Understanding and saving headwater streams in urbanizing areas

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Key Points

- Headwater streams are critical components of river networks but they are rapidly being degraded or lost through agricultural and urban development.
- High-resolution mapping and a pilot monitoring program have increased our knowledge of the location and value of headwater streams across the Greater Melbourne area.
- We have developed practical tools to protect headwater streams that can be applied from the development strategy phase to tactical on-ground implementation.

Abstract

Headwater streams are the smallest streams in a river network and provide multiple, important ecosystem services. However, when urbanization occurs, headwater streams are commonly replaced with underground pipes or enlarged, rock-lined constructed waterways; this has negative consequences for both headwater streams and the downstream river network. This paper presents an overview of a research program that aims to address some of the key knowledge gaps that are hindering the protection of headwater streams from the impacts of urbanization, as well as develop practical management tools. Using recent advancements in mapping techniques, we updated the Melbourne Water stream network, increasing the total length of the stream network by more than 50%. A monitoring program is improving our understanding of the structure and function of headwater streams in the Greater Melbourne area. We also developed three complementary decision-support tools – a set of structural and non-structural tools, a conceptual framework for assessing maturity and identifying next steps, and a co-design process for developing place-based ideas and solutions – to help drive progress towards headwater stream protection.

Keywords

Headwater streams, stream function, ecosystem services, urban development, stormwater, management, monitoring, socio-technical systems

Introduction

Headwater streams are the most upstream natural segments of a river network, that is, the points in the landscape where catchment runoff first accumulates sufficiently to create overland flow paths. Often comprising 75% or more of a river network by length (Barmuta et al. 2009), headwater streams are dominant, but not always obvious, features of many landscapes. They provide important habitat for common, rare, and threatened species and collectively can make a large contribution to regional biodiversity (Mainstone et al. 2016). Headwater streams are also critical to the ecological integrity of the overall river network (US EPA 2015); for example, they contribute to downstream flood control (Gomi et al. 2002), regulate the flow of sediment and nutrients to downstream segments (McKergow et al. 2003), and have a large capacity for processing nutrients compared to larger, downstream segments of the river network (Peterson et al. 2001).

Despite the long-held recognition of the importance of headwater streams, they are rapidly being degraded or lost, particularly through agricultural and urban development. When urbanization occurs, headwater streams are commonly replaced with underground pipes or enlarged, rock-lined constructed waterways capable of conveying the larger volumes of surface runoff generated by urban areas. This has negative consequences for both headwater streams and the downstream river network. In recognition of this in the Greater Melbourne area, the current Healthy Waterways Strategy (Melbourne Water 2018) includes an objective to protect headwater streams to ensure that they are retained as features in the landscape for environmental, social, cultural and economic benefits.

In a recent review of the state of knowledge of headwater streams, Imberger et al (2023) identified the following four critical knowledge gaps that are hampering the management of headwater streams:

- Inadequate mapping of headwater stream locations and extents within catchments;
- Insufficient characterization of headwater stream typologies across a diversity of environmental contexts;
- Incomplete quantification of headwater stream structure, function, and ecosystem services across varying scales; and
- Limited understanding of the effects of urbanization on headwater streams and downstream consequences under a changing climate.

Melbourne Water is working to address these knowledge gaps through its Melbourne Waterway Research-Practice Partnership with The University of Melbourne. This paper describes the interim outcomes of this ongoing research program.

