Understanding the role of small headwater streams in urbanizing catchments for supporting waterway health.

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Acknowledgement of Country

Melbourne Water and the University of Melbourne respectfully acknowledge Aboriginal and Torres Strait Islander peoples as the Traditional Owners and custodians of the land and water on which all Australians rely. This research was conducted on Wurundjeri Country (with research described in Box 1 conducted on Bunurong and Wadawurrung, as well as Wurundjeri Country) and we pay our respects to their Elders past, present and future. We acknowledge and respect the continued cultural, social and spiritual connections that all Aboriginal Victorians, as well as the broader Aboriginal and Torres Strait Islander community, have with lands and waters, and recognise and value their inherent responsibility to care for and protect them for thousands of generations. We are committed to working in partnership with Traditional Owners to ensure meaningful ongoing contribution to the future of land and water management.

Summary

This research sought to increase our understanding of the ecological values and services provided by headwater streams in the Melbourne Water management region. The research also aimed to contribute to the effective management and protection of headwater streams through a clear business case and appropriate policy and design guidelines. The work comprised two parts—1) a literature review and 2) a monitoring program featuring five headwater sites to the west of Melbourne.

The literature review defined headwater streams as the point in the landscape where catchment runoff first accumulates sufficiently to create overland flow paths. The review found that headwater streams are dominant and critical features of many landscapes. They are the primary sources of streamflow, important sources of organic matter and biota (e.g. invertebrates and frogs) to downstream waters, and act as hot spots for retention and transformation of nutrients such as nitrogen and carbon. Their contribution to regional aquatic biodiversity is disproportionately large. For example, several studies have shown that headwater streams provide extensive habitat, with up to ~one-third of aquatic invertebrate species being unique to these running waters. Headwater streams are also the first source of aquatic life in the transition from hillslopes to the river network and thus can be an important source of colonists to lower reaches. The contribution of headwater streams to regional biodiversity and downstream ecological processes is not yet known in the Melbourne region.

The monitoring program collected data on hydrology, water quality, and ecological structure and function. In general, flow behavior at the sites was highly seasonal, with surface flow only occurring during the wetter months. Water draining from the sites was of a very high quality (e.g. filterable reactive phosphorus concentrations less than 0.01 mg/L). Leaf breakdown rates—an indicator of stream decomposition—were found to be lower in the headwater forested sites compared to nearby agricultural streams. The slow rates are indicative of healthy ecosystem function in Melbourne's largely undistributed, forested headwaters. Bores in the stream substrate sampled for groundwater-dwelling aquatic animals (stygofauna) revealed few individuals.

Our results highlight the overarching and critical role that headwater streams play in maintaining downstream river and bay health. These systems however, are particularly vulnerable to degradation or loss in rapidly urbanizing cities such as Melbourne. Even small changes in land-use in the catchments of headwater streams are likely to elicit significant consequences to hydrology, water quality and ultimately stream structure and function.

Further work is required to develop a clear business case and appropriate policy and design guidelines for headwater stream protection.

Recommendations

- Consistent with Regional Performance Objective 16 in the Healthy Waterway Strategy, headwater streams should be protected from urban development. The use of the new stream network layer—which now includes headwater stream extents—will help identify where this Performance Objective needs to be met.
- Quantify the loss of headwater streams to date and estimate the length of headwater streams that are vulnerable to urban development. In doing so, determine the implications for regional hydrology, water quality, biodiversity, and relevant targets set (for key values) within the Healthy Waterways Strategy.
- In locations where urban development occurs, appropriately designed stormwater control measures (SCMs) can ensure headwater stream protection is achieved. The SCMs must be designed in ways that mimic natural flow and water quality regimes.
- Develop guidelines for the protection or restoration of headwater streams in urban developments based on project outcomes, along with data and knowledge from other related studies (e.g. stream monitoring for the Sunbury Integrated Water Management project, Ideas for Aitken Creek project).

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Introduction

This research project sought to investigate and quantify the ecological values and services provided by headwater streams across the Port Phillip and Westernport region; and ultimately facilitate their effective management and protection in areas of rapid urban growth. It is hoped that the work will support the Health Waterways Strategy 2018 and the Regional Performance Objective (RPO) to ensure that "headwater streams are retained as features in the landscape for environmental, social, culture and economic benefits". The mid-term review of the strategy reinforced this objective.

This project summary comprises four sections. In the first section, we provide a literature review on headwater streams. The second section describes the headwater sites and monitoring program. The third section displays and synthesizes the data collected to date. And the final section discusses management implications based on the research.

Literature review

We base this section on Imberger *et al.* (2023) The following text is a (mostly) verbatim reproduction of relevant text in the paper. Some edits to the Imberger paper have occurred in the writing of this report.

Headwater stream function, function, and values

Regional importance

Headwater streams typically constitute 60-80% of the stream network (Allan & Castillo 2007; Barmuta *et al.* 2009; Roy *et al.* 2009; McGarrigle 2014) and play a disproportionately large role in downstream flood control owing to hillslope infiltration, their abundance and channel roughness (Gomi, Sidle & Richardson 2002; Alexander *et al.* 2007; MacDonald & Coe 2007). As the interface between terrestrial and aquatic ecosystems, headwaters are the first receiving point for water, nutrients, organic matter and propagules, as well as the first "line of defence" against potential contaminants (MacDonald & Coe 2007; Wohl 2017). This is mainly a function of their tightly coupled riparian and channel zones (Alexander *et al.* 2007), which are considered biogeochemical hotspots for nutrient processing and strongly influence the degree to which sediment (McKergow *et al.* 2003) and nutrients (Lowrance *et al.* 1984) are passed directly downstream. These systems export water via direct upland groundwater recharge, surface flows and subsequent contributions to subsurface, hyporheic and groundwater aquifers in the lower river network (Barmuta *et al.* 2009; Ebersole *et al.* 2015; Jensen *et al.* 2019). Ultimately, these streams are the dominant sources of water, suspended sediments, nutrients and organic matter, particularly following catchment disturbance (McKergow *et al.* 2003; Olley & Wasson 2003; Houser, Mulholland & Maloney 2006), to the lower stream network (Alexander *et al.* 2007; Barmuta *et al.* 2009).

Headwater streams tend to have higher hydrologic variability than larger downstream segments within any one hydroclimatic region (Woods, Sivapalan & Duncan 1995), including greater and more rapid variations in peak discharge per unit area (Riley *et al.* 2018) and marked discharge intermittence (Nadeau & Rains 2007). While some headwater streams are perennial spring-fed systems, in many regions they are more likely intermittent or ephemeral (Nadeau & Rains 2007; Richardson & Dudgeon 2022). The hydrologic regime of headwater streams is a critical determinant of their stream geomorphology, structure and function (Poff *et al.* 1997) and non-perennial reaches are thus characterised by a telescoping ecosystem model (Fisher *et al.* 1998). Based on this model the expansion and contraction of the telescope are likened to the connection and disconnection of the surface channel to the hyporheic, aquifer and riparian zones in response to variable wetting and drying conditions. This model importantly highlights the extent to which headwater streams expand and contract and the critical role this plays in influencing the retention and transport of water and other materials through the lower stream network (Fisher *et al.* 1998; McDonough, Hosen & Palmer 2011).

Connection to land and catchment processes

All streams are strongly influenced by their catchments (Hynes 1975), however, this is particularly so in the case of headwater streams. Shorter flow paths mean that headwater streams are more tightly coupled with their catchments and that hillslope processes play a much greater role in the fluxes of water, nutrients (e.g. nitrogen and phosphorus), organic matter and pollutants (e.g. heavy metals and pesticides) than that observed in lower stream reaches (McGlynn *et al.* 2004; MacDonald & Coe 2007). These shorter flow paths and smaller catchments also mean that headwater streams can react much more rapidly and significantly to changes in water and material fluxes resulting from catchment land-cover and land-use change, atmospheric inputs and localised disturbance such as storms, bushfires, debris flows and landslides (McGlynn *et al.* 2004; Wohl 2017). This recognition is vital from a management perspective because it highlights that headwater stream structure, function and values cannot solely be protected by approaches targeting the parafluvial zone alone; rather, protection also requires management at the catchment scale.

Processing and transport power

The small size of headwater streams increases their sediment surface area to water volume ratio, increasing their capacity for sediment-associated processing of nutrients relative to larger middle and lower portions of the river network (Peterson *et al.* 2001; Riley *et al.* 2018). Due to their size, headwater systems can also lack the stream power to move large volumes of bedload sediments throughout most of the year (with the exception of extreme events). They can, however, contribute substantial loads of suspended sediments and both fine particulate and dissolved organic matter to lower reaches (Barmuta *et al.* 2009), particularly following catchment and riparian disturbance (Watson & Barmuta 2010). This is in contrast to the downstream network, where higher stream discharge and power allows significantly greater export of bedload sediments, coarse particulate organic matter and large woody debris (Allan & Castillo 2007).

Ecosystem structure and function

Headwater streams provide habitat for common, rare and threatened species [e.g. the Dandenong amphipod; Imberger *et al.* (2016)] and collectively contribute to regional biodiversity (Mainstone, Hall & Diack 2016). Individual headwater streams typically support fewer species than larger rivers (Davy-Bowker *et al.* 2008), however, differences in species composition between headwater streams mean that they collectively make a large contribution to regional biodiversity (Heino 2005; Clarke *et al.* 2008; Finn *et al.* 2011;

Callanan, Baars & Kelly-Quinn 2014; Furse). Several studies have demonstrated that headwater streams provide extensive habitat, with up to 29% of aquatic invertebrate species being unique to these systems (Furse 1995; Feeley *et al.* 2012; Callanan *et al.* 2014). Headwater streams are the first source of aquatic life in the transition from hillslopes to the river network and, as such, can be an important source of colonists to lower reaches of the river network (MacDonald & Coe 2007) and provide refuge from predation and adverse downstream conditions (Covich *et al.* 2009; Cooper *et al.* 2021). Intermittent and ephemeral headwater streams, in particular, can serve as important medium-term storage sites for eggs and seeds of aquatic/semi-aquatic species. Under appropriate conditions, these eggs may hatch and develop into adults and seeds may germinate and establish in situ; other eggs and seeds, however, will ultimately be transported as colonists to lower reaches (Steward *et al.* 2012; Jensen *et al.* 2019). Models predict that the complex hydrological dynamics of intermittent and ephemeral headwater streams increases community heterogeneity and habitat diversity and in turn biodiversity, relative to downstream reaches (Larned *et al.* 2010). Furthermore, their geographical isolation can support genetically isolated species, thus providing an additional, important means of supporting biodiversity at catchment and regional scales (Gomi *et al.* 2002).

