitrogen (TN), and total suspended solids (TSS) entering Lake Tuggeranong under the 'current' and 'predevelopment' model scenarios, for the period 1889-2022.

Parameter	Modelled scenario	Minimum	25th percentile	Median	Mean	75th percentile	Maximum
Annual inflow (GL)	Current scenario	2.50	5.39	7.39	8.86	10.37	32.3
Annual inflow (GL)	Predevelopment scenario	0	0.31	1.44	3.27	4.01	24.56
Annual TP load (kg)	Current scenario	377	857	1,176	1,442	1,705	5,412
Annual TP load (kg)	Predevelopment scenario	0	25	133	324	376	2,622
Annual TN load (kg)	Current scenario	3,019	6,893	9,508	11,894	14,100	46,236
Annual TN load (kg)	Predevelopment scenario	0	195	1,041	2,469	2,920	19,420
Annual TSS load (kg)	Current scenario	93,394	221,932	313,352	397,064	471,056	1,607,545
Annual TSS load (kg)	Predevelopment scenario	0	7,558	40,575	99,673	115,094	808,385

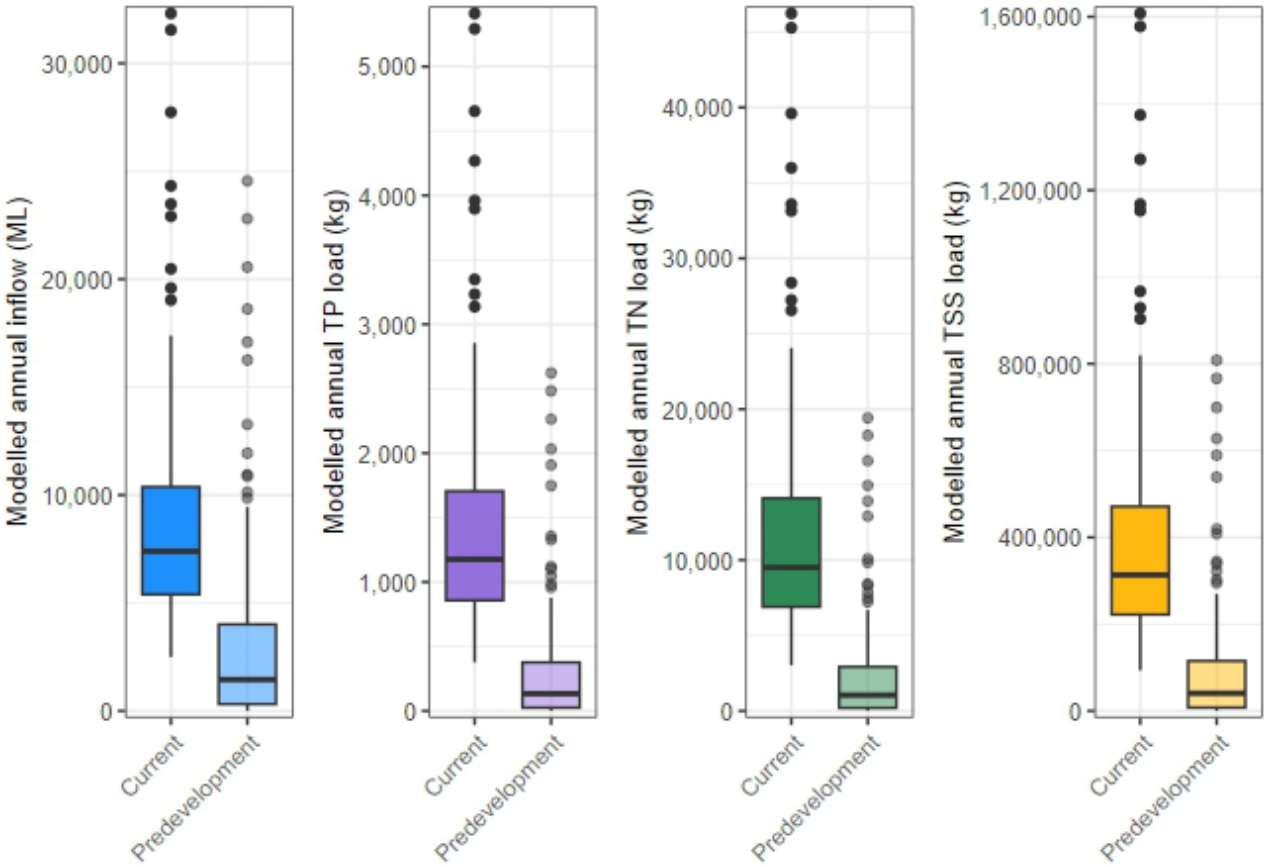

Figure 17. Box-and-whisker plots illustrating the distribution of modelled annual inflows and loads of total phosphorus (TP), total nitrogen (TN), and total suspended solids (TSS) entering Lake Tuggeranong under current and predevelopment catchment conditions, over the period 1889-2022.

Comparing the current and predevelopment scenarios is important for understanding catchment hydrology and pollutant generation before and after development, as well as the impacts of changes in hydrology and pollutant generation on trophic conditions in Lake Tuggeranong. The results from both modelled scenarios were used to parameterise a model of in-lake processes, which estimates the concentrations of phosphorous and chlorophyll a in the lake (Kahn & Dey, 2024). These concentrations were used to predict the distribution of trophic conditions in Lake Tuggeranong under the current and predevelopment scenarios. These analyses help to understand how conditions in the lake are predicted to respond under different inflow and pollutant conditions, and inform management decisions aimed at reducing the occurrence of blue-green algal blooms.

4.4.2 Catchment management option scenarios

The effects of specific management actions aimed at reducing pollutant inputs into the waterways and stormwater network of the Lake Tuggeranong catchment, or filtering or diverting water before it reaches the lake, were investigated in two additional scenarios implemented in the calibrated Source catchment model. Each scenario ('cost-effective' and 'broad benefits') consisted of a combination of different management actions, each with four possible levels of implementation, detailed in the companion to this report, *Lake Tuggeranong Catchment Management Options Assessment* (Booksmythe, Dey, Kahn, Stewart, & Starrs, 2024). The management options included in the two scenarios are detailed in Table 7.

Table 7. Details of the management options included in two scenarios…

Management option	Cost-effective scenario	Broad benefits scenario
Install additional WSUD infrastructure	Investment level 1: install 2 raingardens	Investment level 2: install 5 raingardens
Maintenance of existing WSUD infrastructure	Investment level 3: maintain 4 existing WSUD assets to their designed performance	Investment level 4: maintain 5 existing WSUD assets to their designed performance
Increase frequency of street sweeping	Investment level 4: 48 sweeps per year	Investment level 3: 36 sweeps per year
Manage grass clippings from municipal mowing	Investment level 3: designated street sweeping truck to follow mowers	Investment level 3: designated street sweeping truck to follow mowers
Sports field fertilizer management	Investment level 1: install bioretention swales to intercept 25% of total sports field P	Investment level 3: install bioretention swales to intercept 75% of total sports field P
Household fertilizer management	Investment level 4: very high implementation of community partnership programs aimed at reducing household fertilizer P inputs	Investment level 1: low implementation of community partnership programs aimed at reducing household fertilizer P inputs
Install castellated kerbs	n/a	Investment level 1: install castellated kerb outlets at a rate of 1 per 4 stormwater sumps adjacent to urban open space
Install floating wetlands	n/a	Investment level 4: install 4000 m^2 of floating wetlands
Stormwater recycling for sports field irrigation	Investment level 2: install stormwater recycling infrastructure at 4 sports field sites	Investment level 3: install stormwater recycling infrastructure at 6 sports field sites

Different management actions are implemented in different ways in the catchment model. Some options are explicitly represented by the addition or modification of specified links and nodes in the model:

- **Additional WSUD infrastructure** Proposed raingardens were represented in the catchment model by new storage nodes placed at the locations indicated in the original plans for the raingardens. As for existing assets, each proposed asset was modelled as a splitter node that diverts flow to the asset, and a storage node that applies a water quality decay function, representing the percentage reduction in pollutant loads (TP, TN, and TSS) achieved by the asset. Splitter nodes are configured with a maximum flow rate that is diverted into the asset, and any flow above this bypasses the asset, based on the MUSIC modelled high-flow bypass threshold. The proposed raingarden storage nodes were configured

using the size indicated in the original plans, and the performance details of similar existing WSUD assets.

- **Maintenance of existing WSUD infrastructure** The catchment model includes storage nodes representing each WSUD asset in the Lake Tuggeranong catchment, with the performance of each asset configured to reflect its current phosphorus removal efficiency (Table 2). To represent maintenance of these assets to their designed performance, the performance details were reconfigured to the phosphorus removal rates given in the detailed design reports for each asset.
- **Sports field fertilizer management** For each scenario, we modelled sufficient bioretention swales to intercept the required amount of sports field generated phosphorus (i.e., 25% or 75% of all sports field generated phosphorus, Table 7). We modelled one bioretention swale per subcatchment, starting with the subcatchment containing the largest sports field area, and divided the total swale area across the number of swales included in each scenario, proportionally to the area of sports field in each subcatchment.
    - Each bioretention swale was represented by a storage node configured based on the detailed design of a similar, existing WSUD asset.The percentage removal of TP, TN, and TSS were calculated for each bioretention swale using a MUSIC model consisting of a source, GPT, bioretention, and receiving node.
        - The source node was configured to have the size of the subcatchment's sports field area, and land use set at 100% pervious; remaining parameters used default values.
        - The GPT node was configured with high flow bypass.
        - The bioretention node was configured with size proportional to the subcatchment's sports field area, filter area set to 90% of total swale area, and an extended detention depth of 0.3 m based on recommended MIS08 guidelines; remaining parameters used default values.
        - The MUSIC model for each bioretention swale was run on a 6-minute timestep.
    - As the scale of the catchment model does not delineate sports fields from their subcatchments, a controlled splitter node was added to divert water to the storage node. Because sports fields typically generate higher TP concentrations than the catchment average, but splitters do not allow the adjustment of concentration in the diverted water, we instead increased the load of TP treated by bioretention swales by diverting more water to each sports field storage node. We divided the sports field TP concentration by the subcatchment TP concentration and multiplied this ratio by the proportion of sports field area in the subcatchment, to find the proportion of runoff volume to divert to the storage node.
- **Stormwater recycling infrastructure for sports field irrigation** Each sports field with stormwater recycling infrastructure was represented by a storage node and an irrigator node. A maximum of 1 ML water was diverted to the storage node via a controlled splitter during event flows. The irrigator node was configured as a perennial pasture crop using the crop coefficient from the NSW Environmental Guidelines on the used of effluent by irrigation (NSW Department of Environment and Conservation, 2004), with soil moisture capacity set at 20% and default soil configuration. The subcatchment's sports field area was used to set the size of the irrigated area, determining the water demand for irrigation. Daily rainfall and evapotranspiration (short crop) were obtained from SILO (https://www.longpaddock.qld.gov.au/silo/), covering the climatic period represented in the model (1899 – 2023). During dry periods the irrigation demand specified by the irrigator node was met by the water in the storage node, while in wet periods the demand is first met by rainfall. Excess water was

returned to the stormwater system downstream of the sports field via a link, maintaining water and mass balance.

- **Floating wetlands** To represent floating wetlands in the catchment model, a storage routing link was added just upstream of the Lake Tuggeranong storage node. This was configured using a decay model to reduce the phosphorus concentration in the water passing through the routing link, without affecting water volume. The percentage removal of phosphorus was calculated based on the estimated annual load of TP removed per square metre of floating wetland.

The remaining options cannot be explicitly modelled, and their effects were incorporated in the model by calculating the percentage phosphorus removal attained by each option, compared to the current load of phosphorus available to be intercepted by that option, and adjusting phosphorus concentrations within the catchment model based on these percentage reductions:

- **Household fertilizer management** The percentage reduction in phosphorus concentration due to management of household fertilizer use was applied to all area classified as suburban pervious, and calculated based on the difference in total phosphorus load generated from suburban pervious land across the catchment with and without household fertilizer management.
- **Increase street sweeping frequency | Manage grass clippings from municipal mowing | Install castellated kerbs** The percentage reduction in phosphorus concentration due to these options was applied to all area classified as road. As street sweeping, grass clipping management, and castellated kerbs all act to reduce the load of phosphorus generated from roads, the combined effects of these management options were modelled using a build-up wash-off model (Booksmythe, Dey, Kahn, Stewart, & Starrs, 2024) to predict the total percentage reduction in the phosphorus load from roads for the selected combination of these options in each scenario.

Table 8 presents summary statistics for modelled annual inflows and pollutant loads generated under the cost-effective and broad benefits catchment management scenarios, for the period 1889-2022. The management actions included in these scenarios are not predicted to have a large impact on runoff generation or inflows into Lake Tuggeranong; on average, annual inflows to Lake Tuggeranong under the catchment management scenarios were 97-98% of annual inflows under current conditions. However, the annual TP loads entering Lake Tuggeranong were substantially reduced under the catchment management scenarios. Under the cost-effective scenario annual TP loads were on average approximately 67% of annual TP loads under current conditions, and under the broad benefits scenario annual TP loads were on average approximately 56% of annual TP loads under current conditions.

Table 8. Summary statistics describing modelled annual inflow volumes and loads of total phosphorus (TP) entering Lake Tuggeranong under the 'cost-effective and 'broad benefits' catchment management model scenarios, for the period 1889-2022. Compare to the 'current' scenario, Table 6.

Parameter	Modelled scenario	Minimum	25th percentile	Median	Mean	75th percentile	Maximum
Annual inflow (GL)	Cost-effective scenario	2.36	5.29	7.31	8.76	10.27	32.30
Annual inflow (GL)	Broad benefits scenario	2.31	5.22	7.22	8.64	10.15	31.93
Annual TP load (kg)	Cost-effective scenario	236	551	771	992	1,179	4,076
Annual TP load (kg)	Broad benefits scenario	173	441	639	868	1,041	3,877

5. Summary and future model refinements

5.1 Summary

This report has described the data and methods used to parameterise, configure and calibrate the Lake Tuggeranong catchment model. The model was used to explore four scenarios of different catchment land use and management actions, providing long-term mean annual inflows and pollutant loads to Lake Tuggeranong under each scenario.

The catchment model improves on previous modelling work for the Lake Tuggeranong catchment:

- The model simulates flows and pollutant loads across the Lake Tuggeranong catchment on a daily timestep over 133 years of climate data from 1889-2023.
- The model incorporates updated land use and imperviousness layers to simulate runoff and pollutant generation across six functional land use classes.
- The model is delineated to water quality monitoring locations to facilitate parameterisation with concentrations of three pollutants – total phosphorus (TP), total nitrogen (TN), and total suspended solids (TSS).
- The model is delineated to existing stormwater treatment infrastructure to facilitate estimates of pollutant load reduction after treatment.
- The model hydrology is calibrated to a gauge immediately downstream of Lake Tuggeranong, with a very good fit between observed and modelled flow.
- The model incorporates recently constructed WSUD infrastructure in the Lake Tuggeranong catchment.
- The model incorporates a storage node representing Lake Tuggeranong, simulating flow and pollutant loads entering and leaving the storage.

Key results of the model include:

- Under current catchment land use and management, the model estimates a mean annual inflow to Lake Tuggeranong of approximately 8.8 GL for the period 1889-2022. Under predevelopment conditions, annual flows are on average 75% lower, with an estimated mean annual flow of approximately 3.3 GL.
- Under current catchment land use and management, the model estimates mean annual pollutant loads entering Lake Tuggeranong of 1,442 kg TP, 11,894 kg TN, and 397,064 kg TSS. Under predevelopment conditions, annual pollutant loads to the lake are on average 85% lower.
- By implementing combinations of catchment management options chosen by the ACT Healthy Waterways program, the model estimates that average annual TP loads to Lake Tuggeranong would be reduced to 868-992 kg, a 33-44% decrease compared to current catchment conditions.
- Land use is the major determinant of simulated subcatchment pollutant loads.

5.2 Future model refinements

The reliability and information provided by the Lake Tuggeranong catchment model could be enhanced by improvements to the data used for subcatchment delineation and calibration, and by undertaking assessments of model uncertainty:

- The calibration of water quality (pollutant) estimates in the model was based on observed median concentrations during event flows, which were the only available water quality data. However, observed pollutant loads provide a more robust framework for calibration in Source. Collecting data on pollutant loads requires simultaneous measures of concentration and flow volume and represents a significant change to the water quality and quantity monitoring currently undertaken in the ACT.
- Incorporating observed flow data from additional gauging stations within the Lake Tuggeranong catchment would enhance model reliability by broadening the data available for hydrological calibration.
- Undertaking an uncertainty estimation for the flows and pollutant loads estimated by the catchment model would provide a quantitative assessment of model reliability. Understanding model uncertainty is important when comparing across modelled scenarios, to ensure that differences are explained by modelled management options rather than measurement/estimation error.
- Understanding uncertainty in the model would also allow identification of areas where more hydrological and/or water quality data could improve the reliability of model estimates.

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Appendices

Appendix A: Level-volume-area data for Lake Tuggeranong

To configure the Lake Tuggeranong storage node in the catchment model requires information on the relationship between the water level and volume of the lake. Figure A1 shows the stage-volume rating curve used in configuring the Lake Tuggeranong storage node in the model. The level-volume-area (LVA) relationship for Lake Tuggeranong was derived from bathymetry data collected by Steger and Associates Registered Land Surveyors in 2015, presented in Table A1.

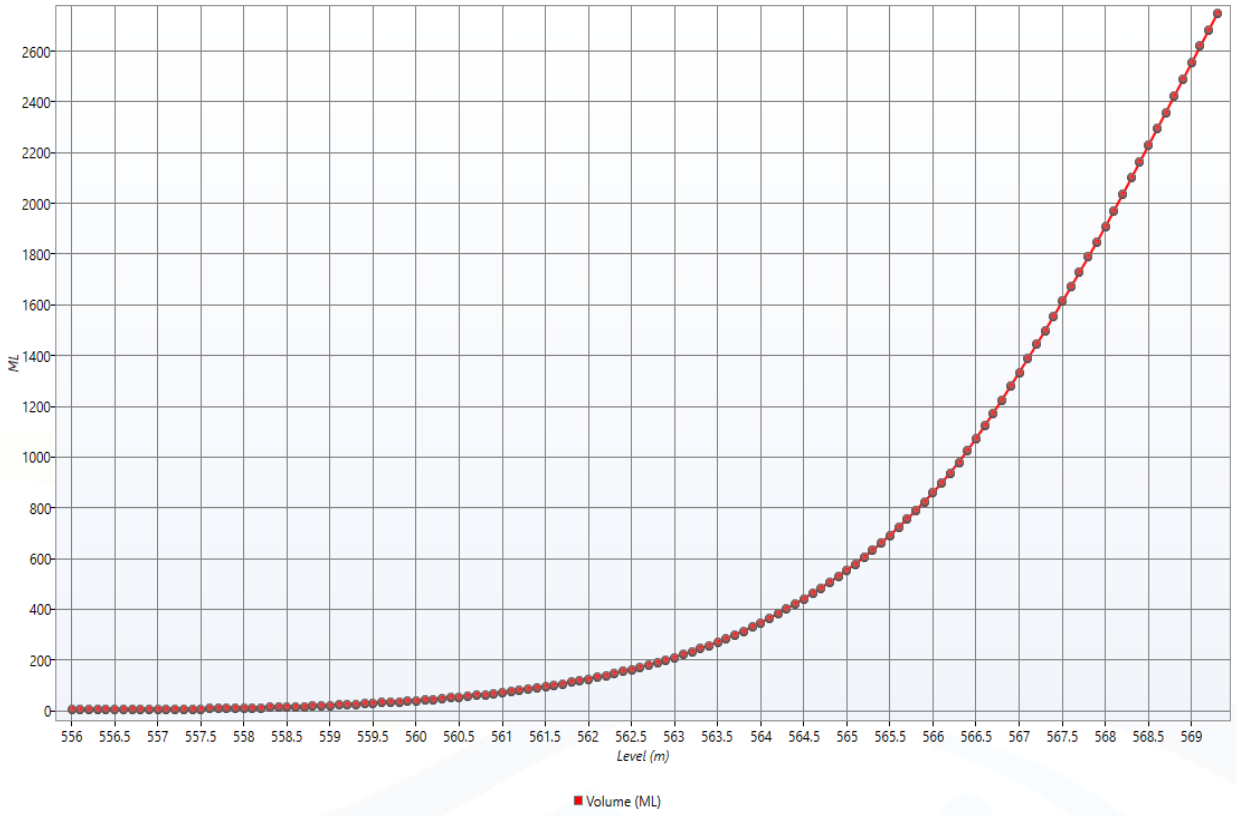

Figure A1. Water level - volume ratings curve for Lake Tuggeranong (gauge 410784) derived from bathymetry data (see Table A1). Source: Steger and Associates Registered Land Surveyors, 2015.

Table A1. Lake Tuggeranong water level, volume, and surface area data. Source: Steger and Associates Registered Land Surveyors, 2015.

Level (m)	Volume (ML)	Surface area (km^2)	Level (m)	Volume (ML)	Surface area (km^2)	Level (m)	Volume (ML)	Surface area (km^2)
556.0	0	0	558.4	10.1361	0.009721	560.8	60.19836	0.035167
556.1	0.014874	0.000119	558.5	11.18874	0.010526	560.9	63.92854	0.037302
556.2	0.036423	0.000215	558.6	12.31101	0.011223	561.0	67.9121	0.039836
556.3	0.072831	0.000364	558.7	13.49978	0.011888	561.1	72.14851	0.042364
556.4	0.122048	0.000492	558.8	14.76326	0.012635	561.2	76.63992	0.044914
556.5	0.222146	0.001001	558.9	16.10082	0.013376	561.3	81.38454	0.047446
556.6	0.374086	0.001519	559.0	17.52169	0.014209	561.4	86.36409	0.049795
556.7	0.570277	0.001962	559.1	19.02266	0.01501	561.5	91.56732	0.052032
556.8	0.808589	0.002383	559.2	20.60679	0.015841	561.6	97.00797	0.054406
556.9	1.104417	0.002958	559.3	22.27321	0.016664	561.7	102.6982	0.056902
557.0	1.442882	0.003385	559.4	24.02014	0.017469	561.8	108.6627	0.059645
557.1	1.824143	0.003813	559.5	25.84861	0.018285	561.9	114.8979	0.062353
557.2	2.241786	0.004176	559.6	27.79639	0.019478	562.0	121.405	0.065071
557.3	2.690724	0.004489	559.7	29.85126	0.020549	562.1	128.2425	0.068375
557.4	3.16953	0.004788	559.8	32.00766	0.021564	562.2	135.4093	0.071668
557.5	3.677818	0.005083	559.9	34.26355	0.022559	562.3	142.8931	0.074838
557.6	4.218615	0.005408	560.0	36.62414	0.023606	562.4	150.7054	0.078123
557.7	4.79095	0.005723	560.1	39.09346	0.024693	562.5	158.8814	0.08176
557.8	5.397505	0.006066	560.2	41.67477	0.025813	562.6	167.4558	0.085744
557.9	6.045165	0.006477	560.3	44.38028	0.027055	562.7	176.4338	0.08978
558.0	6.744306	0.006991	560.4	47.21816	0.028379	562.8	185.8594	0.094256
558.1	7.488318	0.00744	560.5	50.20973	0.029916	562.9	195.7887	0.099293
558.2	8.290076	0.008018	560.6	53.35829	0.031486	563.0	206.241	0.104523
558.3	9.164035	0.00874	560.7	56.6817	0.033234	563.1	217.2403	0.109993

Level (m)	Volume (ML)	Surface area (km²)	Level (m)	Volume (ML)	Surface area (km²)	Level (m)	Volume (ML)	Surface area (km²)
563.2	228.7825	0.115422	565.3	629.1803	0.275842	567.4	1553.159	0.566248
563.3	240.9099	0.121274	565.4	657.9845	0.288043	567.5	1610.312	0.571526
563.4	253.6379	0.12728	565.5	687.9878	0.300033	567.6	1668.006	0.576945
563.5	266.9702	0.133322	565.6	719.1112	0.311234	567.7	1726.277	0.582703
563.6	280.9174	0.139472	565.7	751.5013	0.323901	567.8	1785.19	0.589135
563.7	295.4839	0.145666	565.8	785.1463	0.336449	567.9	1844.844	0.596536
563.8	310.6996	0.152156	565.9	820.0771	0.349308	568.0	1906.38	0.615362
563.9	326.6404	0.159409	566.0	856.4557	0.363786	568.1	1968.905	0.625256
564.0	343.3933	0.167529	566.1	894.2724	0.378167	568.2	2032.357	0.634518
564.1	360.9095	0.175162	566.2	934.0697	0.397974	568.3	2096.546	0.641889
564.2	379.1175	0.18208	566.3	976.8441	0.427744	568.4	2161.172	0.646257
564.3	398.0267	0.189093	566.4	1022.38	0.455357	568.5	2226.008	0.648362
564.4	417.6585	0.196317	566.5	1070.137	0.477574	568.5	2226.008	0.648362
564.5	437.9539	0.202954	566.6	1119.482	0.493452	568.6	2290.955	0.649472
564.6	458.8675	0.209136	566.7	1170.426	0.509434	568.7	2355.947	0.649921
564.7	480.4328	0.215652	566.8	1222.593	0.521672	568.8	2420.965	0.650178
564.8	502.7146	0.222818	566.9	1275.738	0.531451	568.9	2485.993	0.650283
564.9	525.8767	0.231621	567.0	1329.908	0.541698	569.0	2551.028	0.650344
565.0	549.963	0.240863	567.1	1384.869	0.549609	569.1	2616.068	0.650402
565.1	575.1935	0.252304	567.2	1440.435	0.555666	569.2	2681.113	0.650454
565.2	601.5961	0.264027	567.3	1496.534	0.56099	569.3	2746.163	0.650495

Appendix B: Level – discharge data for Lake Tuggeranong outflow

The Lake Tuggeranong outflow was configured as an ungated spillway in the Source model, using the level-discharge relationship from Lake Tuggeranong weir (gauge 410784), presented in Table B1.

