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Lake Tuggeranong Catchment Management Options Assessment

Technical report supporting the Lake Tuggeranong Healthy Waterways Plan

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Contributors

Dr Isobel Booksmythe

Dr Sayani Dey

Dr Joel Stewart

Dr Andrew Kahn

Dr Danswell Starrs

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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, 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 (O'Reilly & Miller, 2024). 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. 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.

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 (assumed to be incurred in the first year of implementation)
- Annual operating costs (in 2024 currency)
- Total 30-year lifecycle costs (capital costs + net present value of annual operating costs over 30 years, using an annual discount rate of 7%; (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 (still to be defined)

- Annual operating cost
- Capital cost
- Discount rate
- 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.
- Net present cost (NPC)
- O&M – Operation and maintenance
- TCCS – Transport Canberra and City Services directorate, ACT Government
- Total lifecycle cost
- Total phosphorus (TP)
- Water-sensitive Urban Design (WSUD) – 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 phosphorus (P) 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 P generated and entering the stormwater network in each sub-catchment, 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 P 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 P removal for each asset over a known climatic period, adopting MUSIC's default P 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 P 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 P load removed by each asset. The total annual load of P 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 P 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 P removed ranges between 0.0048-0.014 kg P 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 P 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 P 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 P 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 P removal rate from Table 1 to the largest two assets, the mean P removal rate to the next three largest assets, the median P removal rate to the next three largest assets, and the minimum P removal rate to the two smallest assets (Table 2).

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

Asset	Asset size (m^2)[1]	Annual P removed (kg/m^2)	Total annual P 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 a net present cost (NPC, i.e. annual discount rate) of 7% each year.

2.1.4 Cost-effectiveness

We calculated the individual cost-effectiveness of each of 10 proposed raingardens based on the assigned rate of P 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 P 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 an NPC with a discount rate of 7% per annum.

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 P removed (kg/year)	Total 30-year lifecycle cost[1]	Cost per unit P 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 an NPC with a discount rate of 7% per annum.

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 phosphorus entering Lake Tuggeranong (Dey, Stewart, Kahn, Booksmythe, & Starrs, 2024). To estimate the amount of P 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 P load between the business-as-usual and optimal asset maintenance model runs was 88 kg/year (Table 5).

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

Asset	Current P removal performance	Marginal increase in P removed with optimal maintenance (kg/year)
TG011N – wetland	60%	23.28
TG029 – raingarden	20%	12.56

Asset	Current P removal performance	Marginal increase in P removed with optimal maintenance (kg/year)
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%.

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 P 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 P 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 an NPC with a discount rate of 7% per annum.

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 P removed (kg/year)	Total 30-year lifecycle cost[1]	Cost per unit P removed ($/kg)
1	Maintain 2 assets	35.84	$10,177,128	$9,465
2	Maintain 3 assets	61.78	$19,086,579	$10,298

Investment level	Number of assets maintained	Total annual P removed (kg/year)	Total 30-year lifecycle cost[1]	Cost per unit P removed ($/kg)
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 an NPC with a discount rate of 7% per annum

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 P available for removal by street sweeping is that which originates as leaf litter on roads. The Lake Tuggeranong catchment model estimates the total annual P load that runs off roads in the Lake Tuggeranong catchment as 582 kg P/year (Dey, Stewart, Kahn, Booksmythe, & Starrs, 2024), and we use this as an estimate of the maximum available load of P 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 P 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 P load, and the influence of sweeping frequency and timing, into our estimate of the P 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 P 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 P 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 NPC with an annual discount rate of 7%.

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 P removed (kg/year)	Annual program cost	Total 30-year lifecycle cost[1]	Cost per unit P 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 an NPC with a discount rate of 7% per annum.

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 P 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 P 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 P 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 P/year (at this rate, P loads from clippings would comprise around 5% of the total P 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 P inputs by 50% (removing between 16.4 - 26.1 kg P/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 P load from clippings (removing 32.7 - 52.3 kg P/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 P 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 P 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 phosphorus (P) 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 P removal	Total annual P removed (kg/year)	Total 30-year lifecycle cost[1]	Cost per unit P removed ($/kg)
1	Method 1 (blowers) – low P removal estimate	16.4	$2,018,874	$4,103

Investment level	Management method and level of P removal	Total annual P removed (kg/year)	Total 30-year lifecycle cost[1]	Cost per unit P removed ($/kg)
2	Method 1 (blowers) – high P removal estimate	26.1	$2,018,874	$2,578
3	Method 2 (sweeping) – low P removal estimate	32.7	$1,521,462	$1,551
4	Method 2 (sweeping) – high P removal estimate	52.3	$1,565,956	$998

1 Total lifecycle cost is calculated over 30 years using an NPC with a discount rate of 7% per annum.

2.5 Management of sports field fertilizer use practices

2.5.1 Background

The use of fertilizers 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 P 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	P applied (kg/year)	Lower P export rate (kg/ha/year)	Medium P export rate (kg/ha/year)	Upper P 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 phosphorus (P) exported from each category.

