A cost–benefit framework for prioritising fish passage remediation across an urban stream network

James J. Shelley[1], Simon Catzikiris[2], Simon Treadwell[1] and Jim Thomson[3]

1 Jacobs Australia Pty Ltd, Melbourne, Victoria, Australia. Email: james.shelley@jacobs.com

2 Melbourne Water Corporation, 990 La Trobe St, Docklands VIC 3008

3 Arthur Rylah Institute for Environmental Research, 123 Brown Street, Heidelberg, Victoria 3084, Australia

Key points

- A transparent fishway prioritisation framework was developed to identify the most cost-effective barriers for remediation across Melbourne Water waterways.
- The framework integrates habitat suitability models, feasibility assessment, cost benchmarking, and genetic algorithm optimisation.
- Barrier position within the stream network strongly influenced prioritisation outcomes, with several relatively small barriers identified as high priorities.
- A small core set of barriers consistently delivered the highest ecological return on investment across the optimisation analysis.
- The framework provides a repeatable and adaptive decision-support tool for long-term fish passage investment planning.

Abstract

Artificial barriers such as weirs, culverts, and road crossings fragment river networks and restrict fish movement, reducing access to critical habitats for native fish. Melbourne Water manages over 700 known fish barriers across the Port Phillip and Westernport region of south-eastern Australia, with recent work identifying potentially thousands more, creating a major challenge for prioritising fish passage investment. This study developed and applied a fishway prioritisation framework to guide investment planning by integrating ecological modelling, feasibility assessment, cost benchmarking, and mathematical optimisation.

The framework involved three stages: (1) a benefit-only optimisation (using a Genetic Algorithm; GA) to identify barriers which prevent access to the most high-quality habitat, (2) a Multi-Criteria Assessment (MCA) to assess feasibility and identify likely fishway options, and (3) a GA optimisation to identify projects that maximised ecological benefit per dollar invested. Fishway costs were estimated using benchmarking data from more than 250 Australian fish passage projects.

The optimisation identified a highly concentrated set of priority barriers, with 17 barriers consistently selected across the highest-performing solutions. Several relatively small barriers ranked highly because of their strategic position within the stream network and the amount of upstream habitat they controlled. The results demonstrate the importance of considering network connectivity, feasibility, and implementation cost when prioritising fish passage investments. The framework provides a transparent and adaptable approach that can support long-term fish passage planning and investment.

Keywords

Fish passage, connectivity, optimisation, barriers, prioritisation, native fish, stream management, genetic algorithm

Introduction

Artificial barriers such as weirs, dams, culverts, and road crossings are widespread throughout Australian river systems and are recognised as a major driver of habitat fragmentation and ecological decline (Barbarossa et al., 2020; Grill et al., 2019). These structures disrupt longitudinal connectivity, limiting the movement of fish between critical habitats required for feeding, dispersal, refuge, and reproduction. In highly modified urban and peri-urban catchments, barriers are often numerous and closely spaced, creating cumulative impacts across stream networks.

The waterways managed by Melbourne Water across the Port Phillip and Westernport region support diverse native fish assemblages, including several migratory species that depend on connected river systems. Previous assessments undertaken as part of Melbourne Water's *Healthy Waterways Strategy 2018* (HWS) (2018) identified approximately 700 known barriers requiring consideration for remediation. More recent spatial analyses have identified thousands of additional potential barriers, highlighting the scale of the connectivity challenge across the region (Walsh, 2023).

Fishway construction and barrier remediation are increasingly recognised as important river restoration actions, but the high cost of implementation means that only a limited number of projects can be delivered within available funding cycles. Consequently, there is a growing need for transparent and defensible prioritisation methods capable of identifying projects that provide the greatest ecological benefit for the resources invested.

Historically, fish passage prioritisation programs have often focused on barrier characteristics such as structure height or perceived severity. However, recent advances in river network analysis and optimisation approaches demonstrate that barrier position within a stream network can strongly influence ecological outcomes (Hermoso et al., 2015; O'Hanley & Tomberlin, 2005). Small or moderate barriers located low in a catchment may restrict access to extensive upstream habitat and therefore provide disproportionately large ecological benefits if remediated.

This study developed and applied a fishway prioritisation framework for Melbourne Water that integrates ecological modelling, feasibility assessment, cost benchmarking, and optimisation analysis. The objective was to identify fish passage projects that maximise ecological benefit per dollar invested while accounting for practical implementation constraints. The framework was designed to guide a pipeline of investments over several funding cycles, provide adaptability within funding allocation periods and be transparent, repeatable, and adaptable to future data updates or changing management objectives.