Table B1. Lake Tuggeranong weir rating table. *Source: ALS Pty Ltd.*

Level (m)	Discharge (ML/d)	Level (m)	Discharge (ML/d)	Level (m)	Discharge (ML/d)	Level (m)	Discharge (ML/d)
0	0	568.14	740.448	568.43	3957.12	568.72	9072
567.86	0	568.15	809.568	568.44	4121.28	568.73	9244.8
567.87	1.08	568.16	881.28	568.45	4285.44	568.74	9417.6
567.88	6.10848	568.17	959.04	568.46	4458.24	568.75	9676.8
567.89	16.848	568.18	1036.8	568.47	4631.04	568.76	9849.6
567.90	34.56	568.19	1123.2	568.48	4812.48	568.77	10022.4
567.91	41.2992	568.20	1209.6	568.49	4993.92	568.78	10281.6
567.92	48.816	568.21	1296	568.50	5184	568.79	10454.4
567.93	57.1104	568.22	1382.4	568.51	5339.52	568.80	10713.6
567.94	66.096	568.23	1468.8	568.52	5503.68	568.81	10886.4
567.95	76.032	568.24	1563.84	568.53	5667.84	568.82	11059.2
567.96	86.4	568.25	1667.52	568.54	5840.64	568.83	11318.4
567.97	98.496	568.26	1771.2	568.55	6013.44	568.84	11491.2
567.98	110.592	568.27	1874.88	568.56	6186.24	568.85	11664
567.99	124.416	568.28	1978.56	568.57	6359.04	568.86	11923.2
568.00	138.24	568.29	2090.88	568.58	6540.48	568.87	12096
568.01	162.432	568.30	2211.84	568.59	6721.92	568.88	12355.2
568.02	189.216	568.31	2324.16	568.60	6912	568.89	12528
568.03	219.456	568.32	2436.48	568.61	7076.16	568.90	12700.8
568.04	251.424	568.33	2557.44	568.62	7240.32	568.91	12960
568.05	285.984	568.34	2678.4	568.63	7404.48	568.92	13132.8
568.06	323.136	568.35	2808	568.64	7577.28	568.93	13392
568.07	362.88	568.36	2937.6	568.65	7750.08	568.94	13564.8
568.08	406.08	568.37	3067.2	568.66	7922.88	568.95	13824
568.09	451.872	568.38	3205.44	568.67	8095.68	568.96	13996.8
568.10	501.12	568.39	3343.68	568.68	8277.12	568.97	14256
568.11	555.552	568.40	3490.56	568.69	8458.56	568.98	14428.8
568.12	613.44	568.41	3646.08	568.70	8640	568.99	14601.6
568.13	675.648	568.42	3801.6	568.71	8812.8		

Appendix C: Land use and imperviousness classification

Table C1 lists the detailed land use classifications included in each of the six functional land use units defined for the Lake Tuggeranong catchment. Table C2 provides a breakdown of the major and minor subcatchments delineated in the Source catchment model, and Figure C1 shows a map of the major subcatchments. Table C3 provides the subcatchment area breakdown in hectares and area ratio based on land use functional units used in the catchment model.

Table C1. Detailed land use classifications based on ACT Government land zoning grouped into 6 functional units for use in the catchment model.

ACT land zoning	Functional unit
Business zone	commercial
Community Facilities	commercial
Core zone	commercial
Leisure and accommodation	commercial
Local centre	commercial
Services	commercial
Services zone	commercial
Medium density residential	suburban
Suburban	suburban
Suburban core	suburban
Transport	open space
Urban open space	open space
Restricted access recreation zone	open space
Hills ridges and buffer areas	bushland
Designated	bushland
River corridor	bushland
Rural	rural
Sports field (estimated)	sports field

Table C2. Major subcatchments of the Lake Tuggeranong catchment and their component minor subcatchments delineated in the Source catchment model.

Major subcatchment	Minor subcatchments
Village Creek (VC)	VC0, VC1, VC2, VC3, VC4, VC6, VC7, VC8, VC9, VC10, VC11
Kambah Creek (KC)	KC0, KC1, KC2, KC3, KC4, KC5, KC6, KC7
Tuggeranong Creek (TC)	TC0, TC1, TC2, TC3, TC4, TC5, TC6, TC7, TC6_NSW, TC8_NSW
Lake Tuggeranong (Lake T)	
East Lake (EL)	EL1, EL2
West Lake (WL)	WL0, WL1, WL2, WL3, WL4, WL5, WL6, WL7, WL8, WL9, WL10, WL11
Downstream of Lake Tuggeranong (DSL)	DSL1, DSL2
Drakeford Drive South (DDS)	DDS1, DDS2
(DLC)	DLC_N, DLC_S
Stranger Pond (SP)	SP1, SP2
Wanniassa (WS)	WS0, WS1, WS2, WS3, WS4
Fadden stormwater (FA)	FA0, FA1, FA2, FA3, FA5, FA6, FA7, FA8, FA9, FA10, FA11, FA12, FA13, FA14, FA15, FA16, FA17, FA9_NSW

Fig. C1. Map of Lake Tuggeranong catchment showing major subcatchment boundaries. VC, Village Creek; KC, Kambah Creek; WS, Wanniassa; FA, Fadden stormwater; TC, Tuggeranong Creek; DSL, Downstream of Lake Tuggeranong; Lake T, Lake Tuggeranong; DLC, XXX; WL, West Lake; EL, East Lake; DDS, Drakeford Drive South; SP, Stranger Pond.

Table C3. Area of land use functional units within Lake Tuggeranong subcatchments (see Table C2), in hectares (ha) and as a percentage of subcatchment area (%).

Functional unit	VC0 (ha)	VC0 (%)	VC1 (ha)	VC1 (%)	VC2 (ha)	VC2 (%)	VC3 (ha)	VC3 (%)	VC4 (ha)	VC4 (%)	VC6 (ha)	VC6 (%)
Commercial road	1.16654	1.28342	0.55272	1.45670	0.06191	0.06184	0.00053	0.00081	0.00000	0.00000	0.52402	2.40107
Commercial hardstand	2.96745	3.26478	3.54531	9.34381	0.09628	0.09617	0.75895	1.17555	0.72954	0.59131	1.30516	5.98024
Commercial roof	3.62099	3.98381	3.96793	10.45763	0.40466	0.40420	0.96058	1.48785	0.96820	0.78476	1.85026	8.47786
Commercial pervious	3.42116	3.76396	2.91630	7.68602	0.33240	0.33202	2.63463	4.08081	1.87153	1.51694	1.60472	7.35280
Commercial water	0	0	0	0	0	0	0	0	0	0	0	0
Suburban road	3.73592	4.11026	1.45375	3.83141	5.77357	5.76696	3.69303	5.72018	6.43127	5.21276	0.40714	1.86552
Suburban hardstand	5.17332	5.69168	1.37583	3.62604	5.56696	5.56059	2.89318	4.48128	5.92845	4.80520	0.73999	3.39064
Suburban roof	17.15034	18.86877	4.56512	12.03155	22.63823	22.61229	11.73104	18.17036	22.69013	18.39110	2.30035	10.54015
Suburban pervious	29.87385	32.86716	7.64501	20.14873	38.47253	38.42845	20.42040	31.62942	36.44461	29.53956	2.69231	12.33615
Suburban water	0	0	0	0	0.01395	0.01393	2.50E-05	3.87E-05	0.00095	0.00077	0	0
Open space road	4.47567	4.92413	2.24256	5.91036	4.15447	4.14971	2.77265	4.29460	4.04727	3.28044	1.83831	8.42312
Open space hardstand	1.61398	1.77570	0.76704	2.02155	2.45150	2.44869	1.30548	2.02207	3.76469	3.05140	0.72845	3.33773
Open space roof	0.20061	0.22071	0.07460	0.19661	0.48495	0.48439	0.25650	0.39730	0.80075	0.64903	0.14520	0.66532
Open space pervious	14.24994	15.67776	8.83674	23.28958	12.97204	12.95718	16.26664	25.19562	29.51479	23.92272	7.48905	34.31473
Open space water	0.03960	0.04357	0	0	0	0	0	0	0	0	0.19962	0.91466
Bushland road	0	0	0	0	0	0	0	0	0	0	0	0
Bushland hardstand	0.04743	0.05218	0	0	0.24205	0.24177	0	0	0	0	0	0
Bushland roof	0.00363	0.00399	0	0	0.00097	0.00097	0	0	0	0	0	0
Bushland pervious	3.15228	3.46813	0	0	6.44823	6.44084	0	0	0	0	0	0
Bushland water	0	0	0	0	0	0	0	0	0	0	0	0
Rural road	0	0	0	0	0	0	0	0	0	0	0	0
Rural hardstand	0	0	0	0	0	0	0	0	0	0	0	0
Rural roof	0	0	0	0	0	0	0	0	0	0	0	0
Rural pervious	0	0	0	0	0	0	0	0	0	0	0	0
Rural water	0	0	0	0	0	0	0	0	0	0	0	0
Sports field	0	0	0	0	0	0	0.86778	1.34411	10.18341	8.25399	0	0
Total subcatchment area	90.89270	100	37.94290	100	100.11470	100	64.56140	100	123.37560	100	21.82460	100

Table C3 cont. Area of land use functional units within Lake Tuggeranong subcatchments (see Table C2), in hectares (ha) and as a percentage of subcatchment area (%).

Functional unit	VC7 (ha)	VC7 (%)	VC8 (ha)	VC8 (%)	VC9 (ha)	VC9 (%)	VC10 (ha)	VC10 (%)	VC11 (ha)	VC11 (%)	Lake T (ha)	Lake T (%)
Commercial road	0	0	0	0	0.01835	0.00688	0	0	0	0	0	0
Commercial hardstand	0	0	0	0	1.02446	0.38388	1.19452	0.64653	0	0	0	0
Commercial roof	0	0	0	0	0.62828	0.23543	1.79132	0.96955	0	0	0	0
Commercial pervious	0	0	0	0	2.96747	1.11196	4.26940	2.31081	0	0	0	0
Commercial water	0	0	0	0	0	0	0	0	0	0	0	0
Suburban road	0.31054	9.59627	0.00158	0.03398	5.07906	1.90321	10.61841	5.74720	2.75089	3.36567	0	0
Suburban hardstand	0.24232	7.48839	0.00455	0.09815	3.93032	1.47275	6.24872	3.38211	1.53092	1.87306	0	0
Suburban roof	0.71997	22.24891	0.00000	0.00000	17.65425	6.61534	29.89265	16.17935	8.30131	10.15654	0	0
Suburban pervious	1.00224	30.97160	0.09433	2.03477	29.37379	11.00684	51.34650	27.79122	16.30805	19.95268	0	0
Suburban water	0	0	0	0	0	0	0	0	2.50E-05	3.06E-05	0	0
Open space road	0.01912	0.59088	0.73261	15.80361	9.13640	3.42356	3.42844	1.85564	0.08557	0.10470	0.16068	0.22103
Open space hardstand	0.07169	2.21524	0.14298	3.08425	4.31557	1.61712	2.79452	1.51253	0.16162	0.19775	0.31379	0.43165
Open space roof	0.01592	0.49202	0.02103	0.45355	0.45775	0.17152	0.31814	0.17220	0.01235	0.01511	0.30226	0.41579
Open space pervious	0.85420	26.39669	3.63864	78.49169	44.29813	16.59923	34.55149	18.70095	5.38125	6.58389	2.76054	3.79745
Open space water	0	0	0	0	0.17846	0.06687	0	0	0	0	69.15733	95.13407
Bushland road	0	0	0	0	3.77569	1.41481	0.43221	0.23393	1.15907	1.41811	0	0
Bushland hardstand	0	0	0	0	1.75254	0.65671	0.10256	0.05551	0.23837	0.29165	0	0
Bushland roof	0	0	0	0	0.24923	0.09339	0.00665	0.00360	0.11275	0.13795	0	0
Bushland pervious	0	0	0	0	142.00602	53.21198	30.50463	16.51058	45.69143	55.90287	0	0
Bushland water	0	0	0	0	0.02273	0.00852	0	0	0	0	0	0
Rural road	0	0	0	0	0	0	0	0	0	0	0	0
Rural hardstand	0	0	0	0	0	0	0	0	0	0	0	0
Rural roof	0	0	0	0	0	0	0	0	0	0	0	0
Rural pervious	0	0	0	0	0	0	0	0	0	0	0	0
Rural water	0	0	0	0	0	0	0	0	0	0	0	0
Sports field	0	0	0	0	0	0	7.25782	3.92829	0	0	0	0
Total subcatchment area	3.23600	100	4.63570	100	266.86850	100	184.75800	100	81.73360	100	72.69460	100

Table C3 cont. Area of land use functional units within Lake Tuggeranong subcatchments (see Table C2), in hectares (ha) and as a percentage of subcatchment area (%).

Functional unit	KC0 (ha)	KC0 (%)	KC1 (ha)	KC1 (%)	KC2 (ha)	KC2 (%)	KC3 (ha)	KC3 (%)	KC4 (ha)	KC4 (%)	KC5 (ha)	KC5 (%)
Commercial road	0	0	0	0	0	0	0	0	0	0	0.22272	0.32619
Commercial hardstand	0.23590	0.18352	0.10135	0.12613	0.11103	0.12613	0.00800	0.12613	0.00045	0.02089	1.68770	2.47178
Commercial roof	0.46683	0.36317	0.10200	0.12693	0.11174	0.12693	0.00805	0.12693	0.00003	0.00116	1.91152	2.79958
Commercial pervious	0.80327	0.62490	0.02740	0.03410	0.03002	0.03410	0.00216	0.03410	0.01793	0.83192	2.24089	3.28197
Commercial water	0	0	0	0	0	0	0	0	0	0	0	0
Suburban road	7.27826	5.66213	6.20275	7.71915	6.79539	7.71915	0.48981	7.71915	0.00000	0.00000	4.54340	6.65420
Suburban hardstand	7.37201	5.73507	5.85418	7.28537	6.41351	7.28537	0.46229	7.28537	0.02456	1.13940	4.10095	6.00621
Suburban roof	28.02338	21.80082	19.67904	24.49003	21.55926	24.49003	1.55399	24.49003	0.15034	6.97445	14.86127	21.76563
Suburban pervious	45.12123	35.10210	33.59659	41.81005	36.80656	41.81005	2.65302	41.81005	0.19061	8.84250	26.44537	38.73156
Suburban water	0	0	0	0	0	0	0	0	5.00E-05	0.00232	2.50E-05	3.66E-05
Open space road	6.75730	5.25685	2.59264	3.22647	2.84036	3.22647	0.20473	3.22647	0.00375	0.17404	2.08079	3.04750
Open space hardstand	2.98208	2.31991	1.45161	1.80649	1.59030	1.80649	0.11463	1.80649	0.41023	19.03093	1.24580	1.82459
Open space roof	0.23348	0.18164	0.19942	0.24818	0.21848	0.24818	0.01575	0.24818	0.06228	2.88910	0.11700	0.17135
Open space pervious	29.18828	22.70705	10.54832	13.12710	11.55616	13.12710	0.83297	13.12710	1.29149	59.91344	8.08024	11.83421
Open space water	0.01618	0.01258	0	0	0	0	0	0	0	0	0	0
Bushland road	0	0	0	0	0	0	0	0	0	0	0	0
Bushland hardstand	0	0	0	0	0	0	0	0	0	0	0	0
Bushland roof	0	0	0	0	0	0	0	0	0	0	0	0
Bushland pervious	0	0	0	0	0	0	0	0	0	0	0	0
Bushland water	0	0	0	0	0	0	0	0	0	0	0	0
Rural road	0	0	0	0	0	0	0	0	0	0	0	0
Rural hardstand	0	0	0	0	0	0	0	0	0	0	0	0
Rural roof	0	0	0	0	0	0	0	0	0	0	0	0
Rural pervious	0	0	0	0	0	0	0	0	0	0	0	0
Rural water	0	0	0	0	0	0	0	0	0	0	0	0
Sports field	0	0	0	0	0	0	0	0	0.00388	0.17984	0.74094	1.08517
Total subcatchment area	128.54280	100	80.35530	100	88.03280	100	6.34540	100	2.15560	100	68.27860	100

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Table C3 cont. Area of land use functional units within Lake Tuggeranong subcatchments (see Table C2), in hectares (ha) and as a percentage of subcatchment area (%).

Functional unit	KC6 (ha)	KC6 (%)	KC7 (ha)	KC7 (%)	SP1 (ha)	SP1 (%)	SP2 (ha)	SP2 (%)	EL1 (ha)	EL1 (%)	EL2 (ha)	EL2 (%)
Commercial road	0	0	0	0	0.34455	0.09473	0.25623	0.65596	0	0	0.1566	0.8058
Commercial hardstand	0.06448	0.04990	0	0	2.55082	0.70133	0.34418	0.88112	0	0	0.7782	4.0044
Commercial roof	0.08659	0.06701	0	0	2.85592	0.78521	1.33480	3.41714	0	0	1.1017	5.6688
Commercial pervious	0.00426	0.00329	0	0	8.95477	2.46205	1.59170	4.07482	0	0	1.6979	8.7366
Commercial water	0	0	0	0	0	0	0	0	0	0	0	0
Suburban road	6.73670	5.21343	0	0	16.71164	4.59474	0.75529	1.93357	1.96217	3.10053	0	0
Suburban hardstand	6.08694	4.71059	0	0	21.71844	5.97132	2.18503	5.59379	5.25066	8.29684	0	0
Suburban roof	23.68161	18.32684	0	0	73.29687	20.15242	5.26468	13.47782	7.70244	12.17103	0.00198	0.01016
Suburban pervious	41.86302	32.39716	0	0	102.74356	28.24856	5.68414	14.55165	10.69712	16.90309	0.03886	0.19994
Suburban water	0	0	0	0	0.00210	0.00058	0	0	0	0	0	0
Open space road	5.30084	4.10224	2.16018	0.69905	12.17165	3.34650	1.47995	3.78873	1.76602	2.79058	1.38581	7.13058
Open space hardstand	2.65729	2.05644	2.24234	0.72564	5.34020	1.46825	1.23752	3.16811	2.27993	3.60263	0.97812	5.03284
Open space roof	0.16133	0.12485	0.10101	0.03269	0.58110	0.15977	0.09868	0.25262	0.39105	0.61793	0.08547	0.43977
Open space pervious	38.37112	29.69483	13.61355	4.40542	58.24083	16.01287	12.63747	32.35250	32.93501	52.04237	12.78198	65.76885
Open space water	0	0	0	0	0	0	4.32094	11.06181	0.30060	0.47500	0.06847	0.35228
Bushland road	0	0	6.17691	1.99888	0.86652	0.23824	0	0	0	0	0	0
Bushland hardstand	0.00225	0.00174	2.42975	0.78628	0.74172	0.20393	0	0	0	0	0	0
Bushland roof	0.00093	0.00072	1.47904	0.47863	0.70985	0.19517	0	0	0	0	0	0
Bushland pervious	4.20082	3.25095	280.72872	90.84543	52.08091	14.31925	0	0	0	0	0	0
Bushland water	0	0	0.08650	0.02799	0	0	0	0	0	0	0	0
Rural road	0	0	0	0	0	0	0	0	0	0	0	0
Rural hardstand	0	0	0	0	0	0	0	0	0	0	0	0
Rural roof	0	0	0	0	0	0	0	0	0	0	0	0
Rural pervious	0	0	0	0	0	0	0	0	0	0	0	0
Rural water	0	0	0	0	0	0	0	0	0	0	0	0
Sports field	0	0	0	0	3.80112	1.04509	1.87120	4.79037	0	0	0.35953	1.84994
Total subcatchment area	129.21820	100	309.01800	100	363.71260	100	39.06180	100	63.28500	100	19.43470	100

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Table C3 cont. Area of land use functional units within Lake Tuggeranong subcatchments (see Table C2), in hectares (ha) and as a percentage of subcatchment area (%).

Functional unit	WL0 (ha)	WL0 (%)	WL1 (ha)	WL1 (%)	WL2 (ha)	WL2 (%)	WL3 (ha)	WL3 (%)	WL4 (ha)	WL4 (%)	WL5 (ha)	WL5 (%)
Commercial road	4.3703	7.9703	0.8347	3.1681	1.0011	6.7299	0	0	0.62984	11.02963	0	0
Commercial hardstand	11.5970	21.1500	6.8472	25.9884	1.2159	8.1740	0.00085	0.01072	2.13908	37.45934	0	0
Commercial roof	25.6801	46.8340	5.6090	21.2888	4.2901	28.8403	0.00085	0.01072	1.99816	34.99153	0	0
Commercial pervious	4.4233	8.0669	3.4839	13.2230	2.1629	14.5404	0.00355	0.04478	0.60119	10.52793	0.13435	2.80000
Commercial water	0	0	0	0	0	0	0	0	0	0	0	0
Suburban road	0	0	0.01252	0.04754	0	0	0	0	0	0	0	0
Suburban hardstand	0	0	0.10727	0.40713	0	0	0	0	0	0	0	0
Suburban roof	0	0	0.09979	0.37877	0	0	0	0	0	0	0	0
Suburban pervious	0	0	0.23981	0.91019	0	0	0	0	0	0	0	0
Suburban water	0	0	0	0	0	0	0	0	0	0	0	0
Open space road	3.84955	7.02060	3.52733	13.38791	2.07414	13.94361	0.01007	0.12708	0.00397	0.06961	0.76260	15.89337
Open space hardstand	2.01038	3.66643	0.97456	3.69894	1.33538	8.97721	0.81178	10.24202	0.06327	1.10804	0.59875	12.47873
Open space roof	0.65246	1.18991	0.17189	0.65240	0.72916	4.90187	0.14906	1.88065	0.04205	0.73636	0.43773	9.12289
Open space pervious	2.24307	4.09078	4.41994	16.77583	2.06527	13.88395	6.94281	87.59543	0.22977	4.02371	2.82017	58.77550
Open space water	0.00605	0.01103	0.01925	0.07306	0	0	0.00702	0.08861	0.00307	0.05385	0.00874	0.18216
Bushland road	0	0	0	0	0	0	0	0	0	0	0	0
Bushland hardstand	0	0	0	0	0	0	0	0	0	0	0	0
Bushland roof	0	0	0	0	0	0	0	0	0	0	0	0
Bushland pervious	0	0	0	0	0.00130	0.00874	0	0	0	0	0.03586	0.74736
Bushland water	0	0	0	0	0	0	0	0	0	0	0	0
Rural road	0	0	0	0	0	0	0	0	0	0	0	0
Rural hardstand	0	0	0	0	0	0	0	0	0	0	0	0
Rural roof	0	0	0	0	0	0	0	0	0	0	0	0
Rural pervious	0	0	0	0	0	0	0	0	0	0	0	0
Rural water	0	0	0	0	0	0	0	0	0	0	0	0
Sports field	0	0	0	0	0	0	0	0	0	0	0	0
Total subcatchment area	54.83220	100	26.34710	100	14.87520	100	7.92600	100	5.71040	100	4.79820	100

Table C3 cont. Area of land use functional units within Lake Tuggeranong subcatchments (see Table C2), in hectares (ha) and as a percentage of subcatchment area (%).

Functional unit	WL6 (ha)	WL6 (%)	WL7 (ha)	WL7 (%)	WL8 (ha)	WL8 (%)	WL9 (ha)	WL9 (%)	WL10 (ha)	WL10 (%)	WL11 (ha)	WL11 (%)
Commercial road	0.22090	9.12689	0.48320	9.59071	0.10770	9.94735	0	0	0.00152	0.00688	0.00052	0.00688
Commercial hardstand	0.75873	31.34842	0.70091	13.91191	0.09505	8.77898	0.09312	8.05055	0.08472	0.38388	0.02891	0.38388
Commercial roof	1.34172	55.43604	1.17561	23.33390	0.22848	21.10234	0.28581	24.70893	0.05195	0.23543	0.01773	0.23543
Commercial pervious	0.07700	3.18144	0.66586	13.21619	0.21683	20.02632	0.09627	8.32271	0.24539	1.11196	0.08373	1.11196
Commercial water	0.00003	0.00103	0.01950	0.38706	0	0	0	0	0	0	0	0
Suburban road	0	0	0	0	0	0	0	0	0.42001	1.90321	0.14331	1.90321
Suburban hardstand	0	0	0	0	0	0	0	0	0.32501	1.47275	0.11090	1.47275
Suburban roof	0	0	0	0	0	0	0	0	1.45989	6.61534	0.49813	6.61534
Suburban pervious	0	0	0	0	0	0	0	0	2.42902	11.00684	0.82882	11.00684
Suburban water	0	0	0	0	0	0	0	0	0	0	0	0
Open space road	0	0	0.00018	0.00347	0.09565	8.83440	0	0	0.75552	3.42356	0.25779	3.42356
Open space hardstand	0.01015	0.41951	0.59345	11.77910	0.07803	7.20652	0.22165	19.16190	0.35687	1.61712	0.12177	1.61712
Open space roof	0.00730	0.30172	0.15618	3.09997	0.03780	3.49127	0.12877	11.13295	0.03785	0.17152	0.01292	0.17152
Open space pervious	0.00448	0.18496	1.22931	24.39981	0.19978	18.45156	0.30532	26.39594	3.66317	16.59923	1.24992	16.59923
Open space water	0	0	0.01400	0.27789	0.02340	2.16126	0.02576	2.22702	0.01476	0.06687	0.00504	0.06687
Bushland road	0	0	0	0	0	0	0	0	0.31222	1.41481	0.10654	1.41481
Bushland hardstand	0	0	0	0	0	0	0	0	0.14492	0.65671	0.04945	0.65671
Bushland roof	0	0	0	0	0	0	0	0	0.02061	0.09339	0.00703	0.09339
Bushland pervious	0	0	0	0	0	0	0	0	11.74298	53.21198	4.00686	53.21198
Bushland water	0	0	0	0	0	0	0	0	0.00188	0.00852	0.00064	0.00852
Rural road	0	0	0	0	0	0	0	0	0	0	0	0
Rural hardstand	0	0	0	0	0	0	0	0	0	0	0	0
Rural roof	0	0	0	0	0	0	0	0	0	0	0	0
Rural pervious	0	0	0	0	0	0	0	0	0	0	0	0
Rural water	0	0	0	0	0	0	0	0	0	0	0	0
Sports field	0	0	0	0	0	0	0	0	0	0	0	0
Total subcatchment area	2.42030	100	5.03820	100	1.08270	100	1.15670	100	22.06830	100	7.53000	100

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Table C3 cont. Area of land use functional units within Lake Tuggeranong subcatchments (see Table C2), in hectares (ha) and as a percentage of subcatchment area (%).

