Department of Planning and Environment

Performance criteria for protecting and improving the blue grid in the Wianamatta–South Creek catchment

Water quality and flow related objectives for use as environmental standards in land-use planning

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Cover photo: Wianamatta–South Creek and Thompsons Creek, Western Sydney. Carl Tippler/CTENVIRONMENTAL

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In Honour of Shane Barter, whose passion for our waterways and kind and humble leadership in the water industry will not be forgotten by those who worked with him.

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1. Protected to the most insignificant jet

‘On 28 August 1826 a truly remarkable public meeting was held in Windsor Courthouse attended by notable local Aboriginal figures of the day. In this remarkable meeting it was resolved “that the rivers be protected to the most insignificant jet”, a poignant resolution still pertinent for the waters of the Wianamatta system.

Water resources have important cultural, spiritual, and practical values for First Peoples. Waterways are crucial for cultural practices and knowledge transfers as part of a healthy, flowing, connected system.

The Cannemegal and Wianamattagal peoples of the Dharug nation still care for the Country of Wianamatta and carry the stories and knowledges of that landscape. Dharug Elders describe Wianamatta as an interconnected system, formed through the Dreaming, this cultural landscape connects from beyond the mountains out to the sea. It is a particularly important place for pregnant women as the place of the mother creek – a female landscape relating to motherhood and creation.

The floodplains of Wianamatta remain a significant place for Aboriginal communities. South, Ropes, Badgerys, and Thompsons Creeks form a major part of the Aboriginal infrastructure which has provided resources such as food, medicine, and recreation over thousands of generations of people. It is imperative to respect these waterways and their dynamic movements, and to learn from their capacity to find the path of least resistance. Allowing one part to become ill through pollution, mismanagement or overuse will cause the whole system to suffer. All the waters must be protected to ensure the health of the whole system – to the most insignificant jet.’

Dr Danièle Hromek is a Budawang woman of the Yuin nation – she has spent some time yarning with the Aboriginal Elders in Wianamatta to help translate cultural values into land-use planning

2. About this document

This document describes the background and methods for developing performance criteria for protecting and improving the health of the blue grid in the Wianamatta–South Creek catchment. The blue grid is made up of waterways, riparian vegetation communities, wetlands and other water dependent ecosystems. The performance criteria are the instream water quality and flows that each of the components or elements of the blue grid require to remain healthy and functioning. These types of performance criteria are used in several NSW Government policies and/or legislation for managing the health of the state's waterways.

The performance criteria apply to the entire Wianamatta–South Creek catchment. They are specified in the Aerotropolis Precinct Plan, as a requirement of the *State Environmental Planning Policy (Precincts – Western Parkland City) 2021*. They have also informed standard planning requirements for stormwater infrastructure in both the Aerotropolis Development Control Plan and Mamre Rd Precinct Development Control Plan. The stormwater quality load reduction targets and stormwater quantity/volumetric flow targets in these development control plans directly achieve the performance criteria.

This document is technical in nature, and its purpose is to summarise the scientific evidence base for the performance criteria. The document provides the technical background for the NSW Government *Wianamatta–South Creek stormwater management targets* (DPE 2022a). It is part of a series of technical documents released by the NSW Government to support precinct planning in Western Sydney, including:

- *Mapping the natural blue grid elements of Wianamatta-South Creek* (DPE 2022b)
- *Review of water sensitive urban design strategies for Wianamatta–South Creek* (DPE 2022c)
- *Technical guidance for achieving Wianamatta–South Creek stormwater management targets* (DPE 2022d).

3. Background

Our waterways are significant city shapers – they define geographic boundaries and the local characteristics of a place. The ecosystem services that waterways provide are well-established and include clean water for drinking, irrigation and domestic uses, drainage and flood management, nutrient cycling, control of pests, recreation and tourism, and increased property values due to amenity (e.g. de Groot et al. 2012; Böck et al. 2018). Also well-established are the intrinsic values that waterways hold (Bennett et al. 2015), and although difficult to monetise, these are partly reflected in the connection communities have with their local waterways for health and wellbeing.

A growing number of studies are quantifying the positive cognitive and physical effects of water (e.g. Nichols 2015; Francis et al. 2016). City planners and governments are also increasingly turning waterways or 'blue spaces' into essential city building infrastructure to promote community health in busy cities. A recent study arising from the BlueHealth initiative, funded by the European Union, showed that urban renewal of a riverside in a socio-economically deprived neighbourhood of Barcelona in Spain led to a 25% increase in use of the riverside for relaxation purposes (Vert et al. 2019). A broader review of up to 35 studies showed a positive association between greater exposure to outdoor blue spaces, and benefits to both mental health and wellbeing and levels of physical activity (Gascon et al. 2017).

Of equal significance is the positive relationship between human wellbeing and the wellbeing or health of the environment itself (Reed 2007; Patrick et al. 2019). This has long been recognised by indigenous knowledge holders in Australia who uphold the axiom ‘if we care for Country, it will care for us’ (WSPP 2020). In clear support of this, the strategic planning for Sydney’s second international airport and surrounding precincts of the new Western Parkland City has been Country or landscape led (WSPP 2020; DPIE 2021a). This has been achieved through the creation of a Blue and Green Infrastructure Framework, which is centred around Wianamatta-South Creek and its major tributaries (WSPP 2021a; Figure 1).

The Blue and Green Infrastructure Framework is designed to be multifunctional, by providing a range of benefits related to liveability, building resilience to city hazards like urban heat and flooding, and protecting the iconic and/or endangered ecological communities that characterise the area (GSC 2018a; DPIE 2021a; WSPP 2021a). Multifunctional infrastructure of this type will help to address the socio-economic divides in the Greater Sydney region, which are known to result in lower health outcomes (e.g. diabetes, South Western Sydney Primary Health Network 2020).

Delivering a healthy and functioning Blue and Green Infrastructure Framework requires a ‘beyond business-as-usual’ approach based on restorative and regenerative actions (Reed 2007; WSPP 2021a, b). This approach strives to reverse the current degraded ecological and hydrological state of the waterways, riparian corridors, wetlands and other water dependent ecosystems that make up the blue grid elements of the Blue and Green Infrastructure Framework (Reed 2007; DPE 2022b).

Costs for restoring and regenerating the blue grid elements vary, with lower costs in areas of the riparian corridor that are more intact, and higher costs in areas that are the most degraded (GSC 2020). The capital investment is ~16% of the total city building infrastructure costs for the Western Parkland City, due mostly to the large area of the blue grid elements. To realise the benefits of this investment into the future, the Environment and Heritage Group (EHG) of the NSW Department of Planning and Environment was tasked with developing performance criteria to not only achieve the ‘beyond business-as-usual’ approach, but to also manage the cumulative impacts of the future urban developments on the health of the blue grid elements.

The performance criteria include instream water quality and flows that each of the blue grid elements require to remain healthy and functioning. This document describes how the performance criteria were developed, and how they have driven an integrated landscape led approach to water infrastructure delivery in the Western Parkland City.

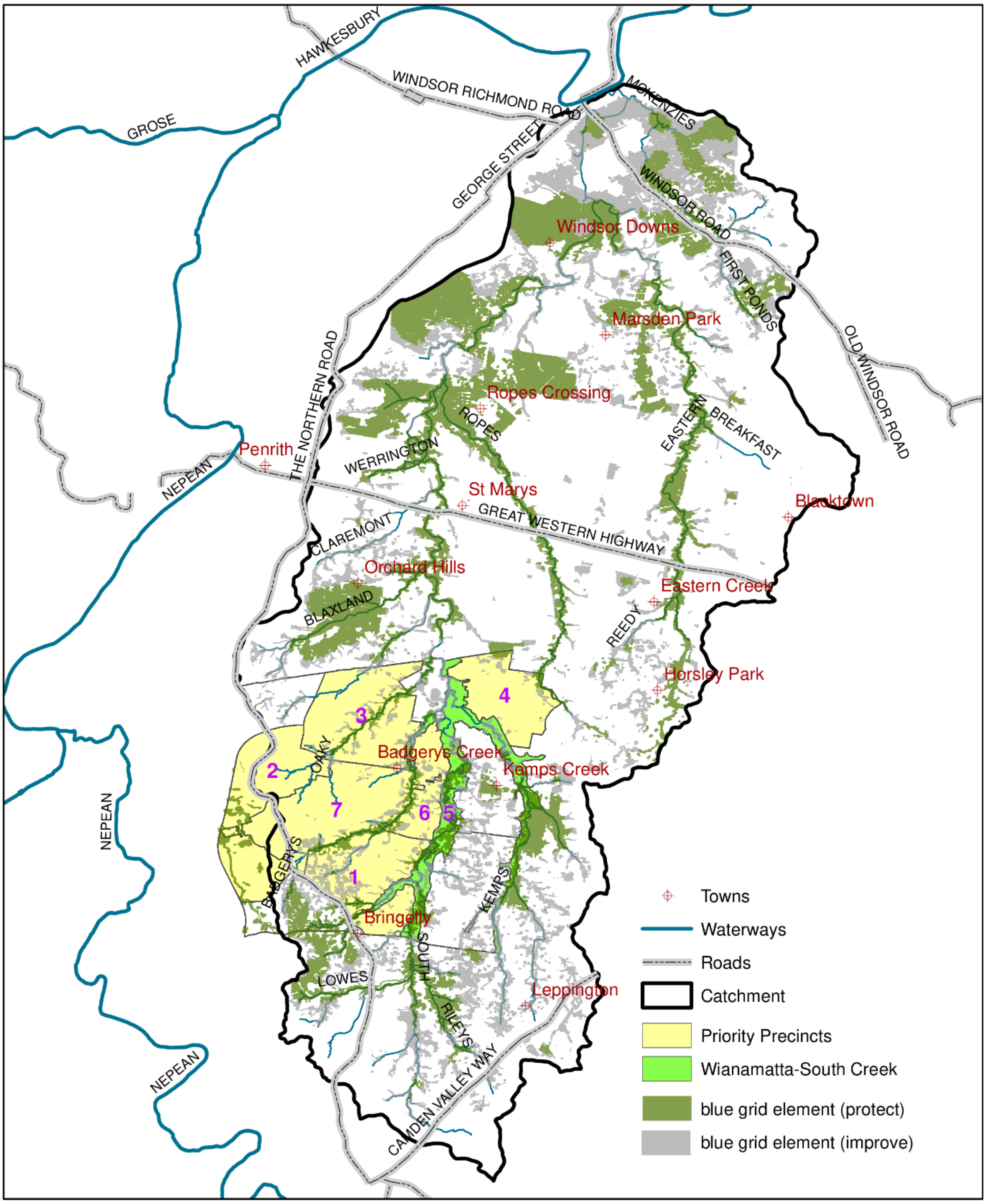


Figure 1 Wianamatta–South Creek catchment, showing the locations of the priority precincts in the Western Sydney Aerotropolis (precincts)

1 Aerotropolis Core, 2 Agribusiness, 3 Northern Gateway, 4 Mamre Rd, 5 Wianamatta–South Creek (Blue and Green Infrastructure Framework), 6 Badgerys Creek, 7 Western Sydney Airport. The natural blue grid elements are shown for the whole catchment.

4. Performance criteria – water quality and flow related objectives

Planning for the Western Parkland City has largely focused on the release of priority precincts to support the activation of Sydney's second international airport. Collectively, these priority precincts are known as the Western Sydney Aerotropolis and include a new Environment and Recreation Zone. This Zone essentially encompasses the Blue and Green Infrastructure Framework, and is predominantly located in the precinct known as Wianamatta–South Creek (Figure 1).

In accordance with the strategic plans for the area (GSC 2018a, b; WSPP 2020), standard planning requirements (viz. development controls) to protect and manage the blue grid elements of the Environment and Recreation Zone have been developed using the NSW Government *Risk-based Framework for Considering Waterway Health Outcomes in Strategic Land-use Planning Decisions* (the Risk-based Framework; Dela-Cruz et al. 2017). This Risk-based Framework brings together existing NSW Government policies and strategies for managing the water quality and health of the state's waterways. The first step of the Risk-based Framework is to establish waterway health objectives, using the NSW Water Quality Objectives (WQOs) as a starting point.

The WQOs are the long-term goals for how the NSW community value and use their local waterways. They consist of 3 components: i) the community's environmental values and uses of a waterway, ii) the indicators, and iii) numerical criteria or guidelines to help assess whether the community environmental values and uses are being met. A common example of a WQO for waterways designated for swimming (community use) includes the use of microbial (indicators) concentrations (numerical criteria/guideline) for assessing public health risks. Typically, the WQOs are used as environmental standards and accordingly, should be used as performance criteria for the blue grid elements of the Blue and Green Infrastructure Framework.

EHG is the current custodian of the WQOs, and is in the process of reviewing and updating them as part of its delivery of the Marine Estate Management Strategy 2018–2028, under the *Marine Estate Management Act 2014*. The work described in this present study is an exemplar of how the WQOs should be updated, and will be included in EHG's final rollout of the updated WQOs. This work also effectively describes how the first step of the Risk-based Framework was applied in the context of planning for the Western Parkland City.

A fundamental change that this work brings, is the need to augment the WQOs with flow related objectives to ensure the total loads of nutrients and sediments in stormwater discharges are managed, to mitigate erosive stormwater flows and subsequent loss of the riparian corridors, and to ensure the water requirements of the blue grid elements are being met. These flow related objectives are distinct from the flow objectives used in the NSW Government water sharing plans, as they specifically manage for excessive flows going into waterways and impacting riparian corridors. By comparison, the flow objectives specified in water sharing plans manage for extractions of water from waterways. A common goal of both types of flow objectives, however, is to protect the health of the waterway.

The importance of including flow related objectives has been known for some time, especially for the Wianamatta–South Creek catchment, which has the longest alluvial creeks in the Sydney Basin. For example, Sharpin and Barter (1997) had already noted that flow volume is a key problem for urban stormwater in NSW and that attempts to manage only water quality are 'insufficient to mitigate the impacts of urbanisation'. There is now a growing awareness of the impacts of changed flow regimes on waterways in other urban catchments of Australia (Walsh et al. 2012; Fletcher et al. 2014; Walsh et al. 2016; Vietz et al. 2016; Kermode et al. 2021), meaning that the importance of including contemporary and locally specific flow related objectives for planning of the Western Parkland City has become acute.

4.1 Community environmental values and uses

The NSW Government policy for managing water quality and waterway health defines community environmental values and uses as what the community believes is important for a healthy ecosystem, for public benefit, welfare, safety or health (DEC 2006). Previous economic valuation studies show the net benefits of protecting and improving the natural blue grid is over $1 billion (Bennett et al. 2015; INSW 2019). These net benefits include those for communities within the Wianamatta–South Creek catchment (e.g. bass fishing, riparian vegetation habitat for birds) and those for communities downstream in the Nepean River and out towards the ocean (e.g. swimming, no infestation of water weeds).

There are up to 7 existing community environmental values and uses of the waterways and riparian corridors in the Wianamatta–South Creek catchment, which were identified in 1999 when the NSW Government released the WQOs. As shown in Figure 2, some of these values and uses are unlikely to be relevant due to the future urbanisation of the catchment while others will need to be restored or regenerated. To determine the contemporary community environmental values and uses, we collected data from multiple sources:

- direct consultation with Aboriginal Elders (Section 1 – To the most insignificant jet)
- direct consultation with state agencies involved in planning for the Western Sydney Aerotropolis
- direct consultation with the 6 main local government authorities in the Wianamatta–South Creek catchment (Table 1, see also Appendix A)
- online community survey, promoted through social media during the austral summer of 2020–21 (Fig. 3)
- desktop assessment of Local Strategic Planning Statements, which set the 20-year vision for land use in the local area and identify the special character and values that need to be preserved and managed into the future
- objects/requirements of the Environment and Recreation Zone of the *State Environmental Planning Policy (Precincts – Western Parkland City) 2021*.

We found that the community environmental values of ‘Protection of Aquatic Ecosystems’, ‘Secondary Contact Recreation’ and ‘Amenity’, were the most common and prominent values that were identified and expressed in various ways by various groups, for example:

- Aboriginal communities identify the floodplains of Wianamatta as a significant place, in which ‘South, Ropes, Badgerys, and Thompsons Creeks form a major part of the Aboriginal infrastructure which has provided resources such as food, medicine, and recreation over thousands of generations of people’.
- The vision for the Western Parkland City ‘puts landscape first. Prioritising the landscape, and using water and other precious resources more efficiently, will help us make the Western Parkland City a better place for residents, workers and visitors.’… ‘above all, it will be a green city, with its waterways and scenic landscapes protected, its tree canopy increased and its biodiversity preserved…’ (WPCA 2019).
- Local governments prefer to ‘rehabilitate/restore native habitats and create healthy ecosystems including naturalised creeks, protecting fish, frogs, birds, etc’. They stated that their local communities enjoyed ‘Being near water, and enjoyed the landscape/outlook, picnics, barbeques, camping, walking, hiking, cycling, etc’.
- Top ranking values in the online community survey were ‘A place where fish, plants and animals live’ and ‘A natural place to look, walk, relax, picnic or camp’.

We also found that the ‘Protection of Aquatic Ecosystems’, ‘Secondary Contact Recreation’ and ‘Amenity’ values are included in all Local Strategic Planning Statements covering the Wianamatta–South Creek catchment:

- Camden Council has priorities for 'Protecting and enhancing the health of Camden's waterways, and strengthening the role and prominence of the Nepean River' (CC 2020).
- Campbelltown City Council has several priorities for managing waterways, including to 'Investigate opportunities to rehabilitate existing waterways within the local government area (LGA) to maximise the benefits to the community' (CCC 2020).
- Liverpool City Council has a range of priorities for ensuring its 'Bushland and waterways are celebrated, connected, protected and enhanced' (LCC 2020).
- Fairfield City Council has priorities for 'Protecting areas of high natural value and environmental significance, and improve the health of catchments and waterways'. The creek corridors are managed to provide the city with 'great outdoor amenity, being cooler in the summer as well as providing for native flora and fauna habitat, and improving water quality' (FCC 2020).
- Blacktown City Council has a priority for 'Protecting and improving the health and enjoyment of waterways' by collaborating 'on a catchment-wide scale to improve waterway health and community access to waterways' and collaborating 'to deliver projects that rehabilitate waterways to a more natural condition' (BCC 2020).
- Penrith City Council recognises that its 'waterways and riparian corridors are an important ecological, hydrological, recreational and cultural resource. They provide habitat for native species and support groundwater-dependent ecosystems….They support recreational activities and are appreciated for their aesthetic quality within the landscape. They also provide a sense of place and identity for many in our community'. A main priority is for the council to 'Collaborate with Infrastructure NSW, other State agencies, water service providers and councils on the South Creek Corridor Project to improve the management of water quality and quantity in the Corridor and implement through planning and development controls, where required' (PCC 2020).
- The Hills Shire Council has priorities to 'Retain and enhance vegetated riparian corridors, bird habitats and wildlife corridors across the Shire to support biodiversity and water quality outcomes' and 'Continue to protect and enhance water quality in local catchment areas'. It recognises that its 'waterways facilitate conservation, recreation and tourism' and there is a 'need to work with partners to monitor, improve and maintain water quality and ensure residents and visitors use these environments responsibly' (THSC 2020)
- Hawkesbury City Council has a priority for 'effective management and protection of our rivers, waterways, riparian land, surface and ground waters, and natural eco-systems through local action and regional partnerships' (HCC 2020).