Threats to headwater streams

Urbanization

The urbanization of catchments is rapidly increasing across the world. Radwan *et al.* (2021) showed that urban landcover over the last three decades has unidirectionally increased at the global scale, with the greatest continental rates observed in Asia, Europe and North America respectively. Globally, 68% of urbanization over this time resulted from the direct conversion of agricultural land, while 15% resulted from the conversion of natural vegetation (Radwan *et al.* 2021). This urbanization of agricultural lands is thought to be even greater in developing countries (Seto *et al.* 2011) and has important implications for the sequential nature of ecological impacts and legacy effects (Maloney *et al.* 2008; Roy *et al.* 2009). Despite extensive research into the effects of urbanization on small to large streams, the effects on headwaters, particularly intermittent and ephemeral reaches, remain poorly understood. Urban headwater streams are often channelised or piped and buried beneath the surface of our growing cities resulting in the development of “urban stream deserts” (Napieralski & Carvalhaes 2016; Weitzell Jr *et al.* 2016). Elmore & Kaushal (2008) found that urban headwater streams were even more extensively buried than larger streams, with 70% of streams with catchments smaller than 260 ha buried in Baltimore City. The effects on ephemeral headwater streams can be even greater, with Roy *et al.* (2009) estimating some urban areas have lost 93% of stream length. The effects of channelising, piping and burying small streams are extensive, with the immediate and total, or near total loss of the natural channel substrate, reach scale benthic habitat, biodiversity, ecosystem function and lateral and vertical connectivity (Beaulieu *et al.* 2014; Hope, McDowell & Wollheim 2014; Napieralski & Carvalhaes 2016; Meyer, Poole & Jones). While some ecological structure and function may persist (Fork *et al.* 2018) or return through time, habitat availability, dispersal and colonisation patterns, thermal regimes, aquatic-riparian mediated nutrient removal, light availability, primary production, and foodweb structure are likely to remain significantly impaired (Wigington Jr *et al.* 2006; Beaulieu *et al.* 2014; Hope *et al.* 2014; Weitzell Jr *et al.* 2016; Meyer *et al.*). We argue that such buried, piped and channelised drains cease being a stream at all. This engineered infrastructure can both directly replace natural stream channels, and also add significant length to the urban drainage network via connection to new impervious surfaces (e.g. roads and roofs) within and outside of natural catchment boundaries (Walsh, Fletcher & Vietz 2016). This infrastructure poses a threat not just to urban headwater streams but also lower river segments.

Climate change

The impacts of urbanization on headwater streams in the coming decades are unlikely to occur in isolation, but rather amidst significant climate change. This highlights the importance of thinking not just about the effects of climate change on headwater streams, but also the potential for additive, multiplicative or antagonistic interactions with concurrent urbanization. Climate change forecasts across the globe are highly variable, however, even small changes in air temperature, rainfall and the frequency of extreme events can have a considerable impact on water availability and subsequent hydrologic regimes. In Australia, climate change predictions using a representative concentration pathway (RCP) of 8.5 and averaged across 32 global climate models show an increase in average annual temperature of 1.0-1.6°C and a decrease in average annual rainfall of 0-10% between 2020-2050 across all four natural resource management super-clusters (CSIRO & Meteorology 2021). Using the same RCP value, climate models and standardised soil moisture index, Kirono *et al.* (2020) predicted an increase in the duration and intensity of drought and an increase in the frequency, duration and intensity of extreme drought by 2050 in each of the four super-clusters. A growing number of studies also predict an increase in the frequency and intensity of sub-daily rainfall extremes (Fowler *et al.* 2021). In Australia, this means a future climate which is hotter, drier and more prone to both droughts and floods (CSIRO & Meteorology 2021; Fowler *et al.* 2021).

Due to their size, headwater streams are particularly vulnerable to changes in climate and these models predict a significant decline in annual water availability which will increase bushfire risks, alter flow intermittence patterns and hydrologic connectivity (Barmuta *et al.* 2009). This will likely produce shifts from perennial to non-perennial flow regimes and increases in the frequency and extent of dry streambeds (Jaeger, Olden & Pelland 2014). This reduction in water availability will likely cause the loss and fragmentation of aquatic habitat, alterations in nutrient retention, in-stream production, and biotic communities (Jaeger *et al.* 2014); however, impacts specific to headwater streams remain rarely studied. While drought is a natural reoccurring disturbance in Australia and many other continents, alterations to its frequency, duration and intensity will exacerbate impacts on headwater streams (Lake 2003).

Protection of headwater streams and knowledge gaps

The literature review demonstrated that headwater streams are important habitats in their own right but also critical regulators of downstream river health. Despite this recognition, we still lack a clear understanding of 1) their ecological structure and function, 2) hydrologic and water quality behavior and 3) management opportunities to protect them in the face of future urban growth and climate change. Melbourne Water has been addressing these critical gaps through a headwater stream monitoring program. The program has involved the instrumentation and sampling of five headwater streams in the west of Melbourne. A description of the program along with monitoring results and implications is described below. As of Dec-2024, the program is still ongoing.

Further, the literature review advises that continued adoption of conventional urban drainage infrastructure will result in ongoing loss of headwater streams and the values and services they provide. Melbourne Water is giving consideration to alterative approaches towards stormwater management in headwater areas. This is through projects such as the Ideas for Aitken Creek project (led by Dr Belinda Hatt)—see description in the Discussion.

Monitoring sites and field work

Site description

In 2019, we commenced the monitoring of four headwater streams in the west of Melbourne (Table 1 and Figure 1). These streams drain fully forested catchments in 1) Macedon Regional Park, 2) Wombat State Forest, 3) Lerderderg State Park, and 4) Mount Charlie Nature Conservation Reserve. An additional site in Mickleham, Aitken Creek, was added to the monitoring program in 2022. The catchment of Aitken Creek is currently mostly paddocks and urban development of a large part of the catchment is planned – providing an opportunity to evaluate the effectiveness of any potential management interventions to protect this headwater stream as part of the new development.

Table 1: Catchment statistics for the study sites. Abbreviated site names are used throughout the report. Reach codes were sourced from the latest MW stream network (https://tools.thewerg.unimelb.edu.au/mwstr/).

Site	Abbreviated name	Reach code	Site number	Catchment.area (ha)	Mapped Lengh (m)
Tributary of Barringo Creek	Barringo	RJ3_4	399999	4	15
Tributary of Jacksons Creek	Jacksons	JZ5_47	371186	47	564
Tributary of Coopers Creek	Coopers	COA_17	370719	17	522
Trib of Charlies Creek us Kent Rd	Charlies	CH4_88	5292	88	5030
Aitken Creek (west branch)	Aitken	HTC_340	27376	340	4014

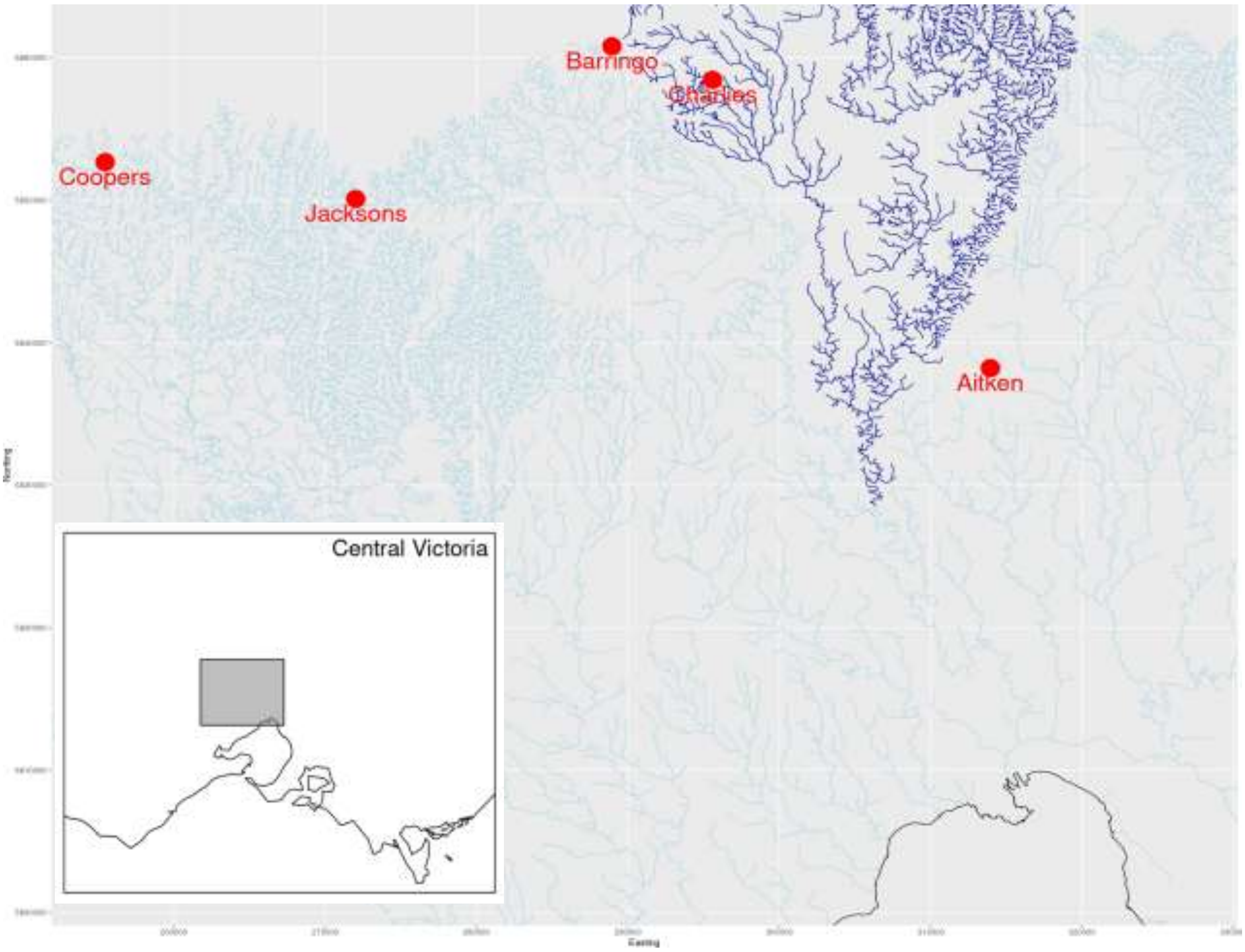

Figure 1: A map of the five study sites (red circles). Light blue lines indicate the stream network. Dark blue lines indicate Deep Creek (for reference). The black line is the coastline of Port Phillip.