Functional unit	DDS1 (ha)	DDS1 (%)	DDS2 (ha)	DDS2 (%)	DSL1 (ha)	DSL1 (%)	DSL2 (ha)	DSL2 (%)	DLC N (ha)	DLC N (%)	DLC S (ha)	DLC S (%)
Commercial road	0	0	0	0	0	0	0	0	0	0	0	0
Commercial hardstand	0	0	0	0	0.00817	0.01807	0	0	0	0	0.08175	0.12357
Commercial roof	0	0	0	0	0.00840	0.01857	0	0	0	0	0.14145	0.21382
Commercial pervious	0	0	0	0	6.11195	13.52072	0	0	0	0	0.03060	0.04626
Commercial water	0	0	0	0	0	0	0	0	0	0	0	0
Suburban road	0.89352	7.67025	1.04632	3.69542	0	0	0	0	0.25714	8.61201	3.97777	6.01283
Suburban hardstand	0.63470	5.44849	2.06447	7.29133	0	0	0	0	0.35156	11.77441	5.04227	7.62195
Suburban roof	1.85668	15.93838	4.99336	17.63565	0	0	0	0	1.31517	44.04747	15.13896	22.88422
Suburban pervious	3.18648	27.35385	5.69499	20.11369	0	0	0	0	0.74893	25.08312	22.82264	34.49895
Suburban water	0	0	0	0	0	0	0	0	0	0	0	0
Open space road	0.74070	6.35840	3.08179	10.88433	0	0	0	0	0	0	3.06436	4.63212
Open space hardstand	0.10360	0.88930	1.21974	4.30791	0.00737	0.01631	0.00040	0.00118	0.02711	0.90785	1.28473	1.94201
Open space roof	0.02935	0.25194	0.11342	0.40059	0.00070	0.00155	0	0	0.00355	0.11892	0.17930	0.27103
Open space pervious	4.20409	36.08938	10.09991	35.67110	0.25166	0.55672	0.09442	0.27857	0.28234	9.45621	14.39076	21.75323
Open space water	0	0	0	0	0	0	0	0	0	0	0	0
Bushland road	0	0	0	0	0	0	0	0	0	0	0	0
Bushland hardstand	0	0	0	0	0.65479	1.44850	0.28300	0.83498	0	0	0	0
Bushland roof	0	0	0	0	0.05969	0.13205	0.00107	0.00317	0	0	0	0
Bushland pervious	0	0	0	0	37.96401	83.98318	33.51431	98.88211	0	0	0	0
Bushland water	0	0	0	0	0.13757	0.30434	0	0	0	0	0	0
Rural road	0	0	0	0	0	0	0	0	0	0	0	0
Rural hardstand	0	0	0	0	0	0	0	0	0	0	0	0
Rural roof	0	0	0	0	0	0	0	0	0	0	0	0
Rural pervious	0	0	0	0	0	0	0	0	0	0	0	0
Rural water	0	0	0	0	0	0	0	0	0	0	0	0
Sports field	0	0	0	0	0	0	0	0	0	0	0	0
Total subcatchment area	11.64910	100	28.31400	100	45.20430	100	33.89320	100	2.98580	100	66.15460	100

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Table C3 cont. Area of land use functional units within Lake Tuggeranong subcatchments (see Table C2), in hectares (ha) and as a percentage of subcatchment area (%).

Functional unit	TC0 (ha)	TC0 (%)	TC1 (ha)	TC1 (%)	TC2 (ha)	TC2 (%)	TC3 (ha)	TC3 (%)	TC4 (ha)	TC4 (%)	TC5 (ha)	TC5 (%)
Commercial road	0.58272	0.22654	0	0	0.32153	0.12952	0.06495	0.12948	0.06495	0.12948	0.33632	0.09282
Commercial hardstand	6.51431	2.53251	0	0	1.28484	0.51756	0.77034	1.53569	0.77034	1.53569	3.38792	0.93498
Commercial roof	7.38043	2.86922	0	0	1.32700	0.53454	0.64949	1.29477	0.64949	1.29477	3.90561	1.07785
Commercial pervious	17.78314	6.91338	0	0	32.92973	13.26479	2.22145	4.42849	2.22145	4.42849	9.11530	2.51558
Commercial water	0	0	0	0	0.05460	0.02199	0	0	0	0	0	0
Suburban road	10.77831	4.19018	0.73186	6.26525	12.30299	4.95590	2.64384	5.27054	2.64384	5.27054	12.01325	3.31534
Suburban hardstand	13.56212	5.27241	1.15220	9.86371	14.49177	5.83759	3.18411	6.34758	3.18411	6.34758	12.88176	3.55503
Suburban roof	49.75319	19.34207	3.12461	26.74904	46.70982	18.81570	11.68760	23.29944	11.68760	23.29944	47.17029	13.01776
Suburban pervious	55.40174	21.53800	3.50165	29.97680	72.67577	29.27533	14.37982	28.66642	14.37982	28.66642	77.11695	21.28225
Suburban water	7.51E-05	2.92E-05	0	0	2.51E-05	1.01E-05	0	0	0	0	0.00033	8.97E-05
Open space road	10.01014	3.89155	0	0	5.67404	2.28562	2.44259	4.86935	2.44259	4.86935	6.28860	1.73549
Open space hardstand	6.52754	2.53765	0.53100	4.54575	4.94635	1.99249	1.51306	3.01630	1.51306	3.01630	5.23212	1.44393
Open space roof	0.72237	0.28083	0.00733	0.06271	0.39423	0.15880	0.12290	0.24500	0.12290	0.24500	0.85361	0.23557
Open space pervious	46.04883	17.90196	2.63256	22.53675	49.70804	20.02344	10.34895	20.63080	10.34895	20.63080	50.24425	13.86609
Open space water	0.52547	0.20428	0	0	0	0	0	0	0	0	0	0
Bushland road	0	0	0	0	0	0	0	0	0	0	3.29003	0.90796
Bushland hardstand	0	0	0	0	0	0	0	0	0	0	0.86734	0.23936
Bushland roof	0	0	0	0	0	0	0	0	0	0	0.11853	0.03271
Bushland pervious	0	0	0	0	4	2	0	0	0	0	116.54473	32.16329
Bushland water	0	0	0	0	0	0	0	0	0	0	0	0
Rural road	0	0	0	0	0	0	0	0	0	0	0	0
Rural hardstand	0	0	0	0	0	0	0	0	0	0	0	0
Rural roof	0	0	0	0	0	0	0	0	0	0	0	0
Rural pervious	30.00000	11.66281	0	0	0	0	0	0	0	0	0	0
Rural water	0	0	0	0	0	0	0	0	0	0	0	0
Sports field	1.63753	0.63661	0	0	1.16687	0.47004	0.13350	0.26613	0.13350	0.26613	12.98638	3.58390
Total subcatchment area	257.22790	100	11.68120	100	248.24920	100	50.16260	100	50.16260	100	362.35330	100

Table C3 cont. Area of land use functional units within Lake Tuggeranong subcatchments (see Table C2), in hectares (ha) and as a percentage of subcatchment area (%).

Functional unit	TC6 (ha)	TC6 (%)	TC7 (ha)	TC7 (%)	TC6 NSW (ha)	TC6 NSW (%)	TC8 NSW (ha)	TC8 NSW (%)
Commercial road	0	0	0	0	0	0	0	0
Commercial hardstand	0	0	0	0	0	0	0	0
Commercial roof	0	0	0	0	0	0	0	0
Commercial pervious	0	0	0	0	0	0	0	0
Commercial water	0	0	0	0	0	0	0	0
Suburban road	0	0	0	0	0	0	0	0
Suburban hardstand	0.00375	0.00369	0	0	0	0	0	0
Suburban roof	0.00153	0.00150	0	0	0	0	0	0
Suburban pervious	0.00685	0.00674	0	0	0	0	0	0
Suburban water	0	0	0	0	0	0	0	0
Open space road	0.20877	0.20533	0.04334	0.00706	0	0	0	0
Open space hardstand	0.07513	0.07389	0.03677	0.00599	0	0	0	0
Open space roof	0.01225	0.01205	0.00597	0.00097	0	0	0	0
Open space pervious	4.06725	4.00025	0.25709	0.04191	0.00258	0.02625	2.64149	0.31220
Open space water	0	0	0	0	0	0	0	0
Bushland road	6.02788	5.92859	6.56298	1.06977	0	0	0	0
Bushland hardstand	0.71094	0.69923	1.62155	0.26431	0	0	0	0
Bushland roof	0.27050	0.26604	0.35840	0.05842	0	0	0	0
Bushland pervious	90.27019	88.78316	298.69189	48.68689	0.00055	0.00561	0.00130	0.00015
Bushland water	0.01985	0.01952	0.10036	0.01636	0	0	0	0
Rural road	0	0	0.24039	0.03918	0	0	0	0
Rural hardstand	0	0	0.53294	0.08687	0	0	5.00E-05	5.91E-06
Rural roof	0	0	0.64118	0.10451	0	0	7.50E-05	8.87E-06
Rural pervious	0	0	304.00698	49.55325	9.82337	99.96815	843.45908	99.68764
Rural water	0	0	0.39566	0.06449	0	0	0	0
Sports field	0	0	0	0	0	0	0	0
Total subcatchment area	101.67490	100	613.49550	100	9.82650	100	846.10200	100

Table C3 cont. Area of land use functional units within Lake Tuggeranong subcatchments (see Table C2), in hectares (ha) and as a percentage of subcatchment area (%).

Functional unit	WS0 (ha)	WS0 (%)	WS1 (ha)	WS1 (%)	WS2 (ha)	WS2 (%)	WS3 (ha)	WS3 (%)	WS4 (ha)	WS4 (%)
Commercial road	0	0	0	0	1.54112	0.82442	0	0	0	0
Commercial hardstand	0.22877	0.74891	1.55212	1.03660	6.70734	3.58810	0	0	0.01836	0.02462
Commercial roof	0.36464	1.19371	2.44706	1.63431	8.64741	4.62595	0	0	0.00633	0.00849
Commercial pervious	1.71141	5.60254	3.03841	2.02924	8.14436	4.35684	0	0	0.07058	0.09467
Commercial water	0	0	0	0	0	0	0	0	0	0
Suburban road	1.18540	3.88057	9.03820	6.03629	7.84594	4.19720	0.67185	6.88093	1.71359	2.29845
Suburban hardstand	2.50062	8.18613	9.28827	6.20331	8.99315	4.81090	0.51682	5.29313	2.21056	2.96504
Suburban roof	8.63839	28.27903	32.95523	22.00964	32.99276	17.64954	2.46192	25.21422	8.27366	11.09754
Suburban pervious	8.11016	26.54977	49.31735	32.93733	54.74475	29.28581	4.14976	42.50066	12.91723	17.32601
Suburban water	0	0	2.50E-05	1.67E-05	0.00105	0.00056	0	0	0.00045	0.00060
Open space road	1.26220	4.13198	4.93795	3.29788	9.44718	5.05379	0.16886	1.72939	5.19069	6.96232
Open space hardstand	0.97098	3.17863	3.53733	2.36246	5.75370	3.07795	0.07289	0.74654	1.88015	2.52187
Open space roof	0.11025	0.36091	0.46175	0.30838	1.12409	0.60134	0.00465	0.04762	0.24454	0.32801
Open space pervious	5.43135	17.78029	31.69643	21.16893	35.70274	19.09925	1.71724	17.58751	15.71887	21.08387
Open space water	0.03285	0.10754	0.00560	0.00374	0	0	0	0	0	0
Bushland road	0	0	0	0	0	0	0	0	0.51420	0.68970
Bushland hardstand	0	0	0	0	0.00187	0.00100	0	0	0.06840	0.09175
Bushland roof	0	0	0	0	0	0	0	0	0.02153	0.02888
Bushland pervious	0	0	0	0	0.32207	0.17229	0	0	25.70486	34.47818
Bushland water	0	0	0	0	0	0	0	0	0	0
Rural road	0	0	0	0	0	0	0	0	0	0
Rural hardstand	0	0	0	0	0	0	0	0	0	0
Rural roof	0	0	0	0	0	0	0	0	0	0
Rural pervious	0	0	0	0	0	0	0	0	0	0
Rural water	0	0	0	0	0	0	0	0	0	0
Sports field	0	0	1.45519	0.97187	4.96317	2.65506	0	0	0	0
Total subcatchment area	30.547	100	149.7309	100	186.9327	100	9.764	100	74.554	100

Table C3 cont. Area of land use functional units within Lake Tuggeranong subcatchments (see Table C2), in hectares (ha) and as a percentage of subcatchment area (%).

Functional unit	FA0 (ha)	FA0 (%)	FA1 (ha)	FA1 (%)	FA2 (ha)	FA2 (%)	FA3 (ha)	FA3 (%)	FA5 (ha)	FA5 (%)	FA6 (ha)	FA6 (%)
Commercial road	0.00155	0.00077	0.00178	0.00390	0	0	0	0	0	0	0	0
Commercial hardstand	0.68547	0.33986	1.27610	2.80488	0	0	0.56164	0.42239	0	0	0	0
Commercial roof	1.04842	0.51982	1.47323	3.23817	0	0	0.68604	0.51595	0	0	0	0
Commercial pervious	3.23227	1.60258	6.71763	14.76535	0	0	4.86537	3.65908	0	0	0	0
Commercial water	0	0	0	0	0	0	0	0	0	0	0	0
Suburban road	12.21125	6.05443	3.05012	6.70417	0.26349	3.19399	8.76270	6.59013	0	0	1.31484	1.83693
Suburban hardstand	12.72037	6.30686	2.42518	5.33055	0.25484	3.08907	9.77361	7.35040	0.00222	0.03223	1.43267	2.00154
Suburban roof	48.91619	24.25304	7.39270	16.24915	1.04438	12.65981	33.22342	24.98620	0.05123	0.74231	5.36633	7.49712
Suburban pervious	74.69462	37.03419	11.53219	25.34776	1.75898	21.32205	50.77288	38.18454	0.10458	1.51540	8.99825	12.57116
Suburban water	0.00150	0.00074	0	0	0	0	0.00090	0.00068	0	0	0	0
Open space road	8.37676	4.15327	2.07507	4.56101	0.00935	0.11339	2.20094	1.65525	0.33517	4.85688	1.70013	2.37520
Open space hardstand	4.42618	2.19454	1.77967	3.91171	0.03974	0.48167	1.71507	1.28985	0.20396	2.95548	2.54351	3.55345
Open space roof	0.47688	0.23644	0.10978	0.24129	0.00427	0.05176	0.20312	0.15276	0.04800	0.69560	1.01666	1.42034
Open space pervious	34.29041	17.00146	6.51373	14.31717	0.42130	5.10688	18.91811	14.22766	2.77117	40.15607	40.27044	56.26052
Open space water	0	0	0	0	0.04402	0.53359	0	0	0	0	5.00E-05	6.99E-05
Bushland road	0	0	0	0	0.15460	1.87402	0	0	0	0	0.00000	0.00000
Bushland hardstand	0	0	0	0	0.01489	0.18053	0	0	0	0	0.00713	0.00995
Bushland roof	0	0	0	0	0.01464	0.17746	0	0	0	0	0.01075	0.01502
Bushland pervious	0	0	0	0	4.22510	51.21578	0	0	0	0	8.91775	12.45869
Bushland water	0	0	0	0	0	0	0	0	0	0	0	0
Rural road	0	0	0	0	0	0	0	0	0	0	0	0
Rural hardstand	0	0	0	0	0	0	0	0	0	0	0	0
Rural roof	0	0	0	0	0	0	0	0	0	0	0	0
Rural pervious	0	0	0	0	0	0	0	0	0	0	0	0
Rural water	0	0	0	0	0	0	0	0	0	0	0	0
Sports field	0.60912	0.30201	1.14873	2.52490	0	0	1.28330	0.96513	3.38467	49.04604	0	0
Total subcatchment area	201.69100	100	45.49590	100	8.24960	100	132.96710	100	6.90100	100	71.57845	100

Table C3 cont. Area of land use functional units within Lake Tuggeranong subcatchments (see Table C2), in hectares (ha) and as a percentage of subcatchment area (%).

Functional unit	FA7 (ha)	FA7 (%)	FA8 (ha)	FA8 (%)	FA9 (ha)	FA9 (%)	FA10 (ha)	FA10 (%)	FA11 (ha)	FA11 (%)	FA12 (ha)	FA12 (%)
Commercial road	0	0	0	0	0.96626	0.58898	0	0	0.15920	0.21730	0	0
Commercial hardstand	0	0	0.09825	0.09336	2.87939	1.75511	0.01547	0.62058	0.81899	1.11787	0.84147	7.30903
Commercial roof	0	0	0.28170	0.26767	2.81759	1.71744	0.01910	0.76595	0.99322	1.35568	1.03335	8.97575
Commercial pervious	0	0	1.17809	1.11941	3.34845	2.04102	0.12335	4.94762	2.15616	2.94302	2.27579	19.76764
Commercial water	0	0	0	0	0	0	0	0	0	0	0	0
Suburban road	0.24393	1.83693	3.40824	3.23849	7.53109	4.59051	0	0	2.25456	3.07734	0.05280	0.45865
Suburban hardstand	0.26579	2.00154	4.42791	4.20736	8.06460	4.91570	0	0	2.19261	2.99278	0.08285	0.71968
Suburban roof	0.99555	7.49712	18.40574	17.48898	28.53998	17.39629	0	0	9.76619	13.33023	0.71281	6.19152
Suburban pervious	1.66934	12.57116	29.18282	27.72928	45.86605	27.95723	0	0	14.57372	19.89220	1.08328	9.40943
Suburban water	0	0	0	0	2.49E-05	1.52E-05	0	0	2.50E-05	3.41E-05	0	0
Open space road	0.31540	2.37520	4.65181	4.42011	3.14482	1.91690	0.41795	16.76375	1.63615	2.23324	0.58038	5.04121
Open space hardstand	0.47187	3.55345	2.44401	2.32228	1.98188	1.20804	0.17292	6.93569	1.13037	1.54288	0.57485	4.99321
Open space roof	0.18861	1.42034	0.20423	0.19406	0.18810	0.11466	0.00655	0.26267	0.17858	0.24375	0.09548	0.82934
Open space pervious	7.47089	56.26052	15.52775	14.75434	17.56257	10.70510	1.50429	60.33586	10.68431	14.58340	4.16896	36.21182
Open space water	9.28E-06	6.99E-05	0.01460	0.01387	0	0	0	0	0	0	0.01068	0.09273
Bushland road	0.00000	0.00000	0.14620	0.13892	2.44566	1.49073	0	0	0.18495	0.25245	0	0
Bushland hardstand	0.00132	0.00995	0.74621	0.70904	0.57236	0.34888	0	0	0.12498	0.17059	0	0
Bushland roof	0.00199	0.01502	0.21660	0.20581	0.06938	0.04229	0	0	0.00813	0.01109	0	0
Bushland pervious	1.65440	12.45869	24.30774	23.09701	34.67503	21.13585	0	0	25.02885	34.16279	0	0
Bushland water	0	0	0	0	0.01220	0.00744	0	0	0	0	0	0
Rural road	0	0	0	0	0	0	0	0	0	0	0	0
Rural hardstand	0	0	0	0	0	0	0	0	0	0	0	0
Rural roof	0	0	0	0	0	0	0	0	0	0	0	0
Rural pervious	0	0	0	0	0	0	0	0	0	0	0	0
Rural water	0	0	0	0	0	0	0	0	0	0	0	0
Sports field	0	0	0	0	3.39245	2.06784	0.23356	9.36789	1.37250	1.87337	0	0
Total subcatchment area	13.27909	100	105.24190	100	164.05787	100	2.49320	100	73.26347	100	11.51270	100

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Table C3 cont. Area of land use functional units within Lake Tuggeranong subcatchments (see Table C2), in hectares (ha) and as a percentage of subcatchment area (%).

Functional unit	FA13 (ha)	FA13 (%)	FA14 (ha)	FA14 (%)	FA15 (ha)	FA15 (%)	FA16 (ha)	FA16 (%)	FA17 (ha)	FA17 (%)	FA9 NSW (ha)	FA9 NSW (%)
Commercial road	0	0	0	0	0	0	0	0	0	0	0	0
Commercial hardstand	0	0	0	0	0	0	0.00048	0.00069	0	0	0	0
Commercial roof	0	0	0	0	0	0	0.01188	0.01718	0	0	0	0
Commercial pervious	0.02585	1.29481	0	0	0	0	0.04275	0.06184	0	0	0	0
Commercial water	0	0	0	0	0	0	0	0	0	0	0	0
Suburban road	0	0	0	0	0.99534	6.47445	4.91072	7.10386	2.05614	3.19399	0	0
Suburban hardstand	0	0	0	0	0.98473	6.40548	4.14411	5.99488	1.98860	3.08907	0	0
Suburban roof	0	0	0	0	4.20349	27.34277	16.32055	23.60934	8.14979	12.65981	0	0
Suburban pervious	0	0	0	0	5.84599	38.02693	24.30567	35.16064	13.72613	21.32205	0	0
Suburban water	0	0	0	0	0	0	0	0	0	0	0	0
Open space road	0.02215	1.10948	0	0	0.84631	5.50505	1.22231	1.76820	0.07299	0.11339	0	0
Open space hardstand	0.01945	0.97424	0.01723	4.25808	0.46344	3.01456	1.04693	1.51450	0.31008	0.48167	0	0
Open space roof	0.02070	1.03685	0.00050	0.12360	0.07351	0.47819	0.07243	0.10477	0.03332	0.05176	0	0
Open space pervious	0.62372	31.24084	0.38697	95.61832	1.84850	12.02407	7.92437	11.46341	3.28757	5.10688	0.02229	0.03109
Open space water	0	0	0	0	0	0	0.00198	0.00286	0.34350	0.53359	0	0
Bushland road	0	0	0	0	0	0	0.04578	0.06622	1.20641	1.87402	0	0
Bushland hardstand	0	0	0	0	0	0	0.00348	0.00503	0.11622	0.18053	0	0
Bushland roof	0	0	0	0	0	0	0.00023	0.00033	0.11424	0.17746	2.50E-05	3.49E-05
Bushland pervious	0	0	0	0	0	0	9.02073	13.04941	32.97031	51.21578	0.00283	0.00394
Bushland water	0	0	0	0	0	0	0	0	0	0	0	0
Rural road	0	0	0	0	0	0	0	0	0	0	0	0
Rural hardstand	0	0	0	0	0	0	0	0	0	0	0	0
Rural roof	0	0	0	0	0	0	0	0	0	0	0	0
Rural pervious	0	0	0	0	0	0	0	0	0	0	71.66356	99.96493
Rural water	0	0	0	0	0	0	0	0	0	0	0	0
Sports field	1.28462	64.34376	0	0	0.11200	0.72851	0.05313	0.07685	0	0	0	0
Total subcatchment area	1.99650	100	0.40470	100	15.37330	100	69.12750	100	64.37530	100	71.68867	100

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Appendix D: Literature-derived EMC and DWC values

Baseline values of the event mean concentrations (EMC) and dry weather concentrations (DWC) of total phosphorus (TP), total nitrogen (TN) and total suspended solids (TSS) generated by functional land use units were derived from the literature for initial parameterisation of the model. The EMC values were then scaled based on date-matched observations. Tables D1-D3 present the baseline EMC and DWC values for each functional unit.

Table D1: Baseline total phosphorus (TP) EMC and DWC values (mg/L) derived from the literature for each combination of functional land use and surface imperviousness.

Land surface imperviousness	Suburban	Commercial	Open space	Rural	Bushland	Sports field
Road	EMC: 0.501 DWC: 0.015	EMC: 0.501 DWC: 0.015	EMC: 0.501 DWC: 0.015	EMC: 0.251 DWC: 0.015	EMC: 0.251 DWC: 0.015	
Hardstand	EMC: 0.251 DWC: 0.015	EMC: 0.251 DWC: 0.015	EMC: 0.251 DWC: 0.015	EMC: 0.251 DWC: 0.015	EMC: 0.251 DWC: 0.015	
Roof	EMC: 0.128 DWC: 0.015	EMC: 0.128 DWC: 0.015	EMC: 0.128 DWC: 0.015	EMC: 0.251 DWC: 0.015	EMC: 0.251 DWC: 0.015	
Pervious	EMC: 0.251 DWC: 0.04	EMC: 0.251 DWC: 0.04	EMC: 0.251 DWC: 0.04	EMC: 0.218 DWC: 0.04	EMC: 0.079 DWC: 0.04	EMC: 0.251 DWC: 0.015
Water	EMC: 0 DWC: 0	EMC: 0 DWC: 0	EMC: 0 DWC: 0	EMC: 0 DWC: 0	EMC: 0 DWC: 0	

Table D2: Baseline total nitrogen (TN) EMC and DWC values (mg/L) derived from the literature for each combination of functional land use and surface imperviousness.