Sports field type	Total area (ha)	Lower total P exported (kg/year)	Medium total P exported (kg/year)	Upper total P 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 P exported from sports fields (based on the upper bound of estimates of P export rate from the literature) are larger than the total P 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 P 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 P 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 P removal performance: of the total infrastructure required to remove 57.9 kg P/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 P 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 P removal ($kg/m^2/year$)	P 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 a net present cost (NPC, i.e. annual discount rate) of 7% each year.

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 P 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 P 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 P load. Investment option 3 builds all the assets in the 'high' and 'average performance' band, addressing 75% of the sports field P load, and investment option 4 builds all the assets in all performance bands, addressing 100% of the sports field P 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 P removed (kg/year)	Total 30-year lifecycle cost[1]	Cost per unit P 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

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 P in the catchment that may be exported from residential blocks. The loss of fertilizer P 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 P 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 P 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 P application in fertilizer products estimated from the survey was 0.59 kg P/year (Table 14).

Table 14. Average annual amounts of phosphorus (P) applied to residential blocks in the ACT from chemical fertilizers, commercial composts and raw manures, and literature-derived rates of P export for these products. 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.

Product type	P applied (kg/household/year)	Lower P export rate (% of applied)	Medium P export rate (% of applied)	Upper P 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 P 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 P (Table 15).

Table 15. Annual amounts of phosphorus (P) from fertilizer products applied to and exported from residential blocks (RZ1 and RZ2) in the Lake Tuggeranong catchment.

Product type	Total P applied in catchment (kg/year)	P applied (kg/ha/year)	Lower total P exported (kg/year)	Medium total P exported (kg/year)	Upper total P 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 P 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 P inputs from suburban pervious land (e.g. any P 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 P 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 P load generated by suburban pervious land use in the Lake Tuggeranong catchment.
- The reported rates of P application suggest that we should see far more P exported from residential blocks than current water quality data indicates. If the survey-derived estimates of P application are broadly correct, several further avenues of investigation are required to understand what is happening to this P, e.g.:
    - how long has P been applied at this rate?
    - how much P can be stored in the soil?
    - is excess P 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 P 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 P export rates from the literature, the amount of P 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 P load reduction of this option, we assume that household fertilizer P exports occur in event flows, and any reduction will not affect the baseflow P loads coming from suburban pervious areas in the Source catchment model. This baseflow P load is estimated to be 0.018 kg/ha/year. This is subtracted from the total modelled P load from suburban pervious areas (~0.12 - 0.16 kg/ha/year) to give the estimated event flow P 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 P exports. This means that the median and upper P 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 P load reduction from banning P in fertilizers, we use the lower P 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 P 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 P 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 P/year.

Table 16. Estimating the reduction in P load from suburban pervious land use resulting from a 17% reduction in current P inputs from household fertilizer use. The range of values in each cell reflects the range of estimated P export rates from the fertilizer applied to residential blocks.

Total P load from suburban pervious land use (kg/ha/year)[1]	Current event-flow P load from fertilizer (kg/ha/year)[2]	Reduced event-flow P load from fertilizer (kg/ha/year)	Reduced event-flow P load from fertilizer, plus baseflow load (kg/ha/year)	Percent reduction in total P 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 P load from household fertilizer use are capped at the model-estimated total event-flow P load from all suburban pervious land use, 0.103 or 0.142 kg P/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 7% annual discount rate, 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 P inputs of the top 20% of users by 20% is predicted to remove between 20 - 58 kg P per year at a cost of between $3,700 - $24,000 per kg P 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 P removed ($/kg) – low performance	Cost per unit P removed ($/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 an NPC with a discount rate of 7% per annum.

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 P 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 P achieved by such a program. We used the lower and upper estimates of P 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 P 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 P inputs in the Lake Tuggeranong catchment.

Investment level	Assumed program implementation	Annual P removed (kg)	Total 30-year lifecycle cost[1]	Cost per unit P 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 an NPC with a discount rate of 7% per annum.