Tributary of Barringo Creek (Mount Macedon): RJ3_4

This shallow, groundwater fed stream drains a small forested (wet eucalypt forest) hillslope (Figure 1). The channel itself is narrow, moderately steep, and is likely the farthest upstream point of surface flow. The riparian zone is dominated by native soils and is largely indistinguishable from the general landscape. Surface soils include forest litter, overlying dark organic loam. Deeper soils are clay.

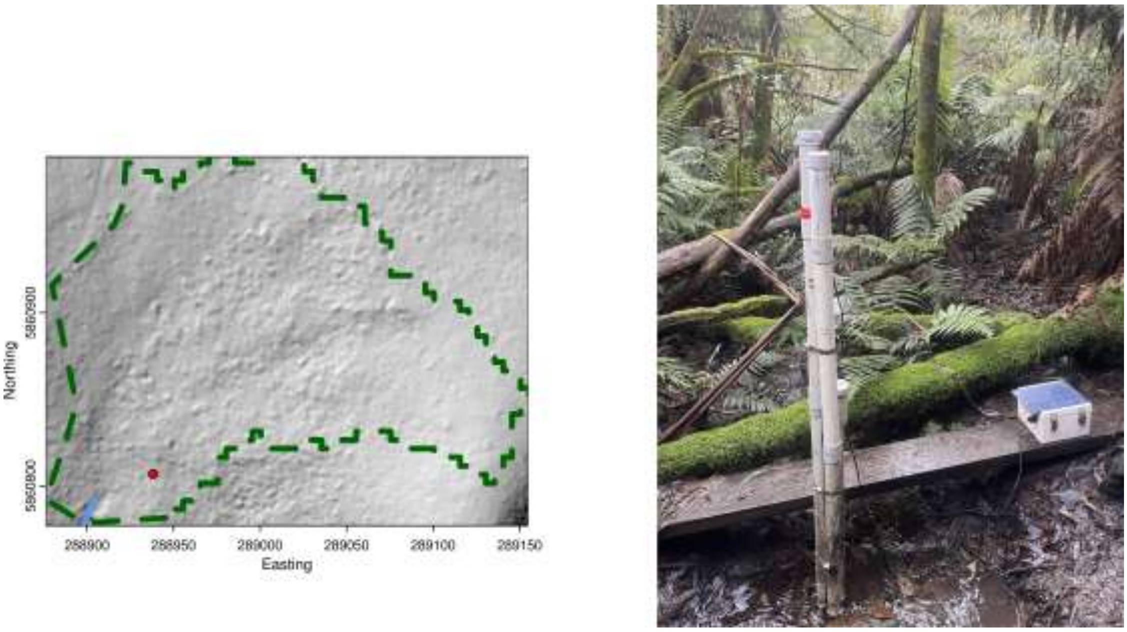

Figure 2: Site diagram for the tributary of Barringo Creek (RJ3_4) (left). Dark green dotted lines = catchment boundary. Headwater stream extension lines shown in blue. Monitoring point = red circle. The background is a grayscale representation of the terrain surface (hillshade). Photo of the site shown on the right.

Tributary of Jacksons Creek (Wombat State Forest): JZ5_47

This stream is a somewhat trapezoidal channel that drains a small forested (dry eucalypt forest) catchment (Figure 2), which is dominated by a number of eucalypt species and a sparse understory of native grasses and shrubs. The head of the channel network is several hundred metres upstream of the monitoring site. There is abundant forest litter, predominantly consisting of bark and eucalyptus leaves. Surface soils are light organic loam. The soil profile was mostly clay and appeared fairly uniform up to one metre in depth.

Figure 3: Site map for the tributary of Jacksons Creek (JZ5_47) (left). Dark green dotted lines = catchment boundary. Headwater stream extension lines shown in blue. Monitoring point = red circle. The background is a grayscale representation of the terrain surface (hillshade). Photo of the site shown on the right.

Tributary of Coopers Creek (Lerderderg State Park): COA_17

This very shallow channel drains a small forested catchment (Figure 3), which is dominated by native trees (eucalypt forest). The slope of the channel banks is gentle, resulting in high floodplain connectivity. The first point of surface flow is likely several hundred metres upstream of the monitoring point. Catchment soils appeared relatively dry and rather loamy.

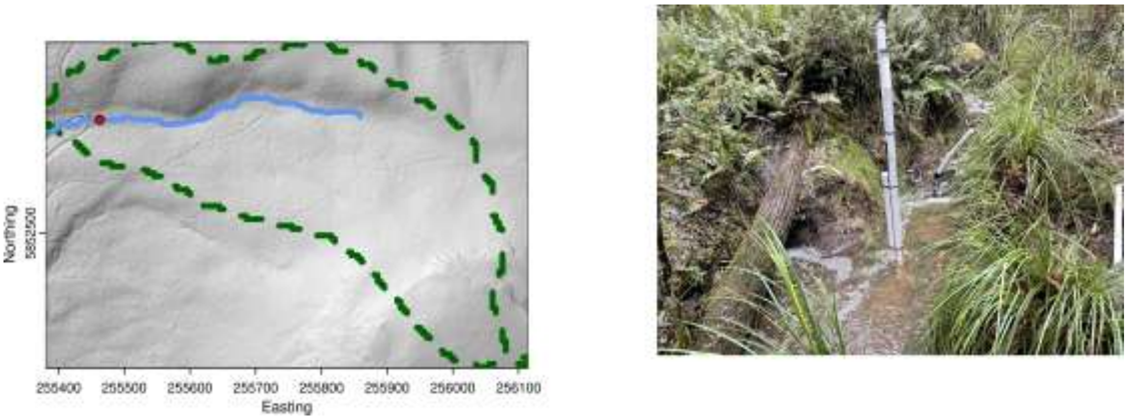

Figure 4: Site map for the tributary of Coopers Creek (COA_17) (left). Dark green dotted lines = catchment boundary. Headwater stream extension lines shown in blue. Monitoring point = red circle. The background is a grayscale representation of the terrain surface (hillshade). Photo of the site shown on the right.

Tributary of Charlies Creek (Mount Charlie Reserve): CH4_88

A well defined and fairly deep channel drains a medium-sized forested (dry eucalypt forest) catchment (Figure 4). There are likely 5-6 active channel heads upstream of the monitoring site. Surface soils appeared rather grey in colour and were friable. Surface flow was never observed at the initial monitoring site (also shown in Figure 4) for the period 27/05/2019-23/04/2021, thus the monitoring site was moved (in April-2021) to a larger catchment to the east (Figure 4).

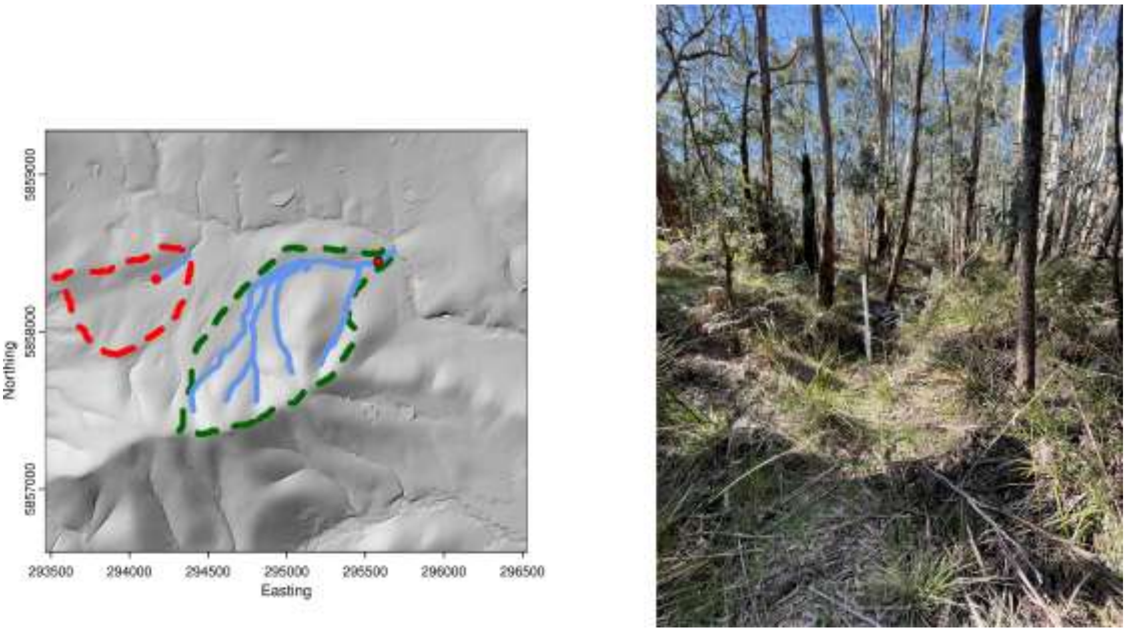

Figure 5: Site map for the tributary of Charlies Creek (CH4_88) (left). Dark green dotted lines = catchment boundary. Headwater stream extension lines shown in blue. Monitoring point = red circles. The abandoned monitoring site in the Mount Charlie Flora Reserve is shown to the west (red lines). The background is a grayscale representation of the terrain surface (hillshade). Photo of the site shown on the right.

Tributary of Aitken Creek: HTC_340

A somewhat poorly defined channel drains a small agricultural catchment (Figure 5), which is slated for urban development. Dense grass and rock surround the monitoring site. Drainage flow paths have been modified in the top half of the catchment. Catchment soils are fractured clays.

Figure 6: Site map for Aitken Creek (west branch, HTC_340) (left). Dark green dotted lines = catchment boundary. Headwater stream extension lines shown in blue. Monitoring point = red circle. The background is a grayscale representation of the terrain surface (hillshade). Photo of the site shown on the right

Field work

Hydrology

At each monitoring site, surface and sub-surface water level is being recorded at 6-minute intervals. We measure surface water level by placing probes into stilling wells—40 mm polyvinyl chloride (PVC) slotted pipes. These pipes are fixed 50 mm below the invert of the stream bed to allow the measurement of very shallow surface water and are secured to metal star pickets. We measure sub-surface water level by placing probes into shallow bores (750 mm depth) installed in the invert of the stream bed. The bores comprise a 40 mm PVC pipe, slotted from 750-500 mm below the surface and surrounded by 7 mm screenings up to 400 mm below the surface. The upper void space surrounding the PVC pipes was replaced with compacted, excavated native soils. The 40 mm PVC pipe protrudes (unslotted) 1,200 mm above the invert of the stream bed. The sub-surface monitoring bore is secured to the same metal star picket mentioned above.