Land surface imperviousness	Suburban	Commercial	Open space	Rural	Bushland	Sports field
Road	EMC: 2.187 DWC: 1.0	EMC: 2.187 DWC: 1.0	EMC: 2.187 DWC: 1.0	EMC: 2.187 DWC: 1.0	EMC: 2.187 DWC: 1.0	
Hardstand	EMC: 2.187 DWC: 1.0	EMC: 2.187 DWC: 1.0	EMC: 2.187 DWC: 1.0	EMC: 2.187 DWC: 1.0	EMC: 2.187 DWC: 1.0	
Roof	EMC: 1.995 DWC: 1.0	EMC: 1.995 DWC: 1.0	EMC: 1.995 DWC: 1.0	EMC: 1.995 DWC: 1.0	EMC: 1.995 DWC: 1.0	
Pervious	EMC: 1.995 DWC: 0.4	EMC: 1.995 DWC: 0.4	EMC: 1.995 DWC: 0.4	EMC: 1.995 DWC: 0.4	EMC: 1.995 DWC: 0.4	EMC: 1.995 DWC: 1.0
Water	EMC: 0 DWC: 0	EMC: 0 DWC: 0	EMC: 0 DWC: 0	EMC: 0 DWC: 0	EMC: 0 DWC: 0	

Table D3: Baseline total suspended solids (TSS) EMC and DWC values (mg/L) derived from the literature for each combination of functional land use and surface imperviousness.

Land surface imperviousness	Suburban	Commercial	Open space	Rural	Bushland	Sports field
Road	EMC: 269.15 DWC: 15.849	EMC: 269.15 DWC: 15.849	EMC: 269.15 DWC: 15.849	EMC: 269.15 DWC: 15.849	EMC: 269.15 DWC: 15.849	
Hardstand	EMC: 269.15 DWC: 15.849	EMC: 269.15 DWC: 15.849	EMC: 269.15 DWC: 15.849	EMC: 269.15 DWC: 15.849	EMC: 269.15 DWC: 15.849	
Roof	EMC: 19.95 DWC: 15.849	EMC: 19.95 DWC: 15.849	EMC: 19.95 DWC: 15.849	EMC: 19.95 DWC: 15.849	EMC: 19.95 DWC: 15.849	
Pervious	EMC: 141.25 DWC: 15.849	EMC: 141.25 DWC: 15.849	EMC: 141.25 DWC: 15.849	EMC: 89.12 DWC: 15.849	EMC: 39.81 DWC: 15.849	EMC: 141.25 DWC: 15.849
Water	EMC: 0 DWC: 0	EMC: 0 DWC: 0	EMC: 0 DWC: 0	EMC: 0 DWC: 0	EMC: 0 DWC: 0	

Appendix E: Modelled annual load of total phosphorous

The table below provides total phosphorous generated for each combination of functional land use and surface imperviousness annually.

Table E1: Modelled annual total phosphorus (TP) load (kg/yr) generated for each combination of functional land use and surface imperviousness.

Land surface imperviousness	Road TP (kg/yr)	Hardstand TP (kg/yr)	Roof TP (kg/yr)	Pervious TP (kg/yr)	Water TP (kg/yr)
Suburban	322	169	314	140	0
Commercial	17	45	30	16	0
Open space	243	76	5	88	0
Rural	0	0	1	132	0
Sports field	0	0	0	58	0
Total annual load (kg/yr)	582	290	350	434	0

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Attachment H

ACT Government

Predicting phosphorus concentration and trophic state of Lake Tuggeranong

Technical report supplement to the Lake Tuggeranong Catchment Model

Water Information Services, ACT Office of Water

December 2024

Environment, Planning and Sustainable Development Directorate

CABINET

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1. Introduction

Vollenweider's (1975, 1976) mass-balance equations, overall, model how the total phosphorous (TP) concentration of a lake ($\mathrm{TP_{lake}}$) is related to the TP concentration of inflows ($\mathrm{TP_{in}}$) and the hydraulic residence/retention time (τ_w). This residence time can be thought of as the average time an incoming water molecule can expect to remain in the lake before leaving the lake through outflow and is calculated by simply dividing the volume of the lake by the outflow rate.

Vollenweider (1976 – Equation 2.13) described this relationship mathematically with the equation below (as re-stated in Brett & Benjamin 2008 – Equation 6):

$$\mathrm{TP_{lake}} = \frac{\mathrm{TP_{in}}}{1+\sigma\tau_w} \qquad (1)$$

Where σ is the first-order rate coefficient of TP loss within the lake due to sedimentation. As this rate is not easily quantified, several different approaches have been proposed to approximate it. Brett & Benjamin (2008) summarised and compared the relative performance of these different approaches using known values from 305 lakes from Europe and North America. They found that all approaches provided a useful fit with real-world values, but that the best-fitting approach was to assume that σ is a function of ${k\tau_w}^x$, where k and x are constants, fitted statistically. This approach was previously used by Larsen & Mercier (1976), who reported a value of x near -0.5.

With this approximation, equation 1 becomes:

$$\mathrm{TP_{lake}} = \frac{\mathrm{TP_{in}}}{1+({k\tau_w}^x)\tau_w} \qquad (2)$$

Brett & Benjamin (2008) found that values of around k=1.12 and x=-0.53 yielded a correlation between predicted and observed TP_{lake} values with r^2>0.8 for the dataset investigated, yielding the following relationship:

$$\mathrm{TP_{lake}} = \frac{\mathrm{TP_{in}}}{1+\left(1.12\times\tau_w^{-0.53}\right)*\tau_w} \qquad (3)$$

If we then approximate k=1 and x=-0.5, equation 3 simplifies to:

$$\mathrm{TP_{lake}} = \frac{\mathrm{TP_{in}}}{1+\sqrt{\tau_w}} \qquad (4)$$

Vollenweider (1976) previously suggested this approximation of the general equation fits with empirical studies, and this relationship was used by Beer *et al.* 1982 in their early work on Lake Tuggeranong.

2. In-Lake Model

2.1 Parameterisation of the modified Vollenweider model

The adjusted Vollenweider model (equation 2) was parameterised using estimates of inflow TP concentrations and inflow and outflow volumes from the Lake Tuggeranong catchment model (Dey et al. 2024), and observed Lake Tuggeranong TP concentrations from the ALS Lakes and Rivers Water Quality Monitoring Program, but with the following caveats:

- The model assumes a steady state of inflows and influent concentrations, which is a limitation to real-world applications, so it is unclear how reliable we should expect its predictions over shorter time periods to be. That being said, past modelling of TP loads has suggested that 3 hydraulic residence times is sufficient for 95% convergence with steady-state predictions (Sonzogni *et al.* 1976), which is <1 year for most years in Lake Tuggeranong. For this reason, our modelling approach will work with annual time steps, with all model inputs and outputs to be interpreted as annual averages.
- In past applications of this model-fitting approach, data across many different lakes were used, with each lake representing a separated datapoint (e.g. Brett & Benjamin 2008, Larsen & Mercier 1976). Here, the datapoints are all from Lake Tuggeranong, just from different years, and are thus pseudo-replicated. However, to provide a Lake Tuggeranong -specific model that will not be applied elsewhere this approach is probably reasonable. It would be informative to repeat this modelling approach in other ACT lakes and compare fitted values later, to investigate the appropriateness of an overall ACT-wide model using data from all different lakes.
- In other applications of Vollenweider model the same value for water inflow and outflow are used (i.e. assumption of no other source of water loss). Since the catchment model have taken into account of the lake water balance.

To parametrise the modified Vollenweider model, we can use annual total TP loads and water inflows and outflows from the Tuggeranong Source Catchment Model. Specifically:

- l_{in}: the annual TP load flowing into Lake Tuggeranong (converted to mg),
- v_{in}: the annual inflow volume of water into Lake Tuggeranong (converted to L)
- v_{out}: the annual outflow volume of water from Lake Tuggeranong (converted to L)

We can then combine these parameters, along with the approximate total volume of Lake Tuggeranong (V= 1,780,000,000L), to calculate the TP concentration of inflows (TP_{in}, measured in mg/L) and the hydraulic residence time (τ_w, measured in years) as follows:

$$\text{TP}_{\text{in}} = \frac{l_{\text{in}}}{v_{\text{in}}} \quad (5)$$

$$\tau_w = \frac{V}{v_{\text{out}}} \quad (6)$$

The predicted annual average TP_{in} and τ_w values from 1990-2022 are summarised in Table 1 and shown in Figure 1.

Table 1. Summary of Lake Tuggeranong annual values of inflow total phosphorus concentration TP_{in} and hydraulic residence time τ_w from 1990-2022.

	$\mathbf{TP_{in}}$ **(mg/L)**	$\boldsymbol{\tau_w}$ **(y)**
Minimum	0.152	0.055
Median	0.163	0.251
Maximum	0.174	0.727

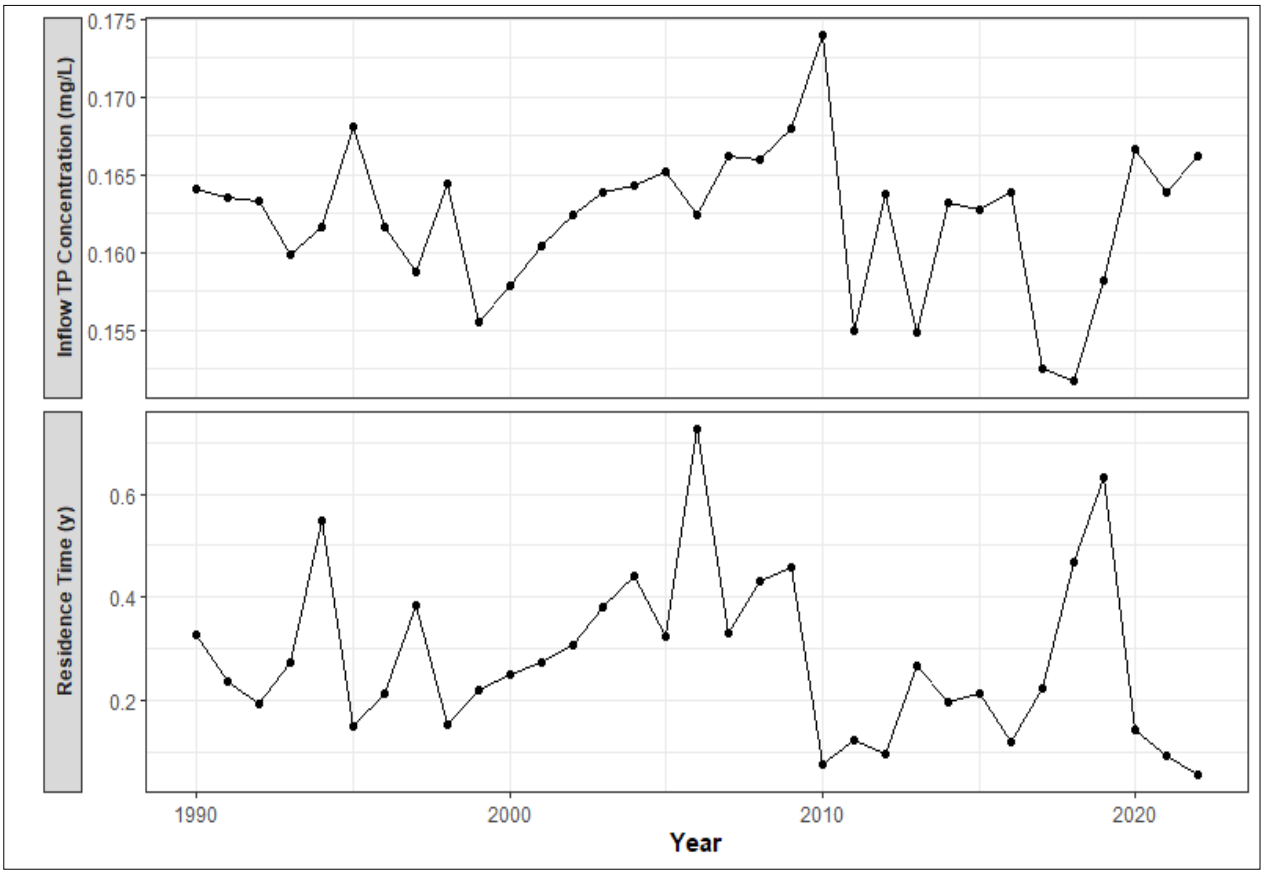

Figure 1. Annual changes in inflow concentrations of total phosphorus (TP_{in}, top panel) and residence time (τ_w, bottom panel) in Lake Tuggeranong, 1990-2022.

2.2 Estimation of total phosphorus and chlorophyll a concentration

Using the modified Vollenweider model (equation 2) $\mathrm{TP_{lake}}$ concentration can be predicted using $\mathrm{TP_{in}}$ and τ_w values. Before estimating the TP_{lake}, fitting of the constants k and x is required such that modelled $\mathrm{TP_{lake}}$ values provide as close-as-possible match to observed $\mathrm{TP_{lake}}$ values. Here, our source of observed $\mathrm{TP_{lake}}$ values come from the ALS Lakes and Rivers Water Quality Monitoring Program from 2005-2022. This period was chosen because it represents the longest run of annual sampling of LT TP concentrations with

relatively constant annual sampling effort (most years had 8 samples from each of two locations within Lake Tuggeranong: LTG248 and LTG249). Other sources of data (e.g. University of Canberra research) did not provide a similar temporal scope, meaning their inclusion would have led to large variability in the underlying sampling effort behind annual averages, which was undesirable here. Waterwatch data was also not used here due to questions about data reliability specifically related to TP measures relative to lab techniques (Harrison *et al.* 2013).

To fit optimal values of k and x to our modified Vollenweider model, an approach similar to Brett & Benjamin (2008) was adopted. Specifically, a function was created in R that would, for given values of k and x, predict lake TP concentrations ($\mathrm{TP}_{\mathrm{predicted}}$) and compare them to average annual observed lake TP concentrations $\mathrm{TP}_{\mathrm{observed}}$ values to calculate the weighted error sum of squares (WESS) as follows:

$$\mathrm{WESS} = \sum \mathrm{weight} \times \left(\mathrm{TP}_{\mathrm{observed}} - \mathrm{TP}_{\mathrm{predicted}}\right)^2 \qquad (7)$$

The number of samples that each annual average was based on as weights was used, such that years that had annual averages based on relatively few datapoints (e.g. 2020 due to lockdowns) contributed relatively less to the WESS. This WESS provides a measure of how closely matched predicted and observed TP values are, with low WESS values indicating a better fitting model.

This function was then used alongside a solver function in R to find a combination of k and x values that minimised the WESS and thus represented the best fit to the observed data. This solver yielded values of $k = 1.093$ and $x = -0.791$. These values are similar to those reported elsewhere (e.g. Brett & Benjamin 2008) and not particularly inconsistent with the unmodified Vollenweider model used by Beer *et al.* 1982 in their early work on LT. Sensitivity analysis of this optimisation was performed by re-calculating the

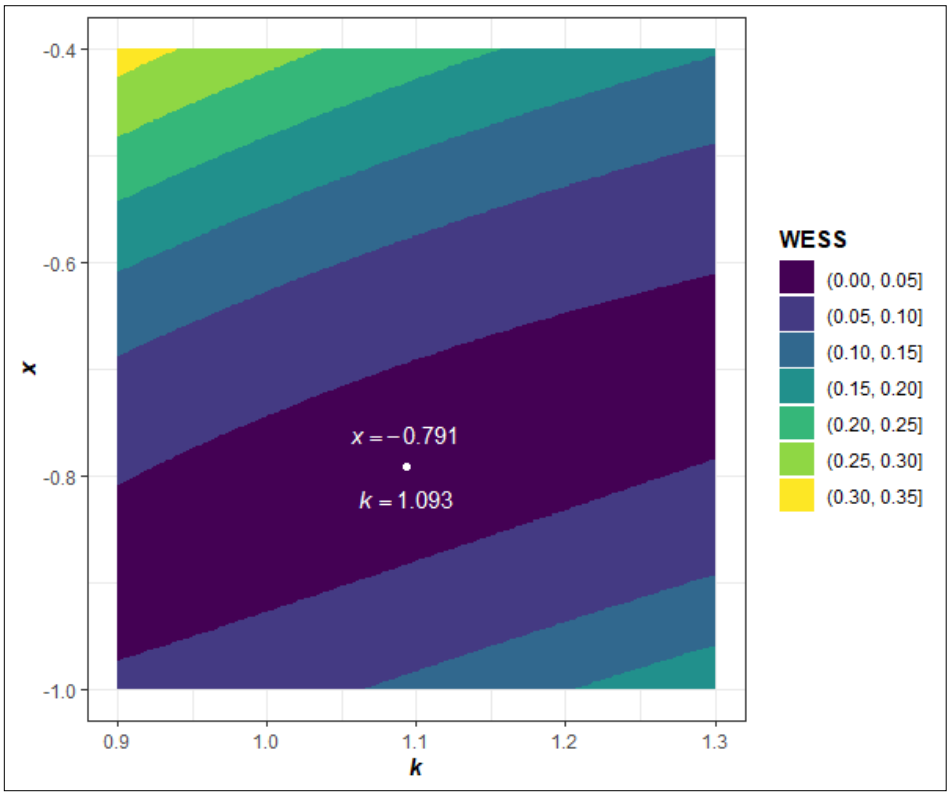

Figure 2. Sensitivity of the Lake Tuggeranong modified Vollenweider model to changes in *k* and *x* in terms of the resultant weighted error sum of squares (WESS). The white point indicates the optimal values.

resultant WESS with a range of k and x values. This analysis indicated that a relatively wide band of k and x values yielded similarly good fits (indicated by relatively low WESS values: Figure 2), which again was consistent with the findings of Brett & Benjamin 2008.

Using the fitted values of k and x, the modified Vollenweider model is represented in equation 8:

$$\mathrm{TP}_{\mathrm{lake}} = \frac{\mathrm{TP}_{\mathrm{in}}}{1+\left(1.093\times\tau_w^{-0.791}\right)*\tau_w} \qquad (8)$$

This yielded predicted $\mathrm{TP}_{\mathrm{lake}}$ values similar to observed values (Table 2, Figure 3).

Table 2. Comparison of observed annual average and predicted total phosphorus concentrations in Lake Tuggeranong (TP_{lake}) from 2005-2022.

	Observed $\mathrm{TP}_{\mathrm{lake}}$ (mg/L)	**Predicted $\mathrm{TP}_{\mathrm{lake}}$ (mg/L)**
Minimum	0.064	0.079
Median	0.086	0.090
Maximum	0.114	0.107

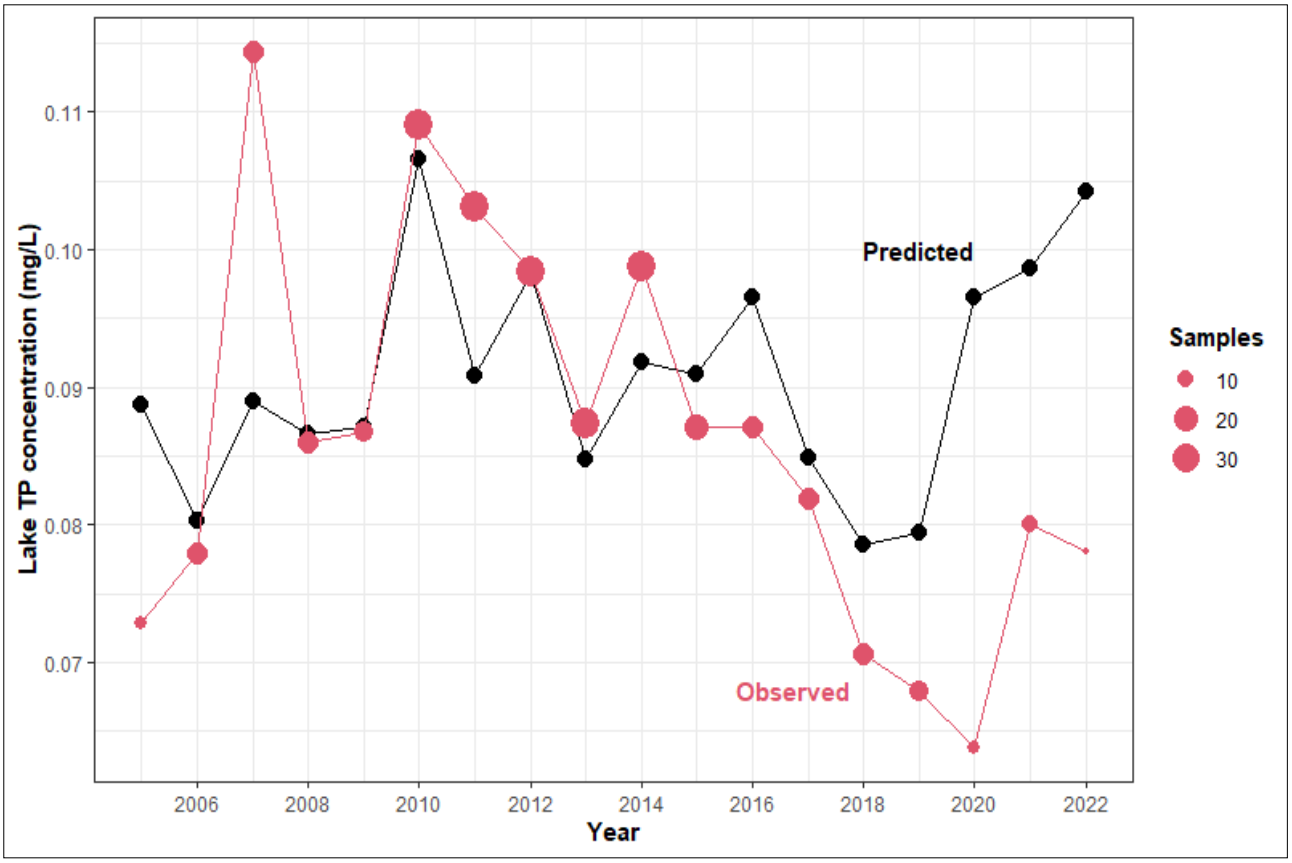

Figure 3. Comparison of observed (red) and predicted (black) annual total phosphorus (TP) concentrations in Lake Tuggeranong from 2005-2022 shows the modified Vollenweider model captures the centre and spread of observed values well with some mirroring of year-to-year trends. Observed values are averages of samples for each year, and data point size represents the number of underlying samples.

The predicted TP concentrations in Lake Tuggeranong had a very similar average and variability to observed TP concentrations, and for many years the two time-series followed similar up/down-wards trajectories (Figure 3). Overall, predicted and observed TP concentrations in Lake Tuggeranong were positively correlated. This was confirmed by a linear regression model relating the two (weighted based on annual sample number), which yielded a significant association between the two variables (ANOVA F-test of slope coefficient: F=8.5889, p=0.0098), and an adjusted r^2 value of 0.3086.

This model can be used to predict the chlorophyll a level using the power relationship described by Lawrence (1980) and applied in Beer *et al.* (1982) in their early work on Lake Tuggeranong:

$$\text{Chlorophyll a} = 0.367 * TP_{Lake}^{0.91} \qquad (9)$$

This relationship was derived from a comparison of several Canberra lakes.

3. Estimation of Lake Trophic State

Using 133 years of annually aggregated Source model output of TP load and inflow water volumes, the above-mentioned models were combined under a range of influent TP reduction scenarios ranging from current/business as usual (BAU: no reduction in TP load), and 100kg to 900kg reduction in annual TP load coming into the lake (with no change to inflow water volumes). Additionally, a predevelopment flow and TP load scenario was considered, which assumed a wholly undeveloped catchment. The Vollenweider model was used to predict annual TP concentrations in the lake for each year under each scenario. This was then converted to predicted chlorophyll a concentration using equation 9. Finally, these predicted concentrations were compared to published cut-offs (e.g. Neil 2012) of chlorophyll a concentration under different trophic states: Oligotrophic <5 µg/L, Mesotrophic <15 µg/L, Eutrophic >15 µg/L.

The predictions for the predevelopment scenario show that, in the absence of development within the catchment, Lake Tuggeranong would likely have experienced a wide range of trophic conditions. In some years the lake would not have received any inflow at all and would likely have reached an oligotrophic state. But in high rainfall years the lake's size and the inflow of TP would have pushed it towards a eutrophic state. This provides a good baseline for considering realistic futures for the lake.

Under the 'current' scenario (BAU), Lake Tuggeranong is predicted to (at the annual, average timescale) remain in a eutrophic state (Figure 4). To avoid a constant eutrophic state, the results of the TP reduction scenarios show that TP load reductions of 600kg or more into Lake Tuggeranong are predicted to result in conditions that are eutrophic less often than not (Figure 4). However, even under high TP load reduction scenarios there will be years of high TP inflow (wet years) where we probably cannot avoid eutrophic conditions developing (as with the pre-development scenario) simply because of the large total TP load entering the lake via stormwater (such that even a >600kg reduction in TP is proportionally fairly insignificant). Conversely, though, dry years with low TP inflows could yield oligotrophic conditions in scenarios with greater than 500kg TP reduction (Figure 4).

Overall, these modelling results suggest that an annual 700kg reduction in TP entering Lake Tuggeranong is an appropriate target for future lake management plans. This level of TP reduction is predicted to lead to

favourable conditions for human recreation in the lake in ~75% of years (~25% oligotrophic, ~50% mesotrophic; Figure 4).