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 P/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 P generated on roads adjacent to public open space is calculated as 249 kg/year (43% of the total road P 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 P generated on this road area – 124.5 kg P/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 P 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 P/year would be diverted from the stormwater network. This represents an upper limit to the amount of P 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 P removal: installing a castellated kerb outlet for every second, third, or fourth sump would remove 31, 20.75, or 15.5 kg P/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 was provided by Dr Ralph Ogden, Director of the ACT Healthy Waterways program, ACT Office of Water, and we used this as our higher cost estimate.

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 phosphorus (P) 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	P removed (kg/year)	Cost per outlet	Cumulative total lifecycle cost[1]	Cost per unit P 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 P 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 P content was recorded as a measure of the amount of P they removed from the lake. From this we can calculate the amount of P removed from the lake per square metre of floating wetland area for each plant species separately. The worst-performing species removed 0.001kg P/m^2/year, and the best-performing species removed 0.005kg P/m^2/year. The average amount of P removed by all three species was 0.003kg P/m^2/year, and we used this as our estimate of floating wetland P 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 P removal performance and costs over a 30-year lifecycle, as $13,622.2/kg P 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 P 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 P removed (kg)	Capital cost	Annual operation and maintenance costs	Total 30-year lifecycle cost[1]	Cost per unit P 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 an NPC with a discount rate of 7% per annum.

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 P 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 P 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 P concentration of 0.15mg/L to calculate the potential load of P 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 P 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)	P 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 (R. Ogden, pers. comm.) 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 (1ML 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 P 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 P 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 an NPC with a discount rate of 7% per annum for 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 P removed (kg/year)	Total 30-year lifecycle cost[1]	Cost per unit P 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 an NPC with a discount rate of 7% per annum.

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 P 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 P removal performance of downstream WSUD infrastructure. Rainwater tanks provide some opportunity to directly capture P 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 P 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 P in runoff from suburban roof area in the Lake Tuggeranong catchment (from the calibrated catchment model) we can calculate the approximate load of P removed per household (Table 25).

Table 25. Estimated loads of P diverted from the stormwater system by plumbed household rainwater tanks.

Roof size (m^2)	Tank size (L)	P removed – dry year (L/year)	P removed – average year (L/year)	P 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 P 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 P 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 P (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 P 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 P 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 P removed (kg)	Total 30-year lifecycle cost[1]	Cost per unit P 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 P 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 P 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 P removed, while constructing WSUD infrastructure had costs of between $7,000-12,000 per kg P. The remaining options all had lower total annual P removal performances and ranged in cost-effectiveness up to $28,000 per kg P.

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	P removed (kg/year)	30-year cost ($)[1]	Cost-effectiveness ($/kg P)
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
Sports field fertilizer management 4	59.70	$31,445,222	$17,557

Management option and level	P removed (kg/year)	30-year cost ($)[1]	Cost-effectiveness ($/kg P)
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 an NPC with a discount rate of 7% per annum.