The objectives of the Environment and Recreation Zone of the *State Environmental Planning Policy (Precincts – Western Parkland City) 2021* also have clear requirements to support the 'Protection of Aquatic Ecosystems', 'Secondary Contact Recreation' and 'Amenity' values, to:

- protect, manage and restore areas of high ecological, scientific, cultural or aesthetic values
- protect the ecological, scenic and recreation values of waterways, including Wianamatta-South Creek and its tributaries
- provide a range of recreational settings and activities and compatible land uses
- protect and conserve the environment, including threatened and other species of native fauna and flora and their habitats, areas of high biodiversity significance and ecological communities.

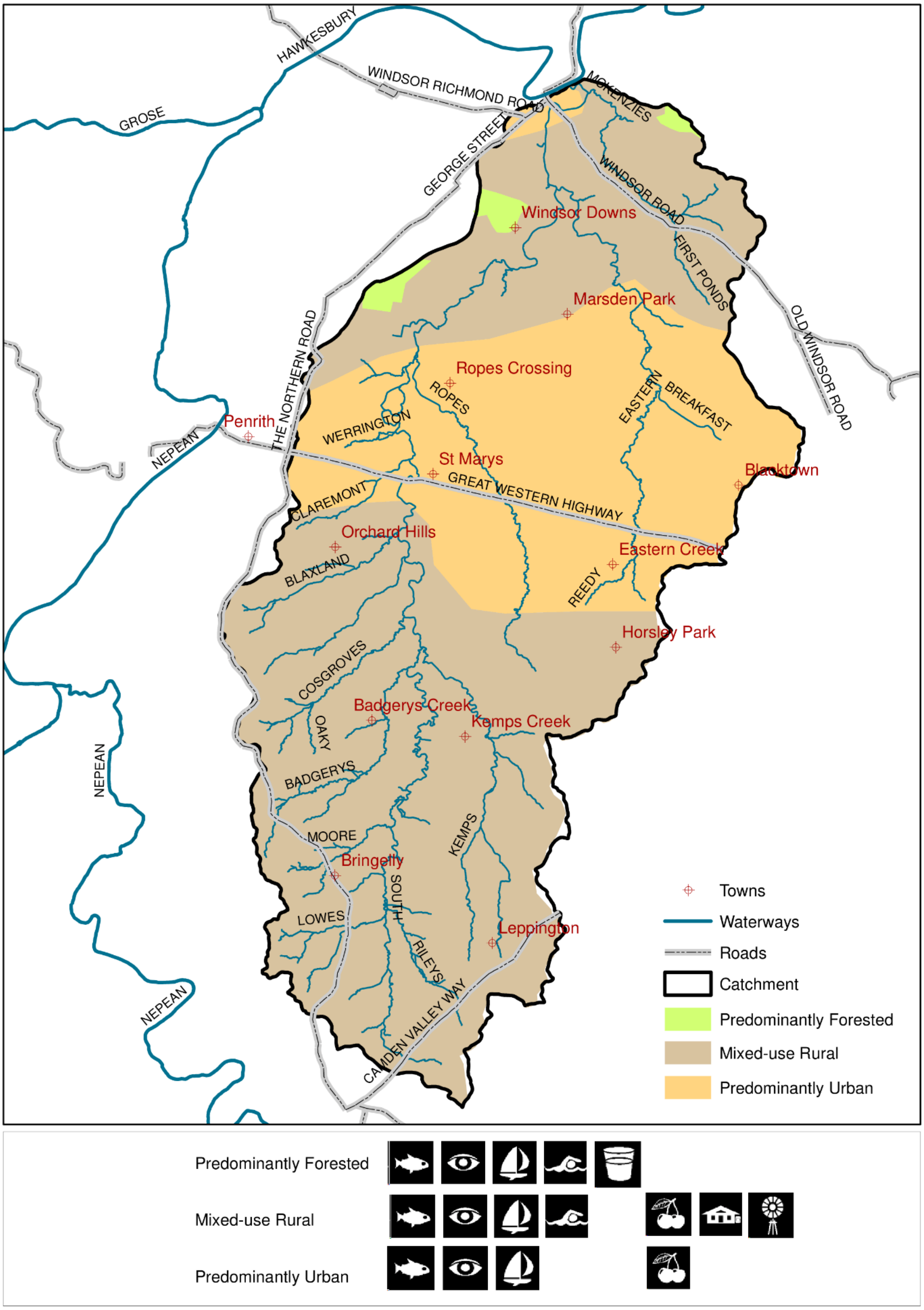


Figure 2 Community environmental values and uses of waterways and riparian corridors in the Wianamatta–South Creek identified in 1999

Some comments from local community members

'…I would like to use it to swim, but the water quality stops me doing that…'

'…Painting pictures of the river and surrounding country, and also photography of the river…'

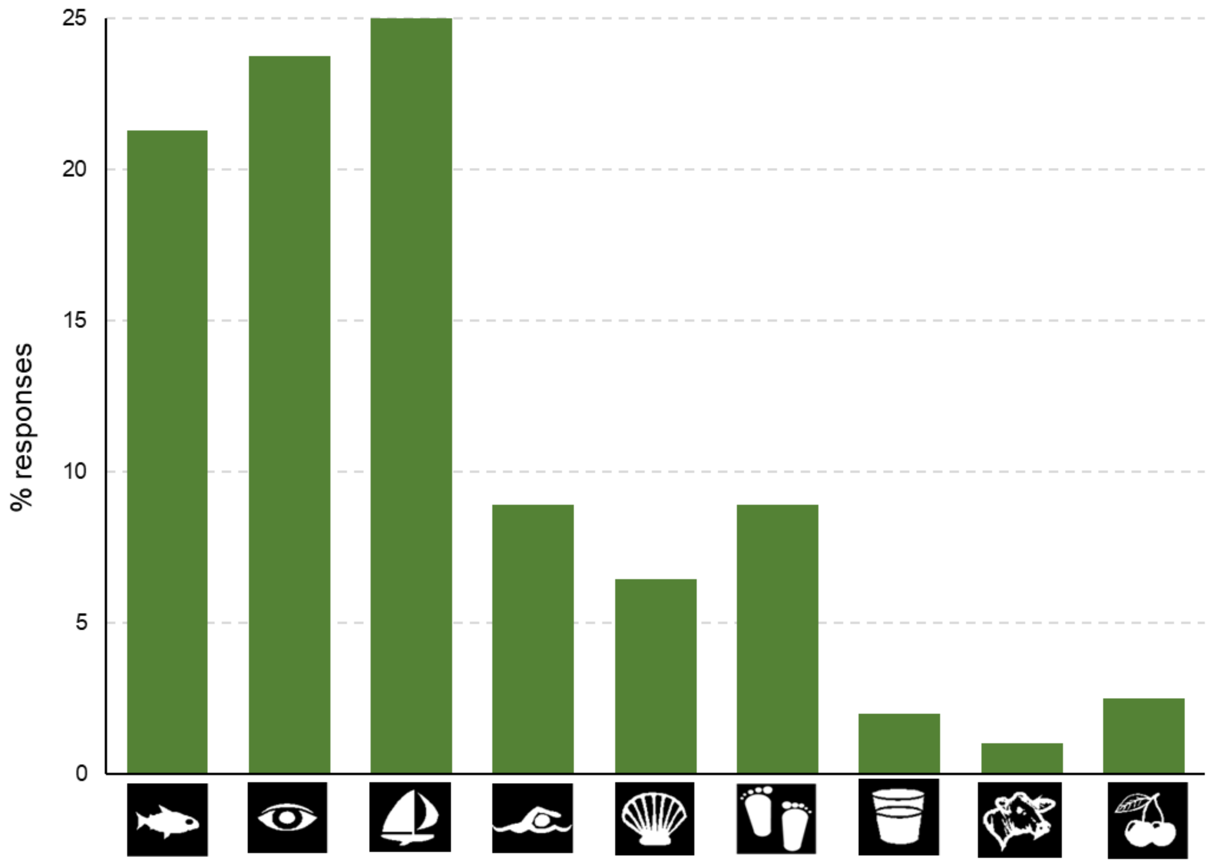


Figure 3 Community environmental values and uses of waterways and riparian corridors in the Wianamatta–South Creek identified in 2020–21

Table 1 Community environmental values and uses of waterways and riparian corridors in the Wianamatta–South Creek catchment, derived through consultation with local governments in February 2021

Community environmental value or use	Icon	Description	CC	CCC	LCC	FCC	BCC	PCC
Protection of Aquatic Ecosystems		**Maintaining or improving the ecological condition of waterways and their riparian zones over time** **Specific to the LGA:** Rehabilitating/restoring native habitats and creating healthy ecosystems including naturalised creeks, protecting fish, frogs, birds	Yes	Yes	Yes	Yes	Yes	Yes
Visual Amenity		**Aesthetic qualities of water** **Specific to the LGA:** Being near water, enjoying landscape/outlook, picnics, barbeques, camping, walking, hiking, cycling, etc.	Yes	Yes	Yes	Yes	Yes	Yes
Primary Contact Recreation		**Maintaining or improving water quality for activities where there is a high probability of water being swallowed** **Specific to the LGA:** Swimming, water skiing	Yes (lake)	Yes	No	No	No	No
Secondary Contact Recreation		**Maintaining or improving water quality for activities where there is a low probability of water being swallowed** **Specific to the LGA:** Kayaking, canoeing and paddle boarding	Yes (lake)	Yes	Yes	Yes	Yes (lake)	Yes
Secondary Contact Recreation		**Maintaining or improving water quality for activities where there is a low probability of water being swallowed** **Specific to the LGA:** Recreational fishing, wading in water	No	Yes	Yes	Yes	Yes	Yes
Cultural Activities		**Indigenous and non-indigenous cultural activities** **Specific to the LGA:** First Nations cultural activities/Care for Country activities, other spiritual and ceremonial uses (e.g. mediation, prayer), visiting cultural or historic sites	Yes		Yes	Yes	Yes	Yes

Community environmental value or use	Icon	Description	CC	CCC	LCC	FCC	BCC	PCC
Irrigation Water Supply		**Protecting the quality of waters applied to crops and pasture**	Yes		Yes	Yes	Yes	Yes
Livestock Water Supply		**Protecting water quality to maximise the production of healthy livestock**	Yes		Yes	Yes	Yes	Yes
Drinking water – groundwater		**Protecting the quality and access to ground or bore water for drinking**	Yes	Yes	Yes	No	No	Yes
Aquaculture and Human Consumption of Aquatic Foods		**Protecting water quality so that it is suitable for the production of aquatic foods for human consumption and aquaculture activities**	No		Yes	No	No	No

CC = Camden Council, CCC = Campbelltown City Council, LCC = Liverpool City Council, FCC = Fairfield City Council, BCC = Blacktown City Council, PCC = Penrith City Council

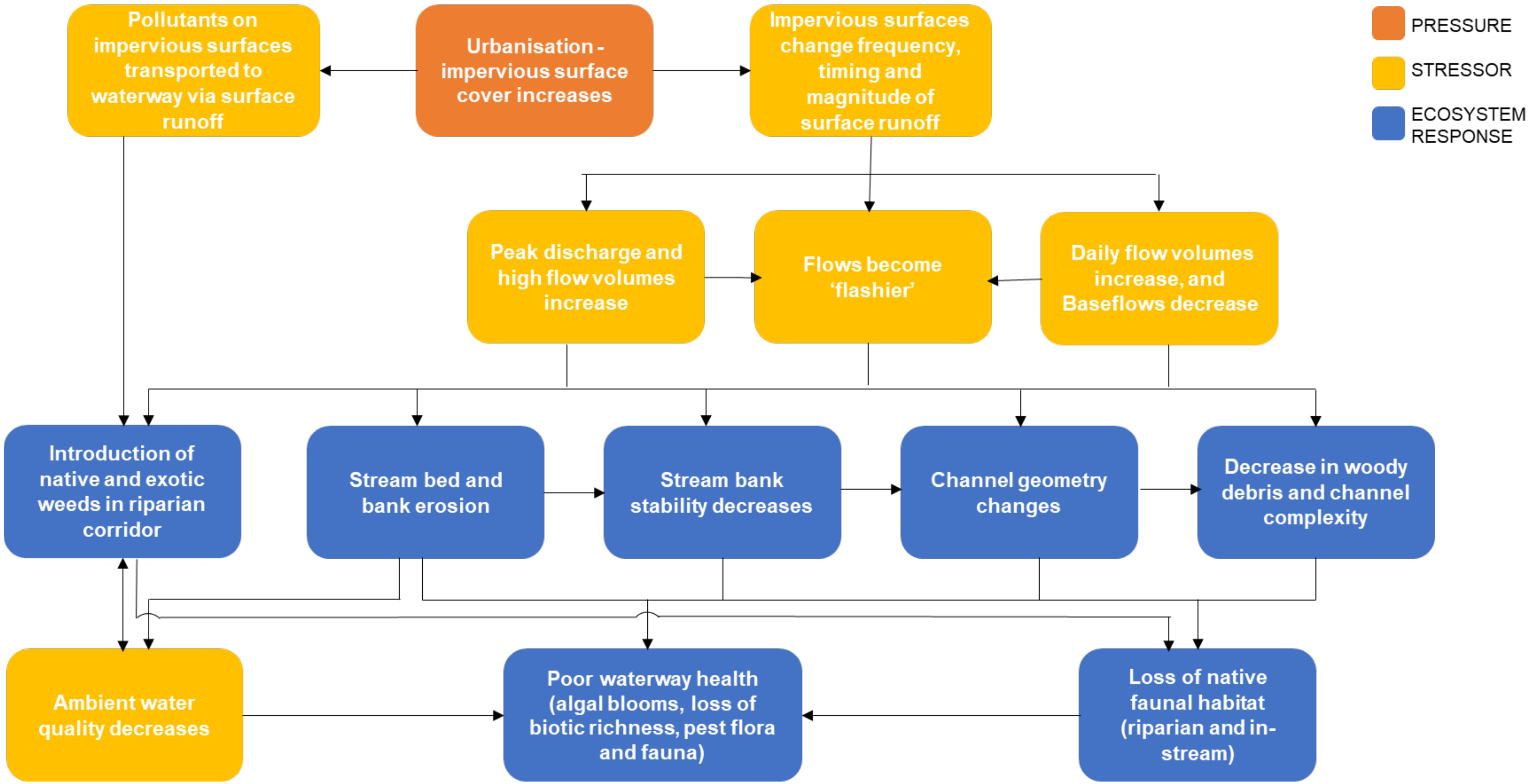


Figure 4 Pressure–stressor–ecosystem response model for streams in urban catchments

4.2 Derivation of indicators and numerical criteria

According to the Australian and New Zealand Guidelines for Fresh and Marine Water Quality (ANZECC and ARMCANZ 2000), many community environmental values and uses will usually be achieved if the numerical criteria for the 'Protection of Aquatic Ecosystems' are being met. These numerical criteria must be derived through methods outlined in the Australian Water Quality Guidelines (Commonwealth of Australia 2018) – most notably, the use of a referential or effects-based assessment approach. The latter method is reflected in the 2nd step of the Risk-based Framework. In addition, the Australian Water Quality Guidelines specify a shift away from default numerical criteria or guideline values to more site-specific guideline values. This shift is important as it requires collection of local field data and will inherently result in a place-based or tailored outcome.

The Australian Water Quality Guidelines also specify that appropriate indicators for the 'Protection of Aquatic Ecosystems' must be identified through a pressure–stressor–ecosystem receptor model. Figure 4 shows the pressure–stressor–ecosystem receptor model that is specific to our case (noting that additional flows from wastewater discharge would contribute to the impact). The underlying pressure arises from stormwater discharges generated from the urban developments, the stressors are the nutrients, sediments and flows, and the ecosystem receptors are the blue grid elements of the Blue and Green Infrastructure Framework.

The causal relationships among the specific set of indicators shown in Figure 4 are best described through the well-established concept of the 'urban stream syndrome', in which waterways that drain urban catchments are consistently ecologically degraded (e.g. Paul and Meyer 2001; Walsh et al. 2005; Tippler et al. 2012; Walsh et al. 2012; Vietz et al. 2014; Vietz et al. 2016). Specific symptoms of the urban stream syndrome include a flashier hydrograph and elevated concentrations of ambient nutrients and contaminants, which combine to alter channel morphology and algal blooms, reduced biotic richness and prevalence of weeds (see Table 8, Appendix C). In Australian streams, these symptoms have been observed in urban catchments with as little as 2–3% effective imperviousness (Vietz et al. (2014), or 10% total imperviousness (Tippler et al. 2012). These measures of imperviousness represent the proportion of impervious (hard) surface cover within a landscape that is directly connected to streams, or total proportion of impervious surface cover in a landscape, respectively.

In consideration of the above, we selected the stressor indicators (instream water quality and flows) as performance criteria for the blue grid elements of the Blue and Green Infrastructure Framework. This is because they provide the pivotal causal links between the pressures that need to be managed and the health and functioning of the blue grid that provides for the community values and uses.

5. Data collection and analyses

The following sections summarise our methods for collecting local field data in the Wianamatta–South Creek catchment, and the subsequent analyses of the data to derive the performance criteria.

5.1 Water quality

Local field data on instream water quality were sourced directly from EHG, Penrith City Council, Liverpool City Council, Blacktown City Council and Sydney Water. All available records, dating back to 1 January 1990 were collated and the data quality checked on the basis of the following criteria:

- SI units of all measures were standardised
- obvious outliers were removed, e.g. pH values reported as 23.7
- measures below detection limits were replaced with half the detection limit value
- measures were limited to the following water quality variables: temperature (T°C), conductivity (µS/cm), pH, dissolved oxygen (DO mg/L, %), turbidity (NTU), total suspended solids (TSS, mg/L), ammonia (NH_3-N, mg/L), oxidised nitrogen (NO_x, mg/L), total nitrogen (TN, mg/L), dissolved inorganic phosphorus (DIP, mg/L), total phosphorus (TP, mg/L) and chlorophyll *a* (Chl *a*, mg/L)
- DO measures that were ≤0% and >110% saturation were excluded
- conductivity measures that were <100 µS/cm were excluded
- turbidity measures that were <1 NTU were excluded.

The total number of data points remaining after the quality checks was 61,622, and these were collected from a total of 108 monitoring sites (Figure 5).

The approach currently used by councils (in the Wianamatta–South Creek) to derive site specific guideline values for water quality is the referential one. This approach is based on the 80th or 20th percentiles of data collected monthly from reference sites over a period of at least 2 years. Reference sites are defined as those where their state is unimpacted or minimally impacted so it can serve as a suitable baseline or benchmark for the assessment and management of impacted sites in similar waterbodies. The 80th percentiles are calculated for the majority of the water quality variables. For DO, the lower 20th percentile is used as detrimental effects usually occur due to a lack of oxygen. For pH, temperature and salinity, both the 80th and 20th percentiles are calculated as impacts are seen at either extreme.