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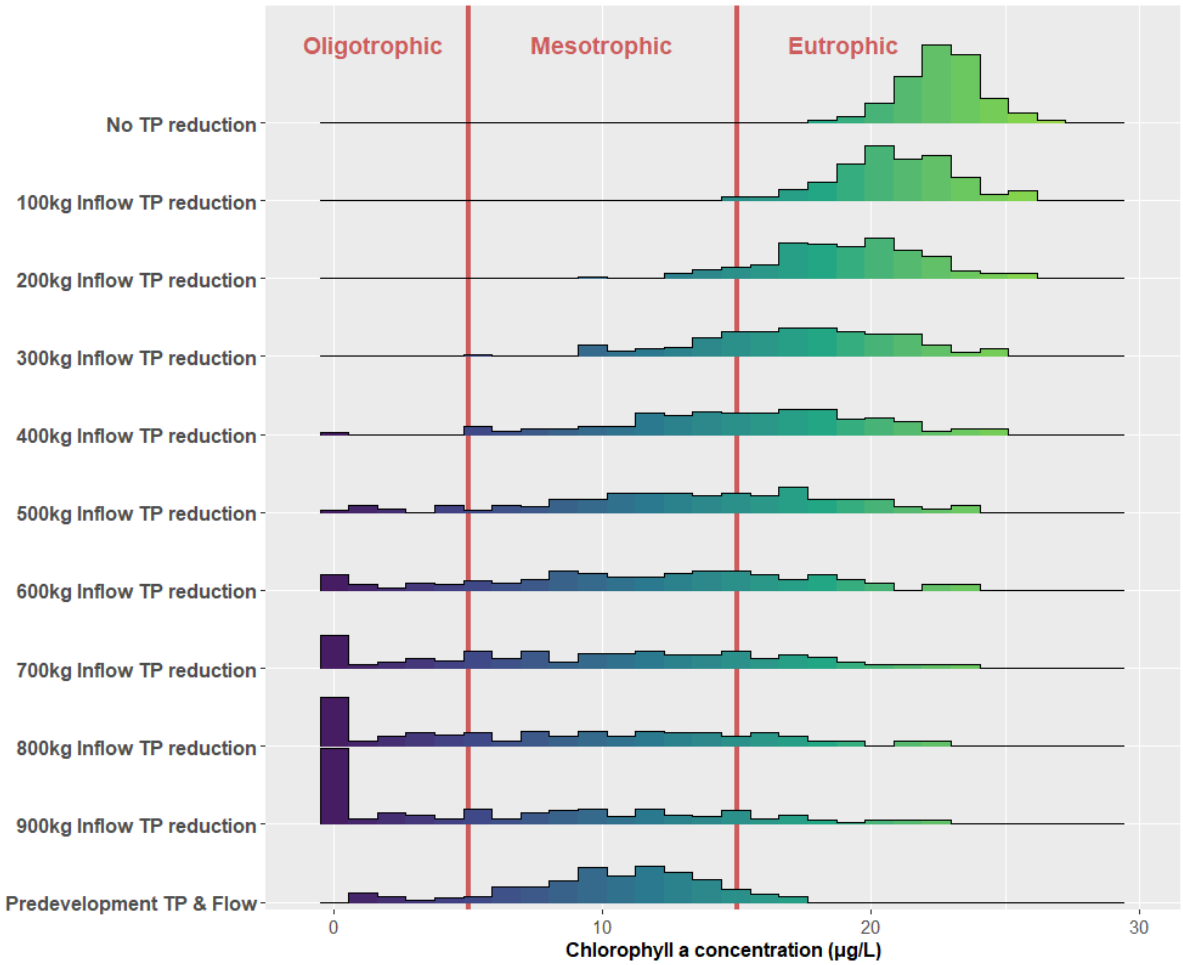

Figure 4. Distribution of annual predicted chlorophyll a concentration (i.e. trophic state) in Lake Tuggeranong under different scenarios of reductions in inflow total phosphorus (TP).

4. Conclusion

Vollenweider's mass-balance model is a simple, but useful, tool for predicting nutrient concentrations in lakes based on influent volumes and concentrations. Whilst they are typically used for comparisons between lakes, in this study the Vollenweider model was modified to derive Lake Tuggeranong specific total phosphorous concentrations. The model produced a reasonable fit with observed values over a 17-year period and could be used in conjunction with catchment model inputs to predict general trends in phosphorous levels in Lake Tuggeranong into the future. The model output was then used to provide an estimate chlorophyll a which is a measure of the trophic state. The estimated chlorophyll a concentration was used to determine the trophic state of the lake under different scenarios. The findings provide an approximate estimate of the target inflow TP load for Lake Tuggeranong to improve the lake trophic conditions, with a target annual reduction of ~700kg of TP yielding favourable predictions.

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Attachment I

ACT Government

Lake Tuggeranong Catchment Management Options Assessment

Technical report supporting the Healthy Waterways Plan for Lake Tuggeranong

Water Information Services, ACT Office of Water

December 2024

Environment, Planning and Sustainable Development Directorate

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The views and opinions expressed in this report are those of the author and do not necessarily represent the views, opinions or policy of funding bodies or participating member agencies or organisations.

Executive Summary

Lake Tuggeranong is a small (57 ha) urban lake in southern Canberra. Lake Tuggeranong was constructed in the late 1980s on Tuggeranong Creek, a 66 km^2 catchment that is predominantly (62%) urbanised. In recent decades, Lake Tuggeranong has been plagued by poor water quality. Since 2017, there has been a concerted effort to improve water quality in the lake through the construction of Water Sensitive Urban Design (WSUD) infrastructure throughout the catchment, and a major research program to understand the causes of poor water quality, and sources of pollutants entering the lake. This work has been undertaken as part of the ACT Healthy Waterways program.

The ACT Government has commited to developing Healthy Waterways Plans for priority catchments in the ACT. The Lake Tuggeranong draft plan provides a suite of potential management options to Government to further improve water quality in Lake Tuggeranong. To acheive this, modelling and analyses have been undertaken to examine a broad range of management scenarios and identify cost-effective options to improve water quality in Lake Tuggeranong, with a focus on reducing the annual load of phosphorus entering the lake.

This report documents the approach taken to assess the predicted performance and cost of 10 proposed catchment management options for reducing the load of phosphorus entering Lake Tuggeranong. For each management option identified, details of the data and information used to calculate the estimates of performance and cost are presented, and summarised in an assessment of cost-effectiveness. To provide a comparison of cost-effectiveness both across and within management options, the cost-effectiveness of four different levels of investment was calculated for each option, ranging from relatively low to relatively high investment. An evaluation of the quality of evidence supporting these estimates and its impact on our confidence in specific values is provided for each management option.

These assessments found that increasing the frequency of municipal street sweeping and the construction of additional WSUD infrastructure were the management options predicted to remove the greatest loads of phosphorus, with street sweeping the most cost-effective option at all levels of investment.

The assessments of management option cost-effectiveness were provided to the ACT Healthy Waterways team who chose options to combine into two proposed management scenarios, with the aim of reducing the phosphorus load entering Lake Tuggeranong (currently ~ 1440 kg/year) by approximately 700 kg/year. A reduction of this amount is predicted to maintain Lake Tuggeranong in a predominantly mesotrophic state, substantially reducing the frequency, extent and duration of blue-green algal blooms (Kahn & Dey, 2024). The proposed management scenarios were then implemented in the catchment model for the Lake Tuggeranong catchment (Dey, Stewart, Kahn, Booksmythe, & Starrs, 2024), to estimate their average annual phosphorus load reductions, accounting for interactive effects of the different options included in a scenario.

Modelling the proposed management scenarios revised down the estimated annual load of phosphorus they were predicted to remove,from 700-750 kg/year to 450-575 kg/year. This is mainly due to the large impact of street sweeping on reducing the concentration of phosphorus in stormwater, which alters the rate of phosphorus removal estimated for management options involving WSUD infrastructure.

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1. Introduction

Lake Tuggeranong is a small (57 ha) urban lake in southern Canberra. The lake was constructed in the late 1980s on Tuggeranong Creek, a 66 km^2 catchment that is predominantly (62%) urbanised. In recent decades, Lake Tuggeranong has been plagued by poor water quality, with high loads of nutrients (phosphorus and nitrogen) and sediments entering the lake, leading to frequent, extensive blue-green algal blooms that result in lake closures. Since 2017, there has been a concerted effort to improve water quality in the lake through the construction of Water Sensitive Urban Design (WSUD) infrastructure such as wetlands, bioretention swales and raingardens throughout the catchment, and a major research program to understand the causes of poor water quality, and sources of pollutants. This work has been undertaken as part of the ACT Healthy Waterways program.

The ACT Government has commited to developing Healthy Waterways Plans for priority catchments in the ACT. The Lake Tuggeranong draft plan aims to provide a suite of potential management options to Government to further improve water quality in Lake Tuggeranong (ACT Government, 2025). To achieve this, modelling and analyses have been undertaken to examine a broad range of management scenarios and identify cost-effective options to improve water quality in Lake Tuggeranong, with a focus on reducing the annual load of phosphorus entering the lake. The availability of phosphorus is the main controllable factor limiting blue-green algal growth (Ubrihien, et al., 2020). While large amounts of phosphorus are bound to sediments on the lake bottom, reducing the phosphorus inputs to the lake is necessary before this in-lake source of phosphorus can be effectively addressed.

This report documents the approach taken to assess the predicted performance and cost of proposed catchment management options for reducing the load of phosphorus entering Lake Tuggeranong. For each management option identified, details of the data and information used to calculate the estimates of performance and cost are presented, and summarised in an assessment of cost-effectiveness. An evaluation of the quality of evidence supporting these estimates and its impact on our confidence in specific values is provided for each management option.

Government experts identified a range of potential management options for mitigating phosphorus pollution. They then narrowed their consideration of options based on the availability of data to support cost-effectiveness analyses. In some instances, cost-effectiveness data were based on local trials of mitigation options.

Ten management options are assessed in this report:

- Construction of additional WSUD infrastructure
- Improved maintenance of existing WSUD assets
- Increased frequency of street sweeping
- Improved management of grass clippings from municipal mowing
- Management of public sports field fertilizer use practices
- Management of household fertilizer use practices
- Installation (retrofitting) of castellated kerbs
- Installation of in-lake floating wetlands

- Installation of stormwater recycling infrastructure for sports field irrigation
- Installation of household rainwater tanks

The assessments used to generate estimates of the cost-effectiveness of each of these management options is detailed in section 2 of this report. Sections 3.1 and 3.2 describe the process of comparing management options and combining them into proposed management scenarios with the aim of reducing the phosphorus load entering Lake Tuggeranong by approximately 700 kg/year. A reduction of this amount is predicted to maintain Lake Tuggeranong in a predominantly mesotrophic state, substantially reducing the frequency, extent and duration of blue-green algal blooms (Kahn & Dey, 2024). Section 3.3 outlines the results of implementing the proposed management scenarios in the catchment model for the Lake Tuggeranong catchment (Dey, Stewart, Kahn, Booksmythe, & Starrs, 2024).

1.1 Management option performance

The performance of each management option is assessed in terms of the amount of total phosphorus (TP) it is predicted to prevent from entering Lake Tuggeranong in a year. To facilitate comparison between different types of management option, we assume a 30-year lifecycle for each option. Total lifecycle performance is estimated by multiplying the annual TP removal by 30.

Phosphorus reduction has been chosen as the primary quantitative metric for management option performance due to its key role in promoting blue-green algal blooms in Lake Tuggeranong. Further assessment could consider other aspects of water quality improvement (e.g. the reduction of total nitrogen, TN, and total suspended solids, TSS), along with non-water quality benefits, as part of performance.

1.2 Management option costs

Costs are estimated in Australian Dollars (AUD) as at 2024. Costs are broken down into three components:

- Capital costs (in 2024 currency; assumed to be incurred in the first year of implementation)
- Annual operating costs (in 2024 currency)
- Total 30-year lifecycle costs (capital costs + annual operating costs over 30 years, using an annual discount rate of 7% after the first year (Infrastructure Australia, 2021))

We assume that management options have no residual value at the end of lifecycle, facilitating a like-for-like comparison between management options with vastly different cost profiles (e.g. infrastructure vs. non-infrastructure options).

1.3 Management option cost-effectiveness

By calculating an estimate of cost-effectiveness we aim to provide a metric allowing direct comparison of different management options. The cost-effectiveness of each management option is calculated by dividing the total lifecycle cost by the total lifecycle performance (TP removal). This produces a standardised metric for comparison between disparate management options in a consistent unit ($/kg). To provide a comparison of cost-effectiveness both across and within management options, the cost-effectiveness of

four different levels of investment was calculated for each option, ranging from relatively low to relatively high investment.

1.4 Quality of supporting evidence

With any process of estimation comes uncertainty. In assessing the cost-effectiveness of phosphorus-reducing management options in the Lake Tuggeranong catchment, uncertainty may arise through three main channels:

- Uncertainty about estimates of the cost of implementing a management option
- Uncertainty about estimates of the efficacy of the management option in removing phosphorus (e.g., uncertainty about the amount of leaf litter prevented from entering the stormwater system by street sweeping)
- Uncertainty about estimates of the amount of phosphorus available for removal by a particular management option (e.g., uncertainty about the pollutant load generated from leaf litter on roads)

We use both quantitative and qualitative approaches to address these sources of uncertainty in our assessment of management options.

1.4.2 Quantitative assessment of estimate uncertainty

A wide range of data and information were collated to estimate the phosphorus-removal performance and cost of each assessed option. In some cases, when incorporating multiple sources of information about the same aspects of performance or cost, a range of estimates was obtained. We assessed this range of estimates statistically, to understand whether it was likely to represent a realistic range of possible variability in outcomes, or to over- or under-estimate the expected variability.

1.4.2 Qualitative assessment of estimate uncertainty

We developed a rubric to systematically assess the quality of evidence sources contributing to the cost-effectiveness estimates of each management option (Appendix A). The data informing the calculations of predicted cost and performance were scored on nine criteria and the scores summed to give an overall uncertainty rating for the cost-effectiveness estimate.

Box 1. Key definitions and abbreviations used in this report

- Annual operating cost – the estimated annual cost of day-to-day operation of a management option, including routine maintenance and staff costs unless otherwise specified.
- Capital cost – the cost of capital works (i.e. construction planning, materials and delivery) of a management option, excluding operation and maintenance costs. Some management options do not have a capital cost (e.g. community partnership programs).
- Discount rate – the interest rate at which future dollar values are adjusted to represent their value in today's dollars. This adjustment is made to account for the fact that money today is more valuable than money in the future.
- EPSDD – Environment, Planning and Sustainable Development directorate, ACT Government
- Gross pollutant trap (GPT) – infrastructure installed upstream of stormwater management infrastructure to capture large debris and prevent it from causing blockage of the infrastructure.
- Model for Urban Stormwater Improvement Conceptualisation (MUSIC) – software that simulates rainfall, stormwater runoff, flows, and pollution. Used to simulate flow reduction and pollution removal through stormwater management infrastructure such as wetlands, bioretention, and sediment ponds.
- O&M – Operation and maintenance
- TCCS – Transport Canberra and City Services directorate, ACT Government
- Total lifecycle cost – the estimated cost of implementing and operating a management option over 30 years, with annual (O&M) costs discounted by 7% per annum after the first year.
- Total phosphorus (TP) – the sum of all forms of phosphorus present in a sample. In this report the term phosphorus refers to total phosphorus (TP) unless otherwise specified, and these terms may be used interchangeably.
- Water-sensitive Urban Design (WSUD) assets – infrastructure such as constructed wetlands, bioretention, and sediment ponds, for the management of stormwater and its pollutants using natural biological and physical processes including sediment settlement, filtration, and uptake by plants.

2. Management option assessments

2.1 Construction of additional WSUD infrastructure

2.1.1 Background

Stages 1 and 2 of the ACT Healthy Waterways program saw the construction of several different types of water-sensitive urban design (WSUD) infrastructure across urban Canberra waterways, including 8 assets in the Lake Tuggeranong catchment. WSUD infrastructure, including constructed wetlands, raingardens, and bioretention swales, can be situated directly on a branch of the stormwater network (online) or receive inflows diverted from the stormwater network (offline), or be positioned to intercept runoff before it enters the stormwater network (at-source). While water is within the infrastructure, a proportion of the nutrient and sediment pollutants in the water are removed through processes including natural settling, filtration, and uptake by plants. Outflows from the infrastructure are returned to the stormwater network. This section assesses the cost-effectiveness of installing additional WSUD infrastructure in the catchment.

The amount of total phosphorus (TP) available for removal by additional WSUD infrastructure is that which is intercepted by the infrastructure as it travels through the catchment. The catchment model for the Lake Tuggeranong catchment estimates the load of TP generated and entering the stormwater network in each subcatchment, allowing calculation of the accumulated load that would be received by a new WSUD asset depending on its location in the catchment (Dey, Stewart, Kahn, Booksmythe, & Starrs, 2024).

2.1.2 Phosphorus removal performance

We estimate the TP removal performance of additional WSUD infrastructure based on the performance of similar existing infrastructure. MUSIC models were developed for each of the WSUD assets constructed as part of Stage 1 of the ACT Healthy Waterways program. These models are configured to reflect the final design of each asset and model the predicted TP removal for each asset over a known climatic period, adopting MUSIC's default TP concentrations for stormwater runoff generated from different land uses in the catchment. The models for the 8 WSUD assets installed in the Lake Tuggeranong catchment were reviewed and updated by eWater (eWater Ltd, 2022), which estimated annual mean percentage reductions in TP of between 15-80% for these assets. These percentage reductions were applied in the Lake Tuggeranong catchment model (Dey, Stewart, Kahn, Booksmythe, & Starrs, 2024) to estimate the TP load removed by each asset. The total annual load of TP removed depends on the type, size, and location of assets. The two constructed wetlands in the Lake Tuggeranong catchment remove an estimated 0.003-0.01 kg TP per square metre of wetland per year. However, we excluded wetlands from the infrastructure used to estimate the performance of additional WSUD infrastructure, as there is very little scope to build further wetlands in the Lake Tuggeranong catchment, and modelling smaller assets is more realistic. For the 6 non-wetland assets (bioretention swales, raingardens, and channel restorations) in the catchment, the annual load of TP removed ranges between 0.0048-0.014 kg TP per square metre of asset area (Table 1).

The installation of additional WSUD infrastructure, and the size of infrastructure that can be built, is limited by the availability of suitable locations in the catchment. This means that specific asset designs, of known type, size, and location, are needed when estimating the impact of additional WSUD infrastructure on reducing the TP load entering Lake Tuggeranong. Here, the size and possible locations of additional WSUD infrastructure were determined from design reports for 10 proposed raingardens in the Lake Tuggeranong

catchment (Alluvium, 2015), undertaken as part of the ACT Healthy Waterways program Stage 1, that were not selected as priorities for construction during that project (Table 2). As there may be planning and feasibility constraints that determined why these particular raingardens were not built at the time, the estimates in this section should be read as an example of the kind of infrastructure that could be installed in the Lake Tuggeranong catchment, not a specific proposal.

Table 1. Summary statistics for the performance of 6 existing non-wetland WSUD assets in the Lake Tuggeranong catchment.

Parameter	Total annual TP removed (kg/m^2)
Minimum	0.0048
Median	0.0074
Mean	0.0081
Maximum	0.0142

We assigned each of these hypothetical assets an annual TP removal rate, assuming that raingarden performance efficacy improves with increasing treatment area. To implement this relationship, we ranked the raingardens by size, and applied the maximum TP removal rate from Table 1 to the largest two assets, the mean TP removal rate to the next three largest assets, the median TP removal rate to the next three largest assets, and the minimum TP removal rate to the two smallest assets (Table 2).

Table 2. Size, assigned rate of TP removal, and estimated total annual TP removed for 10 proposed raingardens in the Lake Tuggeranong catchment.

Asset	Asset size (m^2)[1]	Annual TP removed (kg/m^2)	Total annual TP removed (kg)
TG018	4,800	0.0142	68.16
TG014	2,700	0.0142	38.34
TG004	2,600	0.0081	21.06
TG013	2,600	0.0081	21.06
TG015	2,600	0.0081	21.06
TG016	2,600	0.0074	19.24
TG031	2,600	0.0074	19.24
TG005	2,459	0.0074	18.20
TG007B	1,500	0.0048	7.20
TG009	1,440	0.0048	6.91

1 Assets with no projected treatment area were assigned an area of 2,600 m^2, the average area for a raingarden in the catchment.

2.1.3 Costing

G2W Pty Ltd were engaged to review the capital and ongoing operation and maintenance costs associated with existing WSUD infrastructure in the Lake Tuggeranong catchment (G2W Pty Ltd, 2024). Bioretention assets (raingardens and swales) in the Lake Tuggeranong catchment ranged between 765 - 5,270m^2 in size, and between $774 - 2,532/m^2 in capital construction cost, with a strongly negative relationship between

size and cost such that on average, larger assets had a lower capital cost per square metre. We used this size - capital cost relationship to estimate the capital cost of constructing the 10 proposed raingardens based on the sizes presented in Table 2. We used the capital cost of the cheapest existing raingarden as a lower limit for the cost estimates of the proposed raingardens. Similarly, the annual operation and maintenance (O&M) cost of existing bioretention assets ranged between \$62 – 170/m^2, with larger assets having a lower O&M cost per square metre. We used the asset size - O&M cost relationship to estimate the annual maintenance cost of the 10 proposed raingardens, again using the lowest existing O&M cost as a lower limit for our estimates. We used the capital and O&M cost estimates to calculate the 30-year lifecycle cost of the 10 proposed raingardens, assuming an annual discount rate of 7% each year on the O&M costs.

2.1.4 Cost-effectiveness

We calculated the individual cost-effectiveness of each of 10 proposed raingardens based on the assigned rate of TP removal for each asset (Table 3).

Table 3. Capital costs, annual operation and maintenance costs, 30-year lifecycle costs, and individual cost-effectiveness of 10 proposed raingardens in the Lake Tuggeranong catchment.

Asset	Capital cost	Annual operation and maintenance cost	Total 30-year lifecycle cost[1]	Cost per unit TP removed ($/kg)
TG018	$4,882,560	$338,496	$13,025,856	$6,388
TG014	$4,226,310	$261,846	$8,878,356	$7,740
TG004	$4,137,640	$255,424	$8,620,664	$13,585
TG013	$4,137,640	$255,424	$8,620,664	$13,585
TG015	$4,137,640	$255,424	$8,620,664	$13,585
TG016	$4,137,640	$255,424	$8,620,664	$14,969
TG031	$4,137,640	$255,424	$8,620,664	$14,969
TG005	$4,003,746	$245,941	$8,248,021	$15,143
TG007B	$2,817,750	$168,150	$5,424,900	$24,882
TG009	$2,727,590	$162,513	$5,231,543	$24,995

1 Total lifecycle cost is calculated over 30 years using a discount rate of 7% per annum on O&M costs.

To provide four levels of investment in the additional WSUD infrastructure management option, we grouped the 10 proposed raingardens by their size and cost-effectiveness and created four tiers of installation: to either build the two, five, 8 or 10 most cost-effective of these assets. We re-calculated the overall 30-year lifecycle cost and cost-effectiveness for the group of assets included in each investment level (Table 4), incorporating additional cost scaling factors to account for total construction size, number of assets to be constructed and the number of gross pollutant traps required (we assumed that each asset would need one gross pollutant trap).

Table 4. Costing summary for four levels of investment in additional WSUD infrastructure in the Lake Tuggeranong catchment.

Investment level	Number of assets built	Total annual TP removed (kg/year)	Total 30-year lifecycle cost[1]	Cost per unit TP removed ($/kg)
1	Build 2 assets	106.21	$22,507,500	$7,064
2	Build 5 assets	169.67	$48,369,492	$9,502
3	Build 8 assets	226.22	$73,862,467	$10,884
4	Build 10 assets	240.46	$84,519,403	$11,716

1 Total lifecycle cost is calculated over 30 years using a discount rate of 7% per annum on O&M costs.

2.1.5 Quality of supporting evidence

Using the evaluation rubric (Appendix A), the above estimates of cost-effectiveness of installing additional WSUD infrastructure scored 13/14 for confidence in cost estimates, and 9/16 for confidence in performance estimates.

2.2 Maintenance of existing WSUD infrastructure

2.2.1 Background

WSUD infrastructure requires ongoing maintenance to function at its designed phosphorus removal efficiency. Transport Canberra and City Services (TCCS) undertake this maintenance for the 8 existing WSUD assets in the Lake Tuggeranong catchment.

2.2.2 Phosphorus removal performance

Six of the 8 WSUD assets in the Lake Tuggeranong catchment were visually assessed for their current level of maintenance and treatment efficacy in February 2024. Five of these assets were assessed as performing at between 20% and 70% of their designed efficiency due to maintenance shortfalls. The estimated reduction in performance of each asset was incorporated into the baseline run of the catchment model, used to calculate the current (business-as-usual) annual load of TP entering Lake Tuggeranong (Dey, Stewart, Kahn, Booksmythe, & Starrs, 2024). To estimate the amount of TP that could be removed if all existing assets were maintained to 100% of their designed efficiency, the catchment model was then run without applying the asset performance reductions. The total difference in TP load between the business-as-usual and optimal asset maintenance model runs was 88 kg/year (Table 5).

Table 5. Current asset total phosphorus (TP) removal performance efficiency as a percentage of designed performance, and the additional annual TP load that could be removed if assets were maintained to designed performance.

Asset	Current TP removal performance	Marginal increase in TP removed with optimal maintenance (kg/year)
TG011N – wetland	60%	23.28
TG029 – raingarden	20%	12.56
TG010 – raingarden	70%	25.94
TG011S – wetland	60%	18.15
TG008 – raingarden	50%	8.09

2.2.3 Costing

The costs provided for asset operation and maintenance are based on annualised operational cost estimates from TCCS budget requests, and incorporate costs of major renewal activities such as cleaning GPTs, mucking out sediment forebays and replacing raingarden filter media at regular intervals. We used the costs provided without modification, to calculate the 30-year lifecycle cost of each asset assuming an annual discount rate of 7% after the first year.

2.2.4 Cost-effectiveness

Our estimates of cost-effectiveness assume that there is currently no funding provided for WSUD asset maintenance, and that if the estimated O&M costs (Table 6) *were* to be spent on these assets, the marginal gains in TP removal (Table 5) would be achieved.

Table 6. Annual operation and maintenance costs, 30-year lifecycle costs, and cost-effectiveness of maintaining 5 existing WSUD assets to their designed performance.