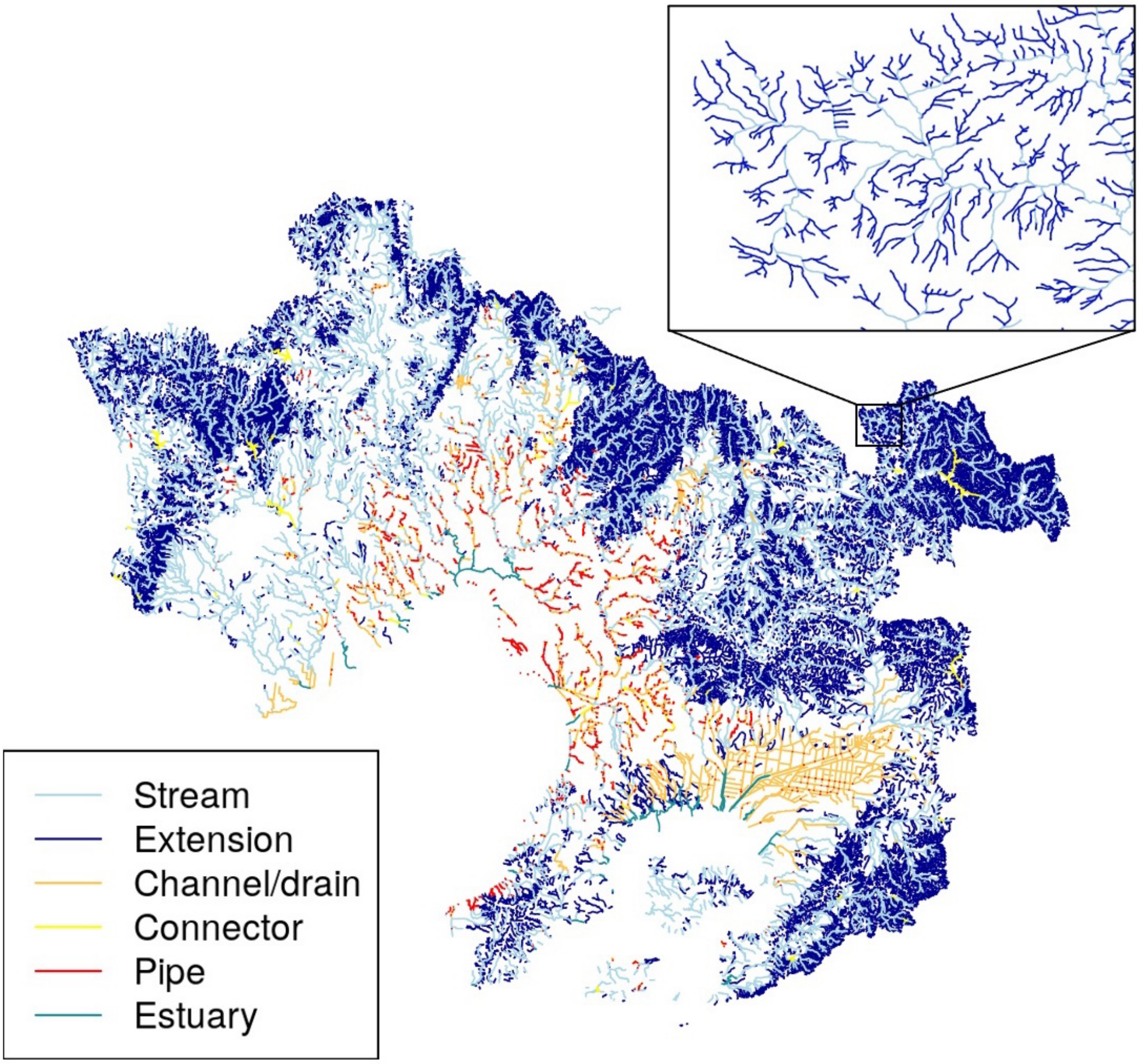
High resolution mapping of the Melbourne Water stream network

Many maps of river networks exclude headwater streams, in part because of the scale at which they are mapped. For example, 1:24,000-scale maps, one of the most common mapping scales used in the United States and Australia, can significantly underestimate the extent of river networks because they can exclude nearly all headwater streams (e.g. 78%, Roy et al. 2009). This is problematic because we cannot measure, understand or protect what we do not know exists (Imberger et al. 2023).

The use of remotely sensed high-resolution digital elevation models (DEMs) to map river networks can overcome the limitations of larger-scale maps. Recent rapid advances have increased the accuracy of this approach. The Melbourne Water stream network was recently updated using 1-m, LiDAR-based DEMs and hill-shade models to identify gully heads and channels. This has added 14,275 km (or 55%) of stream length to the stream network ("stream extensions" in Figure 1). Combined with partial ground-truthing and other lines of evidence (e.g. vegetation change, direct observation of flow), this network accurately maps the alignment and extent of streams across the Greater Melbourne region (Walsh et al. 2022).