Methods

Framework overview

Building on previous work undertaken for the HWS (Melbourne Water 2018), informed by international best-practice, and incorporating feedback from policy makers, subject matter experts from across eastern Australia, we developed and applied a transparent, repeatable, and scientifically rigorous prioritisation process. The framework integrates:

- Habitat Suitability Models (HSMs) for 11 native fish species sensitive to barriers, previously developed by Chee *et al.* (2020; 2023), which quantify the ecological benefit of barrier removal;
- Stream network and barrier datasets used in the HWS, including updated spatial layers and classifications of full and partial barriers;
- MCA to evaluate site-specific constraints and identify viable fishway options;
- A cost estimation model, drawing on benchmarking data to assess the financial cost of proposed fishway options; and
- Mathematical optimisation algorithms, primarily a Genetic Algorithm (GA), to conduct cost-benefit analyses and generate prioritised lists of barrier remediation actions.

The framework consists of three primary components: (1) barrier filtering and pre-assessment, (2) feasibility assessment and cost estimation through a MCA, and (3) cost–benefit optimisation using a Genetic Algorithm (Figure 1). This structure reflects the need to balance computational efficiency, data availability, and implementation constraints when working with large barrier inventories.

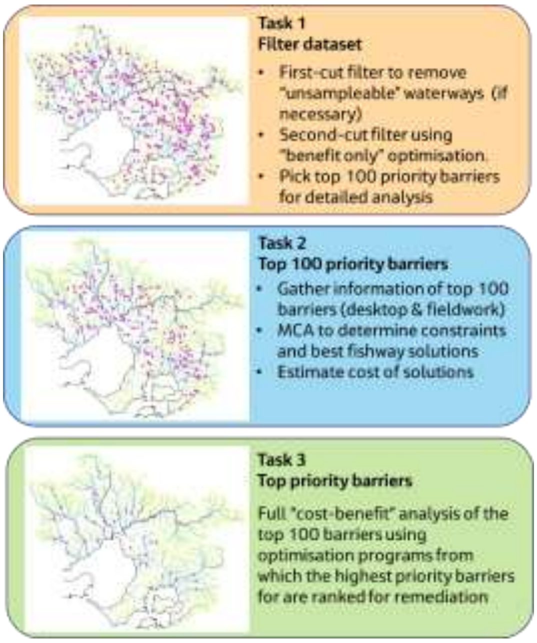

Figure 1 Summary of the fishway prioritisation framework developed for Melbourne Water

Optimisation using a Genetic Algorithm and Habitat Suitability Models

The framework is underpinned by an optimization algorithm, specifically a GA, which identifies optimal combinations of barrier remediation actions. The GA represents candidate solutions as portfolios of barriers and evaluates their performance using an *objective function* that maximises ecological benefit alone or ecological benefit per unit cost.

Ecological benefits were quantified using HSMs developed for multiple native fish species sensitive to connectivity (Chee *et al.* 2020; 2023). These models estimate the probability of occurrence of each species across stream reaches based on environmental predictors and the presence of downstream barriers. The benefit of removing a barrier was calculated as the increase in predicted habitat suitability multiplied by reach length and aggregated across species using weighting factors. This produced a spatially explicit measure of expected ecological gain.

Each potential solution was represented as a combination of barrier remediation projects. The optimisation process compared thousands of different combinations and scored them according to the ecological benefits they delivered. For the benefit-only analysis (Task 1), solutions were ranked based on the total amount of fish habitat expected to become accessible following barrier remediation. For the cost-benefit analysis (Task 3), these ecological benefits were considered alongside the estimated cost of remediation, allowing the model to identify projects that delivered the greatest ecological return per dollar invested. Habitat gains were calculated using HSMs, which estimate changes in the amount of suitable habitat available to fish following barrier remediation. These gains were summed across the stream network and across all modelled fish species, with weighting factors applied to reflect conservation and management priorities.

The objective function adopted to maximises the habitat benefits across species per unit cost is expressed as follows:

$$Objective = \frac{\sum_i w_i \, b_i}{C^*}$$

Where: b_i= benefit for species (with negative values optionally set to 0), w_i= weight for species i, C^*= adjusted cost. Species benefits are estimated as the 'expected gain in occupied length', calculated as $\sum_j \triangle P_{ij} \, length_j$, where $length_j$ is the length of reach j, and $\triangle P_{ij}$ is the predicted change in occurrence probability at reach j for species i given the a set of downstream barrier removals (new fishways).

The algorithm explores a large solution space by iteratively generating and refining candidate portfolios through processes analogous to natural selection. This approach is well suited to problems with complex interactions and non-linear responses, such as river network connectivity. Rather than relying on a single optimal solution, the analysis examined the frequency with which individual barriers appeared across high-performing portfolios. This selection frequency provides a robust measure of priority and reduces sensitivity to uncertainty in inputs.