Asset	Annual operation and maintenance cost	Total 30-year lifecycle cost[1]	Cost per unit TP removed ($/kg)
TG011N – wetland	$485,352	$6,508,917	$9,320
TG029 – raingarden	$221,091	$3,668,211	$9,735
TG010 – raingarden	$340,432	$8,909,451	$11,449
TG011S – wetland	$541,800	$7,265,925	$13,344
TG008 – raingarden	$235,739	$3,999,929	$16,481

1 Total lifecycle cost is calculated over 30 years using a discount rate of 7% per annum on O&M costs.

To provide four levels of investment in the WSUD maintenance management option, we grouped the five assets by the cost-effectiveness of their maintenance and created four tiers of implementation: to maintain either the two, three, four or five most cost-effective of these assets. We re-calculated the overall 30-year lifecycle cost and cost-effectiveness for the group of assets included in each investment level (Table 7).

Table 7. Costing summary for four levels of investment in maintenance of existing WSUD infrastructure in the Lake Tuggeranong catchment.

Investment level	Number of assets maintained	Total annual TP removed (kg/year)	Total 30-year lifecycle cost[1]	Cost per unit TP removed ($/kg)
1	Maintain 2 assets	35.84	$10,177,128	$9,465
2	Maintain 3 assets	61.78	$19,086,579	$10,298
3	Maintain 4 assets	79.93	$26,352,433	$10,990
4	Maintain 5 assets	88.02	$30,352,433	$11,495

1 Total lifecycle cost is calculated over 30 years using a discount rate of 7% per annum on O&M costs.

2.2.5 Quality of supporting evidence

Using the evaluation rubric (Appendix A), the above estimates of cost-effectiveness of maintaining existing WSUD infrastructure scored 4/14 for confidence in cost estimates, and 8/16 for confidence in performance estimates.

2.3 Increased frequency of street sweeping

2.3.1 Background

In the Lake Tuggeranong catchment, research by the University of Canberra (Ubrihien, et al., 2020) indicates that a large amount of nutrients enter the waterways from diffuse, rather than point, sources – i.e. from widespread land uses across the catchment such as residential blocks and roads. One potential contributing factor found across these land uses is leaf litter (here defined as fallen leaves and other plant and soil matter) on impervious surfaces like roads, footpaths and driveways. Water passing over this leaf litter can take up nutrients in both dissolved and particulate forms, and enter the stormwater system via street gutter sumps. Dissolved nutrients may be leached out of leaf litter by the passing water, while particulate nutrients are chemically bound to particles such as soil and leaf fragments. In addition, with sufficient flows intact leaf litter may be washed into the stormwater system and transported to the lakes and waterways where they will break down and release nutrients into the water.

The primary function of the municipal street sweeping program is to prevent blockage of the stormwater system and ensure its effectiveness in flood mitigation. While increasing the frequency of street sweeping is often raised as a possible action to reduce leaf litter as a source of nutrient pollution, the impact of street sweeping on reducing nutrient inputs into the urban waterways of the ACT has not previously been quantified.

Phosphorus generated from leaf litter on roads

The amount of TP available for removal by street sweeping is that which originates as leaf litter on roads. The Lake Tuggeranong catchment model estimates the total annual TP load that runs off roads in the Lake Tuggeranong catchment as 582 kg TP/year (Dey, Stewart, Kahn, Booksmythe, & Starrs, 2024), and we use this as an estimate of the maximum available load of TP generated by leaf litter on roads.

There is strong seasonal variation in leaf fall in *Eucalyptus* species, which are predominant among the street tree and other public tree assets in the Lake Tuggeranong catchment (Ubrihien, et al., 2024), with most leaves falling in the warmer months (Crockford & Richardson, 1998). This variation, as well as seasonal variation in rainfall, will affect the accumulated load of leaf litter on the roads at any given time, and means that not just the frequency but also the timing of street sweeping can impact the amount of TP removed by this management option.

2.3.2 Phosphorus removal performance

We created a simple build-up wash-off model ('leaf load calculator') to incorporate these sources of seasonal variation in TP load, and the influence of sweeping frequency and timing, into our estimate of the TP removal performance of street sweeping. The calculator is based on 24 years of daily rainfall data from the Tuggeranong (Isabella Plains) climatological station (Bureau of Meteorology station ID 070339). It allows manual adjustment of variability in leaf fall, and specification of the frequency and timing of street sweeping. Using these inputs it calculates the cumulative load of leaf litter each day:

Load today = load yesterday + new fall today – load swept today – load washed away by rain today.

We used data from University of Canberra research into the leaf fall and TP content of four *Eucalypt* species in urban Canberra (Ubrihien, et al., 2024) to generate an approximate seasonal leaf fall pattern for the Lake Tuggeranong catchment. We input this seasonal pattern into the leaf load calculator, scaling the daily maximum leaf fall rate to be consistent with the average annual load of 582 kg TP on roads in the catchment estimated by the catchment model (Dey, Stewart, Kahn, Booksmythe, & Starrs, 2024). We then compared different annual street sweeping schedules, from two sweeps per year (business-as-usual) to 48 sweeps per year. We explored schedules of sweeping evenly spaced throughout the year, as well as seasonally focused schedules with increased frequency during high leaf fall periods and reduced or no sweeping during low leaf fall periods. For all schedules we assumed a minimum of one week between sweeps.

To compare each sweeping schedule explored using the leaf load calculator, we calculated their monthly and annual statistics on the leaf litter load on roads, the load collected by street sweeping trucks (and the approximate number of truckloads), and the load washed away into the stormwater network, over the 24 years of rainfall data.

2.3.3 Costing

To find the cost of a single sweep event for the Lake Tuggeranong catchment, we multiplied the current daily cost of one street sweeping truck by the number of truck-days needed to sweep the entire catchment once. We then added the cost of transporting and disposing of the swept material in landfill. We assume an expansion of the current operational model based on leasing trucks, so no capital cost (e.g. outright purchase of trucks) is included in our costings for this management option.

Days needed for one catchment sweeping event A pilot experiment investigating the impact of frequent street sweeping on nutrient concentrations in stormwater included a 12-week period of fortnightly street sweeping in two subcatchments of the Lake Tuggeranong catchment, comprising 10% of the total catchment road area. From records of the number of shifts needed to complete sweeping of this area each

fortnight during the experiment, we calculate that on average 24.17 truck-days would be needed to sweep the entire Lake Tuggeranong catchment.

Daily truck cost An estimate of daily cost per truck, based on the current running costs of a truck in the ACT street sweeping fleet, was provided by the TCCS Street Sweeping team. The fleet runs 5 days per week, with up to two staff shifts per truck per day, allowing each truck to operate for up to 10 hours per day. At the maximum (2 shift/day) rate of operation, the cost of one truck, including leasing, staff, running and maintenance costs, is $1,200-$1,500/day. Here we conservatively use the higher cost estimate. Over 24.17 truck-days, the estimated truck cost to sweep the entire Lake Tuggeranong catchment is $36,255.

Disposal costs The total cost of disposing of material to landfill in 2024 currency is $181/tonne. Of this, tip fees comprise $171/tonne and the cost of transporting collected material to landfill sites is $10/tonne (both excluding GST).

From data provided by TCCS, the estimated tonnage of material removed in one year (260 weekdays) by the fleet of 6 trucks is 2,364 tonnes, or an average of 9.1 tonnes/day. Assuming that each truck spends about 10% of its time non-operational (due to breakdowns, time out for servicing, etc.), this equates to an estimated average of 1.7 tonnes of material removed per truck per day (9.1 / (6 * 0.9)). Given 24.17 truck-days per catchment sweeping event, the disposal cost per sweeping event is $7,437. The total combined truck and disposal cost to sweep the Lake Tuggeranong catchment is $43,692 per street sweeping event. These estimates assume a constant load of material collected at each sweeping event (i.e., no seasonality or decrease due to sweeping frequency is included in disposal cost estimates, due to a lack of data on these possible effects).

2.3.4 Cost-effectiveness

To provide four levels of investment in the street sweeping management option, we considered four sweeping schedules ranging between 12 - 48 sweeping events in a year (1 - 4 per month). The three lower-frequency schedules account for the seasonality of leaf fall to obtain the best performance for each level of investment. The 48-sweep schedule is essentially equivalent to sweeping every week, so no seasonal adjustment is made. We calculated the 30-year lifecycle cost of each schedule using an annual discount rate of 7% on annual program costs after the first year.

Table 8. Costing summary for four levels of investment in increased frequencies of street sweeping in the Lake Tuggeranong catchment.

Investment level	Sweeping schedule	Total annual TP removed (kg/year)	Annual program cost	Total 30-year lifecycle cost[1]	Cost per unit TP removed ($/kg)
1	12 sweeps – seasonal focus	203.7	$524,304	$7,030,414	$1,150
2	24 sweeps – seasonal focus	320.1	$1,048,608	$14,060,827	$1,464
3	36 sweeps – seasonal focus	372.5	$1,572,912	$21,091,242	$1,887
4	48 sweeps – weekly	395.8	$2,097,216	$28,121,656	$2,369

1 Total lifecycle cost is calculated over 30 years using a discount rate of 7% per annum on annual costs after the first year.

2.3.5 Quality of supporting evidence

Using the evaluation rubric (Appendix A), the above estimates of cost-effectiveness of increasing the frequency of street sweeping scored 10/14 for confidence in cost estimates, and 9/16 for confidence in performance estimates.

2.4 Management of grass clippings from municipal mowing

2.4.1 Background

Grass clippings resulting from mowing of public open space can be blown onto adjacent roads, from where they can enter the stormwater system. Public perception is that large amounts of clippings end up on the roads, and if so these clippings may be a sizeable contributor to nutrient pollution of the waterways. Preventing or reducing the input of phosphorus from this source could be achieved by installing catchers on lawnmowers, using blowers to return clippings to the verge, or running designated street sweeping trucks along mown roadsides.

Phosphorus export from municipal mowing activity

The total area of pervious, ground-level (i.e., likely grassed and subject to TCCS mowing) public open space in the Lake Tuggeranong catchment is 928.5 ha. We assume that clippings from areas within 2m of a road are likely to end up on the road - this is probably an overestimate, and gives an area of 98.1 ha of mown area from which grass clippings will reach the road.

The estimated amount of clippings generated from this area in a year is between 327,000 - 523,000 kg dry mass. This is based on a 2016 report for the South Australian Government investigating the effect of watering regime on turf grass yields (Barton, 2016). University of Canberra research (Ubrihien, et al., 2024) estimates the phosphorus content of grass clippings at 0.1% of the dry weight of clippings, which gives between 327 - 523 kg TP for the estimated annual load of clippings on roads in the Lake Tuggeranong catchment.

When considered in light of information from the street sweeping pilot experiment (see section 2.3), this estimate appears unrealistically high. At this rate, the TP load from 12 weeks' worth of grass clippings on the road in the subcatchments monitored in the experiment would comprise around 50% of the total TP load estimated from the experiment. Furthermore, the mass of these clippings would be around 100 times greater than the total mass of material collected during the experiment. Rough visual estimates suggest that only between 0-10% (by volume) of the swept material was grass clippings. To reconcile these different estimates, we assume that current mowing management practices are 90% effective in keeping clippings off the road, so clippings contribute 32.7 - 52.3 kg TP/year (at this rate, TP loads from clippings would comprise around 5% of the total TP load measured in the street sweeping experiment).

2.4.2 Phosphorus removal performance

Only two of the three suggested management methods for municipal grass clippings are assessed here. Through consultation with the Transport Canberra and City Services mowing team, the use of catchers has

been discounted – most of the current fleet of mowers cannot accommodate a catcher, and the team does not have the capacity (time or resources) to dispose of collected clippings.

Management method 1 is to adopt the use of electric blowers towed behind mowers to move clippings away from road edges. This option is assumed to improve current practices to be 95% effective at keeping clippings off the roads, reducing TP inputs by 50% (removing between 16.4 - 26.1 kg TP/year).

Management method 2 is to use street sweeping trucks to immediately remove all remaining grass clippings on roads. A suggestion to do this by coordinating with the current street sweeping program has previously been trialled and found to be logistically infeasible. This option would instead require the lease of a designated street sweeping truck(s) to run immediately after mowing and is assumed to remove the entire TP load from clippings (removing 32.7 - 52.3 kg TP/year).

2.4.3 Costing

Management method 1 To achieve the full reduction in phosphorus inputs estimated for this method would require enough blowers to provide operational coverage to current municipal mowing activities in the Lake Tuggeranong catchment. Based on consultation with the TCCS mowing team, the purchase of two blowers and their ongoing operation and maintenance are costed:

- Capital purchase (2 blowers) = $160,000
- Annual cost (2 staff at $65,000/year + maintenance at $5,000/year) = $140,000/year

Management method 2 Here we assume that operational coverage for current municipal mowing activities in the Lake Tuggeranong catchment would require the lease of one dedicated street sweeping truck running full time (2 shifts per day, 5 days per week). Costing is based on leasing and operational cost information provided by the TCCS street sweeping team:

- No capital cost
- Annual operational cost (truck lease, staff, fuel, and maintenance) = $108,996/year
- Additional annual cost (landfill charges at $171/tonne ex. GST, for 32,700-52,300 kg material) = $5,592-$8,943/year

2.4.4 Cost-effectiveness

These two methods for the management of grass clippings from municipal mowing are predicted to remove between 16 - 52 kg TP per year at a cost of between $998 - $4,103 per kg P removed, over 30 years. We use the high and low estimates of TP removal performance for each method to provide four levels of investment in this management option (Table 9).

2.4.5 Quality of supporting evidence

Using the evaluation rubric (Appendix A), the estimates of cost-effectiveness of managing grass clippings from municipal mowing scored 9/14 for confidence in cost estimates, and 7/16 for confidence in performance estimates.

Table 9. Estimated annual load of total phosphorus (TP) prevented from entering Lake Tuggeranong, total 30-year lifecycle cost, and cost-effectiveness of options for management of grass clippings from municipal mowing.

Investment level	Management method and level of TP removal	Total annual TP removed (kg/year)	Total 30-year lifecycle cost[1]	Cost per unit TP removed ($/kg)
1	Method 1 (blowers) – low TP removal estimate	16.4	$2,018,874	$4,103
2	Method 1 (blowers) – high TP removal estimate	26.1	$2,018,874	$2,578
3	Method 2 (sweeping) – low TP removal estimate	32.7	$1,521,462	$1,551
4	Method 2 (sweeping) – high TP removal estimate	52.3	$1,565,956	$998

1 Total lifecycle cost is calculated over 30 years using a discount rate of 7% per annum on annual costs after the first year.

2.5 Management of sports field fertilizer use practices

2.5.1 Background

The use of fertilizers containing phosphorus on sports grounds and other 'managed' green space is undertaken by both government and private managers. The Lake Tuggeranong catchment includes ~60 ha of actively managed (irrigated and fertilized) sports grounds, and a few additional privately managed assets: Vikings Club football ground, and three school sports grounds (Trinity Christian School, St Mary Mackillop College, Erindale College) with an estimated combined total of 7.5 ha.

Interviews with Canberra sports field and turf managers (Edmondson, 2022) suggest that in general, sports field managers are motivated to use fertilizer efficiently within the constraints of their management priorities. There is likely little to be gained in trying to further reduce fertilizer application rates. An additional option to address fertilizer export from sports fields is to install bioretention swales to intercept runoff from sports fields, and this is the management option we assess here.

Phosphorus application and export rates from sports field fertilizer use

TCCS provided information on the fertilizer application of the public sports grounds in the catchment. Estimates of fertilizer application regimes of privately managed sports grounds are based on information from interviews with Canberra sports turf managers (Edmondson, 2022). Export rates of phosphorus from different fertilizer products (Table 10) were estimated based on a review of experimental studies of TP export rates (Booksmythe, 2023).

Table 10. The amount of phosphorus (P) applied in fertilizers, and literature-derived rates of P export for the fertilizers applied, for three categories of sports field management in the Lake Tuggeranong catchment. Lower, medium, and upper estimates of P export rates are provided, based on the range of values reported for each fertilizer type in the literature.

Sports field type	TP applied (kg/year)	Lower TP export rate (kg/ha/year)	Medium TP export rate (kg/ha/year)	Upper TP export rate (kg/ha/year)
Public sports field	10	0.2	1.2	2.5
'Elite' public sports field	36	0.72	4.32	9
Private sports field	3	0.06	0.36	0.75

We multiplied the annual amount of P applied by the export rates given in Table 10 to calculate a range of estimates of the total P load exported from sports fields in the Lake Tuggeranong catchment (Table 11).

Table 11. The total area of three categories of sports field management in the Lake Tuggeranong catchment, and the estimated total annual load of total phosphorus (TP) exported from each category.

Sports field type	Total area (ha)	Lower total TP exported (kg/year)	Medium total TP exported (kg/year)	Upper total TP exported (kg/year)
Public sports field	58.7	11.74	70.44	146.75
'Elite' public sports field	2.3	1.66	9.94	20.7
Private sports field	7.5	0.45	2.7	5.63
Total	68.5	13.85	83.08	173.08

The median and upper estimates of the total TP exported from sports fields (based on the upper bound of estimates of TP export rate from the literature) are larger than the total TP load of 57.9 kg/year from sports field land use estimated by the Lake Tuggeranong catchment model (Dey, Stewart, Kahn, Booksmythe, & Starrs, 2024).

2.5.2 Phosphorus removal performance

We assess the TP removal performance of installing bioretention swales below public managed sports fields in the Lake Tuggeranong catchment based on the performance of similar existing WSUD infrastructure in the catchment (see Section 2.1.2). We calculated the swale area required to remove the total TP load from sports fields, 57.9 kg P/year, across the range of performance rates in Table 1. In the absence of explicit scoping work investigating possible locations and designs for swales, we made a simplified assumption of the range of TP removal performance: of the total infrastructure required to remove 57.9 kg TP/year, 25% would perform at the highest rate, 25% would perform at the lowest rate, and 50% would perform at the average rate (Table 12). Based on this assumed performance range, the total swale area required to remove the total TP load from sports fields is 7,882 m^2.

Table 12. Phosphorus removal performance bands assumed for bioretention swales installed below sports fields in the Lake Tuggeranong catchment

Performance band	Annual TP removal ($kg/m^2/year$)	TP load addressed (kg)	Swale area required (m^2)
High performance (25% of assets)	0.0142	14.93	1,016
Average performance (50% of assets)	0.0077	29.86	3,878
Low performance (25% of assets)	0.0048	14.93	2,988

2.5.3 Costing

G2W Pty Ltd were engaged to review the capital and ongoing operation and maintenance costs associated with existing WSUD infrastructure in the Lake Tuggeranong catchment (see section 2.1.3) (G2W Pty Ltd, 2024). Bioretention assets (raingardens and swales) in the Lake Tuggeranong catchment ranged between 765–5,270m^2 in size, and between \$774 - 2,532/m^2 in capital cost, with a strongly negative relationship between size and cost such that on average, larger assets had a lower capital cost per square metre. Similarly, the annual operation and maintenance (O&M) cost of existing bioretention assets ranged between \$62 – 170/m^2, with larger assets having a lower annual O&M cost per square metre. We used these asset size - cost relationships to estimate the capital and O&M costs of constructing between 4 and 24 swales with a total combined area of between 1,016 - 7,882 m^2, and used these capital and O&M cost estimates to calculate the 30-year lifecycle cost, assuming an annual discount rate of 7% each year for O&M costs.

2.5.4 Cost-effectiveness

To provide four levels of investment for this management option, we used the performance bands described in Section 2.5.2 to define four tiers of implementation: to build the best-performing 25%, 50%, 75% or 100% of the swales required to remove the TP load from sports fields (Table 13). Investment option 1 is to build all assets in the 'high performance' band, addressing 25% of the sports field TP load. Investment option 2 builds the assets from option 1, and additionally half the assets in the 'average performance' band, in total addressing 50% of the sports field TP load. Investment option 3 builds all the assets in the 'high' and 'average performance' band, addressing 75% of the sports field TP load, and investment option 4 builds all the assets in all performance bands, addressing 100% of the sports field TP load.

Table 13. Costing summary for four levels of investment in constructing bioretention swales below managed sports fields in the Lake Tuggeranong catchment.

Investment option	Costing level	Total annual TP removed (kg/year)	Total 30-year lifecycle cost[1]	Cost per unit TP removed ($/kg)
1	Build best 25%	14.93	$4,204,451	$9,387
2	Build best 50%	29.85	$11,817,327	$13,196
3	Build best 75%	44.78	$19,430,204	$14,463
4	Build all	59.70	$31,445,222	$17,557

1 Total lifecycle cost is calculated over 30 years using a discount rate of 7% per annum on O&M costs.

2.5.5 Quality of supporting evidence

Using the evaluation rubric (Appendix A), the above estimates of cost-effectiveness of installing bioretention swales below managed sports fields scored 13/14 for confidence in cost estimates, and 9/16 for confidence in performance estimates.

2.6 Management of household fertilizer use practices

2.6.1 Background

Household use of fertilizer products was investigated as a source of TP in the catchment that may be exported from residential blocks. The loss of fertilizer TP from residential blocks could be reduced by community partnership programs designed to alter how people use fertilizer on their block, and/or by legislating to reduce the TP content of fertilizer products, e.g. (Environmental Protection (Packaged Fertiliser) Regulations, 2010).

Concepts of Change were contracted to survey Canberra households on their fertilizer use (including purchased compost, manures, and 'chemical' fertilizer products). Based on the detailed information the survey obtained about the usage rates of different types of fertilizer products, Concepts of Change estimated the amount of phosphorus applied to residential properties (Concepts of Change, 2023). Export rates of phosphorus from different fertilizer products were estimated based on a review of experimental studies of TP export rates (Booksmythe, 2023).

Phosphorus application and export rates from household fertilizer use

Survey respondents lived on residential blocks with garden space - i.e. RZ1 or RZ2 -zoned blocks. The total per-household rate of TP application in fertilizer products estimated from the survey was 0.59 kg TP/year (Table 14).

Table 14. Average annual amounts of total phosphorus (TP) applied to residential blocks in the ACT from chemical fertilizers, commercial composts and raw manures, and literature-derived rates of TP export for these products. Lower, medium, and upper estimates of TP export rates are provided, based on the range of values reported for each fertilizer type in the literature.

Product type	TP applied (kg/household/year)	Lower TP export rate (% of applied)	Medium TP export rate (% of applied)	Upper TP export rate (% of applied)
Fertilizers	0.15	2%	12%	25%
Composts	0.36	0.2%	1%	2.5%
Raw manures	0.07	1%	9%	17%

There are ~21,000 RZ1 and RZ2 -zoned blocks (low to medium density residential, detached and semi-detached dwellings with garden) in the Lake Tuggeranong catchment comprising ~1030 hectares of permeable area (out of 1950 ha total area of RZ1 and RZ2 blocks). Chemical fertilizers account for about 25% of the TP applied to household gardens, but their higher export rates compared to composts and manures mean they are estimated to account for about 65% of the exported TP (Table 15).

Table 15. Annual amounts of total phosphorus (TP) from fertilizer products applied to and exported from residential blocks (RZ1 and RZ2) in the Lake Tuggeranong catchment.

Product type	Total TP applied in catchment (kg/year)	TP applied (kg/ha/year)	Lower total TP exported (kg/year)	Medium total TP exported (kg/year)	Upper total TP exported (kg/year)
Fertilizers	3192	3.10	0.06	0.37	0.78
Composts	7644	7.42	0.02	0.07	0.19
Raw manures	1533	1.49	0.02	0.13	0.25
Total	12369	12.01	0.09	0.58	1.21

The Lake Tuggeranong catchment model (Dey, Stewart, Kahn, Booksmythe, & Starrs, 2024) estimates the total TP load from suburban pervious land in the Lake Tuggeranong catchment to be ~0.12 - 0.16 kg/ha/year, or in the vicinity of the lower estimate from the survey data. The catchment model estimate includes all TP inputs from suburban pervious land (e.g. any TP from leaves & grass clippings, pet waste, etc.) so it suggests that our estimates from the survey data might be too high (even the lower value). Caveats to our current understanding of the TP inputs contributed by household fertilizer use include:

- Although the survey was very detailed and thorough, and estimates of fertilizer use included correction factors based on on-the-ground verification of reported product use, these estimates may still over-estimate the amount of fertilizer applied to residential blocks. Information on Bunnings' annual ACT fertilizer sales suggest rates of 'chemical' fertilizer use are between 12 - 20 times lower than survey estimates.
- Estimates of export rates obtained from the literature varied widely between studies and depend on a large number of factors (e.g. soil type, 'rainfall' intensity and duration, vegetation type and presence). The highest export rate reported in the literature for a given type of fertilizer product was used as the upper estimate in these calculations. This is similar to assuming a 1-in-10 year rain event occurring immediately after fertilizer is applied. The lower estimates may be more realistic, and are more

consistent with the catchment model estimates of the TP load generated by suburban pervious land use in the Lake Tuggeranong catchment.

- The reported rates of phosphorus application suggest that we should see far more phosphorus exported from residential blocks than current water quality data indicates. If the survey-derived estimates of phosphorus application are broadly correct, several further avenues of investigation are required to understand what is happening to this phosphorus, e.g.:
  - how long has phosphorus been applied at this rate?
  - how much phosphorus can be stored in the soil?
  - is excess phosphorus taken up by trees?

2.6.2 Phosphorus removal performance

The management option assessed here is to use specialised community partnership approaches to encourage households to reduce the amount of phosphorus fertilizer products they apply to residential blocks.

To estimate the potential TP reduction resulting from this approach, we assume a community partnership program that gets the top 20% of P-inputting households to reduce their inputs by 20% (this outcome is chosen based on advice from Concepts of Change). Using the fertilizer survey data and TP export rates from the literature, the amount of TP applied and exported by the top 20% of users can be calculated. Reducing these inputs by 20% and adding the unaltered inputs from the remaining 80% of users, gives a reduction of 17% of the current total household P exports.

To calculate the estimated TP load reduction of this option, we assume that household fertilizer TP exports occur in event flows, and any reduction will not affect the baseflow TP loads coming from suburban pervious areas in the Source catchment model. This baseflow TP load is estimated to be 0.018 kg/ha/year. This is subtracted from the total modelled TP load from suburban pervious areas (~0.12 - 0.16 kg/ha/year) to give the estimated event flow TP load, of between 0.103 - 0.142 kg/ha/year.