This information is critical for understanding and protecting headwater streams, for reasons including: i) it directs research efforts towards true headwater streams (rather than the 2nd or 3rd order streams that can be mistaken for headwater streams when maps exclude headwater streams), and ii) it identifies the extent of headwater streams under threat from planned urban development, as well as those outside the current urban growth boundary. A particular remaining challenge is to map headwater streams that have already been lost in the existing urban areas of Greater Melbourne to identify opportunities for headwater stream restoration (e.g. stream 'daylighting'). However, restoration of piped or channelized headwater streams is typically costly and, without adequate downstream and landscape connectivity, is expected to result in limited ecological benefit, hence the urgency for headwater stream protection as the best strategy for managing headwater streams across the region.

Figure 1. Melbourne Water stream network colour-coded by type (Source: Walsh 2023). The inset is a close-up of a section of the stream network in the north-east region and shows the extent of additional stream length (stream extensions) provided by the recent update.



Understanding the structure and function of local headwater streams

The characteristics of headwater streams can be extremely diverse, even within a relatively small geographic area. However, much of the research on headwater streams has focused on perennial headwaters in temperate forested areas, meaning there is still much we don't understand about many headwater stream types. To increase our understanding of the values and services provided by local headwater streams, we commenced a pilot monitoring program at four headwater streams, all with forested catchments, in the north-west region of Greater Melbourne in 2019, where we have: i) developed methods for monitoring non-perennial headwater streams, and ii) collected data on hydrology, water quality, and ecological structure and function. We measured surface and sub-surface water levels using probes located in stilling wells and shallow bores, respectively. Water quality samples were collected during dry and wet weather at the surface and two sub-surface depths (250 mm and 625 mm below the base of the stream channel) and analysed for physio-chemical indicators, as well as concentrations of total suspended solids and total and dissolved species of nitrogen and phosphorus. Given the frequent absence of surface water in headwater streams, we measured stygofauna (aquatic macroinvertebrates that live in groundwater) and microbial (bacterial and fungal) diversity and organic matter decomposition potential as indicators of ecological structure and function. For further details of the monitoring program, see Burns et al (2024).

In general, very shallow surface water was present in the headwater streams from winter through to early summer, sometimes for long periods, however, it was only present for short periods following large rainfall events in summer and autumn (see example water level time-series shown for a forested headwater stream in Figure 2). Sub-surface water levels are variable when surface water is absent and sometimes fluctuate rapidly (Figure 2). Consistently high surface and sub-surface water quality was observed at all forested headwater streams (Figure 3; sub-surface water quality not shown, for brevity). Together with low organic matter decomposition rates (data not shown), these results indicate that headwater streams are highly retentive of water and nutrients, despite high organic matter inputs (owing to the extensive shrub and canopy layer present in these temperate forested streams). Microbial richness and diversity within and between streams was high, particularly for bacterial communities (data not shown). While limited data has been collected to date, stygofauna diversity observed at individual streams was generally low, but differences between streams suggests it is important to consider the cumulative contribution of these headwater streams to regional biodiversity.

These observations have some important practical implications. Protection of these types of headwater streams in urbanizing areas will require maintaining the natural seasonality of flow, which means redirecting almost all urban runoff away from headwater streams during summer and autumn. This will require extensive stormwater harvesting across the lot, streetscape, 'end-of-pipe' and precinct scales, along with novel ideas such as stormwater to environmental flows. It will also be necessary to infiltrate stormwater, probably close-to-source in floodplain buffer areas, to preserve baseflows.

Tools and principles for protecting headwater streams in urbanizing areas

Although the Healthy Waterways Strategy seeks to protect headwater streams across Greater Melbourne, similar to many other regions, there is a general lack of practitioner knowledge and capacity to bridge the gap between developing strategies for protecting headwater streams and tangible action. To address this, we i) held a workshop at the Sixth Symposium on Urbanization and Stream Ecology in 2023 that was attended by researchers and practitioners from multiple disciplines, organizations and locations globally, and ii) formed a smaller working group of interested participants following the workshop. Drawing on our collective

Figure 2. Time-series of surface (blue) and sub-surface (red) water level data in a tributary of Jacksons Creek in the Wombat State Forest for the period 1 January 2020 to 1 January 2023. A value of y = 0 mm is the base of the streambed. Flat lines in the groundwater level data indicate the depth of the monitoring bore. Gaps in the time-series indicate periods of missing data.