To apply the referential approach, we filtered the data points further by only including field monitoring sites where:

- sufficient water quality monitoring data is available, and data from the sites have been collected, stored and analysed using approved protocols
- there are no significant point source and diffuse source discharges nearby or upstream
- there is minimal disturbance to the local environment and upstream
- there are minimal alterations to the flow or water regime.

5.2 Ecological condition of ecosystem receptors

In a companion study, we defined and mapped the blue grid elements of the Blue and Green Infrastructure Framework (DPE 2022b). These were represented by a total of 36 indicators of ecosystem receptors. Waterways were represented by the following indicators: Shannon–

Wiener diversity index determined from field measures of macroinvertebrates, River Biodiversity Condition Index, high ecological value aquatic ecosystems, key fish habitat, condition of fish communities, fish nativeness, type or classification of waterways according to the River Styles Framework, and associated indices of the recovery potential and geomorphic condition of the waterways. Riparian vegetation, wetlands and other water dependent ecosystems were represented by 25 indicators, and these were captured either directly by endangered ecological communities that are water dependent or indirectly by the habitats of iconic and/or threatened species of waterbirds, frogs and water dependent bats.

Local field measures for each of the 36 indicators were collected in the companion study to validate the blue grid map (DPE 2022b). Data from a total of 396 monitoring sites were available, but the data for each indicator were not consistently available for all sites (Figure 5). For example, data on the geomorphic state of the streams were only available from 9 monitoring sites, whereas data on the ecological health of vegetation were available from 65 monitoring sites. Gaps in data were filled through a rapid riparian assessment (RRA) previously undertaken by councils in the catchment, and through additional RRAs specifically undertaken for this study in areas where private landholders provided access to their waterways. This resulted in a combined total of 479 RRA monitoring sites, from which the performance criteria were derived (Figure 5).

5.2.1 Rapid riparian assessment

An RRA is a robust, rapid and cost effective method for collecting data on the ecological and geomorphic condition of waterways in urban catchments. It was originally developed for the Kur-ring-gai LGA in the north of Sydney (Taylor et al. 2005; Findlay et al. 2011) but has since been augmented and optimised for several LGAs in Greater Sydney, including Blacktown, Liverpool, Penrith, Camden and those in the Georges River catchment (Dean and Tippler 2016). Figure 6 provides an example of the specific measures collected through an RRA. The example is from a site at Duncans Creek inside the Agribusiness Precinct, where we found the site to be in very good condition. The overall site score was 81%, and this is due to the natural bushland surrounding both sides of the creek, intact vegetation structure and (creek) channel shape. The creek provides relatively good habitat for macroinvertebrates and fish, due to the abundance of large woody debris and overhanging vegetation. In contrast, the overall condition score of a site inside the Environment and Recreation Zone of the Wianamatta–South Creek Precinct is 59%, indicative of poor condition (Figure 7). The site is surrounded by pastoral land and as a result has poor vegetation and (creek) channel structure (e.g. widening and infilling). The vegetation is 20% exotic scrubland and 80% pastoral grass, and there is severe undercutting and slumping of the creek banks.

Note that each measure has a score, based on a positive to negative scale. Highest positive scores indicate streams in very good ecological condition, and the most negative scores indicate streams that have been detrimentally impacted by urbanisation. A score of zero indicates a neutral effect of urbanisation. The scale varies depending on the specific measure to enable a relative assessment of impact (of urbanisation) for that measure, but not between or among different specific measures. The scores are, however, standardised post hoc, to produce the final site score as a percentage.

A new scale was specifically developed in this present study to provide a measure of the complexity of instream habitats for macroinvertebrates and fish. This scale ranged from 0–100, and included field measurements of the native macrophytes, natural bed detritus, gravel bed and rocks, overhanging vegetation, and the presence and size of woody debris in the waterway. These specific measures are the key criteria for fish habitat, as defined in the *Policy and guidelines for fish habitat conservation and management* (DPI – Fisheries 2013).

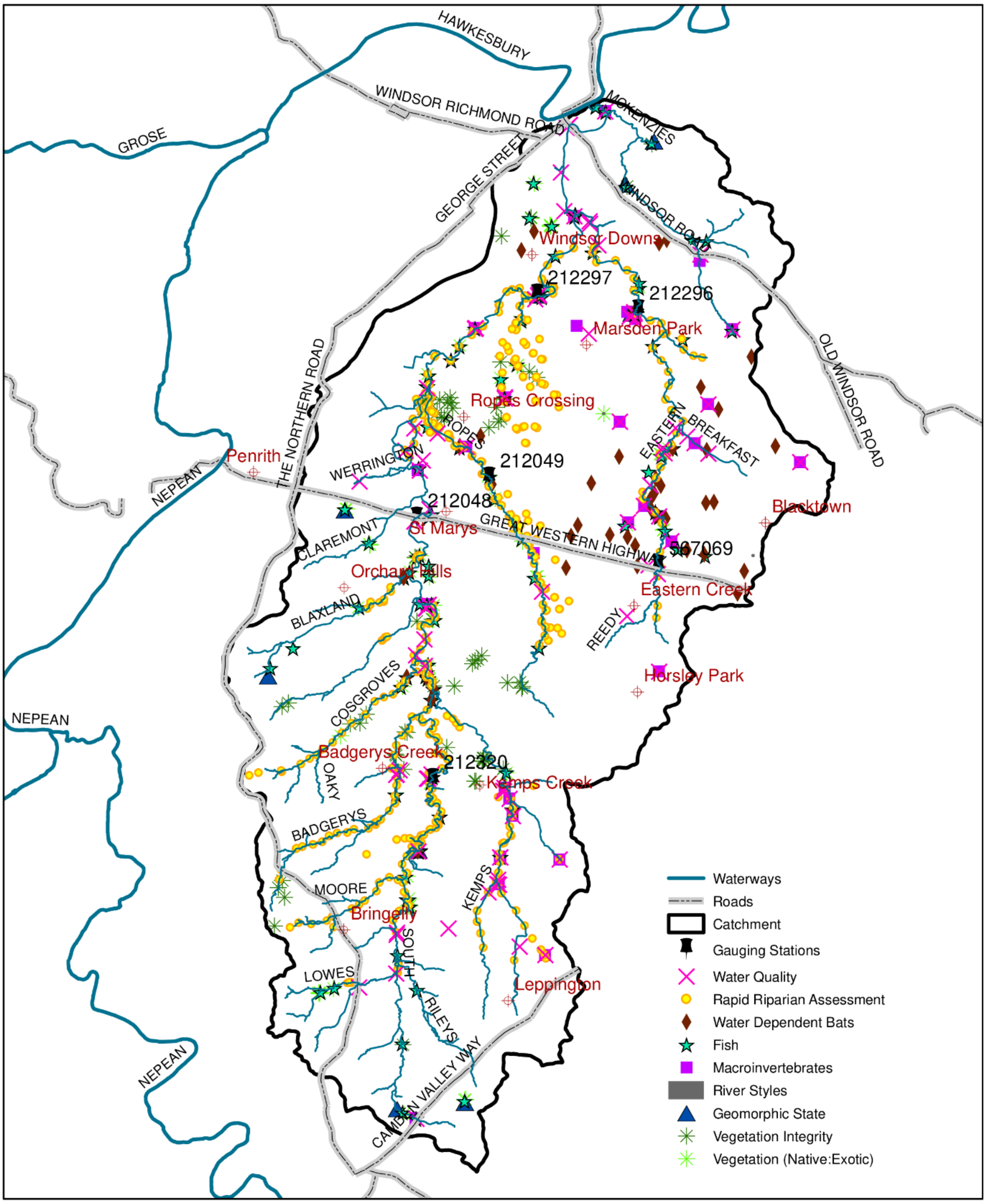
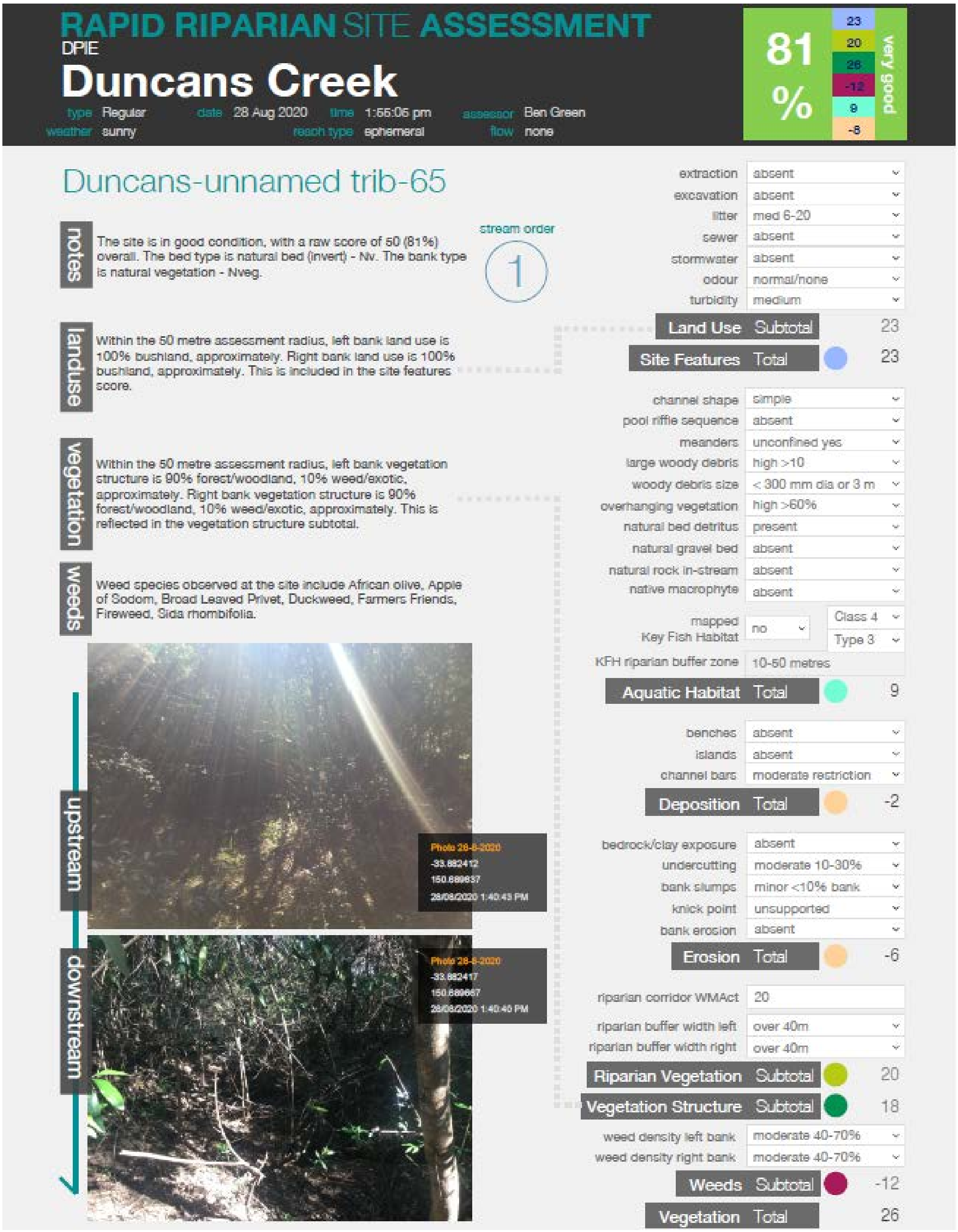


Figure 5 Local field monitoring sites


RAPID RIPARIAN SITE ASSESSMENT
DPIE
Duncans Creek
type Regular date 28 Aug 2020 time 1:55:05 pm assessor Ben Green
weather sunny reach type ephemeral flow none
81 %
23 20 26 -12 9 -6
very good

Duncans-unnamed trib-65

notes: The site is in good condition, with a raw score of 50 (81%) overall. The bed type is natural bed (invert) - Nv. The bank type is natural vegetation - Nveg.

stream order 1

landuse: Within the 50 metre assessment radius, left bank land use is 100% bushland, approximately. Right bank land use is 100% bushland, approximately. This is included in the site features score.

vegetation: Within the 50 metre assessment radius, left bank vegetation structure is 90% forest/woodland, 10% weed/exotic, approximately. Right bank vegetation structure is 90% forest/woodland, 10% weed/exotic, approximately. This is reflected in the vegetation structure subtotal.

weeds: Weed species observed at the site include African olive, Apple of Sodom, Broad Leaved Privet, Duckweed, Farmers Friends, Fireweed, Sida rhombifolia.

upstream: Photo 28-8-2020 -33.882412 150.689637 28/08/2020 1:40:43 PM

downstream: Photo 28-8-2020 -33.882417 150.689667 28/08/2020 1:40:40 PM

extraction	absent
excavation	absent
litter	med 6-20
sewer	absent
stormwater	absent
odour	normal/none
turbidity	medium
Land Use Subtotal	23
Site Features Total	23
channel shape	simple
pool riffle sequence	absent
meanders	unconfined yes
large woody debris	high >10
woody debris size	< 300 mm dia or 3 m
overhanging vegetation	high >60%
natural bed detritus	present
natural gravel bed	absent
natural rock in-stream	absent
native macrophyte	absent
mapped Key Fish Habitat	no; Class 4; Type 3
KFH riparian buffer zone	10-50 metres
Aquatic Habitat Total	9
benches	absent
islands	absent
channel bars	moderate restriction
Deposition Total	-2
bedrock/clay exposure	absent
undercutting	moderate 10-30%
bank slumps	minor <10% bank
knick point	unsupported
bank erosion	absent
Erosion Total	-6
riparian corridor WMAct	20
riparian buffer width left	over 40m
riparian buffer width right	over 40m
Riparian Vegetation Subtotal	20
Vegetation Structure Subtotal	18
weed density left bank	moderate 40-70%
weed density right bank	moderate 40-70%
Weeds Subtotal	-12
Vegetation Total	26

Figure 6 RRA at Duncans Creek in the Agribusiness Precinct of the Western Sydney Aerotropolis
(Image: CTENVIRONMENTAL – ECOSERVER)

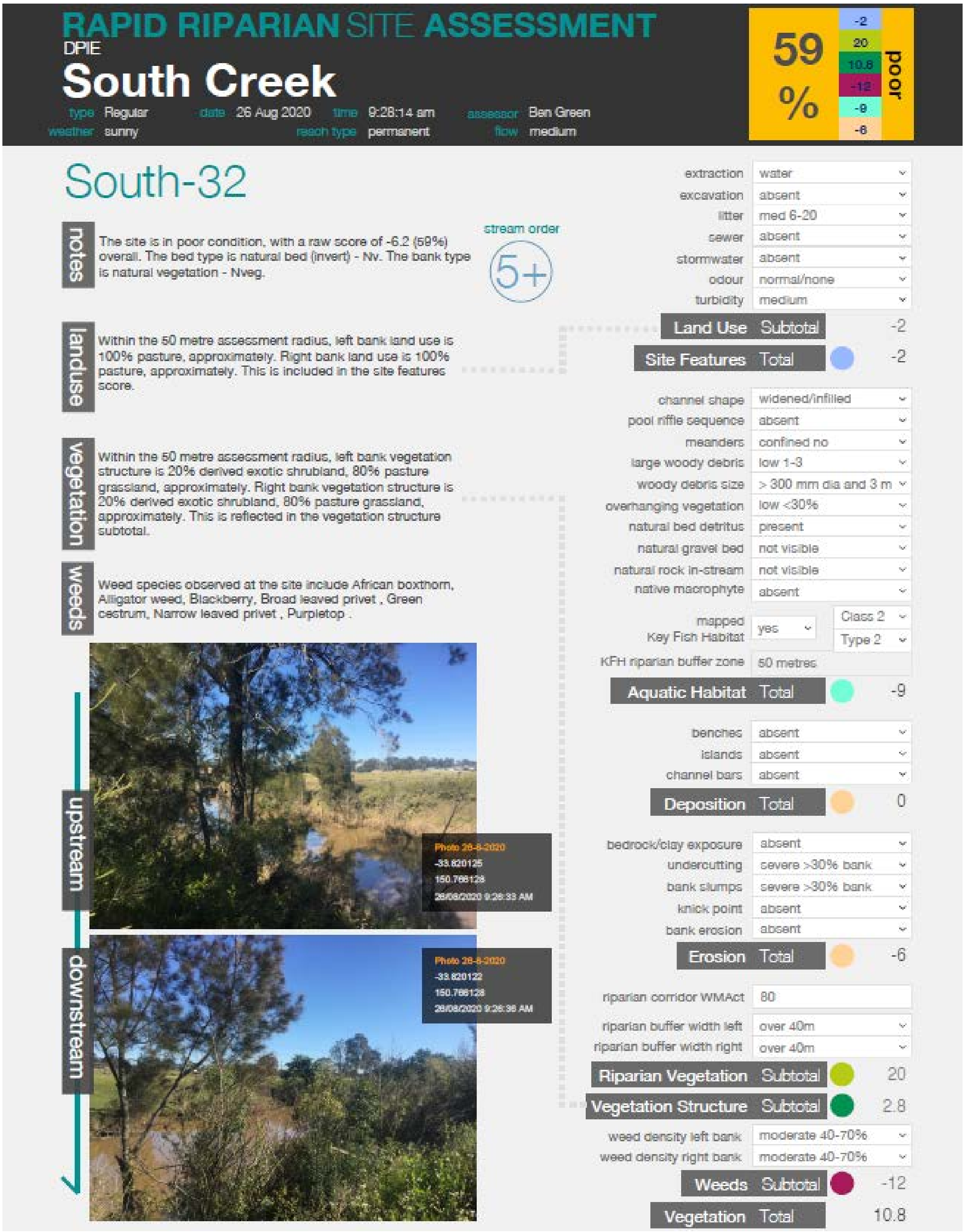


Figure 7 RRA at South Creek in the Wianamatta–South Creek Precinct of the Western Sydney Aerotropolis

(Image: CTENVIRONMENTAL – ECOSERVER)

5.3 Stream flows

Data on stream flows are publicly available from 6 gauging stations in the Wianamatta–South Creek catchment (see the WaterNSW ‘Continuous water monitoring network’ website). The availability and quality of daily flow records vary, with the longest available record (17 October 1995 to present) from the gauging station located in South Creek at Elizabeth Drive (station 212320), which is inside the Wianamatta–South Creek Precinct (Figure 5). Records of daily flow volumes, instantaneous discharge rates and annual average stream flow volumes were acquired for the period 1 January 2000 to 31 December 2019 from all 6 gauging stations. The records were quality checked using the data quality codes provided with the datasets, and further filtered to ensure there were >350 records of daily flows available for each year. Good data records were available from all but one (567069) gauging station.