We also assume that the catchment model estimates represent the upper limit of current household fertilizer TP exports. This means that the median and upper TP export estimates (Table 13) based on the survey data and export rates from the literature are too large to be consistent with the model. In providing an estimated range of the TP load reduction from banning phosphorus in fertilizers, we use the lower TP export estimate from the survey and literature review as the lower bound, and the catchment model estimate of suburban pervious event flow load as the upper bound (Table 16).

To calculate the percent reduction in the suburban pervious TP load resulting from this community partnership program, we add the baseflow loads to the new event flow loads from fertilizer and divide this by the current total suburban pervious load. This gives an estimated maximum TP reduction of between 14 - 41% of the current load contributed by suburban pervious areas, or the removal of between 20 - 58 kg of the current 140.3 kg TP/year.

Table 16. Estimating the reduction in TP load from suburban pervious land use resulting from a 17% reduction in current TP inputs from household fertilizer use. The range of values in each cell reflects the range of estimated TP export rates from the fertilizer applied to residential blocks.

Total TP load from suburban pervious land use (kg/ha/year)[1]	Current event-flow TP load from fertilizer (kg/ha/year)[2]	Reduced event-flow TP load from fertilizer (kg/ha/year)	Reduced event-flow TP load from fertilizer, plus baseflow load (kg/ha/year)	Percent reduction in total TP load from suburban pervious land use (kg/ha/year)
Lower estimate: 0.121	0.092 – 0.103	0.076 – 0.085	0.094 – 0.103	14.5 – 22.2%
Upper estimate: 0.160	0.092 – 0.142	0.076 – 0.118	0.094 – 0.136	15.1 – 41.2%

1 Estimated from the catchment model for the Lake Tuggeranong catchment (Dey, Stewart, Kahn, Booksmythe, & Starrs, 2024).

2 Estimates for the event-flow TP load from household fertilizer use are capped at the model-estimated total event-flow TP load from all suburban pervious land use, 0.103 or 0.142 kg TP/ha/year.

2.6.3 Costing

The lower cost estimate is based on the cost of a 6-month Concepts of Change community partnership program implemented in 2024, scaled up to run over 5 years and reach all households in the Lake Tuggeranong catchment. The higher cost estimate is based on expert opinion provided by Concepts of Change for the cost of a 5-year intensive campaign to achieve the reductions described in this section across all of Canberra. 30-year costings use a discount rate of 7% per annum after the first year, and assume that the intensive 5-year campaign runs twice (years 0-4 and 15-19), and that for all intervening years, maintenance costs of $350,000/year are required for both costing levels.

2.6.4 Cost-effectiveness

Based on the above, management of household fertilizer use by way of a community partnership program aimed at reducing the TP inputs of the top 20% of users by 20% is predicted to remove between 20 - 58 kg TP per year at a cost of between $3,700 - $24,000 per kg TP removed, over 30 years (Table 17).

Table 17. Estimated annual program and maintenance costs, total 30-year lifecycle cost, and cost-effectiveness of options for management of household fertilizer use.

Costing level	Annual program cost (2 x 5-year programs in 30-year lifecycle)	Annual maintenance cost (non-program years)	Total 30-year lifecycle cost[1]	Cost per unit TP removed ($/kg) – low performance	Cost per unit TP removed ($/kg) – high performance
Lower cost estimate	$637,000	$350,000	$6,362,682	$10,604	$3,657
Higher cost estimate	$2,000,000	$350,000	$14,509,794	$24,183	$8,399

1 Total lifecycle cost is calculated over 30 years using a discount rate of 7% per annum on O&M costs.

However, how cost estimates relate to the efficacy of this option is uncertain. We have no information on whether cost-effectiveness would increase or decrease with the scale of investment in a community partnership program to manage household fertilizer use.

In providing four levels of investment for this management option, we therefore assumed a uniform cost-effectiveness of $10,000/kg TP removed at all four levels of investment. This value was chosen as it falls within the cost-effectiveness estimates generated from both cost estimates above, and results in a realistic range of total program costs (between $6 and $17 million) when applied to the lower and upper estimates of the reduction in TP achieved by such a program. We used the lower and upper estimates of TP removal as the amount that would be removed by the lowest and highest levels of investment in this management option, respectively, and interpolated two evenly-spaced levels of TP removal between these extremes (Table 18).

Table 18. Costing summary for four levels of investment in community partnership programs aimed at managing household fertilizer use to reduce TP inputs in the Lake Tuggeranong catchment.

Investment level	Assumed program implementation	Annual TP removed (kg)	Total 30-year lifecycle cost[1]	Cost per unit TP removed ($/kg)
1	Low implementation	20	$6,000,000	$10,000
2	Medium implementation	32.67	$9,800,000	$10,000
3	High implementation	45.33	$13,600,000	$10,000
4	Very high implementation	58	$17,400,000	$10,000

1 Total lifecycle cost is calculated over 30 years using a discount rate of 7% per annum on annual costs after the first year.

2.6.5 Quality of supporting evidence

Using the evaluation rubric (Appendix A), the above estimates of cost-effectiveness of community partnership programs aimed at managing household fertilizer use scored 9/14 for confidence in cost estimates, and 7/16 for confidence in performance estimates.

2.7 Installation of castellated kerbs

2.7.1 Background

The stormwater network of the Lake Tuggeranong catchment was designed and built to be extremely efficient at directing stormwater into the piped network. The prevailing paradigm at the time was to minimise flood risk by getting stormwater out of residential areas as efficiently as possible. Consequently, the Lake Tuggeranong catchment stormwater network is dominated by concrete drains and a significant underground stormwater pipe network.

Almost all stormwater that ends up on sealed roads is diverted directly into the underground stormwater pipe network via the sumps along the kerbs. A small number of sealed roads in the Lake Tuggeranong catchment divert stormwater directly to public open space.

Castellated kerbs are concrete kerbs that include engineered breaks or channels diverting water to adjacent pervious land. Retrofitting castellated kerbs on roads adjacent to public open space in the Lake Tuggeranong catchment has two potential benefits for improving water quality in the lake. Firstly,

stormwater diverted to public open space is able to infiltrate the soil, allowing the capture of nutrients and sediment from the water. Secondly, the flow of the portion of stormwater diverted to public open space is slowed, and the volume of water remaining in the stormwater network is reduced. These effects reduce the hydrological flashiness in downstream areas of the catchment, with benefits for the function of other WSUD infrastructure. Estimating these secondary effects on downstream hydrology is extremely complex and beyond the capability of this assessment. Here, phosphorus removal performance estimates are estimates of the amount of stormwater and pollution diverted from sealed roads.

The Lake Tuggeranong catchment model estimates that 582 kg TP/year is generated from the 388 ha of impervious road surface area in the catchment (Dey, Stewart, Kahn, Booksmythe, & Starrs, 2024). Using ACT Government GIS layers for land zoning and roads, the surface area of road that is adjacent to public open space is 166.15 ha, or 43% of the total road area. Assuming that pollutant generation is uniform, the amount of TP generated on roads adjacent to public open space is calculated as 249 kg/year (43% of the total road TP load). However, in some instances, the road will slope away from the adjacent open space – here we assume that on average, half of the road area adjacent to public open space has a slope suitable to allow drainage towards the open space, and so half of the TP generated on this road area – 124.5 kg TP/year – is currently received by the 1813 stormwater sumps located along kerbs bordering public open space.

2.7.2 Phosphorus removal performance

Not all of the TP currently received by stormwater sumps bordering open space would be diverted to castellated kerb outlets, as these outlets are not able to receive as much road runoff as stormwater sumps, and will be bypassed when the pervious land is saturated. Here we conservatively assume that a castellated kerb outlet can receive half as much runoff as a stormwater sump.

Under these assumptions, if a castellated kerb outlet was installed immediately ‘upstream’ of each of the 1813 stormwater sumps located on kerbs bordering public open space, intercepting half of the road runoff received by each sump, 62 kg TP/year would be diverted from the stormwater network. This represents an upper limit to the amount of TP removed, as it is likely an unrealistically high rate of installation, and does not take into account logistical considerations for construction or issues such as changes to the road flooding risk. Lower rates of installation result in proportionally lower rates of TP removal: installing a castellated kerb outlet for every second, third, or fourth sump would remove 31, 20.75, or 15.5 kg TP/year, respectively.

2.7.3 Costing

The cost to retrofit castellated kerb outlets was reported as $6,872 per outlet in the preliminary sketch plan (PSP) report by Construction Control Australia for a project to construct 36 outlets in the Lake Tuggeranong catchment as part of Stage 2 of the ACT Healthy Waterways project (Construction Control Australia Pty Ltd, 2022). We used this figure as our lower estimate of the cost of this management option. An alternative costing estimate of $10,000 per outlet is is derived from the estimated cost in 2024 for the construction of 51 outlets of $18,802 per outlet (GW2, 2024), and assumes an economy of scale to achieve a reduced per unit cost.

2.7.4 Cost-effectiveness

We assume a lifecycle of 30 years for castellated kerbs, consistent with other management options. However, no reliable estimate of the maintenance costs of castellated kerb outlets was obtained, and our estimates of cost-effectiveness of this management option are based solely on the capital cost of installation.

In calculating the cost-effectiveness of castellated kerbs as a management option, we incorporated a range of installation frequencies (an outlet for every sump – an outlet for every 4 sumps) and costs (between the lower and higher cost estimates obtained, above). We assumed an economy of scale such that installing outlets at the lower rate of one for every four sumps incurs the highest per-outlet cost of $10,000, but there is a marginal decrease in per-outlet costs as more outlets are installed (Table 19).

2.7.5 Quality of supporting evidence

Using the evaluation rubric (Appendix A), the estimates of cost-effectiveness of installing castellated kerb outlets scored 11/14 for confidence in cost estimates, and 7/16 for confidence in performance estimates.

Table 19. Estimated annual load of total phosphorus (TP) prevented from entering Lake Tuggeranong, cost per castellated kerb outlet installed, total 30-year lifecycle cost, and cost-effectiveness of for four levels of investment into retrofitting castellated kerb outlets to divert road runoff from the stormwater network.

Investment level	Number of outlets installed	TP removed (kg/year)	Cost per outlet	Cumulative total lifecycle cost[1]	Cost per unit TP removed ($/kg)
1	453 (1 per 4 sumps)	15.56	$10,000	$4,532,500	$9,708
2	604 (1 per 3 sumps)	20.75	$9,652	$5,990,823	$9,624
3	906 (1 per 2 sumps)	31.13	$8,957	$8,539,901	$9,146
4	1813 (1 per sump)	62.25	$6,872	$14,349291	$7,684

1 Cumulative total lifecycle cost is calculated based on the assumed marginal improvement in per-unit cost between installation tiers. For example, the total cost of installing 453 outlets (the lowest installation rate) is equal to 453 times the unit cost of $10,000. The total cost of installing 604 outlets (the second-lowest installation rate) is equal to the cost of installing 453 outlets at $10,000, plus 153 outlets at the unit cost of $9,652.

2.8 Installation of floating wetlands

2.8.1 Background

Once nutrients are transported into a waterbody, they may become available for uptake by plants, algae, and bacteria, including blue-green algae. Fringing and in-lake vegetation can help to limit blue-green algae blooms by competing with them for these nutrients, particularly phosphorus. One approach to increasing in-lake vegetation is to install floating wetlands.

Floating wetlands are floating structures supporting beds of emergent wetland vegetation, deployed in lakes and ponds to remove nutrients from the water. The plants take up the nutrients they need as they grow, and regular harvesting of the plants prevents the recycling of those nutrients back into the water. The ACT Healthy Waterways program contracted Atlan Stormwater to trial floating wetlands in Lake Tuggeranong in 2023 (Atlan Stormwater, 2023). Three floating platforms totalling 500m^2 were installed, with three species of wetland plants compared for their nutrient uptake rates. The data from this trial inform the estimates of TP removal performance and cost of this management option.

2.8.2 Phosphorus removal performance

In the trial, the floating wetland plants were harvested once, after a year of deployment, and the increase in their TP content was recorded as a measure of the amount of TP they removed from the lake. From this we can calculate the amount of TP removed from the lake per square metre of floating wetland area for each plant species separately. The worst-performing species removed 0.001kg TP/m^2/year, and the best-performing species removed 0.005kg TP/m^2/year. The average amount of TP removed by all three species was 0.003kg TP/m^2/year, and we used this as our estimate of floating wetland TP removal performance.

2.8.3 Costing

G2W Pty Ltd were engaged to review the costs associated with existing WSUD infrastructure in the Lake Tuggeranong catchment (G2W Pty Ltd, 2024). The average capital cost of the trialled floating wetlands was \$1,049/m^2, and the annual maintenance cost was \$13.24/m^2.

2.8.4 Cost-effectiveness

We calculated the cost-effectiveness of floating wetlands based on the above TP removal performance and costs over a 30-year lifecycle, as \$13,622.2/kg TP removed. We assume that both cost and performance scale linearly with floating wetland area, so cost-effectiveness remains the same for any size of wetland. To provide four levels of investment in this management option, we used four sizes of floating wetland area (Table 20).

Table 20. Wetland area, estimated TP removal performance, estimated capital cost and annual operation and maintenance costs, 30-year lifecycle costs and cost-effectiveness for four levels of investment in installation of floating wetlands in Lake Tuggeranong.

Investment level	Wetland area (m^2)	Total annual TP removed (kg)	Capital cost	Annual operation and maintenance costs	Total 30-year lifecycle cost[1]	Cost per unit TP removed ($/kg)
1	1000	3	$1,049,000	$13,240	$1,226,000	$13,622.2
2	2000	6	$2,098,000	$26,480	$2,452,000	$13,622.2
3	3000	9	$3,147,000	$39,720	$3,678,000	$13,622.2
4	4000	12	$4,196,000	$52,960	$4,904,000	$13,622.2

1 Total lifecycle cost is calculated over 30 years using a discount rate of 7% per annum on O&M costs.

2.8.5 Quality of supporting evidence

Using the evaluation rubric (Appendix A), the above estimates of cost-effectiveness of installing floating wetlands in Lake Tuggeranong scored 10/14 for confidence in cost estimates, and 9/16 for confidence in performance estimates.

2.9 Installation of stormwater recycling infrastructure

2.9.1 Background

Urban stormwater contains high concentrations of nutrients because the large area covered by impervious surfaces in the urban environment prevents water from soaking into the ground and being naturally filtered through the soil. Diverting some stormwater for use in the irrigation of public sports fields removes nutrients from the stormwater system. It also slightly reduces the volume of stormwater that continues through the system, reducing hydrological flashiness to the benefit of downstream WSUD infrastructure.

In the Lake Tuggeranong catchment, a stormwater recycling system for sports field irrigation has been installed at one publicly managed sports field (TCCS ID: Kambah 3). A further ten publicly managed sports fields at 8 sites in the Lake Tuggeranong catchment are currently irrigated using potable water, with a combined irrigation water demand of 194 ML/year, at an average cost of $5,478/ML. Here we assess the TP removal performance and cost of installing stormwater recycling infrastructure for sports field irrigation across these sites.

2.9.2 Phosphorus removal performance

As we assume that 100% of the P in stormwater is removed when water is used for irrigation, the amount of TP removed depends on the amount of stormwater used for irrigation. TCCS provided data on the average annual water demand for 10 irrigated sports fields at 8 sites in the Lake Tuggeranong catchment (Table 18). In wet years, irrigation water demand is low and stormwater is abundant, conditions that make it likely that 100% of demand can be met using recycled stormwater. In dry years, however, water demand is high and stormwater is relatively scarce. This, combined with the flashy nature of stormwater hydrographs, make it unlikely that all the irrigation demands will be met by stormwater. We therefore assume that overall, 75% of average annual potable water demands would be met using stormwater (Table

20). We assume a TP concentration of 0.15mg/L to calculate the potential load of TP removed by harvesting stormwater to irrigate these sports fields (Table 21). This value is the average median observed TP in the University of Canberra research data used to calibrate the catchment model (Ubrihien, et al., 2020).

Table 21. Annual irrigation demand, estimated demand met by recycled stormwater, and estimated annual TP load in recycled stormwater, for 8 sports field sites[1] in the Lake Tuggeranong catchment.

Sports field ID	Total annual irrigation water demand (ML)	Demand met by stormwater = 75% of total (ML)	TP load in stormwater used for irrigation (kg)
Calwell 1, 2, 3[1]	47.15	35.36	5.30
Kambah 1	31.18	23.38	3.51
Wanniassa 2	28.40	21.30	3.19
Greenway 1	27.70	20.77	3.12
Gowrie 1	18.68	14.01	2.10
Kambah 2	17.49	13.12	1.97
Chisholm 1	15.21	11.41	1.71
Isabella 1	7.76	5.82	0.87
Total	193.57	145.17	21.78

1 TCCS provided a combined irrigation demand for three Calwell sports fields, which are treated as a single site.

2.9.3 Costing

The estimated costs of installing stormwater recycling infrastructure are based on the realised cost of the infrastructure installed at Kambah 3 (GW2, 2024) and assume that each system will include the same components, namely:

- Stormwater treatment train (gross pollutant trap, sediment forebay, and wetland/pond/raingarden)
- Pumps and pipe infrastructure
- Water treatment plant (sand filter and UV filter)
- Water holding tanks (1 ML capacity)
- Operation and maintenance

These costs will be offset by the savings accrued as a result of the 75% reduction in the use of potable water and its associated cost of $5,478/ML.

The infrastructure installed at sports field Kambah 3, which has an average annual water demand of 26.6 ML, had capital costs of approximately $1,500,000, and annual operation and maintenance costs of $65,000. This site had existing water tanks for irrigation, which is not the case for all of the sites costed here. We therefore take these as the lower bound of cost estimates, and assign this minimum cost to sports fields with an average annual water demand equal to or less than that of Kambah 3. We assume that more infrastructure will be required to divert, filter, store, and irrigate more water, and that operation and maintenance of larger facilities will increase similarly. Both the capital costs and O&M costs for stormwater

recycling infrastructure installed at sports fields with larger water demands than Kambah 3 are scaled up in proportion to their demand (Table 22).

2.9.4 Cost-effectiveness

While sports fields with the highest annual irrigation demands have the highest capital and O&M costs, they also experience the largest savings from reduced potable water expenses and remove the largest TP loads, representing the most cost-effective options (Table 22).

Table 22. Capital cost, annual operation and maintenance cost, savings from reduced potable water use, 30-year lifecycle cost, and cost-effectiveness for the installation of stormwater recycling infrastructure for irrigation at 8 sports field sites in the Lake Tuggeranong catchment.

Sports field ID	Capital cost	Annual operation and maintenance cost	Savings from potable water expenses	Total 30-year lifecycle cost[1]	Cost per unit TP removed ($/kg)
Calwell 1, 2, 3	$2,661,034	$115,311	-$193,726	$1,609,575	$10,115
Kambah 1	$1,759,537	$76,247	-$128,096	$1,064,288	$10,115
Wanniassa 2	$1,602,639	$69,452	-$116,681	$969,446	$10,115
Greenway 1	$1,563,316	$67,744	-$113,811	$945,600	$10,115
Gowrie 1	$1,500,000	$65,000	- $76,748	$1,342,472	$21,295
Kambah 2	$1,500,000	$65,000	- $71,868	$1,407,903	$23,850
Chisholm 1	$1,500,000	$65,000	- $62,496	$1,533,578	$29,875
Isabella 1	$1,500,000	$65,000	- $31,887	$1,994,008	$74,221

1 Total lifecycle cost is calculated over 30 years using a discount rate of 7% per annum on both annual O&M costs and savings from reduced potable water expenses.

To provide four levels of investment in this management option, we grouped the 8 sports field sites by size and cost-effectiveness and created four tiers of installation: either build the best two, best four, best six, or all 8 stormwater recycling systems (Table 23).

Table 23. Costing summary for four levels of investment in installing stormwater recycling infrastructure for sports field irrigation in the Lake Tuggeranong catchment.

Investment option	Costing level	Total annual TP removed (kg/year)	Total 30-year lifecycle cost[1]	Cost per unit TP removed ($/kg)
1	Build best 2	8.81	$2,673,863	$10,115
2	Build best 4	15.12	$4,588,909	$10,115
3	Build best 6	19.19	$7,339,284	$12,748
4	Build all 8	21.78	$10,816,870	$16,558

1 Total lifecycle cost is calculated over 30 years using a discount rate of 7% per annum on O&M costs.

2.9.5 Quality of supporting evidence

Using the evaluation rubric (Appendix A), the above estimates of cost-effectiveness of installing stormwater recycling infrastructure for sports field irrigation scored 10/14 for confidence in cost estimates, and 10/16 for confidence in performance estimates.

2.10 Installation of household rainwater tanks

2.10.1 Background

Residential properties make up a large proportion of the Lake Tuggeranong catchment area, and consist of large areas of impervious surface in the form of rooftops. Residential properties are therefore expected to be a significant contributor to the generation of nutrient pollutants and runoff in the catchment.

Encouraging the installation of plumbed household rainwater tanks on residential properties, by covering some or all of the associated costs to property owners, is a potential approach to reducing this source of runoff. Installation of plumbed rainwater tanks at residential properties diverts runoff, and the phosphorus it carries, from the stormwater system, instead directing it to non-potable household uses and on to the wastewater (sewage treatment) system, or to garden uses from where it completes the water cycle either via evapotranspiration or by entering the groundwater. When properly plumbed in and used, household rainwater tanks help to reduce the intensity of rises in water level and flow during rainfall events (i.e. flatten the hydrograph), which should be beneficial for the TP removal performance of downstream WSUD infrastructure. Rainwater tanks provide some opportunity to directly capture phosphorus when particulate forms are deposited within the tanks, although this effect is likely to be small.

2.10.2 Phosphorus removal performance

To calculate the amount of TP diverted from the stormwater system by rainwater tanks we used estimates of the annual amount of water captured and used by plumbed rainwater tanks, from a study that modelled the savings in potable water offered by residential rainwater tanks in Canberra (Imteaz, Yilmaz, Santos, & Ahsan, 2023). Their estimates account for seasonal variability in rainfall, the typical non-potable water demands of a household, and the spillover of water to the stormwater system when tanks are over capacity, and are broadly summarised for a range of roof and tank sizes in Table 24.

Table 24. Potable water savings from plumbed household rainwater tanks, estimated by Imteaz et al. 2023.

Roof size (m^2)	Tank size (L)	Water saved – dry year (L/year)	Water saved – average year (L/year)	Water saved – wet year (L/year)
100	2,500	35,000	50,000	55,000
200	5,000	40,000	55,000	60,000
100	2,500	50,000	60,000	65,000
200	5,000	60,000	75,000	80,000

These estimated water savings represent the amount of residential runoff diverted from the stormwater system by plumbed rainwater tanks. By multiplying these by the estimated concentration of TP in runoff from suburban roof area in the Lake Tuggeranong catchment (from the calibrated catchment model) we can calculate the approximate load of TP removed per household (Table 25).

Table 25. Estimated loads of TP diverted from the stormwater system by plumbed household rainwater tanks.

Roof size (m^2)	Tank size (L)	TP removed – dry year (L/year)	TP removed – average year (L/year)	TP removed – wet year (L/year)
100	2,500	3.82	5.45	5.99
200	5,000	4.36	5.99	6.54
100	2,500	5.45	6.54	7.09
200	5,000	6.54	8.18	8.72

While the annual load of TP removed from the stormwater system per household is small, ranging between approximately 4-8 g/year, multiplying by the number of residential properties in the Lake Tuggeranong catchment (~21,000 RZ1- and RZ2-zoned blocks) gives an upper estimate of annual TP removal of between 84-168 kg/year.

However, this assumes 100% uptake in rainwater tank installation, which is unlikely for several reasons. An estimated 36% of households in the ACT already have rainwater tanks installed, and therefore do not contribute to this source of TP (Schirmer & Dale, 2023). Some households may not be willing or able to install rainwater tanks, and others may not make full use of the water captured by their tanks, which increases spillover and reduces the amount of water diverted from the stormwater system. In costing this option we assume that the highest rate of uptake of new household rainwater tanks would be 10,000 households, or around 50% of residential properties in the Lake Tuggeranong catchment.

2.10.3 Costing

For this management option we estimate costs for a government grant scheme that covers the capital cost of rainwater tank installation for residential properties in the Lake Tuggeranong catchment. Rainwater tanks installed on suburban residential properties are typically of 1,000 - 3,000 L capacity, and cost between $1,000 - $2,000. Adding the costs of installation and plumbing, here we assume a total cost per household of $5,000 that would be provided by government funding. Rainwater tanks are fairly low maintenance, and we assume any operation and maintenance costs would be left to property owners in costing this management option.

2.10.4 Cost-effectiveness

We assume an average rainwater tank TP removal performance of 6 g/year, at a cost of $5,000 per tank installed. Over a 30-year lifecycle, this gives a cost-effectiveness estimate of $27,778 per kg TP removed. To provide four levels of investment in this management option, we costed rates of uptake of rainwater tank installation of between 2,500 and 10,000 households (Table 26).

Table 26. Costing summary for four levels of investment in installing household rainwater tanks on residential properties in the Lake Tuggeranong catchment.

Investment level	Number of households	Total TP removed (kg)	Total 30-year lifecycle cost[1]	Cost per unit TP removed ($/kg)
1	2,500	15	$12,500,000	$27,778
2	5,000	30	$25,000,000	$27,778
3	7,500	45	$37,500,000	$27,778
4	10,000	60	$50,000,000	$27,778

1 30-year lifecycle cost is the capital cost of tank installation, as we assume no operation and maintenance costs for this option.

2.10.5 Quality of supporting evidence

Using the evaluation rubric (Appendix A), the above estimates of cost-effectiveness of a government grant scheme that covers the capital cost of rainwater tank installation for residential properties in the Lake Tuggeranong catchment scored 6/14 for confidence in cost estimates, and 9/16 for confidence in performance estimates.