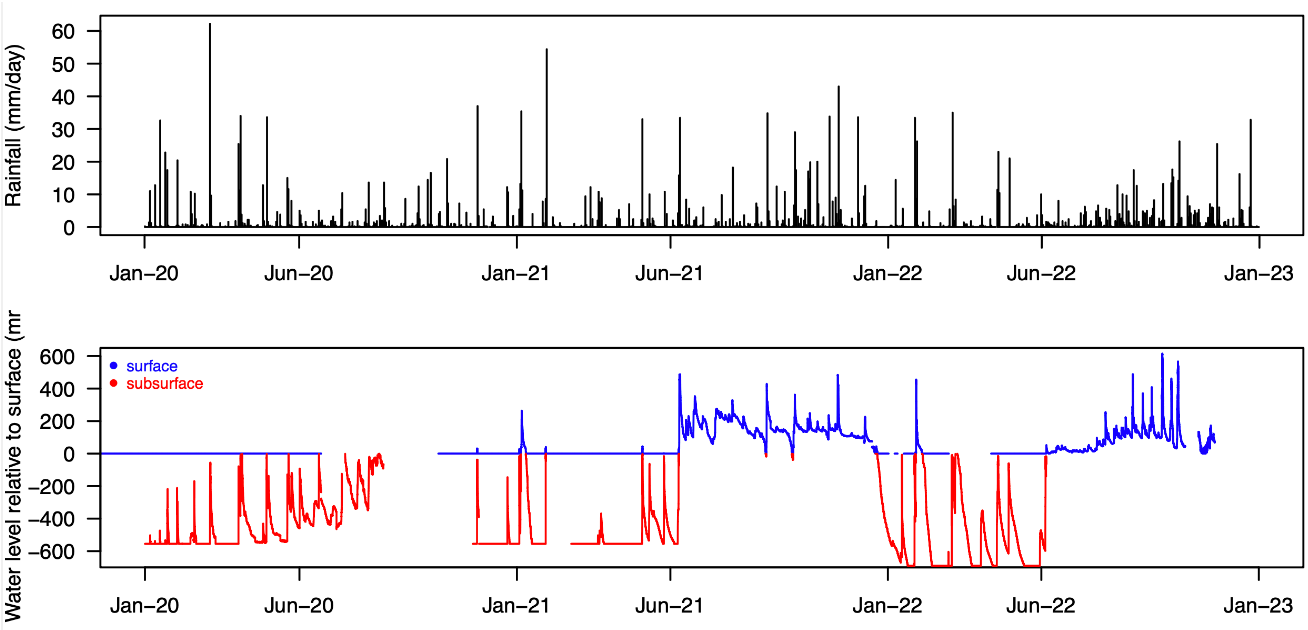
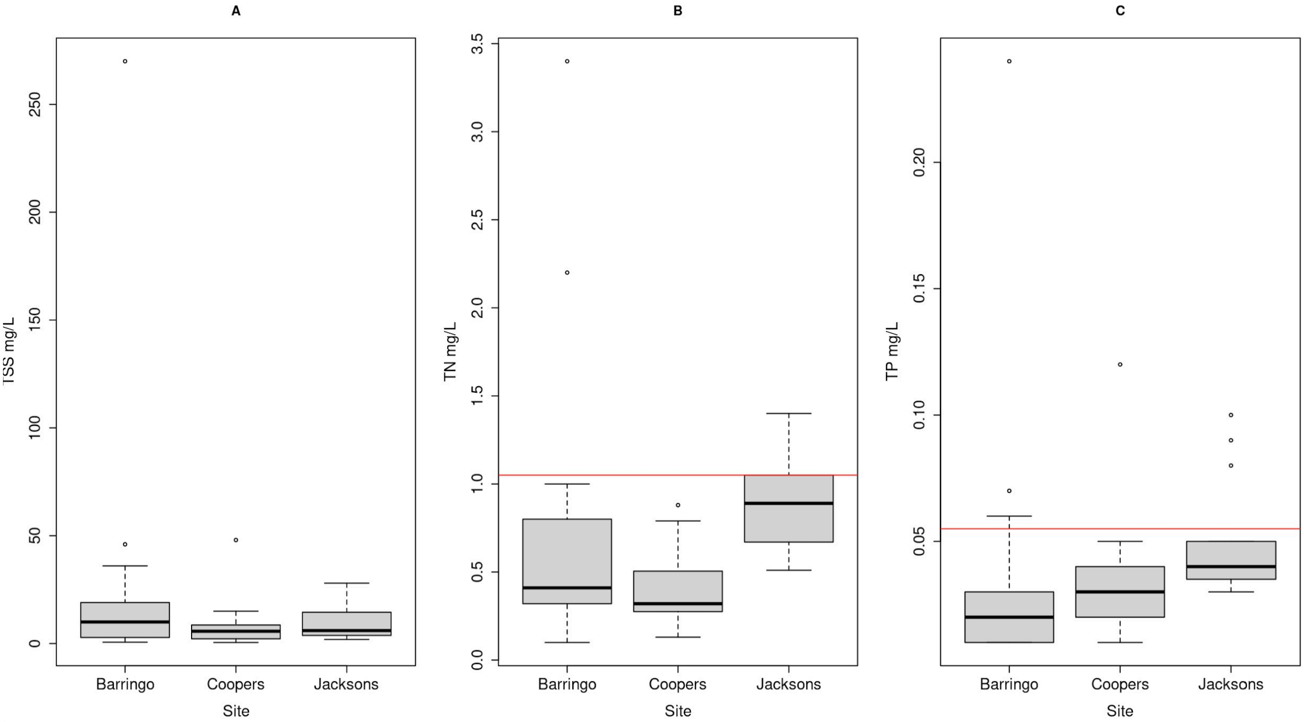