Capacitance water level probes (Odyssey brand) were initially used in the monitoring program. They were subsequently replaced with custom-made submersible pressure sensors—technology which is superior for measuring groundwater level. Water level has been downloaded every 1-2 months and processed to remove data spikes and check against manual measurements taken on site. On site measurements not only verify the data being recorded, but also allow water level to be accurately compared to the stream bed even if the stream bed changed. We found that while some of the early data recorded using the Odyssey probes was trustworthy, other periods of data were not reliable. Use of our custom-made loggers (James et al., 2024; https://ssrn.com/abstract=4909740)has greatly increased the reliability and accuracy of the observations.

Water quality

Water quality samples is beingcollected from the sites during both dry- and wet weather. When possible, water is sampled from four locations —1) the surface, 2) the shallow bore, 3) hyporheic soils 250 mm below the stream bed, and 4) hyporheic soils 625 mm below the stream bed. Most of the samples collected to date have been from below the surface due to surface water not being present at the time of sampling. We use a YSI Exo 3 Multiparameter WQ Sonde to measure the following properties of water: dissolved oxygen (DO), electrical conductivity (EC), pH, redox potential, and temperature. Water samples were also sent to accredited laboratories for the measurement of: filterable reactive phosphorus (FRP), total phosphorus (TP), ammonia (NH_3), nitrate/nitrite (NO_x), total nitrogen (TN), total suspended solids (TSS), and the stable isotopes of water (deuterium and oxygen-18). We present the variability of the various water quality parameters. We also compare the quality of surface waters to the relevant objectives set out in the Environment Reference Standard (ERS) (EPA Victoria 2021). Our data percentiles do not comply with the ERS requirement that they be calculated for a minimum of 11 data points collected from monitoring over one year, therefore we only use the ERS objectives as an indicative comparison.

Stream ecology

A fundamental ecological process, rates of organic matter decomposition, is being quantified over time in both surface (riparian and benthic zone) and sub-surface (bore and hyporheic zone) environments. We have used the cotton-strip approach to measure the overall decomposition potential of the sites (Tiegs *et al.* 2013). For this method, cotton strips and temperature loggers were installed at each of the sites in four locations—1) riparian zone, 2) stream bed surface, 3) shallow bore (250 mm from the surface), and 4) buried 250 mm below the stream bed surface. The strips are collected from the field after five weeks and their strength tested and compared to controls at the end of this period. The relative loss in strength correlates with microbial degradation processes at each location. At the time of collection, a 5 mm sample of cotton strip from each location is also collected for DNA analysis. They are sent to AGRF for DNA analysis to determine microbial diversity present at each location. Data analysis of the microbial data involved non-metric multidimensional scale and is presented below.

We have also sampled the bores for invertebrates inhabiting the sub-surface (stygofauna). A 6L sample is collected from the shallow bore at each site, filtered through a 63 micron sieve and preserved in ethanol. These are sorted and identified to the lowest possible taxa (mostly order or family) in our laboratory. Samples collected in 2019 were sent onto StygoEcologia for identification to lower taxonomic levels (mostly genus or species). Data collected in 2019 is presented in the results.

Results

Hydrology

The presence of surface water at the forested sites has been highly seasonal (Figure 7). In general, surface flow begins in winter and quickly recedes sometime during summer. Such flow behavior is expected for headwater streams located in regions with a temperate climate. When surface flow is present, the rainfall-runoff response is rather dampened for Barringo—sharp rises and falls in water level occur very infrequently (Figure 7). In contrast, the surface water level in Jacksons and Coopers can rise fairly sharply. The presence of surface water has been rare in Charlies, even at the replacement monitoring site, and is generally only observed for short periods following very wet conditions (e.g. the winter of 2022). Mostly continuous surface flows have been observed at Aitken over the monitoring period (Figure 7).

Ground water behavior appears fairly complex. In the wetter months, groundwater levels can be higher than surface levels e.g. clearly illustrated at Barringo, where groundwater levels of up to 0.4 m above the base of the streambed were observed (Figure 7) compared to surface water levels in the order of 0.05-0.1 m above the base of the streambed (Figure 7). This likely occurs when the piezometer (the bore) intersects a line of equal hydraulic head, and signals a saturated aquifer with lateral flow paths. The saturated aquifer is recharged from the vadose (unsaturated) zone above. This lateral flow process shuts off during the drier months. Contrasting behavior has been observed at Jacksons and Aitkens (Figure 7), with surface and sub-surface water levels converging. This likely occurs when the entire catchment is saturated due to moderate permeability soils, and any rain causes runoff to the stream.

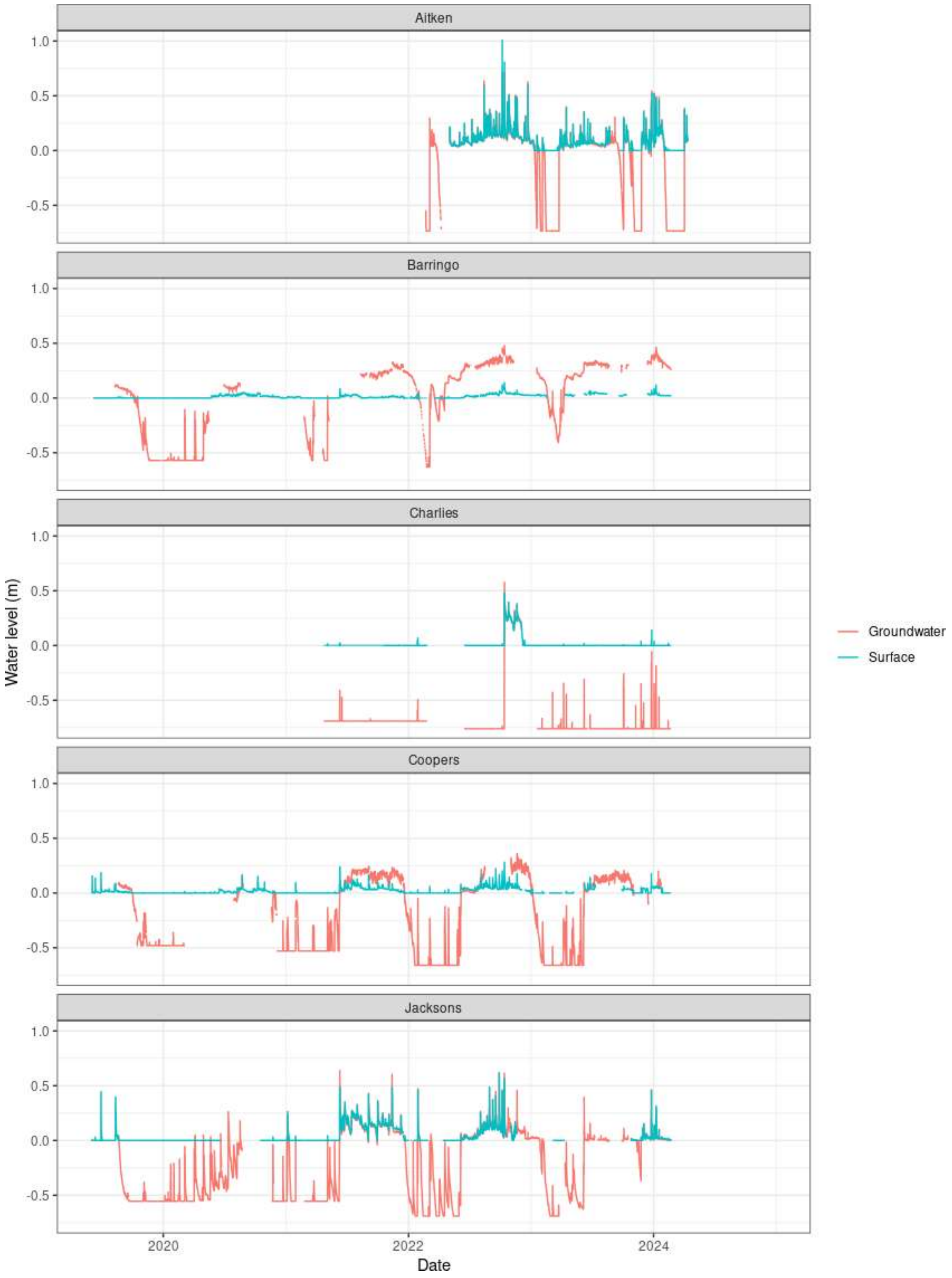

Figure 7: Water level measured in the headwater stream sites. A value of y = 0 m is the base of the streambed. Gaps in the time-series indicate periods of missing data. Flatlines in the groundwater data indicate the de The timeseries for Charlies begins in 2021, when the monitoring site was moved to the second site following the complete absence of surface water across two years of monitoring at the first site.

Water quality

We observed consistently high quality surface water at the three forested sites where we have been able to collect surface water samples: Barringo, Coopers and Jacksons (Figures 8 and 9). The 75th percentile surface water concentrations of TN and TP are below the local ERS objectives at all three sites, with the exception of TN at Jacksons, which is equal to the ERS (Figure 8, Table 2). As noted in the methods above, the comparison to the ERS objectives is indicative only as the sampling frequency does not meet the requirements of the ERS. TSS concentrations are also low (<20 mg/L) and indicative of clean water. This is not surprising, given that these are small streams with low slope and therefore low sediment transport capacity.

The 75th percentile EC levels are well below the maximum ERS objective at all three forested sites, however, the 25th percentile DO levels are slightly less than the corresponding minimum ERS objective (Figure 9 and, Table 2). However, there are limited data on the water quality of headwater streams, both globally and locally, so it is not known whether the low observed DO indicates some level of impairment or if this is typical of headwater streams with low slope, low discharge and an ephemeral flow regime. It is suggested that, although the latter is more likely, given that the streams' catchments are largely undisturbed. It could also be possible that a large component of the surface water is recently emerged groundwater and re-emerged hyporheic flow containing low DO. Decomposition of organic inputs from the forested catchment may also contribute to low DO. pH data for the three forested sites provide support for this latter explanation, in that all observations were below the lower limit set by the ERS (Figure 9 and Table 2); this could be due to the release of organic acids as plant material and soil organic matter decomposes.

Sub-surface concentrations of total and dissolved nutrients were generally, and sometimes substantially, higher compared to surface waters at all three forested sites (Figure 10, Table 2), perhaps due to inputs from soil organic matter. Indeed, with the exception of surface water at Barringo, only a small proportion of TN (<20%) was comprised of NH_3 and NO_x, indicating that TN was dominated by organic nitrogen.