The stream flow data were used to assess the hydrological changes resulting from land-use pressures in the upstream drainage area/sub-catchment, and cross-check modelled stream flow data that we acquired from Sydney Water. The data were modelled using the eWater Source model, which Sydney Water developed and calibrated to inform water balances as part of their Water Servicing Masterplan for the Western Parkland City (Sydney Water 2021a). The set-up and calibration of Sydney Water’s model were independently reviewed by subject matter experts. A comparison between the modelled and measured daily stream flow data indicated an overall good model fit (see Moriasi et al. 2007), with an average Nash–Sutcliffe efficiency of 0.68 ± 0.3 and bias of 5.29 ± 1.88% (Sydney Water 2021b).

Sydney Water discretised the Wianamatta–South Creek catchment into 195 drainage areas of variable size for their variable purposes and produced modelled stream flows for the period between 1 October 1993 and 30 June 2020. In this present study, we used the modelled records of daily stream flow for the period 1 January 2000 to 31 December 2019, and aggregated the 195 drainage areas into 47 to correspond with an upland drainage area of ≥3rd order streams (Appendix B).

5.3.1 Literature review of flow related objectives for streams in urban catchments

Several flow related objectives were derived using the modelled daily stream flow data from each of the 47 drainage areas (Table 2). The specific set of flow related objectives was determined from a review of contemporary literature that focused on identifying the components of the hydrograph that affect the ecological and geomorphic health of waterways in urban catchments (Appendix C), and maintain the (typically natural) flow requirements of associated ecosystems (Sánchez-Montoya et al. 2017).

The resulting flow related objectives reflect the most common type identified in the literature (Appendix C), and directly align with well-established flow objectives for water sharing plans and coastal harvestable rights in NSW (DPIE – Water 2020a, b). The flow objectives identified in the recent industry recognised ‘Urban Streamflow Impact Assessment’ (USIA; Vietz et al. 2018; Kermode et al. 2021) are conceptually similar; however, there are some key differences in the calculation of the numerical criteria. For example, the USIA method for calculating freshes is based on 3 times the median flow volume, whereas our method for calculating freshes follows the standard method reported in the literature based on the ≥75th and ≤90th percentiles of daily flow volumes (see DPIE – Water 2020a).

The suite of flow objectives in the USIA method also includes erosion thresholds, based on the mobilisation of the stream bed and bank material. These are inherently captured in our high spell flow objective (Table 2), and have been explicitly quantified by the 95th percentile daily flow volume in our companion study (DPE 2022a). We selected percentiles as the basis for numerical criteria as they are relatively easily measured and modelled.

Table 2 Flow related objectives that affect the ecological and geomorphic health of waterways in urban catchments, and maintain the flow requirements of associated ecosystems

Flow related objective	Function
Daily flows	• Specifies amount of natural, climatic and anthropogenic flow in the system • Indicative of mean habitat flows for aquatic species, support for riparian vegetation, downstream geomorphic processes and biological responses • Urbanisation typically causes higher variation to daily flow
Baseflow	• Specifies the amount of natural flow, due to bedrock, soil and riparian zones in the system • Moderates water temperature, water quality, nutrient and carbon processing • Provides habitat for aquatic species and support for riparian vegetation • Urbanisation typically causes base flow to decrease (volume), however in some instances it increases
High spell extent (Q90) and frequency	• Specifies periods of high flow for the system • Provides habitat connectivity, complexity and ecological triggers • Redistributes sediment and forms channels • Contributes to a 'dynamic flow regime' that sustains freshwater biodiversity of high conservation value • Urbanisation typically causes high spells to increase (volume and frequency) and can cause erosion
Low spell extent (Q10) and frequency	• Specifies periods of low flow for the system • Provides habitat and refuge during low/dry periods, especially for young/developing species • Indicates periods when connectivity, migration, habitat requirements for species or water quality may not be being met • Sustains wet riverbed and lower banks, helping to maintain riparian vegetation • Contributes to a 'dynamic flow regime' that sustains freshwater biodiversity of high conservation value • Urbanisation typically causes low spells to decrease (volume and frequency)
Freshes extent (Q75) and frequency	• Specifies flows producing substantial rise in river height due to short bursts of rain • Maintains water quality by refilling pools and providing inputs of fresh water • Provides habitat connectivity, complexity and ecological triggers • Redistributes food by drifting macroinvertebrates and organic matter around the stream • Replenishes soil moisture for riparian vegetation • Cleans the bed habitat by dislodging excessive algal growth and sediment • Urbanisation typically causes freshes to increase (volume and frequency)
Cease to flow	• Specifies periods when there is no detectable flow of water • Indicates periods when connectivity, migration, habitat requirements for species or water quality may not be being met • Demonstrates times for essential refuge for species during low/dry periods • Urbanisation typically causes cease to flow spells to decrease (volume and frequency)

5.4 Pressure–stressor–ecosystem receptor relationships

Rather than a referential approach to determining flow related objectives, we undertook an effects-based assessment by quantifying the relationships between the pressure–stressor–ecosystem receptor indicators. This is because the ecology and hydrology of the Wianamatta–South Creek catchment have been altered through historical vegetation clearing and urbanisation (H–N CMA 2007).

The relationships between the pressure–stressor–ecosystem receptor indicators were quantified through empirical statistical analyses of processes captured in the model shown in Figure 4, and further illustrated in Figure 8 and Figure 9 to help visualise the changes to the waterway and riparian corridor. The model starts with an undisturbed or predeveloped state, where the hydrology has not been altered, the floodplain and riparian corridors are characterised by native vegetation, there is no erosion of the stream bed or banks and the habitats in the stream are described as 'complex' due to the presence of woody debris, fine sediment and native leaf litter and detritus. In the Wianamatta–South Creek catchment, the riparian and instream habitats are home to several threatened and iconic species, including frogs, water dragons and water dependent birds and bats (DPE 2022a).

Under current approaches to greenfield development, the native vegetation in the floodplain and riparian corridors is predominantly cleared and controls for managing stormwater flows are minimal. The net result is erosion of the stream bed and banks, increased turbidity and TSS, loss of instream habitats and associated flora and fauna, and the onset of ecosystem degradation. These negative processes become fully established once the urban development is complete. Over time, the streams become increasingly incised and widen, until significant financial investment is required to stabilise the streams to a new altered state.

The review by Schueler et al. (2009) shows that the trajectory of change (if not mitigated) described above is non-linear, with clear thresholds or tipping points aligned with the percentage of total imperviousness within a catchment:

- <10% total imperviousness – streams are classed as sensitive and are generally able to retain their hydrologic function and support good to excellent aquatic diversity
- 10–25% total imperviousness – streams are classed as being impacted and show clear signs of declining stream health
- 25–60% total imperviousness – streams are classed as non-supporting as they no longer support their designated uses in terms of hydrology, channel stability, habitat, water quality, or biological diversity
- >60% total imperviousness – streams are extensively modified and primarily function as a conduit for flood waters. These streams are classed as urban drainage and consistently have poor water quality, highly unstable channels, and very poor habitat and biodiversity.

5.4.1 Pressure–stressor

To quantify the pressure–stressor relationship, we initially categorised each of the 47 drainage areas into one of 3 groups on the basis of the flow related objectives listed in Table 2. The number of groups was determined through hierarchical clustering in R statistical software (version 4.1.1). We selected the Gower distance to calculate a dissimilarity matrix, which determines how different, or distant, the drainage areas are from each other. Drainage areas sharing similar flow related objectives are clustered together while those that are dissimilar are added to a different cluster/group. We used both divisive and agglomerative clustering methods and assessed the clusters using a silhouette plot to display how close each drainage area in one group is to drainage areas in neighbouring groups (Appendix D).

Once the groupings were defined, an average and standard error value for each flow related objective was calculated for each group. The averages were then compared with the mean extent (%) of land-use pressures determined for the group. We initially used non-parametric locally weighted smoothing (LOESS) to identify the relationship between the indicators, and then assessed the differences in means of percentage land-use pressures between groups via a one-way analysis of variance (ANOVA) with unequal sample sizes and post hoc Tukey’s HSD test.

Pressures were represented by a range of landscape features that capture either anthropogenic changes or inherent landscape hazards. These include features like the extent of total impervious area and dominant land uses, or salinity and water erosion hazards, respectively (Figure 10, Appendix E).

5.4.2 Stressor–ecosystem receptor

The stressor–ecosystem receptor relationship was quantified in a similar manner to the pressure–stressor relationship. The average of each flow related objective for each group was compared to the average condition or health of the blue grid elements for the group. LOESS was used to identify the relationship between the indicators, and the differences among the mean condition of the blue grid elements of each group was assessed via a one-way ANOVA with unequal sample sizes and post hoc Tukey’s HSD test.

For these analyses, the blue grid elements were limited to a range of condition indictors for the riparian and other water dependent vegetation communities, and condition indicators for the stream itself. Measures for the water dependent faunal species such as bats and fish were not included due to the limited sample size. It was assumed, however, that the vegetation and stream indicators were appropriate surrogates as they are the key habitats of the faunal species. If the habitats are lost or degrade, it is expected that associated fauna will also be lost.

It is important to note that the current condition of all blue grid elements is generally poor, with only limited areas of the Wianamatta–South Creek catchment remaining intact (HN–CMA 2007; BCC 2021; LCC 2021; DPE 2022b). Many of the condition measures of the first order stressor and/or ecosystem response indicators (e.g. ambient water quality or macroinvertebrate sensitivity scores) exceed current environmental standards for stream assessments.

Stage 1 – Undisturbed State

- Natural hydrology
- Native vegetation riparian and floodplain community
- Minimal or no erosion and deposition
- Large woody debris provides in-stream habitat
- Sediment, native leaf litter and detritus provide in-stream habitat
- Channel shading regulates in-stream temperature, and macrophytes and algal growth

Stage 2 – Greenfield Development

- Onset of altered hydrology
- Native riparian and floodplain vegetation cleared
- Erosion and deposition
- Increased instream turbidity and sediment
- Clay and fine sediment smother in-stream habitat
- Loss of species dependent on benthic habitat
- Onset of ecosystem degradation

Stage 3 – Development Complete

- Onset of altered hydrology
- Native riparian and floodplain vegetation cleared
- Weed invasion of edge habitat
- Erosion and deposition
- Increased instream turbidity and sediment
- Clay and fine sediment smother in-stream habitat
- Loss of species dependent on benthic habitat
- Onset of ecosystem degradation

Stage 4 – Incision

- Altered hydrology, including decreased baseflow, increased volume and frequency of flows, increased bankfull and floodplain engagement
- Accelerated erosion and channel incision
- Frequent fine sediment, native leaf litter and detritus mobilisation
- Invasive plant species begin to colonise bars, banks and floodplain
- Ecosystem degradation

Figure 8 Conceptual model of impacts of unmitigated urban development on waterways and riparian corridors – Stages 1 to 4

(Images: Carl Tippler and Duncan Reed Architects)

Stage 5 – Widening

- Altered hydrology, including increased volume and frequency of flow
- Accelerated erosion triggers channel incision and widening
- Loss of fine sediment, native leaf litter and detritus
- Large woody debris transport downstream
- Channel widening causes loss of native vegetation
- Colonisation of invasive plant species (weeds)
- Increased floodplain engagement promotes spread of weeds

Stage 6 – Baseflow Channel Re-establishment

- Further channel deepening
- Loss of temperature and sunlight penetration promotes nuisance macrophyte and algae
- Exotic shrubs and grasses replace natives
- Invasive plants colonise floodplain
- Further degradation and loss of in-stream and riparian habitats
- Simplification of habitat and biodiversity loss

Stage 7 – Further Channel Widening

- Channel widening continues
- Large woody debris, fine sediment, native leaf litter and detritus removed from stream
- Exotic shrubs and grasses replace natives
- Loss of amenity
- Degraded ecosystem

Stage 8 – Management via armouring

- Extensive armouring of stream and bank
- No inclusion of WSUD
- Ongoing weed control required

Stage 8 – Management via integration of WSUD in drainage area (not shown)

- WSUD in drainage areas to manage stormwater flows
- Minimum armouring and weed control required

Figure 9 Conceptual model of impacts of unmitigated urban development on waterways and riparian corridors – Stages 5 to 8

(Images: Carl Tippler and Duncan Reed Architects)

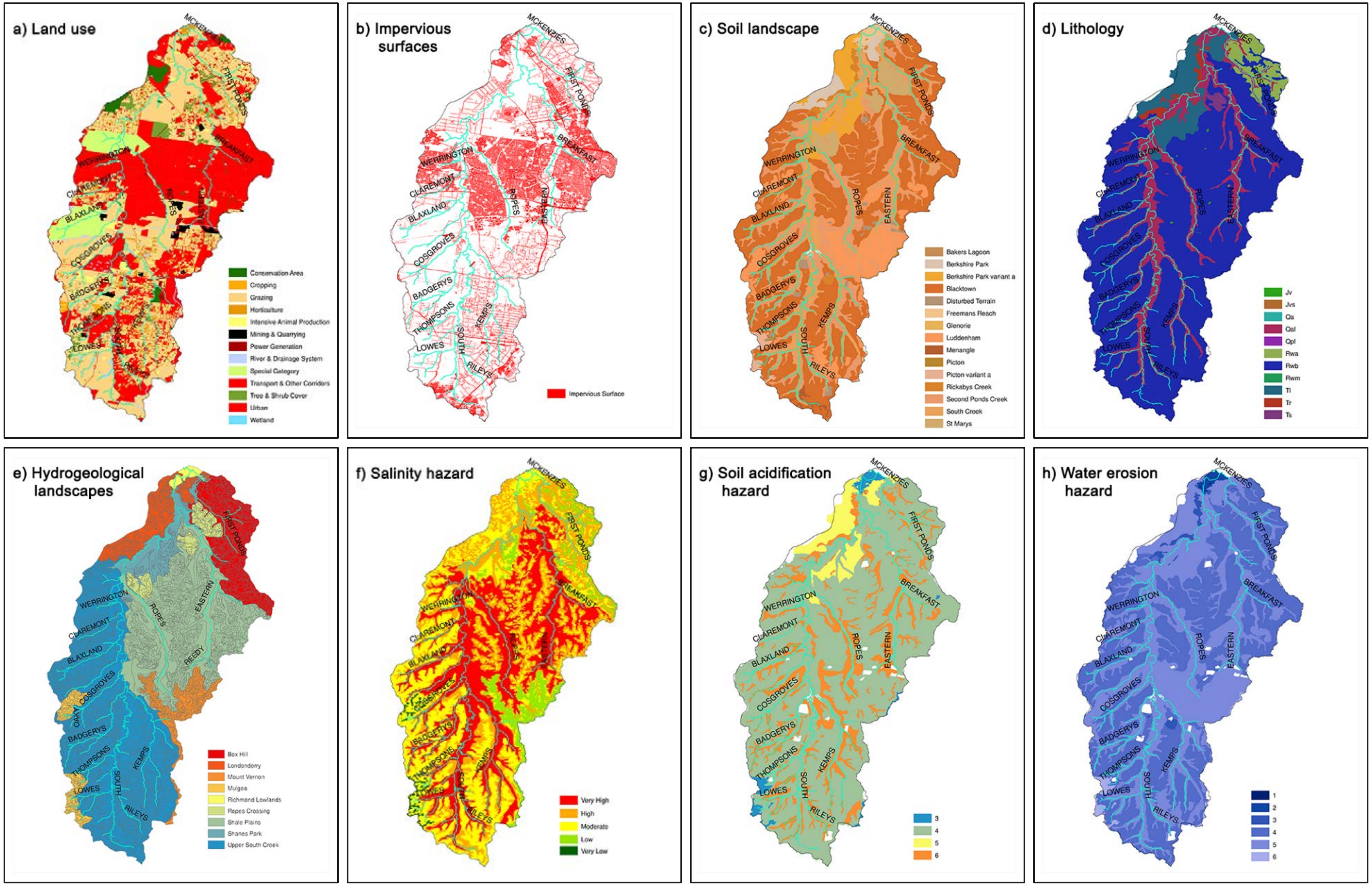


Figure 10 Pressures (a, b) and inherent landscape features (c–h) of the Wianamatta–South Creek catchment
(see Appendix E for further details on the data)

6. Key findings

6.1 Referential sites for deriving water quality objectives

Waterways in the Wianamatta–South Creek catchment have been described as the most degraded in the Hawkesbury–Nepean River system (H–N CMA 2007). Despite this, we identified a handful of sites that are in relatively better condition using the criteria specified for the referential approach in the Australian Water Quality Guidelines (Commonwealth of Australia 2018). Of the 108 water quality monitoring sites (Figure 11a), only 63 met the sampling frequency criterion, which was based on sites having ≥24 data points (Figure 11b). This number of data points enables robust estimates of percentiles and was considered a good surrogate for monthly sampling over 2 years. Of the 63 sites, an additional 16 were eliminated as they were located downstream of the discharge points of sewage treatment plants (STPs; Figure 11b). All but 4 (Figure 11d) of the remaining water quality monitoring sites were subsequently eliminated as they did not meet the criteria for minimal disturbance (Figure 11c). These criteria were assessed through the percentage of natural bushland within the drainage area, and the overall condition of riparian vegetation determined via the RRA. Specifically, water quality monitoring sites were eliminated if they were located in drainage areas with <20% natural bushland and where the score for overall vegetation condition at the site was <0.

Of the 4 remaining water quality monitoring sites, 2 are located just upstream of the Wianamatta Regional Park on South Creek (site names NS23, NS26), one located in Kemps Creek adjacent to Cecil Park (site name KC10) and the last located in an unnamed tributary of Little Creek running through Shanes Park. The last site is the 'referential' site that Blacktown City, Penrith City and Liverpool City councils are currently using for their state of the environment reporting. We compared the water quality data at this referential site to the water quality at the 3 remaining sites (Table 3), and found that the water quality at Kemps Creek and one site at South Creek (NS23) significantly exceeded the site specific guideline values/numerical criteria of the councils' referential site. For example, the 80th percentiles of TN and TP at the South Creek site identified as NS23 were 2 and 5 times greater than at the councils' referential site. At the Kemps Creek site, the 80th percentiles of TN and TP concentrations were 3.5 and 10.5 times greater than at the councils' referential site. This large difference is most likely due to the time series of water quality data available for the Kemps Creek site, which was limited to monitoring over long periods of drought, with very little or no stream flow.

The water quality of the one site at South Creek that was retained (NS26) was within the ranges of the site specific guideline values/numerical criteria at the councils' referential site. The difference between the 80th percentiles of TN and TP concentration at the sites was only 1.4%, but the ratios of dissolved inorganic forms of nitrogen and phosphorus were different, with higher concentrations at the South Creek site (Table 3). Generally, the 80th percentiles of the water quality measures at the South Creek site were greater (albeit within the range) than at the councils' referential site (Table 3). It is worth noting however that the councils' referential site is located on a 2nd order stream in a part of the Wianamatta–South Creek catchment that has inherently different soil and lithology characteristics compared to the broader catchment, especially the Western Sydney Aerotropolis area (Figure 10, Appendix E). These inherent differences would affect the ambient/instream concentrations of TSS, conductivity and pH. For example, the site at South Creek sits within the Upper South Creek Hydrogeological Landscape (HGL) which has a higher and more severe salinity hazard and impact rating than the Shanes Park HGL where the councils' referential site is located. Accordingly, the 80th percentile of the ambient/instream conductivity concentration at the South Creek site (1,103 µS/cm, Table 3) is almost double the councils' referential site (575 µS/cm).