Figure 3. Boxplots of surface water concentrations of Total Suspended Solids (A), Total Nitrogen (B), and Total Phosphorus (C) for three headwater streams: a tributary each of Barringo Creek, Coopers Creek and Jacksons Creek. Surface water samples were not collected at the fourth site, a tributary of Charlies Creek, due to the absence of surface water. The red horizontal lines are the Environmental Reference Standard objectives (upper limit, Victorian Government 2021) for the region.



knowledge and experience, we developed a set of 25 structural and 31 non-structural tools that could be used to protect headwater streams in urbanizing areas. We assessed these tools in terms of their potential to deliver a range of stream protection objectives (e.g. maintaining or restoring a pre-development flow regime, improving water quality, capacity building, problem prevention) and additional benefits (e.g. water supply, urban heat mitigation, amenity) as well as a range of considerations that influence their suitability for a given context (e.g. scale, climate, soil type, land ownership). This comprehensive set of tools can be used to support initial conversations about how to protect headwater streams and develop a shortlist of tools that are likely to be suitable that can be taken forward to a more detailed investigation.

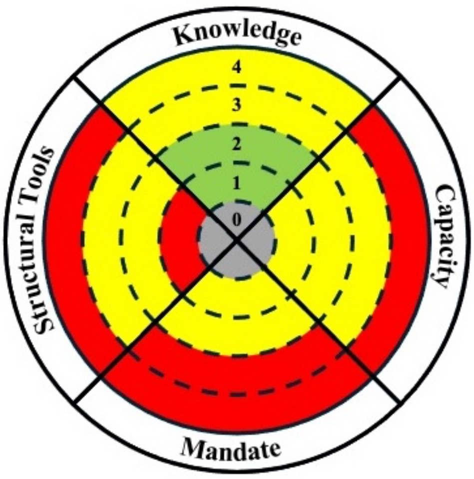
While protecting headwater streams in urbanizing areas can deliver a range of additional benefits (see above examples), realising this requires significant socio-technical change and this is made even more challenging in the current context of population growth, housing affordability, economic uncertainty, and climate change. To help policy makers, planners and other waterway practitioners assess the current status of headwater stream protection approaches in their region and identify opportunities to increase headwater stream protection maturity, we developed a conceptual framework of enabling factors for headwater stream protection (Hatt et al. 2024). Inspired by the Water Sensitive Cities Transition Dynamics Framework (Water Sensitive Cities Australia 2022), the framework includes four enabling factors that drive progress towards protection of headwater streams (Table 1). The framework describes each of these enabling factors at varying levels of maturity, ranging from not recognizing the importance of headwater streams through to an ideal state, where comprehensive, integrated protection of headwater streams is mainstream practice. The framework is additive, in that each maturity level builds on previous levels, and maturity levels are not fixed i.e., it is possible that some regions will span maturity levels for some enabling factors. There are also links between enabling factors, which means it is unlikely that one enabling factor can reach a high level of maturity if the other enabling factors are still immature (e.g. without knowledge of the importance of headwater streams, it is unlikely that the capacity to protect them will be mature).