A smaller number of water quality samples (n = 6-7) have been collected at Aitken as monitoring at this site commenced later than at the forested sites. Preliminary data for Aitken shows that concentrations of TSS, TN and TP were higher and more variable in surface water at Aitken compared to the three forested sites (Figure 8). It is not unsurprising that these concentrations were different; even if Aitken were not an agricultural site, it was a grassland, rather than forested, area prior to disturbance. All surface TN and TP observations exceeded the ERS objectives, which could be a legacy of past agricultural land-use. Like the forested sites, all EC observations were well below the ERS objective and the 25th percentile DO (% saturation) was less than the lower limit set by the ERS (Figure 9). In contrast, pH observations were within the upper and lower ERS objectives (Figure 9); perhaps because there are smaller inputs of plant material and soil organic matter.

Figure 11 shows stable isotope samples for surface waters and groundwater. The global and Melbourne Meteoric Water Lines (MMWL) are also plotted. The samples plot at or above the MMWL and thus do not show an evaporation signature and therefore, suggest the flow in the headwater streams is dominated by recent rainfall. Had the samples plotted below the meteoric water lines, there would be evidence to suggest evaporative enrichment over time (and thus suggest flows are dominated by older groundwater flow pathways?). To further interpret the isotopic results, Figure 12 plots surface water delta-O-18 next to values from the Global Network of Isotopes in Precipitation (GNIP, Melbourne site). Water samples from the headwaters generally matched the isotopic signature of winter rainfall.

**Caption for Table 2 below: Surface and subsurface water quality at three monitoring sites and corresponding objectives from the Environment Reference Standard (ERS). Subsurface data are summarized for two depths below the base of the stream channel: 250mm and 625 mm. The number of samples used to calculate each statistic is shown in parentheses. Summary statistics could not be calculated for Charlies or Aitken due to the small number of samples collected at these sites (n = 0 and 6-7 for Charlies and Aitken, respectively). N.D., no data; N/A, no ERS objective.*

Variable	Statistic	Site									ERS[a]
		Barringo			Coopers			Jacksons			
		Surface	Subsurface		Surface	Subsurface		Surface	Subsurface		
			250 mm	625 mm		250 mm	625 mm		250 mm	625 mm	
TSS (mg/L)	75th percentile	19 (21)	N.D.	N.D.	8.5 (18)	N.D.	N.D.	14.5 (15)	N.D.	N.D.	N/A
TP (mg/L)	75th percentile	0.0275 (22)	0.5325 (20)	0.25 (32)	0.04 (19)	0.3225 (24)	0.6875 (18)	0.05 (15)	0.43 (22)	0.505 (23)	£0.055
FRP (mg/L)	75th percentile	0.003 (22)	0.00325 (20)	0.003 (31)	0.004 (19)	0.006 (25)	0.00325 (16)	0.006 (15)	0.01125 (20)	0.01075 (22)	N/A
TN (mg/L)	75th percentile	0.775 (22)	3.2 (20)	1.5 (32)	0.505 (19)	1.85 (24)	2.775 (18)	1.05 (15)	3.84 (21)	2.64 (23)	£1.05
NH$_3$ (mg/L)	75th percentile	0.01525 (22)	0.02875 (20)	0.0155 (31)	0.008 (19)	0.022 (25)	0.3825 (16)	0.0165 (15)	0.05775 (20)	0.04675 (22)	N/A
NO$_x$ (mg/L)	75th percentile	0.3475 (22)	0.3275 (20)	0.135 (31)	0.002 (19)	0.014 (25)	0.10375 (16)	0.001 (15)	0.00375 (20)	0.00575 (22)	N/A
DO (% saturation)	25th percentile	57.45 (22)	2.9 (17)	2.875 (26)	55.65 (19)	14.975 (16)	4.475 (6)	63.2 (15)	4.2 (13)	1.975 (16)	³70
	Maximum	99.2 (22)	73.6 (17)	61.8 (26)	102 (19)	75.8 (16)	24 (6)	100.3 (15)	43.4 (13)	47 (16)	130
EC (mS/cm @ 25°C)	75th percentile	77.6 (22)	88 (17)	91.75 (26)	68.15 (19)	84.125 (16)	119.6 (6)	105.65 (15)	120 (13)	167.3 (16)	£2,000
pH	25th percentile	5.03 (22)	4.9 (17)	4.91 (26)	5.41 (19)	5.5275 (16)	5.385 (6)	4.835 (15)	5.21 (13)	5.1875 (16)	³6.4
	75th percentile	5.2775 (22)	5.06 (17)	5.2925 (26)	5.645 (19)	5.7025 (16)	5.54 (6)	5.16 (15)	5.43 (13)	5.4725 (16)	£7.4

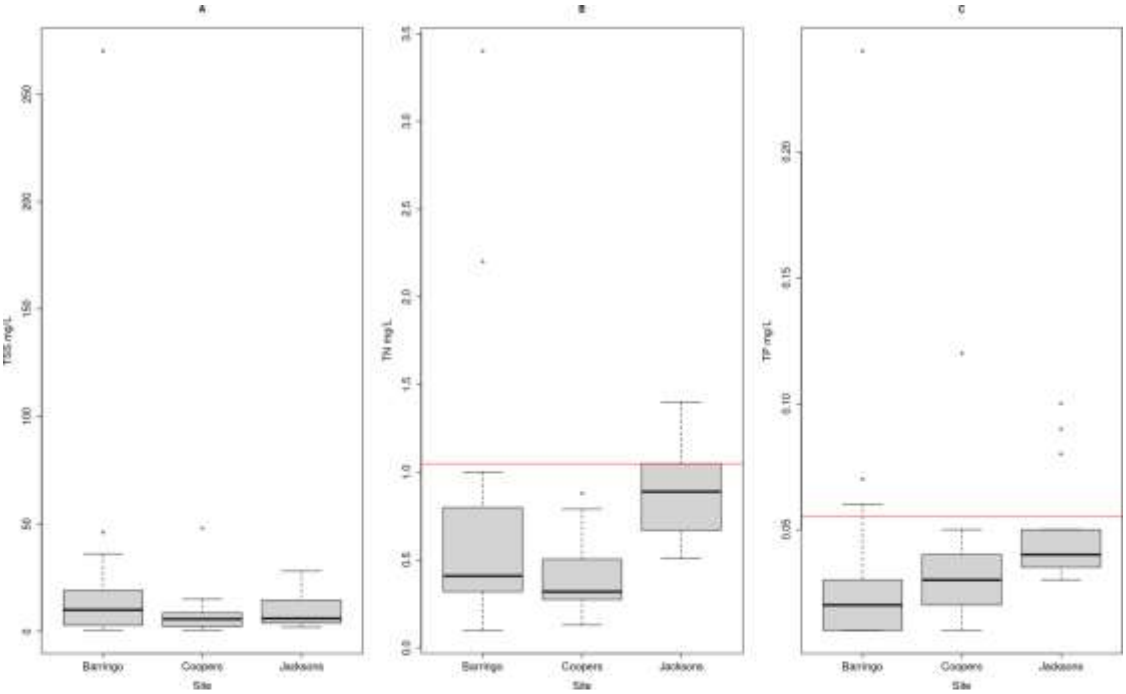

Figure 8: Boxplots for concentrations total suspended solids (TSS, mg/L) (A), total nitrogen (TN, mg/L) (B) and total phosphorus (TP, mg/L) (C) for surface waters at the headwater sites. The red horizontal lines are the Environmental Reference Standard objectives (upper limit) for the region.

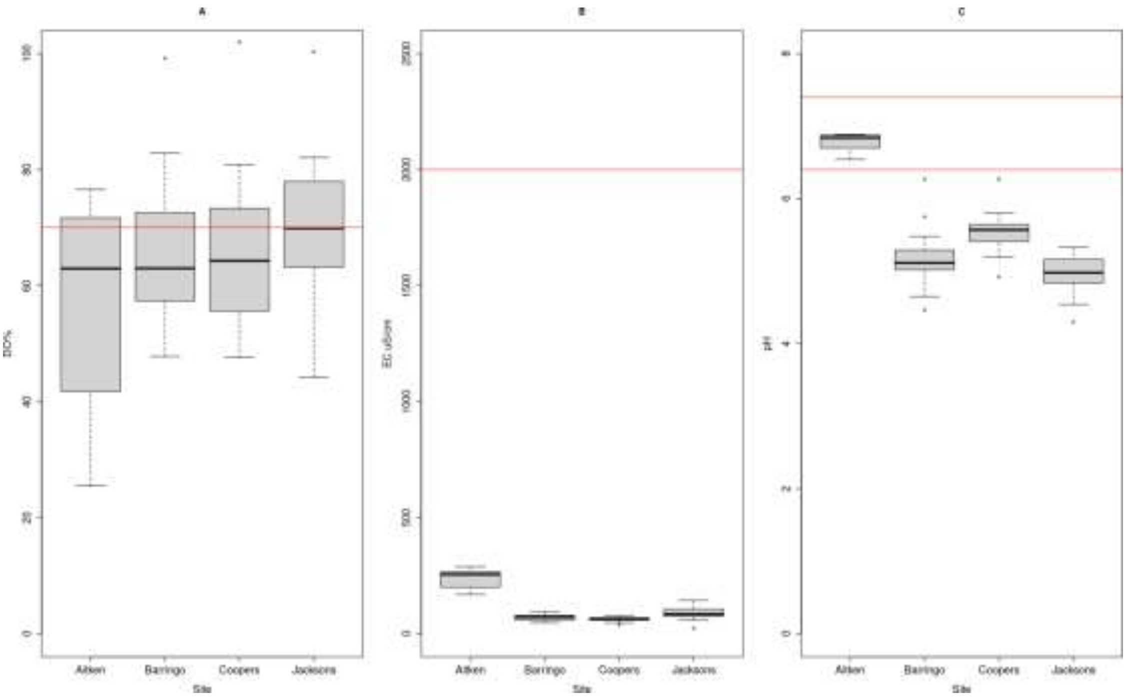

Figure 9: Boxplots for dissolved oxygen (DO, % saturation) (A), electrical conductivity (EC, mS/cm) (B) and pH (C) for surface waters at the headwater sites. The red horizontal lines are the Environmental Reference Standard objectives for the region. Note that the ERS objective is the lower limit for DO, upper limit for EC, and includes an upper and lower limit for pH.