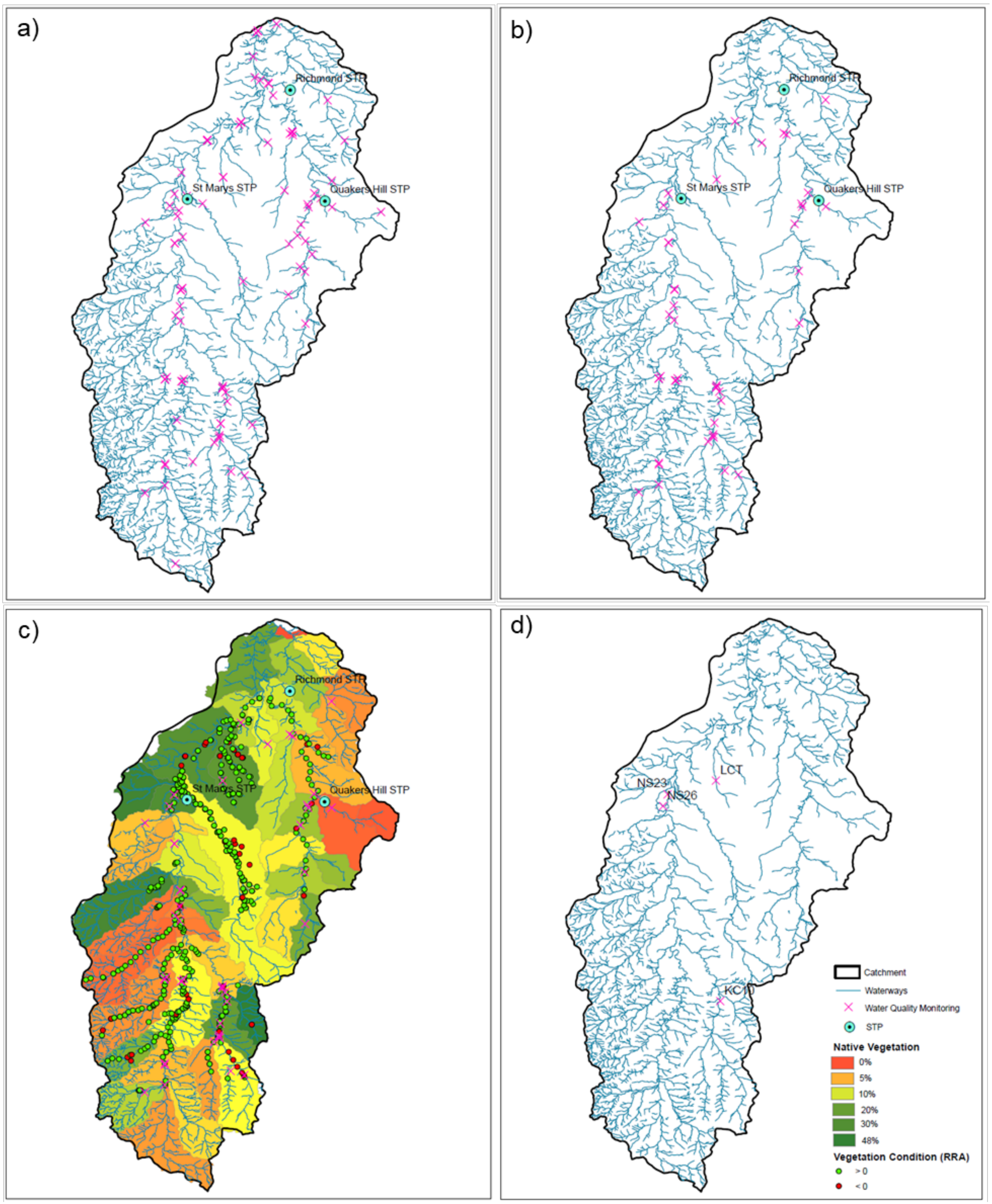


Figure 11 Identification of potential referential sites for setting instream WQOs

From a total of 108 monitoring sites (a), only 4 sites (d) remained after assessing the number of data points available for each site (b), whether the sites were upstream of STPs (b), and whether the sites were in a disturbed drainage area (c).

Table 3 The 80th percentiles of water quality measures at 4 sites in the least disturbed areas of the Wianamatta–South Creek catchment, and default ('ANZECC') guidelines for lowland rivers in the Australian and New Zealand Guidelines for Fresh and Marine Water Quality

	South Creek (NS26)	South Creek (NS23)	Kemps Creek (KC10)	Unnamed tributary of Little Creek	ANZECC
					
TN (mg/L)	1.72	9.04	6.08	1.80	0.5
DIN (mg/L)	0.74	7.57	3.92	0.05	–
NH_3-N(mg/L)	0.08	0.11	0.14	0.04	0.02
NOx (mg/L)	0.66	7.46	3.78	0.01	0.04
TP (mg/L)	0.14	0.29	1.43	0.19	0.05
DIP (mg/L)	0.04	0.25	–	0.01	–
Turbidity (NTU)	50	35	20	9	50
TSS (mg/L)	37	20	–	20	–
Conductivity (µS/cm)	1,103	897	2,472	564	2,200
pH	7.16–7.60*	7.19–7.69	7.31–7.64	6.20–7.00	6.5–8
DO (%SAT)	43–75	64–90	23–42	9–49	85–110
DO (mg/L)	8	9	–	–	–

* performance criteria for pH widened to 6.20–7.60 to include the lower pH value for the unnamed tributary of Little Creek

It is also worth noting that the 80th percentiles for the water quality measures at both the councils' referential site and the South Creek site are different to the default guideline values provided in the Australian and New Zealand Guidelines for Fresh and Marine Water Quality (ANZECC & ARMCANZ 2000). Specifically, the 80th percentiles of the nutrient concentrations at both sites are predominantly greater than the default guideline values. The 80th percentile of turbidity at the councils' referential site was lower than the default, but at the South Creek site, the 80th percentile for turbidity is the same as the default. The range in pH values for the councils' referential site and the South Creek site was within the range of the default guideline value, whereas the range in DO values was lower than the minimum DO default guideline value.

Rather than selecting the 80th percentiles for the water quality measures at the councils' referential site as the performance criteria, we recommended the 80th percentiles for the water quality measures at the South Creek site. Our only exception was to extend the range of the pH values, to encompass the lower pH range (6.20) at the councils' referential site.

Our overall recommendation to use the South Creek site was based on a compromise between the water quality at the councils' referential site (i.e. within the range), the need for representativeness, and practical achievability. Our assessment of achievably was based on the reported performance of stormwater quality improvement devices in the literature (eWater 2014; Stormwater Australia 2018; Wright et al. submitted). The concentrations of the dissolved fractions of the nutrients would not be met through conventional treatment, such as via wetlands, ponds, swales and bioretention systems. We also consulted with state and local governments, and leading stormwater industry practitioners on the WQOs prior to their release in the draft Aerotropolis Precinct Plan (Appendix F). Many raised issues with the ability to achieve the objectives, especially given that the Wianamatta–South Creek catchment will never be in a pre-European or undisturbed state.

6.2 Characterising stream flows

Figure 12 compares the daily stream flows at the 5 gauging stations that had good quality data for use in analyses. There is a distinct gradient in daily stream flows from the lowest flows at the gauging station located at Elizabeth Drive within the Wianamatta–South Creek Precinct (212320), to the highest flows at the gauging station at Ropes Creek (212049). At these 2 extremes, the dominant land uses of the drainage areas are agricultural and urban, respectively. The gauging station located in South Creek at Great Western Highway (212048) drains an upland area of mixed land uses, as does the gauging station located further downstream near Richmond Rd (212297). However, it's important to note that this latter gauging station is also affected by sewage discharges from the St Marys STP. The gauging station located in Eastern Creek, near Garfield Rd (212296), drains an upland area of predominantly urban land and is also affected by sewage discharges from the Quakers Hill STP.

Not all spatial differences in daily stream flow across the Wianamatta–South Creek catchment can be attributed to land-use impacts. As shown in Table 4, the flow characteristics determined from the gauging station at Elizabeth Drive (212320) are relatively drier, and those at the gauging stations in the north-east corner of the catchment (212296, 212297) are relatively wetter. These spatial differences align with the gradients/distribution of annual average rainfall within the catchment (see Singh et al. 2009).

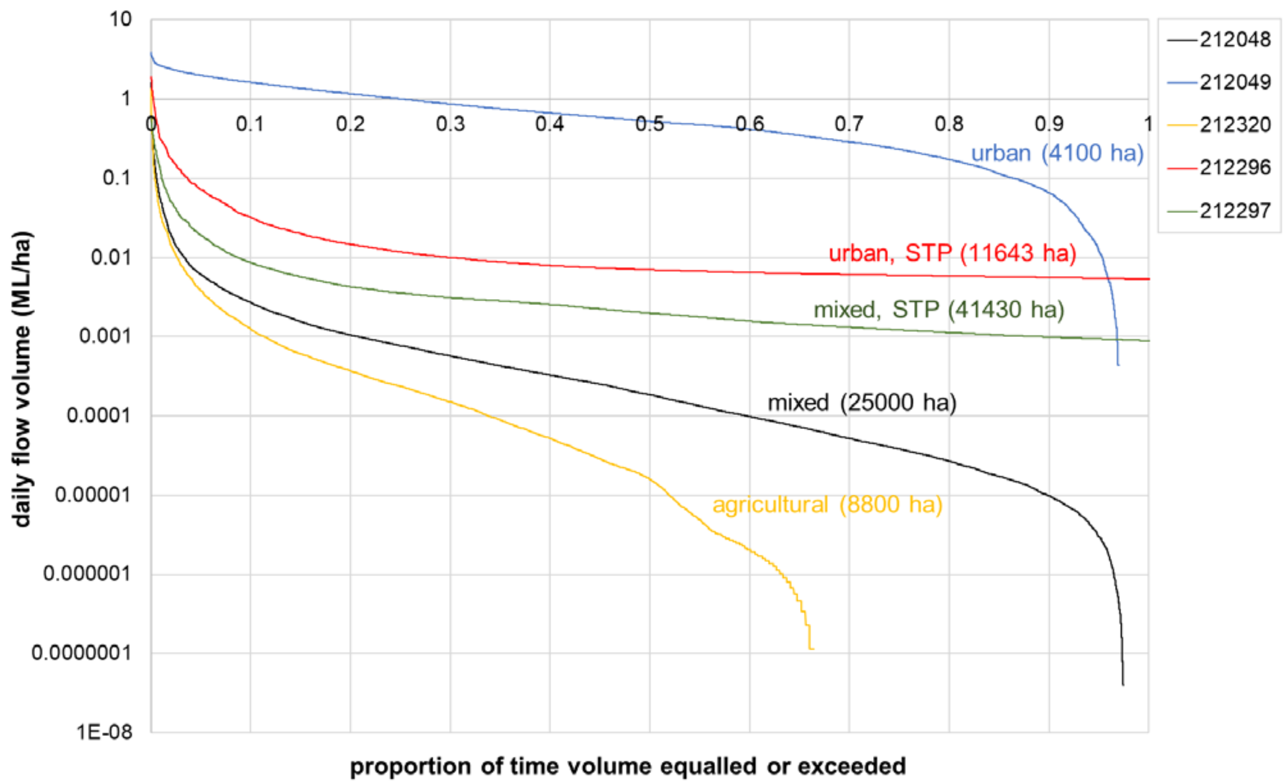


Figure 12 Flow-duration analyses of daily flow volumes of streams that drain agricultural, urban and mixed use areas in the Wianamatta–South Creek catchment, including those with STPs

The total catchment area (ha) is shown in brackets.

Table 4 Flow characteristics determined at gauging stations in the Wianamatta–South Creek catchment for the period 2000–2019

	212048	202049	212320	212296	212297
Median daily flow volume (L/ha/day)	256.2 ± 43	684.8 ± 105.7	68.8 ± 23.5	5,179.6 ± 441.1	1,012.9 ± 156.4
Mean daily flow volume (L/ha/day)	2,530.1 ± 546.8	6,205.5 ± 1,067.5	1,493.5 ± 419.9	13,184.2 ± 2,069.3	4,249.9 ± 736.9
High spell (L/ha/day) ≥90th percentile daily flow volume	2,850.4 ± 466.2	11,160.7 ± 3,075.3	1,520.9 ± 375.1	14,397.3 ± 1,934.5	5,311.3 ± 867.2
High spell – frequency (number/y)	9.1 ± 0.5	13.3 ± 0.9	6.8 ± 0.6	15 ± 0.7	12.7 ± 0.5
High spell – average duration (days/y)	4.3 ± 0.2	3.1 ± 0.4	6.3 ± 0.6	2.5 ± 0.1	3.1 ± 0.1
Freshes (L/ha/day) ≥75th and ≤90th percentile daily flow volume	897.9 – 2,850.4	3,078.7 – 11,160.7	308 – 1,520.9	6,740 – 14,397.3	1,823.8 – 5,311.3
Freshes – frequency (number/y)	6.4 ± 0.6	8.4 ± 0.7	2.8 ± 0.5	10.8 ± 1.1	7.4 ± 0.9
Freshes – average duration (days/y)	2.2 ± 0.2	1.7 ± 0.20	3.2 ± 0.8	1.8 ± 0.1	1.8 ± 0.2

	212048	202049	212320	212296	212297
Low spell (L/ha/day) ≤10th percentile daily flow volume	17.6 ± 3.6	93.5 ± 19.8	0.8 ± 0.3	3,950.2 ± 343.6	702.7 ± 139.1
Low spell – frequency (number/y)	6.7 ± 0.6	7.7 ± 0.6	3.7 ± 0.4	13.8 ± 1.8	12.2 ± 1.3
Low spell – average duration (days/y)	6.7 ± 0.8	5.3 ± 0.6	54.5 ± 19.6	2.8 ± 0.3	3.4 ± 0.4
Cease to flow (proportion of time/y)	0.01 ± 0.004	0.03 ± 0.01	0.34 ± 0.05	0	0
Cease to flow – duration (days/y)	2.6 ± 0.9	3.9 ± 1.2	39.2 ± 8	0	0
Baseflow index	0.29 ± 0.02	0.30 ± 0.02	0.14 ± 0.02	0.73 ± 0.01	0.63 ± 0.03
Drainage area (ha)	25,000	4,100	8,800	11,643	41,430

Figure 13 shows the spatial variation of the modelled flow related objectives (see Table 2) across the 47 drainage areas in the Wianamatta–South Creek catchment (see Section 5.3 and Appendix B). The last plot in the figure (Figure 13f) shows the subsequent categorisation of the drainage areas into 3 groups.

The first of the groups has been shaded in light blue to denote that these drainage areas have the lowest daily flows, high spells and freshes but greater baseflow and low spell volumes than the drainage areas shaded in the darker blues. The drainage areas in this first group are predominantly located in the southern upstream part of the Wianamatta–South Creek catchment and include the Western Sydney Aerotropolis precincts. This first group is distinct because they have long periods of no flows (i.e. cease to flow 34% of the time).

The drainage areas shaded in the darkest blue (identified in this study as group 3) are those located in the north-east corner of the Wianamatta–South Creek catchment, and have the highest daily flows, high spells and freshes. While these drainage areas have lowest baseflows and low spells, the streams are flowing for most of the year, with only 3% of the time recorded as cease to flow.

Most drainage basins have been categorised into a large group (group 2) in which the ranges of the flow related objectives sit between the other 2 groups. For example, the mean daily flow volume (5,542.2 ± 320.9 L/ha/day) is around double the first group (1,748 ± 106), and half the volumes of those in drainage areas located in the north-east corner (9,432.7 ± 868.9). The differences are not always linear, however, with the high spell volumes (10,091.7 ± 769.7 L/ha/day) and freshes (2,642.9–10,091.7 L/ha/day) in this large group being 5 and 8 times greater than those of the first group, respectively. Appendix B provides a summary table of the modelled flow dataset used to define the groupings.

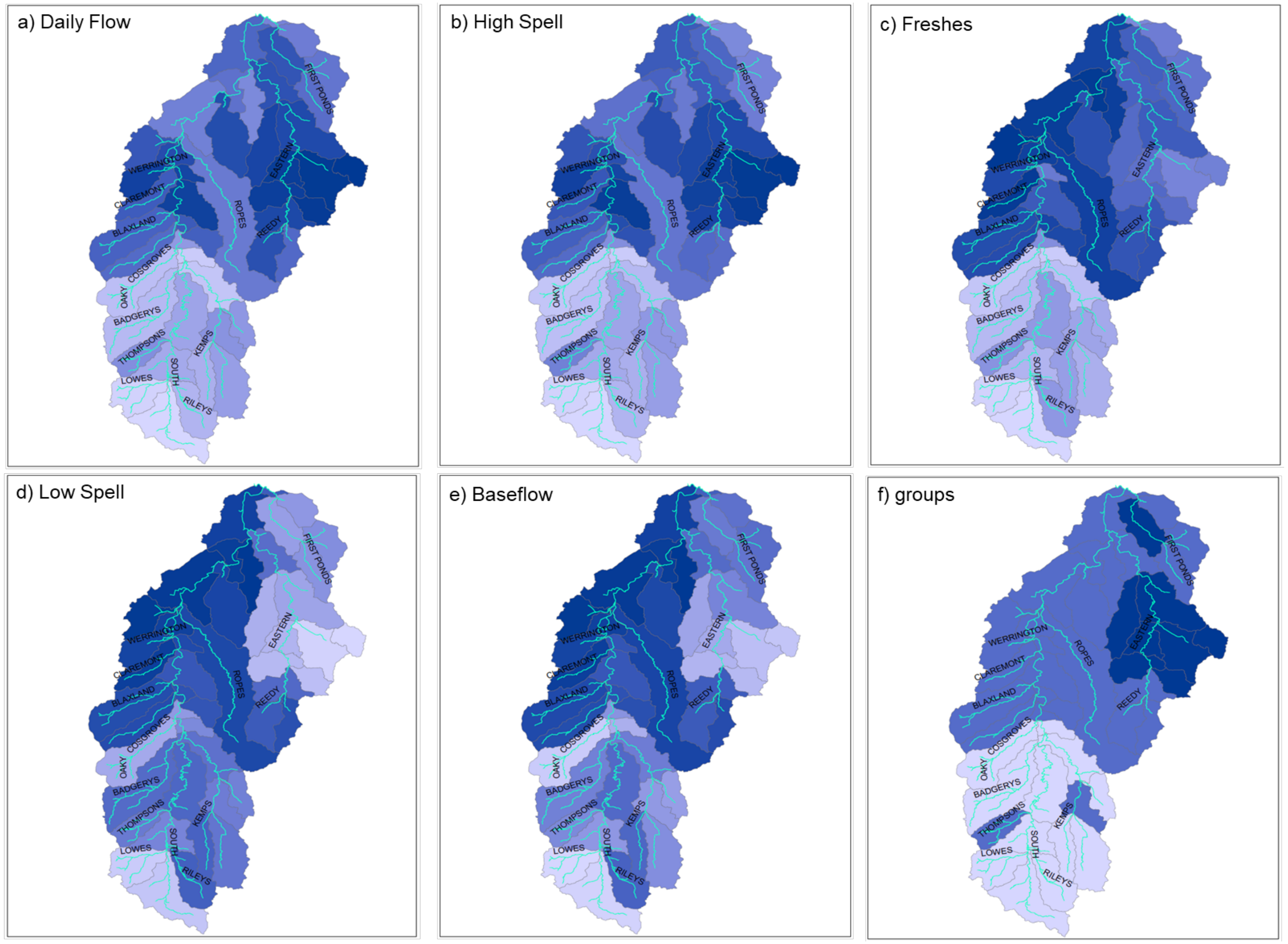


Figure 13 Spatial variation of flow related objectives across 47 drainage areas in the Wianamatta–South Creek catchment, and subsequent categorisation of the drainage areas into 3 groups

Dark blue denotes high flow and light blue denotes low flow.