Table 1. Enabling factors for progressing protection of headwater streams in urbanizing areas (Hatt et al. 2024)

Enabling factor	Description
Knowledge	Do we know why and how to protect headwater streams?
Capacity	Do we have the ability to protect headwater streams?
Mandate	Do we want or have to protect headwater streams?
Structural tools	Is the selection and application of structural tools achieving holistic outcomes?

The framework has now been applied to four case studies from Australia and the US to test its robustness and relevance. The results of the example case study shown in Figure 4 are illustrated using a traffic light assessment and indicate that knowledge of the importance of headwater streams in Greater Melbourne is relatively advanced but capacity, mandate and the appropriate use of structural tools are less mature. Based on the outcomes of this maturity assessment, it is recommended that next steps focus on advancing capacity (e.g. establishing formal communities of practice), mandate (e.g. legislative protection, planning amendments) and the use of structural tools (e.g. spatially explicit design tools, emphasis on at-source stormwater treatment).

Figure 4. Traffic light assessment for a headwater stream located in Melbourne, Australia. The lowest level of maturity (0) is the default starting position. Green = achieved, yellow = some progress, red = not yet started (Adapted from Hatt et al. 2024).



Pilot co-design approach for protecting headwater streams in urbanizing areas

Urban development is a complex process that requires collaboration and consultation with a range of different partners and agencies. Protecting waterways from urban development also requires a place-based response to specific local constraints and opportunities. Together, this can mean that, even though the science on what is required to protect headwater streams in urban areas is well established, the pathway to on-ground solutions is less clear.

To address this challenge, Melbourne Water collaborated with Water Sensitive Cities Australia to trial a co-design approach to develop ideas for practical and innovative design solutions for the protection of a headwater stream in an urbanizing area. We drew on the facilitated design process pioneered by the Cooperative Research Centre for Water Sensitive Cities to explore opportunities for protecting Aitken Creek, an ephemeral headwater stream that rises in Melbourne's northern growth corridor.

We ran a two-part workshop series to develop ideas and solutions towards a central question: how might we protect Aitken Creek as part of sustainable and affordable development? Implicit in this question is considering how ideas and solutions to protect headwater streams could help to deliver additional benefits for urban areas (e.g. urban cooling, terrestrial biodiversity, increased health and wealth), that is, to create places that deliver a net benefit to both people and nature. The workshops were attended by 31 participants from 15 organisations, including local and state governments, water utilities, consulting groups, Traditional Owners, and universities. Workshop participants were selected to represent multiple disciplines and perspectives, including policy, planning, traditional knowledge and western science, engineering, landscape and building architecture, and urban design. The design challenge began by agreeing on a problem definition, then developing novel design solutions and, finally, considering pathways to implementation, including real and perceived barriers to achieving better outcomes. Bringing together a cross-section of researchers and practitioners enabled us to use the latest science on headwater streams, as well as current knowledge and existing tools, to inform new and innovative design solutions, including designs to avoid. We are also working with stakeholders who were not able to fully participate in the workshops (e.g. developers, community groups) to incorporate their perspectives.

The outcomes of the workshop, which are compiled and illustrated in a synthesis report (in prep), include:

- High-level guidance, describing core principles, scale of application, water sources, and barriers to implementation;
- Technical ideas e.g. tailored drainage schemes to retain low flows in the landscape, biodiversity sensitive streetscape design; and
- Enabling ideas e.g. defining responsibilities with respect to impacts, rethinking alternate water objectives.

Some of the ideas and solutions identified by the workshops are not possible under the Precinct Structure Plan (PSP) that encompasses the study area, although there is still scope for developers to incorporate the core principles, as well as some of the technical and enabling ideas, into their development designs for Aitken Creek. Regardless, the intent of Aitken Creek as a case study was as a catalyst for a discussion of actions that could support future headwater stream protection across the region. Therefore, some of the ideas and solutions were more future-focused (e.g. creating an adaptive PSP process) and point to socio-technical changes that are required to achieve better outcomes for headwater streams. In addition, this co-design ideas process can be used early in the planning process to develop place-based solutions for other headwater streams.

Conclusions

Despite the long-held recognition of the importance of headwater streams, they often receive the least protection in urbanizing areas. Our research program is helping to address some of the key knowledge gaps that are hindering the protection of headwater streams, as well as develop practical tools that can be used by policy makers, planners and other waterway practitioners to develop and implement co-designed, place-based management actions.