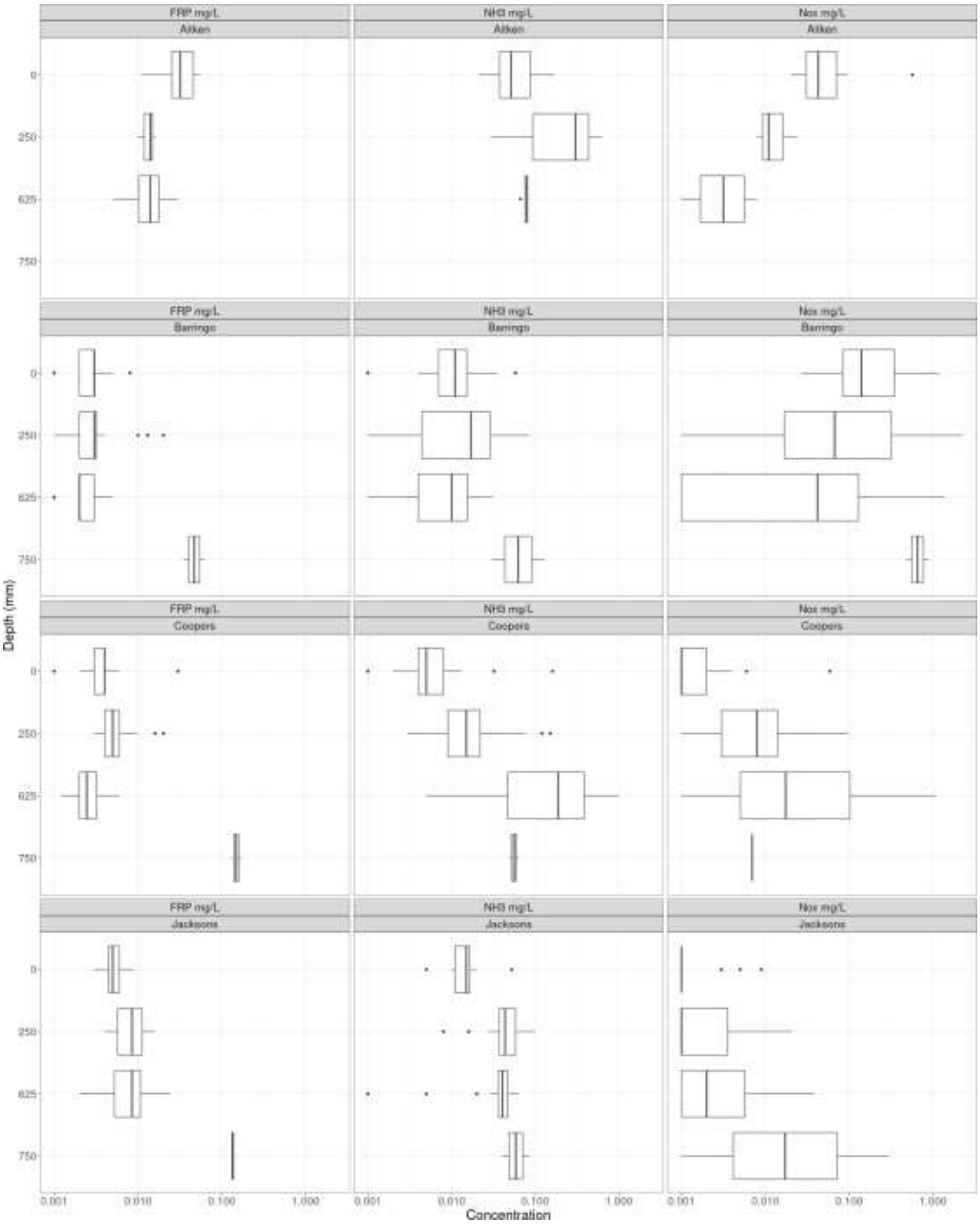

Figure 10: Boxplots for concentrations of dissolved nutrients, sampled from 4 locations (surface (0 mm) and 3 depths below the base of the stream channel: 250 mm, 625 mm and 750 mm) at the headwater sites: Aitken, Barringo, Coopers and Jacksons. Data are not shown for Charlies due to the small number of samples collected at that site. FRP, filterable reactive phosphorus; NH_3, ammonia; NO_x, oxidized nitrogen. X-axis has been $\log_{10}$ transformed.

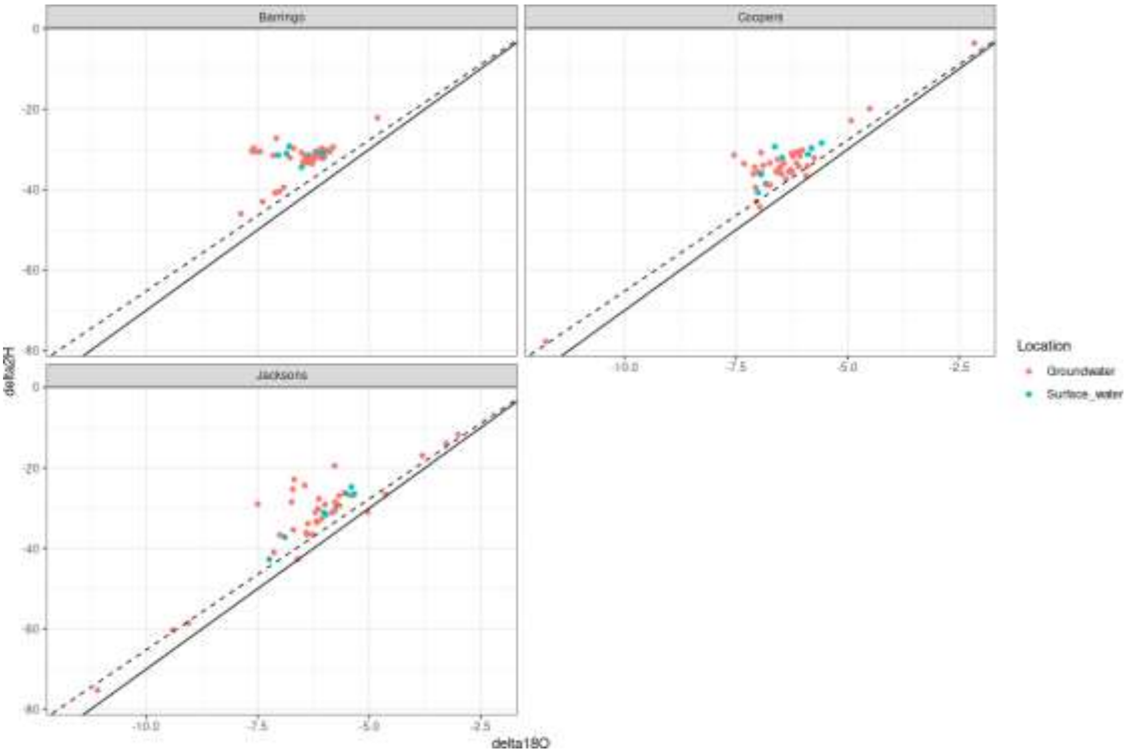

Figure 11: Isotope sample results for surface waters (above, red points) and groundwater (below, green points). The Melbourne Meteoric Water Line (dashed) and Global Meteoric Water Line (solid) are shown.

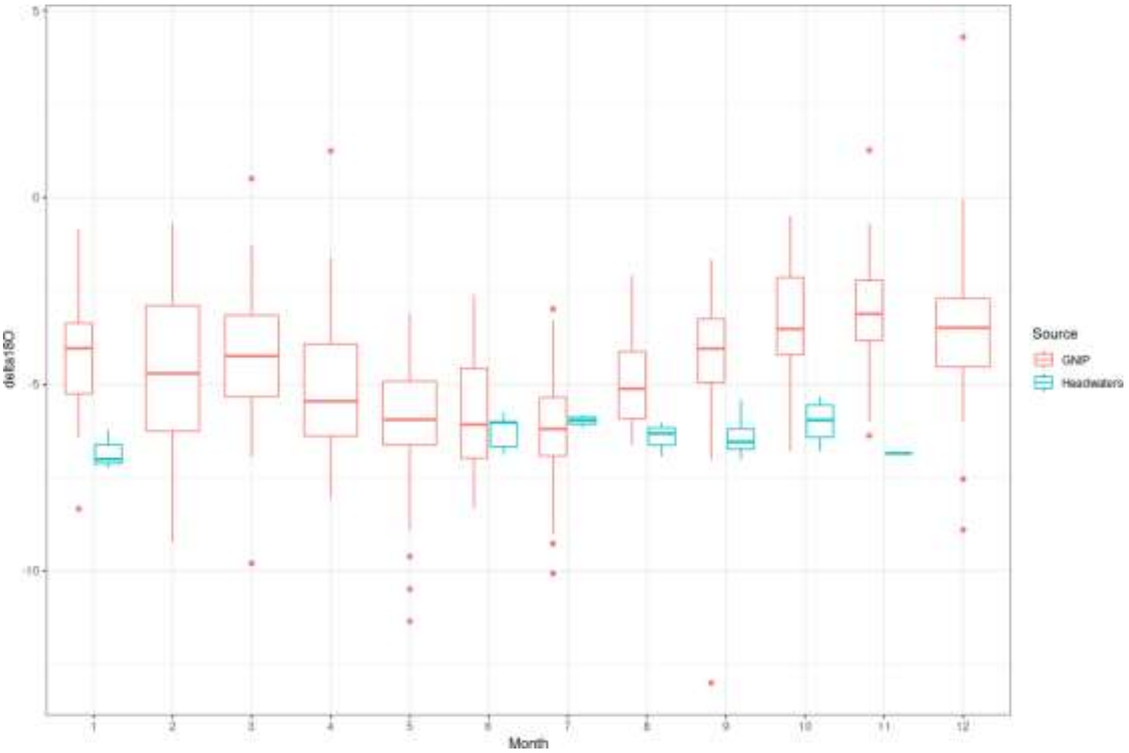

Figure 12: Isotopic composition of precipitation in Melbourne (GNIP data, red boxes) matched against the isotope sample results for the headwater sites (blue boxes).

Stream ecology

Cotton strip breakdown

Rates of cotton decomposition were most variable in groundwater (hyporheic bore), with a high degree of within-site variation for most sites (Figure 13). Cotton strip decomposition was equal to or lower than, reported global values for streams and rivers draining forest catchments (1.8 TSL [/degree day]), Figure 13). Rates of cotton decomposition were on average, twice as fast in the stream compared to both the riparian zone and hyporheic bore (Figure 13). Among sites, the fastest rates of cotton decomposition in surface environments were generally observed in the site (Barringo) with more frequent and consistent periods of surface and sub-surface water availability and higher nitrate concentrations, highlighting the important role of water and nutrient availability for mediating rates of organic matter decomposition.

Rates of cotton decomposition were highly variable among sites, sampling times, and environments. Decomposition in the riparian zone and hyporheic bore were the least variable across sites, while rates in the stream itself were most variable between sites. In the broader context however, when data is compared to studies across impact gradients, differences between years and streams were relatively low. Further investigation is required to (a) determine whether there are consistent differences among paired samples at each site (e.g. between surface and hyporheic locations) and (b) unravel the key factors driving the observed variation; this includes the role of water temperature, nutrients, and water availability, which are all known to play important roles in regulating rates or organic matter decomposition. It is anticipated that further investigation of the data will uncover similar findings as a broader, student-led and Melbourne Water supported study on headwater streams found—this study is summarized in Box 1 and refer to Brown (2022) to further details.