As inferred above, the extent and type of land-use change (disturbance) in the drainage areas can influence the spatial variation in stream flows across the Wianamatta–South Creek catchment. The group (group 3) with the highest daily flows, high spells and freshes is predominantly made up of drainage areas that are urbanised, with an average total impervious area of 28% (Figure 14). The (first) group with the lowest mean daily flows, high spells and freshes is predominantly made up of drainage areas that are agricultural, and the large group (group 2) of drainage basins has mixed land uses with a marginally greater area of remnant native vegetation. As shown in Appendix E, there is a clear relationship between the pressures (land use, % total impervious area) and flows. The differences in the percentage of urban land and imperviousness between all groups are significant ($p<0.01$). The differences in the percentage of agricultural land between the first group and third group are significant ($p<0.01$), but not significant between the first and second group.

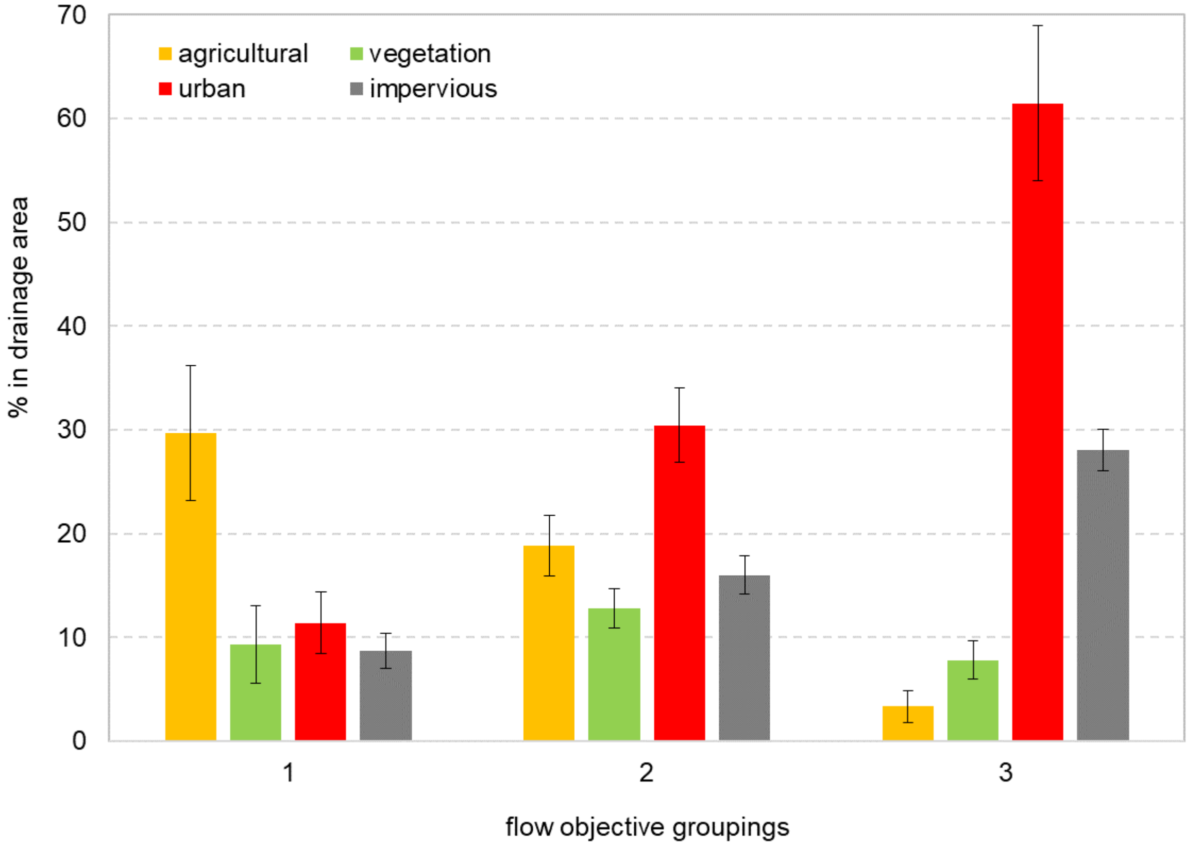


Figure 14 Effects of land-use type and extent on stream flows in the Wianamatta–South Creek catchment

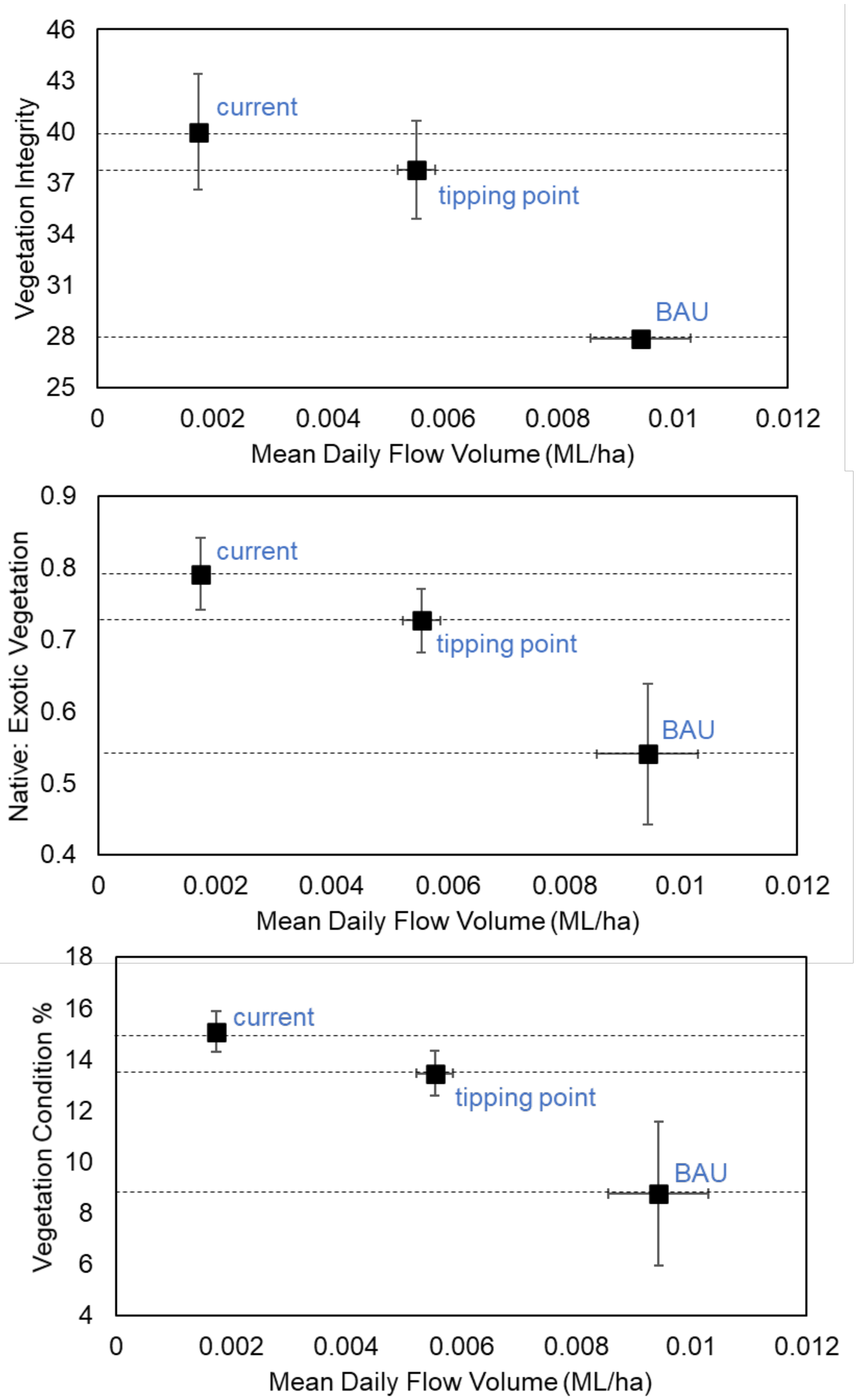


Figure 15 Relationships between instream daily flow volumes and condition of riparian vegetation

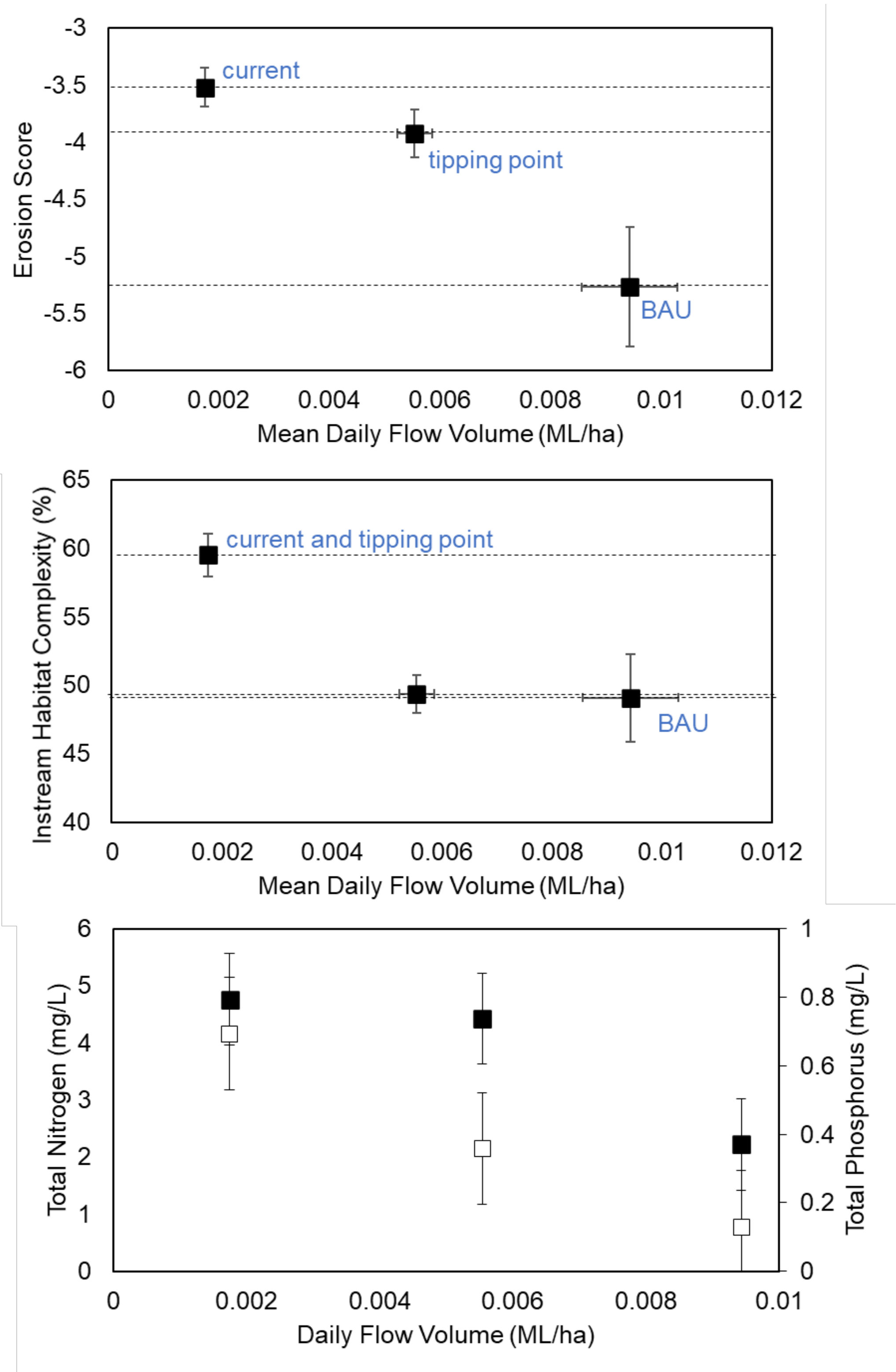


Figure 16 Relationships between instream daily flow volumes and condition of the stream bank and instream habitats

6.3 Impacts on blue grid elements

The spatial variation in flow objectives is reflected in the condition or health of the riparian and instream habitats (i.e. ecosystem receptors). The plots in Figure 15 and Figure 16 show the empirical relationships between the mean daily stream flow volume and various condition indicators for riparian vegetation, stream bed and bank erosion, and instream habitats of fish and macroinvertebrates. The mean daily flow volumes were used as a surrogate for all flow related objectives listed in Table 2, as daily flows are typically indicative of both the amount of natural, climatic and anthropogenic flow in the system, and mean flows required to support aquatic species, riparian vegetation, downstream geomorphic processes and biological responses (Table 9, Appendix C).

As described above, the lowest daily flow volumes correspond with the first grouping of drainage areas that are predominantly agricultural and located in the southern part of the Wianamatta–South Creek catchment. These have been labelled as 'current' daily flow volumes in Figure 15 and Figure 16 as these represent the current or pre-development flows in the Western Sydney Aerotropolis. The condition of all ecosystem receptors is better under current daily flows, but progressively worsens as the flows increase. The highest flows are the drainage areas that are predominantly urbanised and located in the north-east part of the catchment. These have been labelled as 'BAU' daily flow volumes in Figure 15 and Figure 16 on the assumption that these flows are an outcome of the business-as-usual approach to land-use planning and stormwater management in urban catchments. The daily flows in these drainage areas are up to 4–5 times greater than the current flows, consistent with independently modelled estimates in our companion studies (DPE 2022a, c).

As shown in Figure 15, the daily flows from drainage areas with the mixed land uses were considered the 'tipping point' at which the health, ecology and biodiversity of the riparian vegetation habitats declined. The results of the non-parametric locally weighted smoothing (LOESS), which was used to identify the (non-linear) nature of the relationship between the flows and the condition of the riparian vegetation indicated that there is an inflection (downward) when daily flows are 0.004–0.006 ML/ha/day (Section D.1, Appendix D), i.e. between the second and third group of drainage basins. This inflection occurs at a point when there is the greatest relative change in the average condition of riparian vegetation of drainage areas among the groups (Figure 15). The change is not statistically significant however (Section D.1, Appendix D), most likely due to the overall poor ecological state of the riparian vegetation in the catchment.

The middle plot in Figure 16 indicates that the (tipping) point at which the daily flows cause a decline in the condition of instream habitats occurs between 0.002 and 0.004 ML/ha/day, characteristic of current daily flows. This lower tipping point is presumably due to the sensitivity of these habitats, which are instream and are easily washed away (see Figure 8, Figure 9). This lower tipping point occurs when there is the greatest relative change in the average condition of the stream bank and instream habitat complexity among the groups (Figure 16), with mean differences in condition being statistically significant (Section D.1, Appendix D).

The last plot in Figure 16 shows the empirical relationship between the daily flow volumes and ambient water quality. The TN and TP concentrations are relatively lower than in the drainage areas with the lowest daily flows. This would seem counter-intuitive based on the concepts of the urban stream syndrome, but not unexpected in this specific catchment due to the intense agricultural land uses. Exports of nutrients and sediments from fruit and vegetable market gardens and turf farms in the catchment are up to 30 times greater than exports from urban areas (Young et al. 1996; Wells and Chan 1997; Baginska et al. 1998; Hollinger et al. 2001; Haine et al. 2011). These exports represent up to 78% of the total nutrient (438 TN tonnes/y; 83 TP tonnes/y) and sediment exports (21,333 TSS tonnes/y) from the Wianamatta–South Creek catchment to the Hawkesbury River system (Dela-Cruz et al. 2019).

Irrespective of the distribution of average annual rainfall, 2 processes appear to be occurring in the Wianamatta–South Creek catchment – symptoms of the urban stream syndrome in existing urban areas and eutrophication in existing agricultural areas. It is expected that the urbanisation of the agricultural areas will help improve the eutrophication issues in that part of the catchment in the short term, but the cumulative impacts of the future urbanisation will still need to be considered in setting standard planning requirements for stormwater quality management. The impact of flows on the health of streams in urban areas is almost universally implied in many existing local government development control plans, with standard controls requiring minimal changes to the flow regime. For example, Penrith City Council's Mamre West Land Investigation Area Development Control Plan (PCC 2016) specifies that 'Any changes to the flow rate and flow duration within the receiving watercourses as a result of the development shall be limited as far as practicable. Natural flow paths, discharge point and runoff volumes from the site should also be retained and maintained as far as practicable'. If this same control was applied to the Western Sydney Aerotropolis precincts, we would need to recommend flow related objectives based on the current or pre-development flow regime, in which the mean annual daily flow volume is limited to 0.9 ML/ha/y. However, as shown in this present study, it is practicable to adopt the flow related objectives represented by tipping point flows, in which the mean annual daily flow volume (2 ML/ha/y) is double the current flows.

7. Recommendations

In 2018, the Greater Sydney Commission released the Greater Sydney Region Plan – A Metropolis of Three Cities. The plan included a clear vision for Wianamatta–South Creek (and its tributaries) to become a cool green corridor through the Western Parkland City and be the core element of liveability and amenity for the residents. This vision relies on urban planners to explicitly integrate waterways into the design of the city and residential neighbourhoods, and for the waterways and other water dependent ecosystems to be healthy so they can provide the essential services and functions expected of a cool green corridor. Accordingly, all strategic planning for the Western Parkland City has since focused on achieving the vision, through a 'beyond business-as-usual' approach (WSPP 2020; WSPP 2021a, b).

The work presented in this study delivers this vision through a restorative and landscape led approach, at the direction of the Western Sydney Planning Partnership Office. This partnership was established between Commonwealth, state and local governments for the specific purpose of developing relative planning instruments for the Aerotropolis. Other strategic drivers for this work include the NSW Government direction under the Marine Estate Management Strategy 2018–2028 to address the priority threat of urban discharges to the state's coastal catchments. Stakeholder consultation and detailed threat and risk assessments under this strategy have indicated that current approaches to stormwater management in NSW, such as via the 'one-size fits all' stormwater quality post-development load reduction targets, is insufficient to protect the community environmental values and uses of the state's waterways (MEMA 2017).