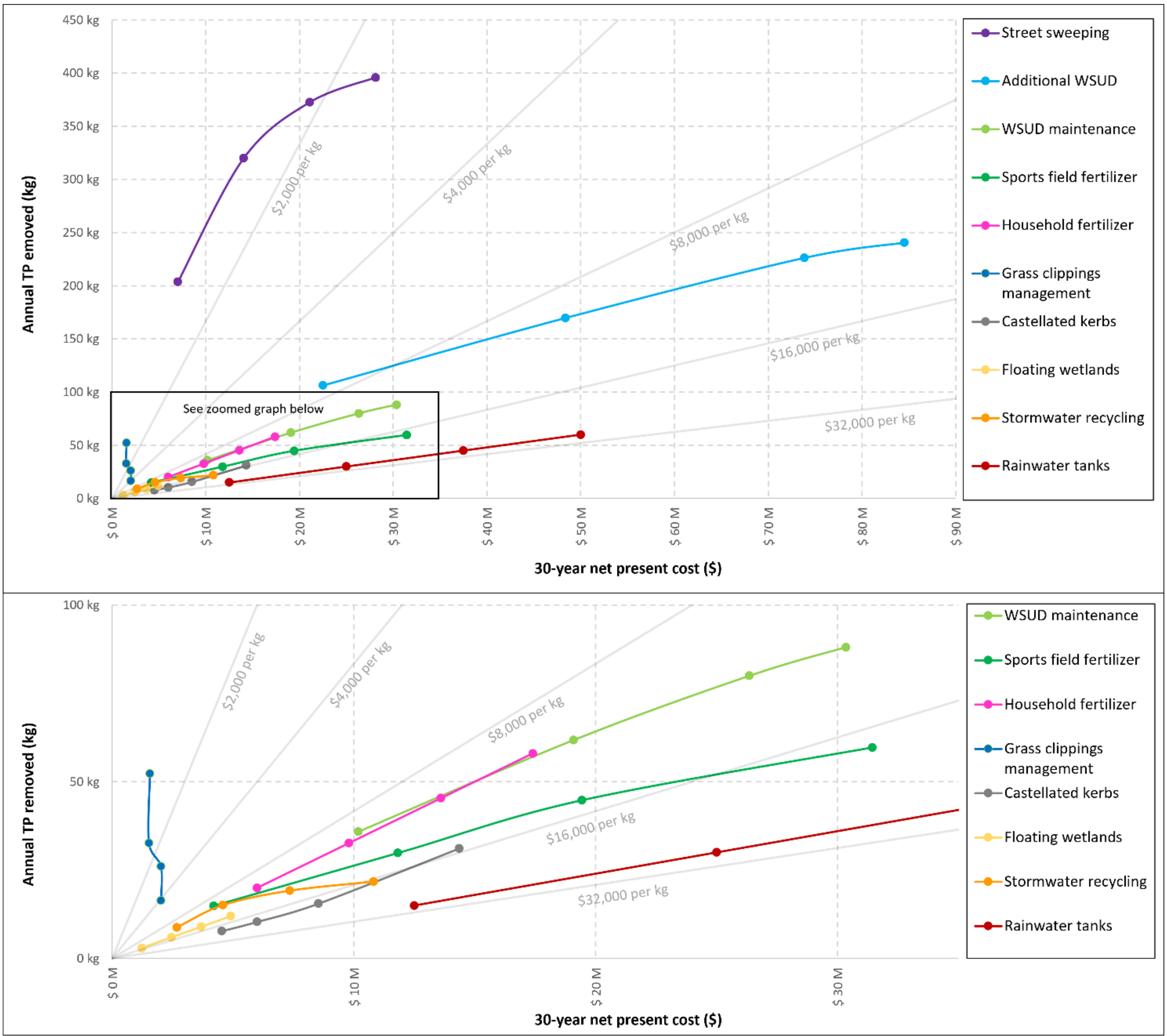

Figure 1. Annual total phosphorus load removed, and 30-year lifecycle cost, of each investment level for the 10 management options assessed in Section 2. Coloured lines connect the four estimates for each management option. Grey lines are a guide indicating the cost-effectiveness (cost per kg P removed) 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 P 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 P 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 sub-catchment, with swale size proportional to the area of sports field in each sub-catchment. 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 sub-catchments, a controlled splitter was used to divert water to the node representing each swale, in proportion to the swale: sub-catchment 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 P/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 P/year (a reduction of 574 kg/year; Figs. 2, 3).

The estimated reductions in P 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 P from entering the stormwater system, such as street sweeping and household fertilizer management, and options that intercept and remove P from stormwater, such as WSUD infrastructure. Options that prevent P from entering stormwater have the effect of reducing P 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.

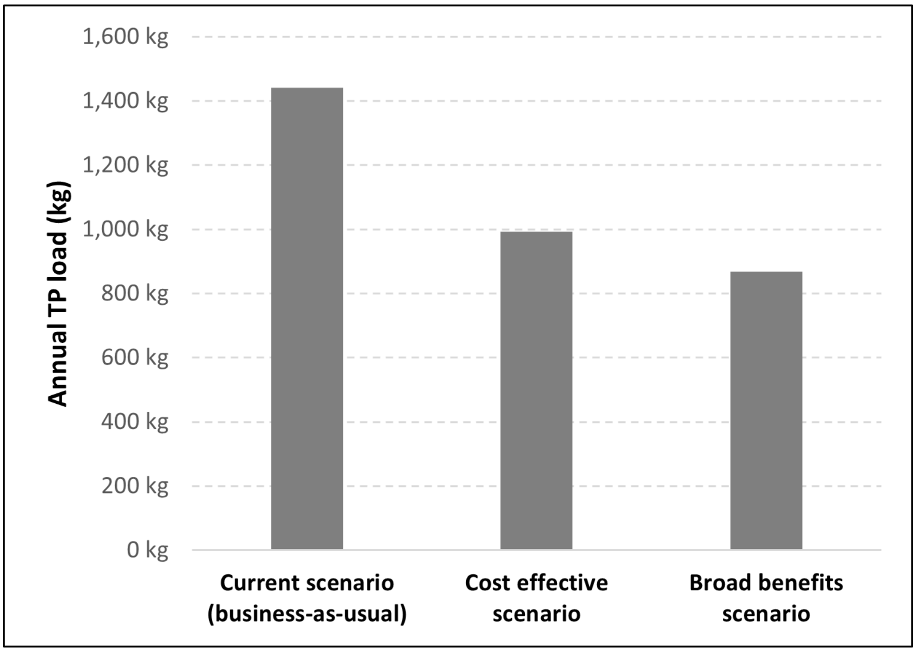

Figure 2. Modelled average annual load of total phosphorus (TP) generated in the Lake Tuggeranong catchment under three management scenarios.