Microbial data

Fungal community richness and diversity at the class range from 8-35 and 0.10-2.5, respectively, across sites and years. While bacterial community richness and diversity similarly ranged from 20-88 and 0.10-2.5 respectively. Both fungal and bacterial community richness and diversity varied minimally through time. Patterns of fungal and bacterial richness and diversity were very similar across headwater *stream* sites and also to other *stream* sites in the Sunbury region. In contrast however, fungal and bacterial community richness and diversity was consistently lower in riparian environments than stream sediments or subsurface environments, irrespective of site.

When assessed at the phyla level, fungal community composition varied significantly between headwater sites, however variation was still low enough to detect a significant difference in community composition between forested headwater sites and other more agriculturally impact Sunbury sites. In the case of bacterial community composition, the patterns remained the same, with a significant difference between forested headwater sites, and a significant effect of agricultural and urban land use.

Box 1. Summary of a Melbourne-wide study investigating the patterns and drivers of organic matter decomposition in small, headwater streams. The text has been adapted from Brown (2022).

Organic matter decomposition experiments were conducted in 30 headwater streams across greater Melbourne to measure rates of decomposition and identify how environmental conditions affect rates of decomposition in perennial and non-perennial headwater streams. Cotton strip assays and the relative tensile strength loss of the cotton was used to measure rates of decomposition in the surface and hyporheic environments.

Three main research questions were posed:

1. What are the rates of decomposition in these headwater streams?

2. Do rates of decomposition differ between the surface and hyporheic environments?

3. Which environmental variables most significantly affect rates of decomposition?

The decomposition rates of cotton strips bracketed the global median for larger (further downstream) temperate forested streams (Tiegs et al., 2019). Rates of decomposition differed between the surface and hyporheic environments of headwater streams when considering the interactive effects of the stream wetness, with the greatest divergence in rates of decomposition occurring in dry streams. Across all stream environments and wetness regimes, rates of decomposition were fastest in the surface of wet sites and the hyporheic zone of dry sites. There was strong evidence that site surface temperature, catchment imperviousness and catchment forest cover all influence rates of decomposition across all streams and environments, and that NOx concentrations influence processing rates in the surface environment of flowing streams.

This research provides a baseline of rates of decomposition for headwater streams in the Melbourne research and identifies relationships with several environmental stressors that expands our current understanding of how rates of organic matter decomposition vary in nonperennial headwater streams. It was recommended that scientists and waterway managers use these findings to begin building an interpretive framework aiming to allow rates of organic matter decomposition to be used as a functional ecological indicator in rapid bioassessments of ecosystem health.

Finally, we need to continue improving our understanding of headwater streams and their ecological processes to protect these streams in their own rights and protect the vital ecological services they provide to entire river networks.

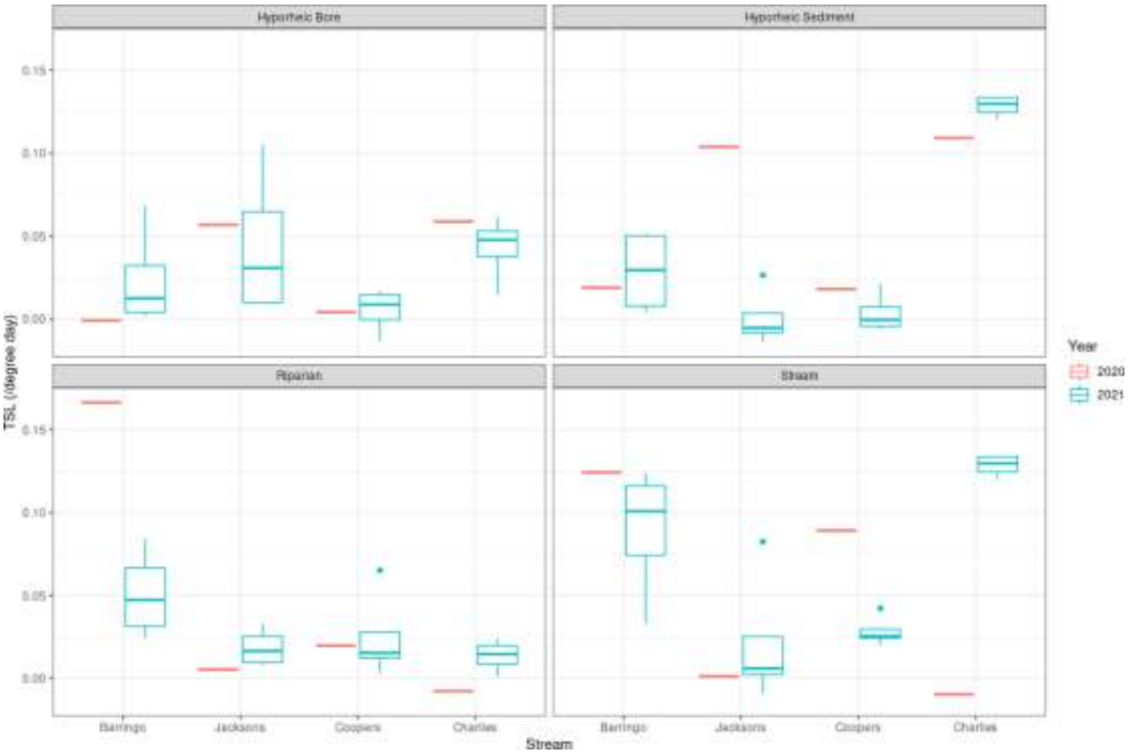

Figure 13: % tensile loss/degree day from four locations within the headwater sites.

Fungal community composition at the phyla level varied significantly through time; although, patterns across sites and environments remained stable. Fungal community composition was similar across stream sediment and subsurface environments independent of time. However, fungal community composition in riparian environments was always significantly different to that in all other environments, irrespective of site; meaning 2 distinct communities were evident across our environments. In the case of bacteria, phyla level community composition varied significantly through time. Similar to fungal community composition, bacterial community composition (at the phyla level) was similar in both sub-surface environments, but significantly different to those in riparian environments. In contrast to fungi however, there was also a significant difference between bacterial riparian and stream sediment communities; meaning 3 distinct communities were evidence across our environments.

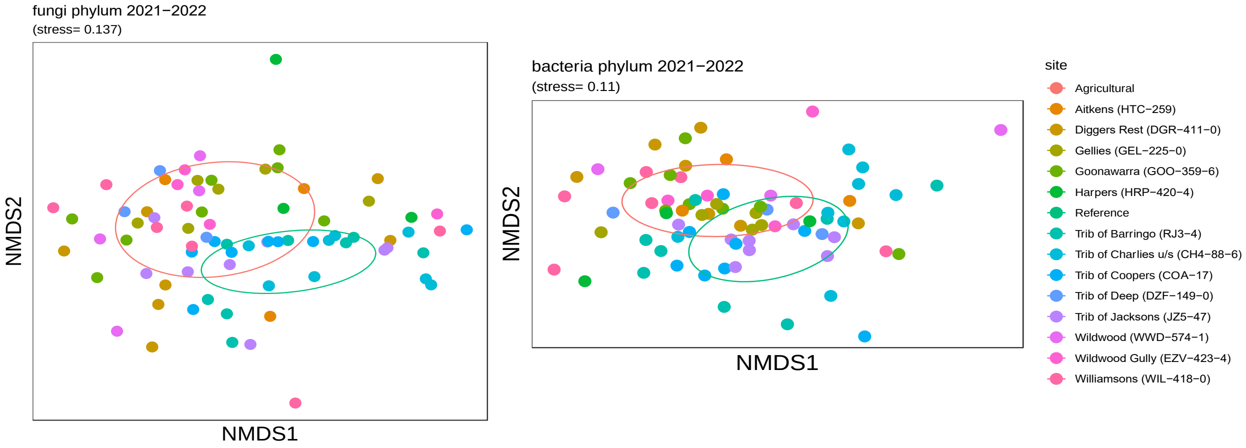

Figure 14: Non-metric multi-dimensional scaling plot showing fungal and bacterial community composition at the phyla level as a function of site. Circles show significantly different groupings (p value <0.05) based on land-use (Sunbury agricultural sites verses reference headwater sites). Plots show high dissimilarity between and within sites, but significant differences in community composition based on land-use.

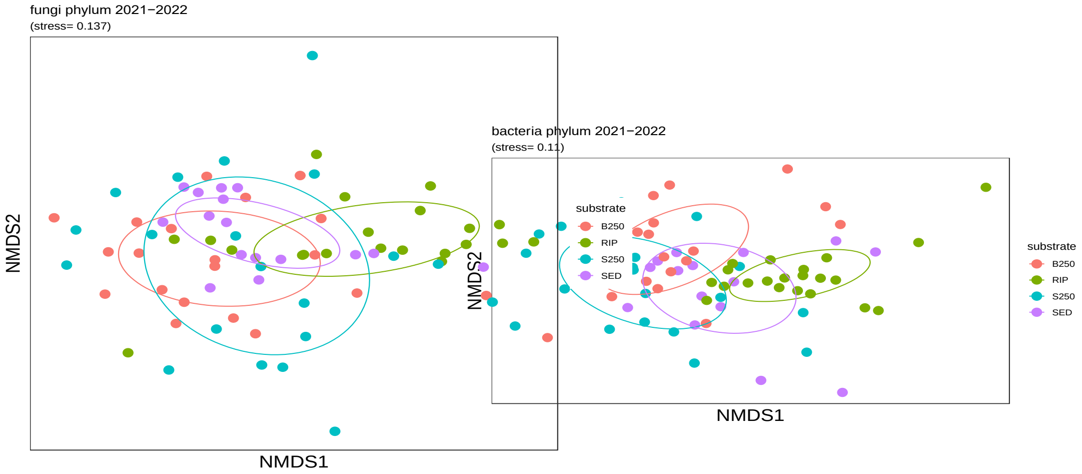

Figure 15: Non-metric multi-dimensional scaling plot showing fungal and bacterial community composition at the phyla level as a function of environment. Circles show groupings based on environments while pooling sites and years. Plots show high dissimilarity between sites, but significant differences in community composition based on environments within and across sites.