The key recommendations arising from this study are the performance criteria for the Western Sydney Aerotropolis Precinct Plan, which seek to deliver the following goals for keeping 'Water in the Landscape':

- the protection, maintenance and/or restoration of waterways, riparian corridors, waterbodies, and other water dependent ecosystems that make up the blue grid elements of the Blue and Green Infrastructure Framework
- a landscape led approach to integrated stormwater management and water sensitive urban design (WSUD).

The performance criteria are instream or ambient water quality and flow related objectives (Table 5 and Table 6) which are consistent with the types of environmental standards that the NSW Government currently uses for managing the water quality and health of the state's waterways. They will help operationalise the Environmental and Recreational Zone requirements under the *State Environmental Planning Policy (Precincts – Western Parkland City) 2021*.

It is important to note that the instream or ambient water quality and flow related objectives do not represent existing or pre-development conditions, nor do they represent a pre-European state. So unlike recommendations in contemporary literature, they do not mimic natural conditions (Walsh et al. 2012; Tippler et al. 2013; Walsh et al. 2016) and the qualitative specifications in many existing development control plans; rather, they are based on the tipping point at which the health, ecology and biodiversity of water dependent ecosystems is expected to decline according to best available data at the time of this study. The tipping point occurs at a level of imperviousness (~10%, see Figure 25 in Appendix E) that is consistent with previous findings for the Greater Sydney Region (Tippler et al. 2012) and follows the well-established pressure–stressor–ecosystem response model for the urban stream syndrome.

Given the highly dispersive soils in the Wianamatta–South Creek, it is expected that some level of stream stabilisation will still be required. As an additional 'safeguard', we have recommended 2 sets of flow related objectives. The first set reflects the current or pre-development flows based on the flow data at the gauging station at South Creek near Elizabeth Drive (212320), which we recommend for use in more sensitive and intermittent stream types like chain of ponds and 1st and 2nd order streams. The second set reflects the modelled flow related objectives derived from the group of drainage areas with mixed land uses and identified as the tipping point in this study. This second objective is recommended as the post development flows that should be achieved for larger perennial waterways in the Wianamatta–South Creek catchment such as ≥3rd order streams. The range and characteristics of flows for this second set of objectives is within the ranges for the gauging stations in South Creek at Great Western Highway (212048) and Ropes Creek at Debrincat Avenue (212049).

The flow volumes in the first set of objectives will do a better job at protecting the instream habitats for macroinvertebrates and fish (see Figure 16) and may also minimise the extent to which the 1st and 2nd order streams are lost through re-alignment and piping. Degradation of these stream types results in poorer water quality, less reliable water flows, and less diverse aquatic life in downstream ecosystems (Wohl 2017). This is because these headwater streams have a pivotal ecosystem function in flood control, recharging of groundwater, nutrient attenuation and recycling, and trapping sediment.

The ambient WQOs presented in Table 5 are relevant to protecting aquatic ecosystems. For recreational uses of the waterways and waterbodies, it is recommended that the relevant National Health and Medical Research Council guidelines be consulted for managing human health risks (NHMRC 2008).

Overall, our approach to developing the performance criteria has been necessarily pragmatic to address key stakeholder concerns related to achievability and costs (Appendix F) in accordance with the strategic impact assessment step of the Risk-based Framework (Dela-Cruz et al. 2017). NSW Government endorsement of this approach is through the adoption of the performance criteria in the Western Sydney Aerotropolis Precinct Plan and associated development control plan. It is also worth highlighting again that the South Creek Sector Review, led by Infrastructure NSW as part of its delivery of the State Infrastructure Strategy 2018, identified that a business-as-usual approach to land-use and water cycle management would compromise the Western Parkland City outcomes, and that an integrated land-use and water cycle management approach would best deliver the outcomes (INSW 2019).

Table 5 Ambient water quality of waterways and waterbodies in the Wianamatta–South Creek catchment

Water quality objectives	
Total Nitrogen (TN, mg/L)	1.72
Dissolved Inorganic Nitrogen (DIN, mg/L)	0.74
Ammonia (NH_3-N, mg/L)	0.08
Oxidised Nitrogen (NOx, mg/L)	0.66
Total Phosphorus (TP, mg/L)	0.14
Dissolved Inorganic Phosphorus (DIP, mg/L)	0.04
Turbidity (NTU)	50
Total Suspended Solids (TSS, mg/L)	37
Conductivity (µS/cm)	1103
pH	6.20–7.60
Dissolved Oxygen (DO, %SAT)	43–75
Dissolved Oxygen (DO, mg/L)	8

Table 6 Ambient stream flows to protect waterway and water dependent ecosystems in the Wianamatta–South Creek catchment

Flow related objectives		
	Current* (apply to 1st and 2nd order streams)	**Tipping point** (apply to ≥3rd order streams)
Median daily flow volume (L/ha/day)	71.8 ± 22.0	1,095.0 ± 157.3
Mean daily flow volume (L/ha/day)	2,351.1 ± 604.6	5,542.2 ± 320.9
High spell (L/ha/day) >90th percentile daily flow volume	2,048.4 ± 739.2	10,091.7 ± 769.7
Freshes (L/ha/day) ≥ 75th and <90th percentile daily flow volume	327.1 to 2,048.4	2,642.9 to 10,091.7
Cease to flow (proportion of time/y)	0.34 ± 0.05	0.03 ± 0.01
Cease to flow – duration (days/y)	39.2 ± 8	3.9 ± 1.2
Baseflow index	0.13 ± 0.02	0.30 ± 0.02

* gauging station data (1990–2019) in South Creek at Elizabeth Drive (212320)

8. Technical support to demonstrate compliance with the performance criteria

The performance criteria are relevant to waterways in the entire Wianamatta–South Creek catchment. Notably they are a mandatory consideration for all new urban developments on land in the Western Sydney Aerotropolis and Mamre Rd Precinct, where they must inform the stormwater and WSUD requirements. The performance criteria were developed using the protocols outlined in the Australian Water Quality Guidelines (Commonwealth of Australia 2018), which have been operationalised in NSW via the *Risk-based Framework for Considering Waterway Health Outcomes in Strategic Land-use Planning Decisions* (Dela-Cruz et al. 2017). The Risk-based Framework has been used in 2 companion studies, to develop stormwater quality and quantity management targets and exemplar WSUD strategies that achieve the performance criteria (DPIE 2022a, c). The targets are included as standard planning requirements in respective development control plans (DPIE 2021b; WSPP 2021a), and the WSUD strategies are included in a technical compliance guide that is referenced in the Western Sydney Aerotropolis Precinct Plan (WSPP 2022).

The technical compliance guide (DPE 2022d) was specifically commissioned to address stakeholder feedback on the need for technical support to shift towards the new or 'beyond business-as-usual' approach to stormwater management (Appendix F). As such, the purpose of the technical compliance guide is to support state and local government planning teams in their assessments of state significant developments, state significant infrastructure and development applications. The technical compliance guide responds to widely used industry standard software and includes calibrated modelling parameters, a (MUSIC) model and a post processing tool to make it easy for stormwater engineers to assess whether their WSUD strategies comply. The exemplar WSUD strategies provided with the technical compliance guide include options to achieve the performance criteria at the allotment, estate or more regional catchment scale and have been optimised to be as cost effective as possible. The preferred regional strategy involves integration of WSUD with a reticulated stormwater harvesting system that is best managed by a regional trunk drainage manager. A staged approach to regional delivery has been provided as an interim measure for the trunk drainage manager. The approach is based on setting aside a proportion of the site for WSUD (e.g. onsite wetland, storage and irrigated pasture) to achieve the objectives initially and then decommissioned and developed into industrial lots with all drainage contributing to a regional treatment and harvesting scheme.

8.1 A note on transferability

The numerical values of the performance criteria are specific to the Wianamatta–South Creek catchment. This means that they cannot be used as instream water quality and flow related objectives in other waterways. It is most likely that the *types* of performance criteria are transferable however, and current work is now underway to specifically assess the transferability of the flow related objectives *types* to other waterways in coastal NSW.

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11. More information

- Australian Land Use and Management Classification Version 8
- Australian Water Quality Guidelines
- Blacktown City Council Local Strategic Planning Statement
- Camden Council Local Strategic Planning Statement (PDF 14.5MB)
- Campbelltown City Council Local Strategic Planning Statement
- Elvis – Elevation and Depth – Foundation Spatial Data
- eWater Source model
- Fairfield City Council Local Strategic Planning Statement (PDF 11MB)
- Geoscape Buildings
- Hawkesbury City Council Local Strategic Planning Statement (PDF 9.1MB)
- Land and Soil Capability Mapping for NSW
- Liverpool City Council Local Strategic Planning Statement (PDF 10MB)
- NSW Government Water Sharing Plans
- NSW Landuse 2017 v1.2
- NSW Marine Estate Management Strategy 2018–2028 (PDF 12.3MB)
- Penrith 1:100 000 Geological Map
- Penrith City Council Local Strategic Planning Statement (PDF 17MB)
- Risk-based Framework for Considering Waterway Health Outcomes in Strategic Land-use Planning Decisions (PDF 1.4MB)
- Soil and Land Resources of the Hawkesbury-Nepean Catchment
- State Environmental Planning Policy (Precincts – Western Parkland City) 2021
- The Hills Shire Council Local Strategic Planning Statement (PDF 13MB)
- WaterNSW Continuous water monitoring network
- Western Sydney Hydrogeological Landscapes: May 2011 (First Edition)
- Wollongong Port Hacking 1:100 000 Geological Map

Appendix A – Community environmental values and uses identified through local government consultation

On 13 February 2020, the Environment, Energy and Science Group of DPIE convened a workshop with 16 council representatives from 6 LGAs making up the Wianamatta–South Creek catchment. Representatives from The Hills Shire Council and Hawkesbury City Council were unable to attend.

The purpose of the workshop was to:

- identify key community groups for an engagement strategy
- collect data on community environmental values and uses as defined under the National Water Quality Management Strategy and reflected in the NSW WQOs. The underlying assumption is that council representatives have in-depth knowledge of their waterways and community expectations based on past engagement activities.

Table 1 in Section 4.1 of this document provides a summary of the data collected at the workshop, and the figures below capture the location of key environmental assets and management issues within each LGA.

Blacktown City Council identified the following key assets that their local communities use for recreation, amenity and a sense of place to value: chain of ponds/unnamed tributary of Little Creek, several fishing locations along the tidal and freshwater parts of South Creek, freshwater wetlands, Blacktown Showground, Nurragingy Reserve near Eastern Creek, Lake Woodcroft, Bells Creek, Marsden Creek, Angus Creek and Bungambie Creek. Representatives highlighted management issues related to flood prone land downstream of Richmond Rd and Marsden Rd, water quality and weeds.

Penrith City Council only listed Tench Reserve as an asset but highlighted the need for blue and green infrastructure in the new urban release areas. Representatives highlighted management issues related to flooding, weeds and major changes to the flow regime of ephemeral creeks in newly urbanised areas like Erskine Park.

Fairfield City Council identified the Western Sydney Parklands as their key asset and raised concerns about the management of creeks in private ownership. Liverpool City Council indicated they were mapping the blue and green grid, and flagged that the planning for the Western Sydney Aerotropolis will be determining how the blue and green grid will be managed into the future.

Camden Council identified that their WSUD infrastructure and many of their creeks are the key assets their local communities use for secondary contact recreation and amenity. The main management issue is the risk that private ownership of creeks poses to these values, and a main management strategy is the harvesting of stormwater and roof water. The LGA of Campbelltown City Council is mostly outside of the Wianamatta–South Creek catchment, but the council identified visual amenity of the waterways as a key value of their local communities and stormwater runoff as a key management issue.

A total of 83 community groups were identified by the councils as key stakeholders for engagement. Unfortunately, these groups were not engaged directly (through a face-to-face workshop) due to COVID-19 restrictions. The online public consultation that was conducted in the summer of 2021 returned a combined total of 202 votes for the full range of environmental values and uses in the area (see Figure 3, Section 4.1).

Figure 17 Key environmental assets and management issues in the Blacktown City Council and Penrith City Council LGAs

Figure 18 Key environmental assets and management issues in the Fairfield City Council, Liverpool City Council, Camden Council and Campbelltown City Council LGAs

Appendix B – Aggregation of drainage areas

This appendix describes the aggregation of Sydney Water's 195 drainage areas into 47 drainage areas (see Section 5.3). The number of drainage areas needed to be reduced to ensure there was enough ecological data in each drainage area to develop empirical stressor–ecosystem response relationships.

The boundaries of the 47 drainage areas were delineated using 5 m resolution elevation and depth data (Elvis – Elevation and Depth – Foundation Spatial Data) and the hydrological terrain modelling tools available in ArcGIS version 10.4. The boundaries of the resulting drainage areas were then manually edited using the stormwater network to reflect changes to the natural drainage from urbanisation. The stormwater network datasets were sourced from all councils in the Wianamatta–South Creek catchment.

The alignment between Sydney Water's 195 drainage areas and the 47 drainage areas developed in this study was assessed by intersecting the 2 spatial datasets, and determining the proportion in which Sydney Water's drainage areas fell within the 47 drainage areas. Note that in most cases, the boundaries of the 47 drainage basins aligned with the boundaries of groups of Sydney Water's drainage areas. This means that the daily flows from Sydney Water's drainage areas could either be simply summed or multiplied by the proportional area. Figure 19 provides a summary of the key steps for the alignment.

B.1 Quantifying the magnitude, duration and frequency of each flow related objective

The mean value of daily flows, high spells, freshes, low spells, baseflow indices and cease to flow were calculated following the methods outlined in the hydrostats package (Bond 2021) available in R statistical software (version 4.1.1). This package uses the Lyne and Hollick baseflow filter to derive the baseflows, and standard percentiles to estimate the magnitude of the daily flows, high spells and low spells. The numerical range of the freshes were determined manually in excel, as were the frequency and duration of the different flow related objectives including the cease to flow. Frequency was determined by counting the number of times the percentile was encountered in a calendar year, and the duration was determined by counting how long each of the flow events lasted within that percentile. The average duration of all events for a calendar year was calculated using the following equation: total duration in a calendar year/frequency of event in a calendar year. The frequency and duration statistics were double checked by manually inspecting each time series of flows. An example of the events is shown in Figure 20 and Table 7 provides a summary of the flows for each of the 47 sub-catchments.

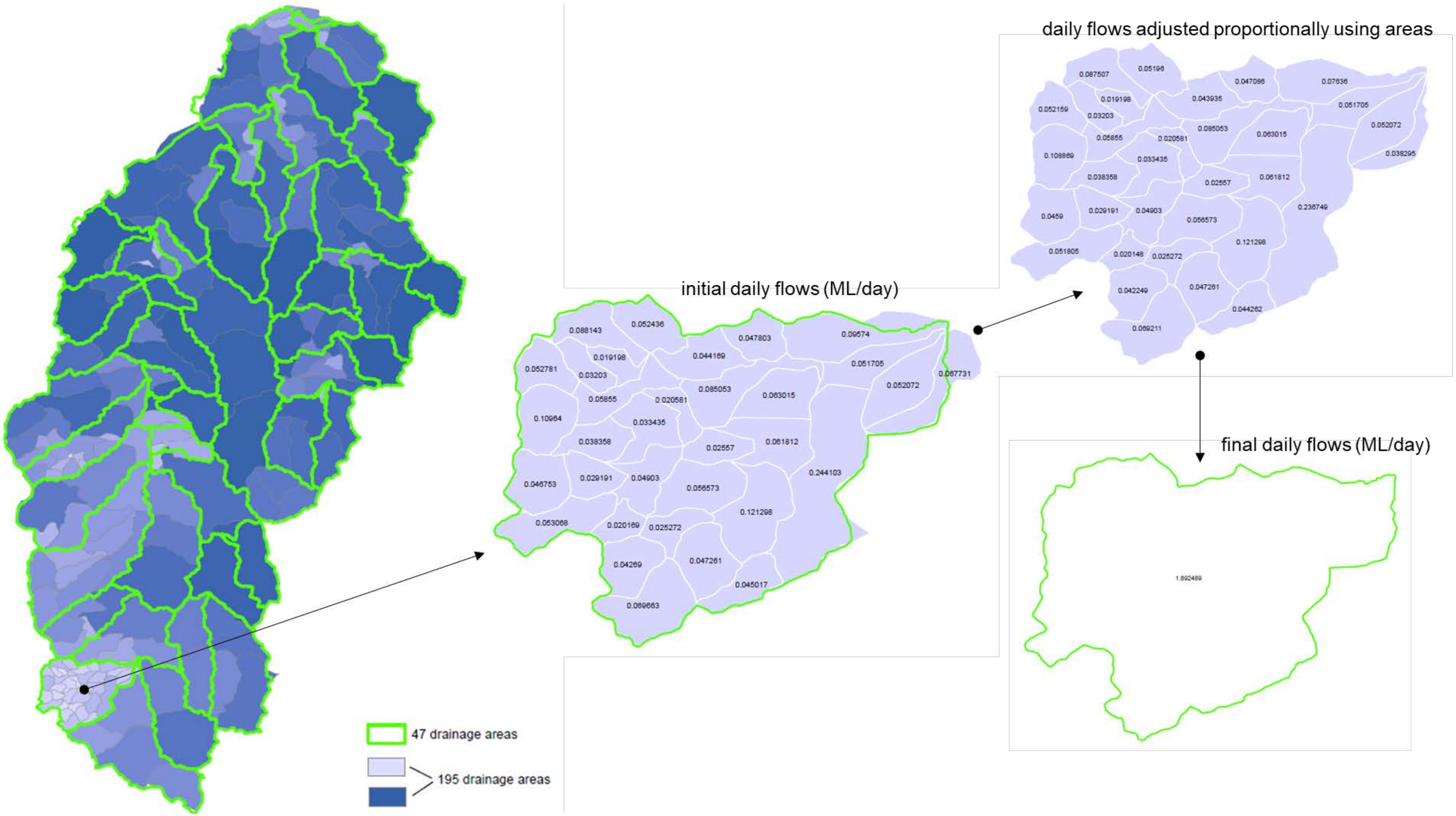

Figure 19 Checking the alignment between Sydney Water's 195 drainage areas and the 47 drainage areas used in this study