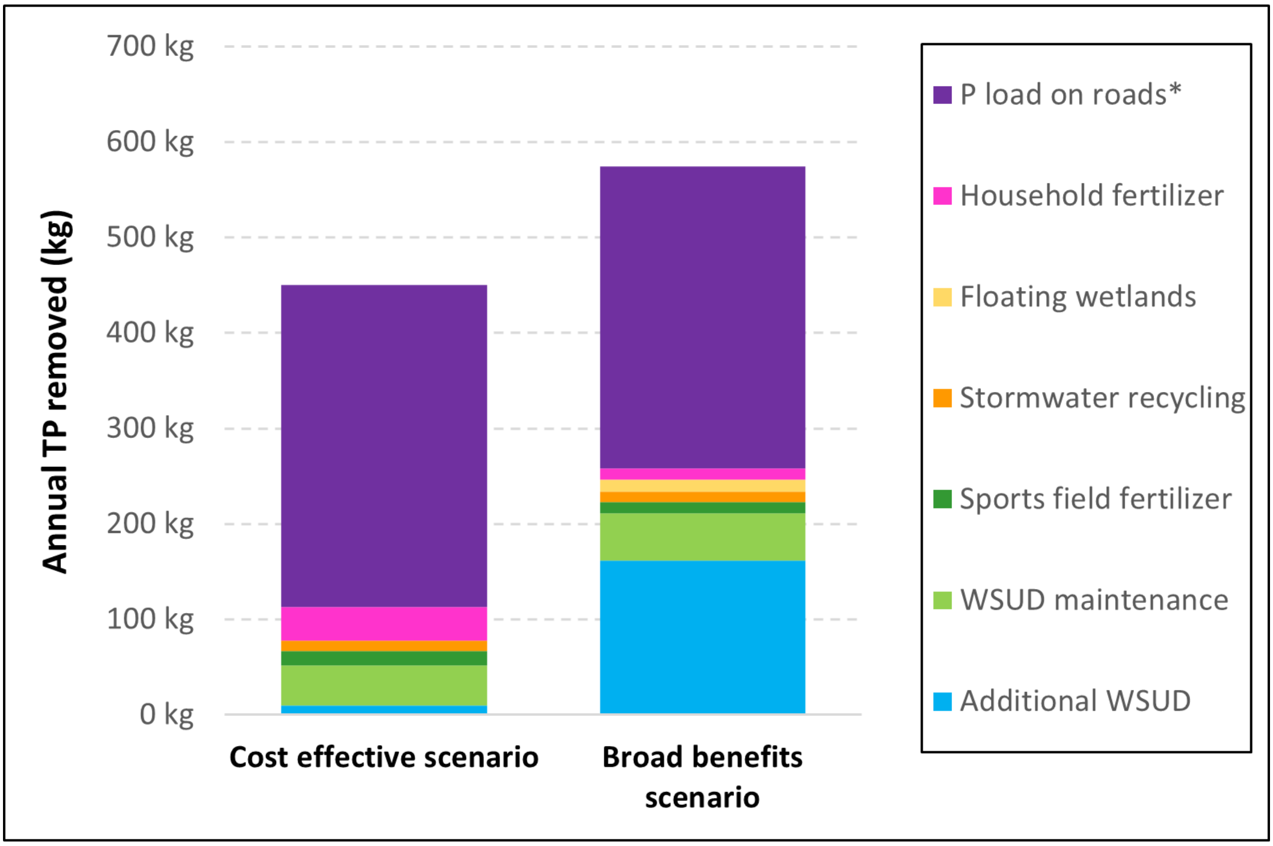

Figure 3. Modelled average annual reduction in the load of total phosphorus (TP) generated in the Lake Tuggeranong catchment, under the cost effective and broad benefits management scenarios. Colours indicate the reduction due to different management options in each scenario. * P load on roads includes the reductions in P 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)	