3. Designing management scenarios

3.1 Comparing the cost-effectiveness of management options

Table 27 presents the annual load of TP removed, the 30-year cost, and the cost-effectiveness of the four levels of investment for the management options assessed in Section 2. We plotted the range of TP removal performance and cost of each management option across the levels of investment to provide a visual comparison of the management options and the range of cost-effectiveness for each option (Fig. 1). Increasing street sweeping frequency and constructing additional WSUD infrastructure were estimated to remove the largest amounts of phosphorus annually, in the range of 100-400 kg/year. Street sweeping was the more cost-effective of these two approaches, estimated at $1,000-2,500 per kg TP removed, while constructing WSUD infrastructure had costs of between $7,000-12,000 per kg P. The remaining options all had lower total annual TP removal performances and ranged in cost-effectiveness up to $28,000 per kg TP.

Table 27. Summary of phosphorus removal performance, total cost, and cost-effectiveness for four levels of investment for each of 10 management options assessed in this report. See Section 2 for details of the investment levels for each management option.

Management option and level	TP removed (kg/year)	30-year cost ($)[1]	Cost-effectiveness ($/kg TP)
Install additional WSUD 1	106.21	$22,507,500	$7,064
Install additional WSUD 2	169.67	$48,369,492	$9,502
Install additional WSUD 3	226.22	$73,862,467	$10,884
Install additional WSUD 4	240.46	$84,519,403	$11,716
Maintenance of existing WSUD 1	35.84	$10,177,128	$9,465
Maintenance of existing WSUD 2	61.78	$19,086,579	$10,298
Maintenance of existing WSUD 3	79.93	$26,352,433	$10,990
Maintenance of existing WSUD 4	88.02	$30,352,433	$11,495
Increase street sweeping 1	203.7	$7,030,414	$1,150
Increase street sweeping 2	320.1	$14,060,827	$1,464
Increase street sweeping 3	372.5	$21,091,242	$1,887
Increase street sweeping 4	395.8	$28,121,656	$2,369
Manage grass clippings 1	16.4	$2,018,874	$4,103
Manage grass clippings 2	26.1	$2,018,874	$2,578
Manage grass clippings 3	32.7	$1,521,462	$1,551
Manage grass clippings 4	52.3	$1,565,956	$998
Sports field fertilizer management 1	14.93	$4,204,451	$9,387
Sports field fertilizer management 2	29.85	$11,817,327	$13,196
Sports field fertilizer management 3	44.78	$19,430,204	$14,463

Management option and level	TP removed (kg/year)	30-year cost ($)[1]	Cost-effectiveness ($/kg TP)
Sports field fertilizer management 4	59.70	$31,445,222	$17,557
Household fertilizer management 1	20	$6,000,000	$10,000
Household fertilizer management 2	32.67	$9,800,000	$10,000
Household fertilizer management 3	45.33	$13,600,000	$10,000
Household fertilizer management 4	58	$17,400,000	$10,000
Install castellated kerbs 1	15.56	$4,532,500	$9,708
Install castellated kerbs 2	20.75	$5,990,823	$9,624
Install castellated kerbs 3	31.13	$8,539,901	$9,146
Install castellated kerbs 4	62.25	$14,349,291	$7,684
Install floating wetlands 1	3	$1,226,000	$13,622.2
Install floating wetlands 2	6	$2,452,000	$13,622.2
Install floating wetlands 3	9	$3,678,000	$13,622.2
Install floating wetlands 4	12	$4,904,000	$13,622.2
Stormwater recycling for irrigation 1	8.81	$2,673,863	$10,115
Stormwater recycling for irrigation 2	15.12	$4,588,909	$10,115
Stormwater recycling for irrigation 3	19.19	$7,339,284	$12,748
Stormwater recycling for irrigation 4	21.78	$10,816,870	$16,558
Household rainwater tanks 1	15	$12,500,000	$27,778
Household rainwater tanks 2	30	$25,000,000	$27,778
Household rainwater tanks 3	45	$37,500,000	$27,778
Household rainwater tanks 4	60	$50,000,000	$27,778

1 Total lifecycle cost is calculated over 30 years using a discount rate of 7% per annum on annual (O&M) costs after the first year.

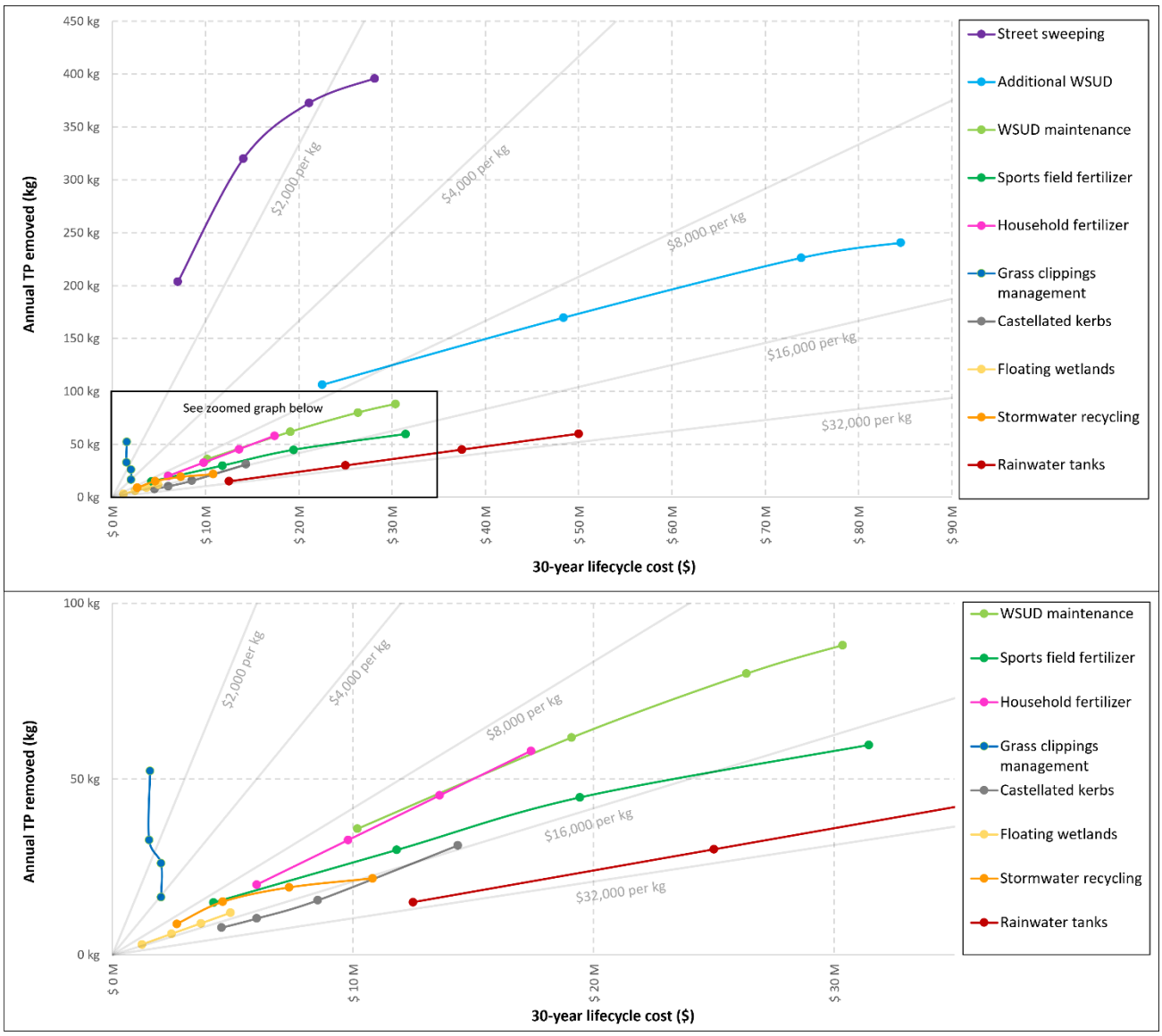

Figure 1. Annual total phosphorus load removed, and 30-year lifecycle cost, of each investment level for the 10 management options assessed in Section 2. Coloured lines connect the four estimates for each management option. Grey lines are a guide indicating the cost-effectiveness (cost per kg TP removed) of the estimates. The top panel shows all estimates; the bottom panel shows a zoomed in view of the estimates within the inset box.

The results of the management option assessments show that there is no single option capable of achieving the estimated ~700 kg reduction in annual phosphorus load required to maintain Lake Tuggeranong in a predominantly mesotrophic state (Kahn & Dey, 2024). To approach this target reduction, a combination of several management options aimed at reducing and intercepting catchment sources of phosphorus will be necessary.

3.2 Combining options to build management scenarios

The Healthy Waterways planning team used the information in Section 2, Table 27 and Figure 1 to create two scenarios, consisting of different combinations of management options, that achieved a reduction in the total annual phosphorus load entering Lake Tuggeranong of around 700 kg (Table 28).

Table 28. Comparison of the investment levels of management options selected for inclusion in the Cost-effective and Broad benefits scenarios designed to achieve a 700 kg reduction in the annual phosphorus load entering Lake Tuggeranong.

Management option	Cost-effective scenario	Broad benefits scenario
Install additional WSUD infrastructure	Investment level 1	Investment level 2
Maintenance of existing WSUD infrastructure	Investment level 3	Investment level 4
Increase frequency of street sweeping	Investment level 4	Investment level 3
Manage grass clippings from municipal mowing	Investment level 3	Investment level 3
Sports field fertilizer management	Investment level 1	Investment level 3
Household fertilizer management	Investment level 4	Investment level 1
Install castellated kerbs	n/a	Investment level 1
Install floating wetlands	n/a	Investment level 4
Stormwater recycling for sports field irrigation	Investment level 2	Investment level 3
Sum of annual TP removed	702.65 kg	766.62 kg
Total 30-year cost	$104,696,482	$143,540,616

The **Cost-effective scenario** systematically ranked the investment levels of each management option by cost-effectiveness, and selected the most cost-effective investment level of the most cost-effective options until the total annual phosphorus load removed met the 700 kg target. This scenario prioritized management options that prevent pollutants from entering the stormwater system, such as street sweeping and fertilizer management, as these have high cost-effectiveness. Options involving WSUD infrastructure were given lower priority under this approach, as they tend to have high costs for more limited phosphorus removal capacity. Some options, including rainwater tanks, floating wetlands, and castellated kerbs, were not considered to be sufficiently cost-effective for inclusion in this scenario.

The **Broad benefits scenario** considered additional information, as well as cost-effectiveness, when selecting management options to meet the 700 kg phosphorus removal target. This approach took into account the quality of evidence underlying each management option assessment, avoiding large investments into options with less certainty around their cost or performance estimates. Broader community and government values, including wellbeing, climate resilience, and public amenity, were also considered when selecting options to include in this scenario. This led to a wider variety of options being

selected for the broad benefits scenario compared to the cost-effective scenario, including more options involving WSUD infrastructure (Table 28).

The TP removal and cost-effectiveness estimates obtained for each management option do not consider the way that options may interact and affect each other's performance. For example, decreasing the load of phosphorus entering stormwater by frequent street sweeping in the catchment should result in lower phosphorus concentrations in the stormwater intercepted by a raingarden further downstream, reducing the phosphorus available for the raingarden to remove. Some of these interacting effects can be estimated by implementing combinations of management options in the catchment model, and calculating the total reduction in the phosphorus load entering Lake Tuggeranong under different combinations.

3.3 Modelling management scenarios

The two scenarios summarised in Table 28 were implemented in the catchment model, to generate estimates of the total annual load of phosphorus entering Lake Tuggeranong under each scenario, while accounting for interactive effects of different management options (Dey, Stewart, Kahn, Booksmythe, & Starrs, 2024).

Different management options are implemented in different ways in the catchment model. Some options are explicitly represented by the addition or modification of specified links and nodes in the model:

- **Additional WSUD infrastructure** Proposed raingardens were represented in the catchment model by new storage nodes placed at the locations indicated in the original plans for the raingardens. The raingarden nodes were configured using the size indicated in the original plans, and the performance details of similar existing WSUD assets.
- **Maintenance of existing WSUD infrastructure** The catchment model includes storage nodes representing each WSUD asset in the Lake Tuggeranong catchment, with the performance of each asset configured to reflect its current phosphorus removal efficiency. To represent maintenance of these assets to their designed performance, the performance details were reconfigured to the phosphorus removal rates given in the detailed design reports for each asset.
- **Sports field fertilizer management** For each scenario we modelled sufficient bioretention swales to intercept the required amount of sports field-generated phosphorus (i.e., 25% or 75% of all sports field generated phosphorus). We modelled one swale per subcatchment, with swale size proportional to the area of sports field in each subcatchment. Bioretention swale performance was configured using the performance details of similar existing WSUD assets. As the scale of the catchment model does not delineate sports fields from their subcatchments, a controlled splitter was used to divert water to the node representing each swale, in proportion to the swale : subcatchment area ratio.
- **Stormwater recycling infrastructure for sports field irrigation** Each sports field with stormwater recycling infrastructure was represented by a storage node and an irrigator node. A maximum of 1 ML water was diverted to the storage node via a controlled splitter during event flows. The water in the storage node was used to meet the irrigation demand specified by the irrigator node. Excess water was returned to the stormwater system downstream of the sports field.
- **Floating wetlands** To represent floating wetlands in the catchment model, a storage routing link was added just upstream of the Lake Tuggeranong storage node. This was configured using a decay model to reduce the phosphorus concentration in the water passing through the routing link.

The remaining options were implemented in the model by calculating the percentage phosphorus removal attained by each option, compared to the current load of phosphorus available to be intercepted by that option, and adjusting phosphorus concentrations within the catchment model based on these percentage reductions:

- **Increase street sweeping frequency** The percentage reduction in phosphorus concentration due to increased street sweeping was applied to all area classified as road, and calculated based on the difference in total phosphorus load generated from roads across the catchment with and without an increase in street sweeping frequency.
- **Manage grass clippings from municipal mowing** The percentage reduction in phosphorus concentration due to management of grass clippings from municipal mowing was applied to all area classified as road, and calculated based on the difference in total phosphorus load generated from roads across the catchment with and without management of grass clippings.
- **Install castellated kerbs** The percentage reduction in phosphorus concentration due to the installation of castellated kerbs was applied to all area classified as road, and calculated based on the difference in total phosphorus load generated from roads across the catchment with and without the installation of castellated kerbs.

  As street sweeping, grass clipping management, and castellated kerbs all act to reduce the load of phosphorus generated from roads, the combined effects of these management options were modelled using a build-up wash-off model as described in 2.3.2 and used to predict the total percentage reduction in the phosphorus load from roads due to the selected combination of these options in each scenario.
- **Household fertilizer management** The percentage reduction in phosphorus concentration due to management of household fertilizer use was applied to all area classified as suburban and permeable, and calculated based on the difference in total phosphorus load generated from suburban pervious land across the catchment with and without household fertilizer management.

The catchment model for the Lake Tuggeranong catchment estimates the current load of phosphorus entering Lake Tuggeranong at 1,442 kg/year (Dey, Stewart, Kahn, Booksmythe, & Starrs, 2024). Under the cost-effective scenario, the model estimates that this load would be reduced to 992 kg TP/year (a reduction of 450 kg/year) and under the broad benefits scenario, the model estimates that the load would be reduced to 868 kg TP/year (a reduction of 574 kg/year; Figs. 2, 3).

The estimated reductions in TP load for each proposed management scenario generated by the catchment model are substantially lower than the reductions calculated by adding the individual estimated reductions for each management option (~ 450-575 kg/year vs. ~ 700-750 kg/year, respectively). The major interactive effects explaining this difference are those between management options that prevent TP from entering the stormwater system, such as street sweeping and household fertilizer management, and options that intercept and remove TP from stormwater, such as WSUD infrastructure. Options that prevent TP from entering stormwater have the effect of reducing TP concentrations in the stormwater that will be intercepted by WSUD-type options, which lowers the rate at which these can remove P. Considering management options that act to reduce runoff generation and flatten the peaks of storm flows, might help to improve the performance of WSUD management options in these scenarios.

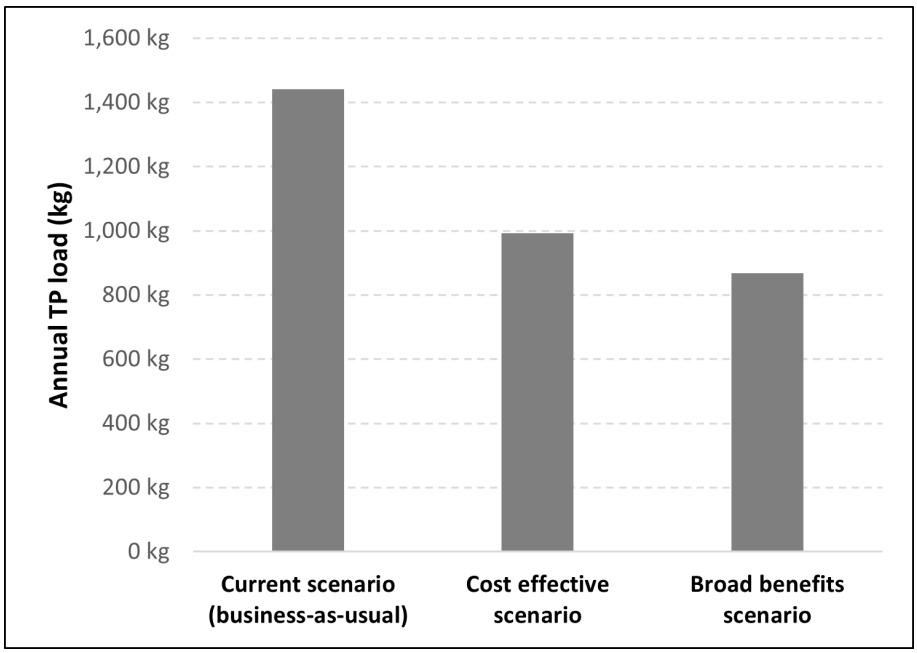

Figure 2. Modelled average annual load of total phosphorus (TP) generated in the Lake Tuggeranong catchment under three management scenarios.

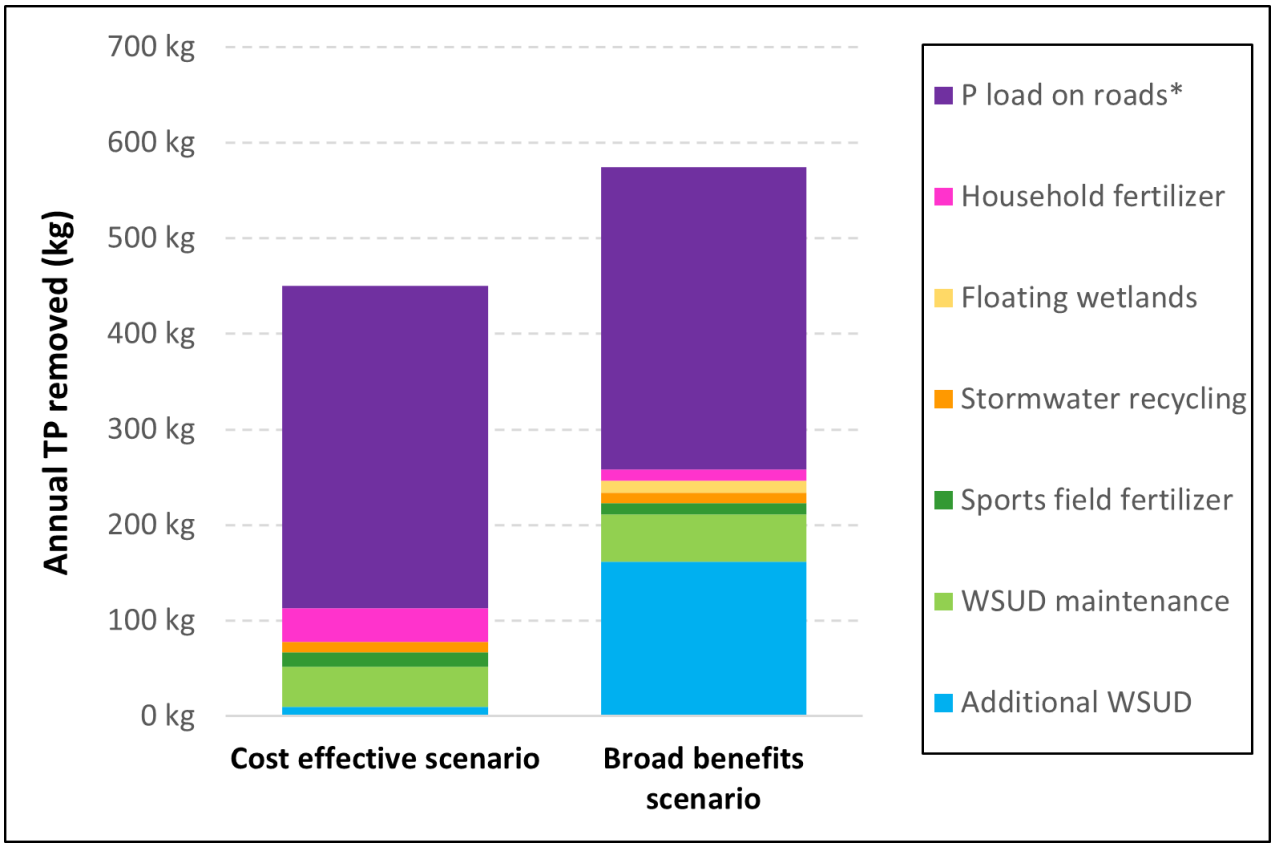

Figure 3. Modelled average annual reduction in the load of total phosphorus (TP) generated in the Lake Tuggeranong catchment, under the cost effective and broad benefits management scenarios. Colours indicate the reduction due to different management options in each scenario. * P load on roads includes the reductions in TP load due to street sweeping, grass clippings management and installation of castellated kerbs.

3.4 Summary

This report has described the approaches used to estimate the phosphorus removal performance and implementation cost of proposed management options for the Lake Tuggeranong catchment. These estimates were used to compare the cost-effectiveness of different management options, and create combinations of options aimed at achieving a ~700 kg reduction in the annual phosphorus load entering Lake Tuggeranong. The Lake Tuggeranong catchment model was used to simulate the effects of these combinations of management options and estimate long-term mean annual inflows and phosphorus loads to Lake Tuggeranong under each scenario.

The management option assessments aimed to provide evidence-based estimates of cost-effectiveness:

- Estimates of the phosphorus removal performance and implementation costs of management options were based on multiple sources, including local implementation of similar management options wherever possible.
- Estimates of the cost of implementation were calculated over a 30-year lifespan for all management options, to allow for the comparison of options with disparate cost distributions.
- A range of estimates was produced for both performance and cost wherever possible, to understand and incorporate uncertainty in the predicted cost-effectiveness of each management option.
- Cost-effectiveness was calculated for each option at four levels of investment to allow its assessment within as well as between management options.
- Confidence in the estimates provided by these assessments was evaluated systematically using a rubric to score the quality of supporting evidence for both the performance and cost estimates for each management option.

Key results of the management options assessment exercise include:

- Increasing the frequency of street sweeping and installing additional WSUD infrastructure are the management options with the largest predicted impacts on reducing phosphorus loads entering Lake Tuggeranong each year.
- Increasing the frequency of street sweeping is estimated to be the most cost-effective management option of those assessed.
- Management scenarios created by combining management options with the aim of achieving a 700 kg reduction in the annual load of phosphorus entering Lake Tuggeranong are estimated to have a total 30-year cost of between $100-145 million.
- Simulating these management scenarios in the Lake Tuggeranong catchment model allows estimation of the predicted reduction in phosphorus entering the lake while accounting for interactions between the different management options included. The model estimates that the average annual phosphorus load to Lake Tuggeranong would be reduced to between 868-992 kg, a 33-44% decrease compared to current catchment conditions.

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5. Appendices

5.1 Appendix A: Quality of evidence assessment rubric

To evaluate the sources of evidence used to inform our assessments of the cost-effectiveness of catchment management options, we designed a rubric to score each option against 9 criteria addressing the information on option cost (4 criteria) and option efficacy (5 criteria) (Table A1).

Table A1. Rubric used to score the quality of evidence informing the assessments of cost-effectiveness of the 10 catchment management options included in this report.

Criterion	Maximum score	1 (weak)	2 (fair)	3 (good)	4 (very good)
Estimates of cost	14				
C1: How recent are cost estimates?	4	Based on implementation 5-10 years ago; **not** 2024 currency	Based on implementation 5-10 years ago; 2024 currency	Based on implementation within the last 5 years; **not** 2024 currency	Based on implementation within the last 5 years; 2024 currency
C2: Source of cost estimates?	4	Not based on previous implementation	Based on implementation overseas	Based on implementation in Australia	Based on implementation in the ACT
C3: Number of independent sources of cost estimates?	3	Costs inferred, from a single source	Based on implementation, from a single source	Based on implementation, from multiple independent sources	
C4: How is variability in cost estimates considered?	3	Based on a single point estimate (+/- 50% or more)	Based on a limited range of estimates (+/- 20-50%)	Based on a substantial range of estimates (+/- 20% or less)	
Estimates of performance	16				
P1: Source of pollutant estimates?	4	Poorly understood	Indirectly inferred from Australian/ overseas data	Indirectly inferred from local empirical data	Directly quantified from local empirical data
P2: Source of performance estimates?	3	Not based on empirical data	Indirectly inferred from local data, or quantified elsewhere	Directly quantified from local empirical data	

Criterion	Maximum score	1 (weak)	2 (fair)	3 (good)	4 (very good)
P3: Is the option explicitly modelled?	3	Represented indirectly in the catchment model, conceptually inconsistent	Represented indirectly in the catchment model, conceptually consistent	Represented explicitly in the catchment model	
P4: Confidence in scaleability of performance?	3	Not understood or not explicitly represented	Inferred from conceptual understanding, explicitly represented	Based on empirical data, explicitly represented	
P5: How is variability in performance estimates considered?	3	Based on a single point estimate (+/- 50% or more)	Based on a range of estimates (+/- 20-50%)	Based on statistical analysis of empirical/ modelled data (+/- 20% or less)	