Acknowledgments

This research was funded by Melbourne Water through the Melbourne Waterway Research-Practice Partnership and by Water Sensitive Cities Australia. We thank Genevieve Hehir, Claudia Niklason, Rob James and Peter Poelsma for their contribution to the monitoring program; Chamantha Athapaththu, Jonny Behrens, Sally Boer, Ryan Burrows, Riley de Jong, Caroline Elsner, Vaughn Grey, Brianna Williams and participants in the headwater streams workshop at the 6th Symposium on Urbanization and Stream Ecology for their contributions to the tools and framework project; and organisers, facilitators and participants in the Aitken Creek co-design workshops.

References

Barmuta, L., A. Watson, A. Clarke and J. Clapcott (2009), “The importance of headwater streams”, National Water Commission, Canberra

Burns, M., B. Hatt, R. Burrows, M. Imberger, P. Poelsma, G. Hehir, R. James, C. Walsh and R. Coleman (2024), “Understanding the role of small headwater streams in urbanizing catchments for supporting waterway health. Melbourne Waterway Research-Practice Partnership Technical Report 24.3”, Melbourne Waterway Research-Practice Partnership Technical Report 24.3, The University of Melbourne, Burnley, Victoria

Gomi, T., R. C. Sidle and J. S. Richardson (2002). "Understanding processes and downstream linkages of headwater systems." Bioscience **52**(10): 905-916.

Hatt, B. E., C. Athapaththu, J. Behrens, S. L. Boer, M. J. Burns, R. M. Burrows, R. de Jong, C. Elsner, V. Grey, M. J. Imberger, B. M. Williams and R. A. Coleman (2024). "Practical pathways for protecting headwater streams in urbanizing areas [Manuscript in preparation]."

Imberger, M., B. E. Hatt, S. Brown, M. J. Burns, R. M. Burrows and C. J. Walsh (2023). "Headwater streams in an urbanizing world." Freshwater Science **42**(3): 323-336.

Mainstone, C., R. Hall and I. Diack (2016). A narrative for conserving freshwater and wetland habitats in England. Natural England Research Reports.

McKergow, L. A., D. M. Weaver, I. P. Prosser, R. B. Grayson and A. E. G. Reed (2003). "Before and after riparian management: sediment and nutrient exports from a small agricultural catchment, Western Australia." Journal of Hydrology **270**(3): 253-272.

Melbourne Water (2018), “Healthy Waterways Strategy”,

Peterson, B. J., W. M. Wollheim, P. J. Mulholland, J. R. Webster, J. L. Meyer, J. L. Tank, E. Marti, W. B. Bowden, H. M. Valett, A. E. Hershey, W. H. McDowell, W. K. Dodds, S. K. Hamilton, S. Gregory and D. D. Morrall (2001). "Control of nitrogen export from watersheds by headwater streams." Science **292**(5514): 86-90.

Roy, A. H., A. L. Dybas, K. M. Fritz and H. R. Lubbers (2009). "Urbanization affects the extent and hydrologic permanence of headwater streams in a midwestern US metropolitan area." Journal of the North American Benthological Society **28**(4): 911-928.

US EPA (2015), “Connectivity of Streams and Wetlands to Downstream Waters: A Review and Synthesis of the Scientific Evidence”, Office of Research and Development, U.S. Environmental Protection Agency, Washington, DC

Victorian Government (2021). Environment Reference Standard.

Walsh, C. J. (2023), “The Melbourne Water stream network: user’s manual. Version 1.3. Melbourne Waterway Research-Practice Partnership Report 19.4d”, Waterway Ecosystem Research Group, School of Agriculture, Food, and Ecosystem Sciences, The University of Melbourne,

Walsh, C. J., M. J. Burns, G. Hehir, P. Poelsma, B. E. Hatt, J. Kunapo, R. Burrows, M. Imberger, S. Brown, Y. E. Chee, L. Smith and B. Lovell (2022), “A new dataset for designating headwater streams in the Port Phillip and Westernport region. Melbourne Waterway Research-Practice Partnership Technical Report 22.5”, The Unviersity of Melbourne, Burnley, Victoria

Water Sensitive Cities Australia (2022), “WSC Transitions Tools Manual Version 1”, Water Sensitive Cities Australia, Melbourne, Australia