Stygofauna

Stygofauna samples have been picked and identified to Spring-2022 (sample of the data shown in Table 3). The most abundant taxa include the Oligochaetes (worms) and Clycopodia (a common microcrustacean). Interestingly following the high rainfall in Spring-2022, we collected the only sample to date from Charlies—this site had high numbers of Clycopodia compared to the other headwater sites. Clycopodia have eggs that can survive drying out, and it would appear hatch very quickly in response to sufficient water.

The only true Stygofauna collected from the headwater sites were 2 specimens, both from Coopers—one Bathynellacea in 2021 and an immature Syncardia in 2022.

Table 3: Stygofauna found in the shallow bores at two headwater sites (identified by StygoEcologia) in 2019.

Site	No.of.animals	Phylum	Subphylum	Class	Order	Family	Species
Barringo	8	Annelida	Clitellata	Oligochaeta	Tubificida	Enchytraeidae	Cognettia antipodum c.f.
Barringo	1	Arthropoda	Chelicerata	Arachnida	Mesostigmata	Undetermined	Undetermined
Barringo	1	Arthropoda	Chelicerata	Arachnida	Sarcoptiformes	Sarcoptidae	Sarcoptes scabieic.f.
Barringo	1	Arthropoda	Chelicerata	Arachnida	Sarcoptiformes	Sarcoptidae	Sarcoptes scabieic.f.
Barringo	1	Arthropoda	Hexapoda	Insecta	Coleoptera	Scarabidae	Terrestrial/undetermined
Barringo	1	Arthropoda	Hexapoda	Insecta	Coleoptera	Staphylinidae	Terrestrial/undetermined
Barringo	1	Arthropoda	Hexapoda	Insecta	Diptera	Tabanidae	Terrestrial/undetermined
Barringo	1	Arthropoda	Hexapoda	Insecta	Hemiptera	Pentatomidae	Terrestrial/undetermined
Barringo	1	Arthropoda	Clitellata	Maxillopoda	Entomobryomorpha	Isotomidae	Australotomurus sp.
Barringo	1	Arthropoda	Crustacea	Maxillopoda	Harpacticoida	Canthocampidae	Canthocamptus sp.
Coopers	1	Arthropoda	Clitellata	Maxillopoda	Entomobryomorpha	Isotomidae	Australotomurus sp.

Discussion and management implications

Hydrology

Our hydrology results are consistent with other studies. For example, both Godsey & Kirchner (2014) and Mahoney *et al.* (2023) showed how headwater streams can feature highly seasonal flow regimes. Jencso *et al.* (2009) linked runoff in headwater streams to upslope groundwater levels. We made similar findings. In the wetter months, groundwater levels were near the surface which meant that the streams received water from the local, unconfined aquifer. The isotopic results suggest that this water is mainly from winter rainfall. When conditions were dry, the water table was below the streambed and thus the streams became surface water losing ones. The rapid rise and fall of sub-surface water levels during the warmer months were somewhat surprising. We can attribute this finding to the reverse Wieringermeer effect—water in the capillary fringe becomes groundwater in response to small amounts of input (Gillham 1984).

Water quality

The good surface water quality observed matched our expectations. Despite being in eucalypt forests, where there is continual delivery of leaf litter, the small size of headwater streams means there is a high sediment surface area to water volume ratio, supporting high nutrient uptake rates and long turnover times. Most nitrogen and phosphorus processing in streams occurs on the benthos, thus there is a large opportunity for processing of these nutrients to occur (Newbold *et al.* 1983; Peterson *et al.* 2001). For example, headwater streams typically export less than half of the input of dissolved organic nitrogen from their catchments during seasons of high biological activity (Peterson *et al.* 2001). However, during dormant periods, concentrations of soluble nitrogen and phosphorus may increase along headwater stream reaches (Bernal *et al.* 2015). The coupling of variable hydrological and nutrient processes has important implications for the ecology of headwater streams themselves and the lower stream network because it influences the retention and delivery of nutrients to downstream reaches. Dodds & Oakes (2007) showed that water chemistry of downstream reaches was most closely correlated to riparian land cover or land use in the catchments of headwater streams, even during times when those headwater streams were unlikely to be flowing. This suggests that management strategies aimed at protecting water quality in the lower reaches of river networks should consider the influence of headwater streams.

Stream ecology

The rates of cotton decomposition were lower than reported in Sunbury agricultural headwater streams and lower or equal to similar systems globally (Imberger *et al*., 2010; Tiegs *et al*. 2019). Elevated rates of organic matter decomposition can increase atmospheric CO_2 emissions, alter the timing of resource availability to aquatic larval consumers, reduce the availability of organic habitat material and alter rates of nutrient cycling. Conversely, low rates of decomposition can limit the availability of DOC and POC to downstream reaches and reduce the availability of carbon resources available to higher trophic level consumers. The decomposition rates observed in this study were moderate and likely indicative of well functioning headwater stream ecosystems.

Similar to the published literature, rates of cotton decomposition were greatest in the surface and hyporheic sediments where access to dissolved nutrients, moisture and interstitial sediment were greatest. This trend was likely driven by microbial requirements for nutrients, water and habitat. By comparison, cotton decomposition was low in the riparian zone where moisture and nutrient availability was limited; and similarly constrained in the hyporheic bore where cotton lacked contact with interstitial sediments. Decomposition rates with in the hyporheic bores were not only low, but they failed to match patterns observed in the hyporheic sediments; suggesting decomposition rates in this environment are unlikely to be an effective indicator of changing ecosystem health.

Cotton decomposition rates in the hyporheic sediments and stream were higher and allowed for more differentiation between sites. We found preliminary evidence that rates of cotton decomposition were greatest in headwater streams that are subject to more frequent flow and higher nutrient concentrations—if confirmed with further investigation, this would support the findings of a larger study conducted on headwater streams across the Melbourne region (Brown, 2022) as well as numerous studies in other fluvial environments (Burrows *et al*., 2017; Tiegs *et al*. 2019). The study by Brown (2022) found that rates of cotton decomposition are more likely to be greater in hyporheic compared to surface environments as stream hydrology becomes more intermittent. This highlights the critical ecological role that the hyporheic zone can play in headwater streams and emphasizes the importance of managing, and valuing, the entire stream channel not just the surface environment. Surface temperature (positive effect), effective imperviousness (positive effect), and effective forest-cover (negative effect) have all been found to account for a significant amount of variation in cotton decomposition in headwater streams across the Melbourne region (Brown, 2022). All these variables are strongly impacted by urbanization and climate change. It is therefore likely that the on-going destruction and alteration of headwater streams will impact organic matter processing which is a fundamental ecosystem process.

Overall, bacteria dominated the observed microbial communities by measures of richness and diversity; with fungi representing a much smaller fraction of the community. Fungal and bacterial richness and diversity was quite stable through time and across sites and land-use categories. In contrast, microbial community composition was more variable through time and between sites. Notwithstanding this variability, microbial community composition was significantly different between forested reference streams and Sunbury agricultural streams. These differences in microbial community composition were likely a key driver of the differences in cotton decomposition rates observed across the land-use categories. We also found that fungal and bacterial community composition in riparian environments was significantly different to all other environments (i.e. stream sediments and subsurface environments) and this was again a likely driver of the reduced rates of cotton decomposition observed in these settings. The different microbial communities and rates of decomposition observed in drier riparian habitats and nutrient rich agricultural landscapes highlight the potential of reduced ephemerality and increased nutrient runoff as a function of urbanization, to alter microbial communities, increase rates of carbon decomposition and atmospheric CO_2 emissions, alter the timing of resource availability to aquatic larval consumers and reduce the availability of organic habitat material.

We also found that microbial richness, diversity and community composition in hyporheic bores and hyporheic stream sediments were similar; suggesting that existing bores can be used to assess microbial communities where direct stream access is restricted. However, the same is not true for cotton decomposition rates, suggesting microbial richness, diversity and community composition were not the sole driver of decomposition in these environments.

Practical implications

There are some important practical implications of this work. Firstly, protection of headwater streams in newly developing areas will require maintenance of natural seasonality. In dry locations like the ones studied, this will require almost complete retention of stormwater during the warmer months. Doing so will require significant stormwater harvesting, along with novel ideas such as stormwater to environmental flows. Some stormwater overflows would be permissible during the wetter months if the discharge quality is very high (e.g. low nutrient concentrations). Preservation of dry-weather (base) flows will require stormwater infiltration, probably at-source. Constraining stormwater infiltration to the riparian zone does not mimic natural, groundwater flow paths.

Where to next?

The monitoring of headwater sites described in this report is continuing as part of the Melbourne Waterway Research-Practice Partnership *Sunbury Project* (W3). The current plan is to monitor the sites until at least 2025. In subsequent years, findings from this research will be used to inform and potentially extend our monitoring of headwater streams to other physiographic and land-use regions of Melbourne, with a targeted focus on priority stormwater management areas. This could be really important as none of our current study sites are located to the wetter east of Melbourne, nor on sandy soils in the south-east. Another focus area of future work is improving our understanding on how upstream ecological structure and function regulate downstream river health (Project W10).

Our research work into headwater streams has inspired two pieces of work to provide practical guidance on headwater stream protection—1) Ideas for Aitken Creek Project and 2) a manuscript entitled "*Practical pathways for protecting headwater streams in urbanizing areas*". The first piece of work trialed a pilot co-design approach to develop innovative and practical design solutions using our monitoring site at Aitken Creek as a case study. The approach involved facilitated workshops which delivered 14 on-ground and enabling ideas. The co-design trial catalyzed a discussion of actions that could support future headwater stream protection across the region. The co-design process could also be applied early in planning to develop place-based solutions for other headwater streams across Greater Melbourne. A report on this project is set to be delivered in December 2024. The second piece of work was instigated following a workshop held during the 6th Symposium on Urbanization and Stream Ecology in 2023 (Brisbane, Australia). Working with practitioners and scholars from Australia and the United States, we developed a framework that can be used to benchmark headwater stream protection and support structured stakeholder conversations about potential pathways for progress. We also documented a comprehensive set of 56 structural (i.e. engineering solutions) and non-structural (e.g. policy, behaviour change) tools that could be used to protect headwater streams in urbanizing areas. This manuscript is currently being considered (under review) for publication in a Special Series of *Freshwater Science* in 2025. It is our intention to apply the framework to Greater Melbourne to identify next steps for headwater stream protection in response to the recently completed Healthy Waterways Strategy mid-term review.

While not formally planned, other potential work on headwater streams could include:

- Further development of a draft technical document which investigated novel monitoring methods for headwater streams.
- Scientific publication of Brown’s Masters thesis which studied drivers of organic matter decomposition of headwater streams across the Melbourne Water Region.
- Research into the social benefits of headwater streams. Many headwater streams in the Melbourne Water Region are located in National and State Parks and it would be interesting to determine how often people interact with these unique features of the landscape.

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