Task 1 – Initial filtering of whole barrier dataset

The first task involved filtering the barrier dataset to identify a manageable subset of high-benefit candidates. Fishways that have been identified as needing maintenance or upgrades were included as partial barriers. Filtering was achieved using a “benefit-only” optimisation using a Genetic Algorithm that evaluated the ecological benefit of mitigating each barrier without considering cost or feasibility constraints.

The analysis was applied to the Melbourne Water HWS (2018) barrier dataset, which includes approximately 700 well-characterised barriers. Using the HSM-derived benefit metric, the optimisation identified the top 100 barriers that provide the greatest potential ecological gain if remediated.

This filtering step is critical for reducing the size of the problem while retaining the most ecologically significant sites. It ensures that subsequent detailed assessment efforts are focused on barriers with the greatest potential impact.

Task 2 - Multi-criteria assessment (MCA) and cost estimates

The second task involved (1) applying a structured MCA to evaluate the feasibility and viability of fish passage remediation at each shortlisted barrier, and (2) estimating the cost of mitigation solutions.

The MCA was designed to capture a broad range of factors influencing project delivery, including:

- Technical feasibility, such as hydraulic conditions, head loss, and structural configuration
- Constructability considerations, including site access, footprint constraints, and construction complexity
- Operational and maintenance requirements, including safety risks and long-term performance
- Cultural and heritage constraints, including Aboriginal and historical values
- Ecological context, including species present and habitat condition

Each barrier was assessed using a scoring framework that combined these criteria into an overall feasibility rating. For barriers considered feasible, one or more candidate fishway options were identified based on site conditions and engineering judgement. These options were characterised in terms of their likely performance, risks, and applicability.

Cost estimates were derived from a benchmarking dataset comprising more than 250 fishway and barrier mitigation projects across Australia. Costs were standardised to present-day values and grouped into categories using statistical classification methods. Each fishway option was assigned a cost range (minimum, mean, and maximum) based on its likely construction complexity and site conditions. This approach captures the uncertainty inherent in early-stage cost estimation while ensuring consistency across sites.

Task 3 – Cost-benefit analysis

The third task simply involved re-running the optimisation analysis on the list of feasible barriers with the estimated costs included. The output is a list of priority fishway projects ranked by the highest benefit to the fish community per dollar spent (see Figure 2).

Results

The optimisation identified a highly concentrated set of priority barriers, including some fishways requiring maintenance. Seventeen barriers were consistently selected across the highest-performing solutions, while many other candidate barriers were rarely selected once feasibility and cost were incorporated.

Priority barriers were concentrated within the Maribyrnong River, Plenty River, and Kororoit Creek catchments, with additional important sites identified within Diamond Creek, Werribee River, Dandenong Creek, and the Bunyip River system.

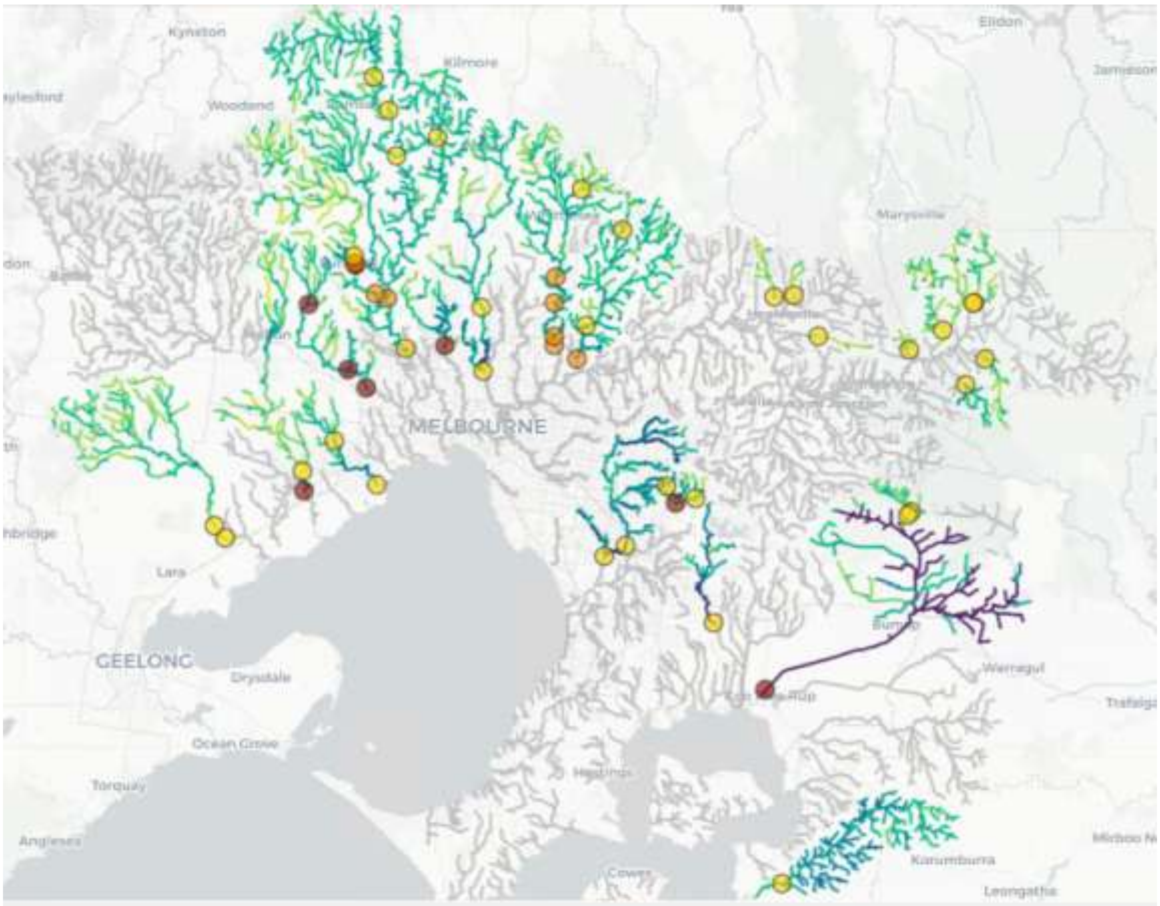

Figure 2 Map of waterways managed by Melbourne Water, the top priority fishways identified through the prioritisation framework (circles), and the net habitat benefit predicted following the removal of those barriers (coloured stream segments). Priority order 1-9 (red circles), 10-17 (orange), 18-50 (yellow). Net habitat benefit can be interpreted as low benefit (dark purples/blues) to high benefit (light greens/yellows)

Barrier position within the stream network strongly influenced prioritisation outcomes. Several relatively small or moderate barriers ranked highly because they restricted access to extensive upstream habitat.

Conversely, some barriers with high stand-alone ecological benefits were consistently deprioritised because remediation costs were disproportionately high relative to the additional connectivity gained.

The optimisation consistently favoured barriers with a combination of:

- moderate remediation cost;
- high upstream habitat gain; and
- strategic network position.

The results support a staged implementation approach in which lower-cost, high-return projects are delivered first, followed by progressively more expensive or complex projects as funding becomes available.

Discussion

Insights from findings

The optimisation results revealed a highly concentrated prioritisation outcome. A relatively small subset of barriers was consistently selected across high-performing portfolios, indicating that these sites provide exceptional ecological return on investment. These high-priority barriers shared several characteristics. They were typically partial barriers with moderate construction costs and substantial upstream habitat gains. Many were located in positions where their mitigation unlocked access to large areas of previously inaccessible habitat, resulting in strong benefit–cost ratios. Selection frequency declined rapidly beyond this core set of barriers. A large proportion of candidate sites were rarely or never selected in optimal portfolios. This indicates that, while these sites may provide ecological benefits, they are less efficient investments when considered in combination with other opportunities.

The results also highlight the importance of cost in shaping prioritisation outcomes. High-cost barriers with large stand-alone ecological benefits were often excluded from optimal portfolios due to their lower cost-effectiveness. This demonstrates that ecological value alone does not determine priority; rather, it is the interaction between benefit and cost that drives investment decisions.

Connectivity effects were also evident in the results. In several cases, barriers with relatively modest individual benefits were prioritised because their mitigation enabled access to larger upstream networks when combined with other removals. These interactions highlight the importance of considering the river network as an interconnected system rather than a collection of independent sites.

From a management perspective, the results support a staged investment strategy. Early investment can focus on a small number of high-return projects that deliver substantial connectivity gains at relatively low cost. As these barriers are remediated, the structure of the network changes, and subsequent prioritisation can identify the next best set of opportunities, raising the priority of barriers that scored poorly in the current analysis.

Importance of feasibility assessment

The integration of the MCA with optimisation analysis was a major strength of the framework. Optimisation approaches alone may identify theoretically high-benefit projects that are impractical or prohibitively expensive to deliver.

By incorporating feasibility, constructability, operational, safety, and heritage considerations early in the process, the framework constrained the optimisation to projects that were more realistically achievable and reduced the likelihood of selecting projects with major implementation risks.

Conclusions

This study developed and applied a transparent and repeatable fishway prioritisation framework for Melbourne Water waterways. The framework integrated ecological modelling, feasibility assessment, cost benchmarking, and genetic algorithm optimisation to identify fish passage projects that maximise ecological benefit per dollar invested.

The optimisation revealed that a relatively small number of strategically positioned barriers consistently delivered the greatest ecological return on investment. Barrier position within the stream network strongly influenced prioritisation outcomes, often more so than barrier size or severity alone. The results support a staged and adaptive approach to fishway investment planning and demonstrate the value of integrating ecological, engineering, and economic considerations within river-restoration decision making.

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