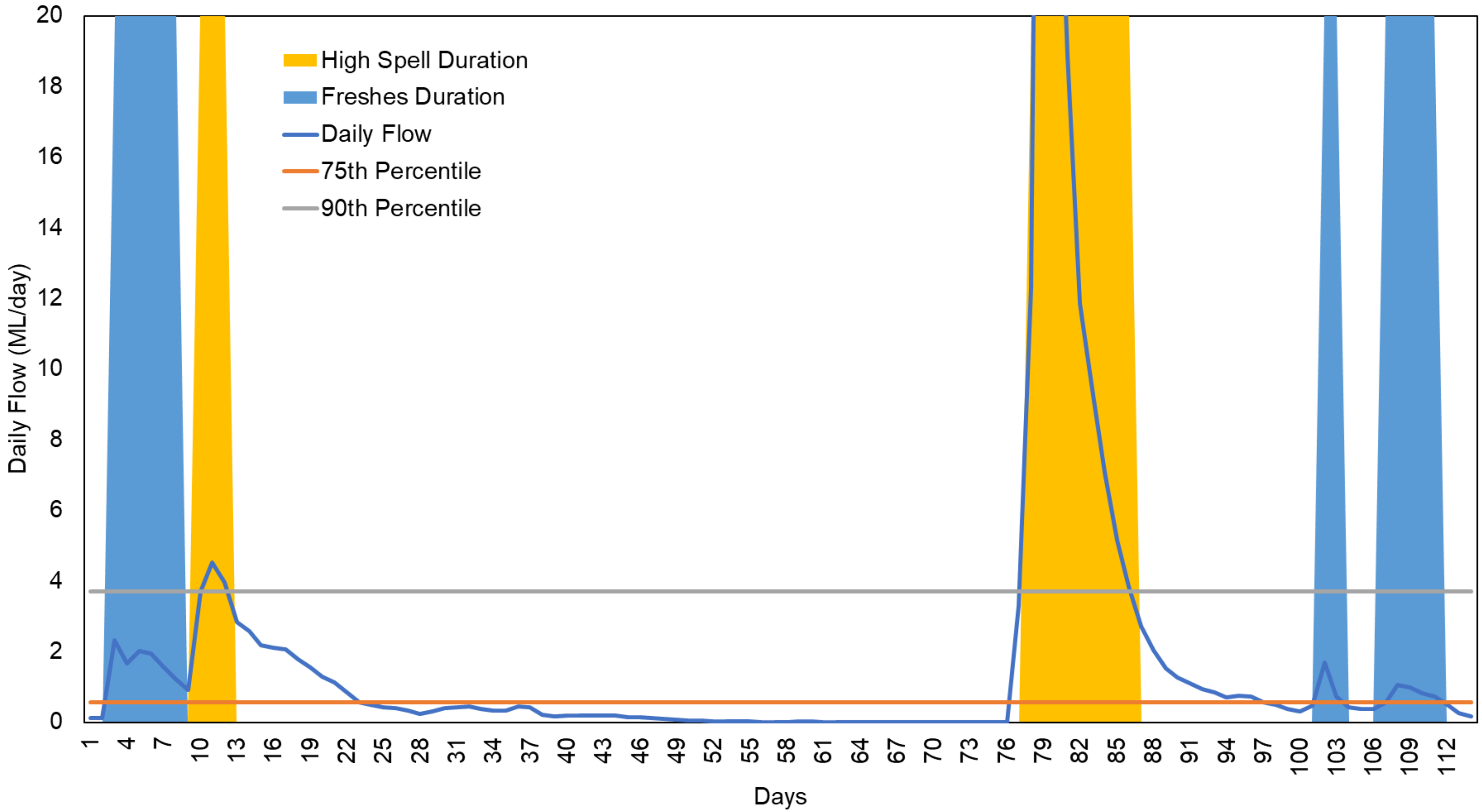

Figure 20 Characterisation of flow events observed at the gauging station in South Creek at Elizabeth Drive (212320)

Table 7 Modelled flows* for 47 main drainage areas in the Wianamatta–South Creek catchment, derived from the Sydney Water Source Model

Drain-age area #	Area (ha)	Median daily flow (L/ha/d)	Mean** daily flow (L/ha/d)	High spell – Q90 (L/d)			Freshes – lower limit Q75 (L/d)			Low spell – Q10 (L/d)			Base** flow (L/ha/d)	Flow group
				Vol.** (L/ha/d)	Freq. (#/y)	Dur. (d/y)	Vol.** (L/ha/d)	Freq. (#/y)	Dur. (d/y)	Vol.** (L/ha/d)	Freq. (#/y)	Dur. (d/y)		
1	657.6	236.9	13,103.9	29,611.4	24.0	1.6	1,736.0	13.3	1.1	236.9	5.4	8.4	86.6	1
2	791.8	206.3	2,412.6	4,552.5	21.1	1.8	770.3	11.8	1.2	196.8	6.5	6.7	133.1	2
3	2,203.8	297.7	1,985.8	3,550.7	20.4	1.8	743.3	11.0	2.0	70.7	7.1	6.1	208.9	2
4	1,038.3	207.5	2,417.2	4,559.3	21.2	1.8	772.4	11.7	1.2	150.1	6.5	6.7	134.0	3
5	965.4	221.3	3,459.7	6,682.2	22.5	1.7	881.0	11.5	1.3	161.4	6.6	6.6	140.3	3
6	1,381.2	207.0	1,883.9	3,337.3	18.6	2.0	662.6	11.3	1.2	112.8	7.1	6.1	134.8	2
7	1,083.4	301.6	1,883.6	3,271.3	19.4	1.9	702.4	10.9	1.2	143.8	7.1	6.2	211.5	2
8	1,420.8	106.4	1,331.4	1,862.3	14.8	2.6	451.0	11.0	1.2	109.7	6.4	6.3	57.4	2
9	1,895.5	208.3	2,178.9	3,997.9	20.8	1.8	699.6	11.6	1.2	82.2	7.0	6.3	138.1	2
10	1,490.6	328.6	1,812.8	3,004.8	20.0	1.9	715.3	11.0	1.2	104.5	6.7	6.5	232.3	2
11	2,207.5	104.6	1,230.8	1,757.9	15.8	2.4	437.7	10.8	1.2	70.6	6.9	6.3	59.4	2
12	115.1	440.3	4,176.4	4,747.9	13.0	2.9	1,433.1	9.9	1.2	1,354.1	6.1	7.1	239.8	3
13	842.0	388.7	4,631.3	5,833.4	14.3	2.6	1,615.2	9.0	1.2	185.0	5.5	8.9	177.9	3
14	1,402.3	383.9	6,138.3	10,367.5	20.8	1.8	1,976.3	9.0	1.2	111.1	5.5	8.0	171.1	1
15	1,215.5	391.0	4,847.0	6,096.0	15.1	2.5	1,617.8	7.9	1.2	128.2	5.4	10.0	180.7	3
16	1,214.0	384.5	6,185.7	10,580.5	21.5	1.7	1,922.6	8.8	1.2	128.3	5.9	8.4	193.1	3
17	754.6	2,382.2	4,910.9	8,738.4	22.2	1.6	3,886.6	6.9	1.2	206.5	7.3	5.0	1,826.2	3
18	1,049.2	391.0	4,964.4	7,422.1	18.0	2.1	1,771.7	9.0	1.2	148.5	5.4	9.2	174.7	3
19	1,021.1	2,576.4	3,770.1	6,227.0	17.0	2.4	3,934.0	5.2	1.2	152.6	6.7	6.6	2,061.1	3
20	2,600.0	2,374.9	4,400.0	7,907.4	20.8	1.8	3,936.5	6.7	1.3	59.9	7.0	6.3	1,843.7	3

Drainage area #	Area (ha)	Median daily flow (L/ha/d)	Mean** daily flow (L/ha/d)	High spell – Q90 (L/d)			Freshes – lower limit Q75 (L/d)			Low spell – Q10 (L/d)			Base** flow (L/ha/d)	Flow group
				Vol.** (L/ha/d)	Freq. (#/y)	Dur. (d/y)	Vol.** (L/ha/d)	Freq. (#/y)	Dur. (d/y)	Vol.** (L/ha/d)	Freq. (#/y)	Dur. (d/y)		
21	2,218.2	350.6	7,715.1	14,348.4	23.2	1.6	2,125.6	10.7	1.2	70.2	5.2	9.0	148.9	1
22	606.6	2,087.1	6,441.0	12,014.3	24.0	1.5	3,681.3	8.3	1.1	256.8	7.2	6.2	1,595.1	3
23	1,103.3	2,592.3	6,111.5	11,373.1	22.7	1.6	4,520.9	8.4	1.2	141.2	6.6	7.0	1,996.9	3
24	2,091.2	1,304.3	7,046.7	13,534.3	24.5	1.5	2,482.4	9.7	1.2	74.5	7.1	6.2	964.7	3
25	304.8	597.1	8,001.7	16,582.9	24.5	1.5	1,627.4	11.2	1.2	511.2	6.5	6.6	414.7	3
26	1,465.9	278.5	7,971.9	15,068.5	23.4	1.6	1,769.9	10.3	1.2	106.3	5.3	8.0	131.0	1
27	847.4	259.7	9,223.0	17,874.5	24.3	1.5	1,687.4	10.5	1.2	183.9	5.5	9.3	123.3	1
28	1,068.9	1,448.3	8,568.0	16,712.5	24.7	1.5	2,988.1	11.0	1.2	145.8	7.1	6.6	1,081.3	3
29	1,033.4	258.0	9,057.0	17,375.0	24.0	1.6	1,737.1	10.5	1.2	150.8	5.7	8.1	121.3	1
30	1,658.3	233.7	12,017.6	26,384.3	24.2	1.5	1,656.6	12.3	1.2	94.0	5.8	7.9	89.3	1
31	1,064.0	2,196.3	5,791.0	10,443.8	23.1	1.6	3,821.7	8.2	1.2	146.4	6.9	6.5	1,667.6	3
32	665.0	242.7	10,234.7	20,794.5	23.7	1.6	1,674.7	11.5	1.2	234.3	5.4	9.5	108.5	1
33	1,467.4	613.8	8,896.7	19,421.2	23.6	1.6	2,360.3	10.5	1.1	106.2	6.1	7.5	374.8	3
34	269.8	840.7	5,993.0	13,595.3	16.1	2.3	3,478.6	10.5	1.2	577.5	6.1	7.1	446.3	3
35	1,077.7	478.5	7,858.9	15,001.6	22.7	1.7	2,329.9	10.8	1.2	144.6	6.4	6.7	257.5	3
36	273.7	253.4	2,388.8	4,673.0	16.7	2.3	1,159.7	10.5	1.2	569.3	6.2	6.8	137.7	3
37	657.5	838.3	5,691.3	12,645.0	15.8	2.4	3,386.3	10.4	1.2	237.0	6.0	7.1	447.1	3
38	443.9	175.2	1,362.1	2,091.8	17.6	2.1	516.1	10.5	1.2	351.0	6.8	6.4	121.4	2
39	2,304.6	978.6	5,678.3	9,923.3	6.9	5.7	3,197.7	5.8	2.3	67.6	6.0	7.4	489.5	3
40	1,292.0	914.5	5,385.5	9,499.8	6.5	6.2	2,996.7	5.0	2.6	120.6	5.4	8.2	462.1	3
41	1,205.2	638.2	6,238.6	9,994.2	20.6	1.8	2,397.8	9.2	1.1	129.3	6.1	7.0	373.3	3

Drain-age area #	Area (ha)	Median daily flow (L/ha/d)	Mean** daily flow (L/ha/d)	High spell – Q90 (L/d)			Freshes – lower limit Q75 (L/d)			Low spell – Q10 (L/d)			Base** flow (L/ha/d)	Flow group
				Vol.** (L/ha/d)	Freq. (#/y)	Dur. (d/y)	Vol.** (L/ha/d)	Freq. (#/y)	Dur. (d/y)	Vol.** (L/ha/d)	Freq. (#/y)	Dur. (d/y)		
42	814.7	777.3	5,449.8	9,558.0	17.5	2.1	2,663.8	8.3	1.2	191.2	6.0	7.4	453.0	3
43	5,104.7	1,499.7	4,689.5	8,271.3	17.4	2.2	3,294.0	7.9	1.2	30.5	7.1	6.4	992.0	3
44	1,388.7	222.7	1,601.1	2,679.8	18.9	2.0	629.6	10.9	1.2	112.2	7.4	5.9	153.8	2
45	2,137.0	138.9	1,609.7	2,610.8	17.4	2.2	575.1	11.9	1.2	72.9	7.1	6.3	86.0	2
46	2,774.1	226.6	1,683.3	2,791.0	17.7	2.1	641.9	11.4	1.2	56.2	7.4	5.8	153.0	2
47	1,892.3	1,748.5	5,646.3	10,438.2	23.8	1.6	3,201.3	9.3	1.2	82.3	7.2	6.0	1,299.4	3

* Cease to flow estimates for the 1st–2nd order streams and ≥3rd order streams were sourced directly from the available gauging stations that were located within the sub-catchment(s) of the specific flow group. These were the gauging station in South Creek at Elizabeth Drive (212320) and the gauging station in Ropes Creek at Debrincat Ave, respectively.

** Flow related objectives used for the hierarchical clustering of drainage areas.

Appendix C – Review of literature

C.1 Pressure–stressor–ecosystem response model (urban stream syndrome)

This section provides a summary of the literature that was used to inform the pressure–stressor–ecosystem response model described under Section 4.2 of this document. The model is based on the concept of the urban stream syndrome, with the percentage imperviousness in an urban area as a key pressure of the extent of ecological impact.

The following key words were used in the literature search: impervious surface cover, imperviousness, urbanisation, urban stream syndrome, urban ecology, urban hydrology.

Table 8 Literature used to inform the pressure–stressor–ecosystem-response model

Indicator	Response	Literature (see Section C.3 below)
Hydrological	Increased peak flow Decreased 'lag time' Decreased flood/flow duration Frequency of high-flow events Decreased baseflow	CWP 2003; Walsh et al. 2005a, b, Huang et al. 2008, Kauffman et al. 2009; Gholami et al. 2010; Haase 2009; Hawley and Bledsoe 2011; Miller et al. 2014
Physical	Increased channel size Altered channel geometry Decreased bank stability Decreased embeddedness Decreased baseload sediment Decreased bars and benches Decreased woody debris	CWP 2003; McBride and Booth 2005; Walsh et al. 2005a; Scheuler et al. 2009; Vietz et al. 2014; Blauch and Jefferson 2019
Water quality	Poor water quality	CWP 2003; Walsh et al. 2005a, b; Schueler et al. 2009; Davies et al. 2010; Wright et al. 2011; Tippler et al. 2012, Liu et al. 2013; Kim et al. 2016; Luo et al. 2018
Ecological	Decreased diversity of macroinvertebrate assemblages Decreased sensitivity of macroinvertebrate assemblages Degraded riparian conditions	CWP 2003; Walsh et al. 2005a, b; Davies et al. 2010; Barnum et al. 2017

*Details provided in Chirgwin W and Dela-Cruz J (2022) *Nominal impervious surfaces 2018: A dataset to quantify nominal impervious surfaces in the Greater Sydney Region*, NSW Department of Planning and Environment, Parramatta.

C.2 Flow related objectives

This section provides a summary of the literature that was used to identify the types of flow related objectives listed in Table 2, under Section 5.3.1 of this document. The focus of the review was to identify components of the flow regime or hydrograph that are essential for protecting and improving the health of waterways and water dependent ecosystems in urban areas. Note that many of the studies listed below are also reviews of the literature and almost all studies recommend that stream flows should be characterised according to the magnitude, duration and frequency of the specific flow related objective.

The following key words were used in the literature search: flow, ecology, urban stream, ecosystems, hydrology, environmental flow, stormwater, water requirements, flow regime, ecological response, flow requirements, flow metrics, storm flows, flow component.

Table 9 Literature used to inform flow related objectives that affect the ecological and geomorphic health of waterways in urban catchments, and maintain the flow requirements of associated ecosystems

Flow related objective	Literature (see Section C.3 below)
Daily flows	Poff et al. 1997; Olden and Poff 2003; Monk et al. 2007; Chowdhury et.al. 2012; McIntosh et al. 2013; Webb et al. 2013; Duncan et al. 2014; Kermode et al. 2016; Steel et al. 2017; Zeiger and Hubbart 2018; Yarnell et al. 2020
Baseflow	Poff et al. 1997; Mitchell et al. 2007; Monk et al. 2007; Chowdhury et.al. 2012; Walsh et al. 2012; Duncan et al. 2014; Fletcher et al. 2014; Yarnell et al. 2015; Bhaskar et al. 2016; Walsh et al. 2016; Gawne et al. 2018; Palmer and Ruhi 2019; Yarnell et al. 2020
High spell extent (Q90), duration and frequency	Richter et al. 1996; Poff et al. 1997; Cottingham et al. 2003; Olden and Poff 2003; Mitchell et al. 2007; Monk et al. 2007; Poff and Zimmerman 2010; Poff et al. 2010; Steuer et al. 2010; Shenton et al. 2011; Chowdhury et al. 2012; Walsh et al. 2012; McIntosh et al. 2013; Webb et al. 2013; Duncan et al. 2014; Fletcher et al. 2014; Yarnell et al. 2015; Steel et al. 2017; Opperman et al. 2018; Zeiger and Hubbart 2018; Horne et al. 2019; Palmer and Ruhi 2019; Pander et al. 2019; Yarnell et al. 2020
Low spell extent (Q10), duration and frequency	Richter et al. 1996; Jowett 1997; Poff et al. 1997; Cottingham et al. 2003; Olden and Poff 2003; Monk et al. 2007; Poff and Zimmerman 2010; Poff et al. 2010; Steuer et al. 2010; Shenton et al. 2011; Chowdhury et al. 2012; Walsh et al. 2012; Bradford and Heinonen 2013; McIntosh et al. 2013; Duncan et al. 2014; Fletcher et al. 2014; Yarnell et al. 2015, Kermode et al. 2016; Steel et al. 2017; Opperman et al. 2018; Zeiger and Hubbart 2018; Horne et al. 2019; Palmer and Ruhi 2019; Yarnell et al. 2020
Freshes extent (Q75), duration and frequency	Cottingham et al. 2003; Shenton et al. 2011; MDBA 2012; NCCMA 2017; Gawne et al. 2018; MDBA 2018; DPIE 2020a; DPIE 2020b; Amtstaetter et al. 2021;
Cease to flow	Jowett 1997; Cottingham et al. 2003; Shenton et al. 2011; Duncan et al. 2014; Gawne et al. 2018

C.3 Literature

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Appendix D – Hierarchical clustering

Figure 21 and Figure 22 show the results of our hierarchical clustering of the flow related objectives, which were used to quantify how the stream flows varied spatially across the Wianamatta–South Creek catchment. The hierarchical clustering was done on the modelled estimates of daily flow, high spells, freshes, low spells and baseflow objectives. The modelled estimates were initially categorised into quartiles to reduce the variability.

The main output of the hierarchical clustering is a dendrogram, which is shown in the top panel of each figure. The main use of a dendrogram is to work out the best way to allocate objectives, in our case drainage areas, into clusters or groups. The differences between the dendrograms in the figures relates to the clustering algorithm used. The agglomerative hierarchical clustering algorithm starts with 'n' clusters, where n is the number of drainage areas, and assumes that each drainage area is its own separate cluster (i.e. starts with n=47). The algorithm then tries try to find the most similar drainage areas (based on the flow related objective data) and group them, so they start forming clusters. The divisive hierarchical clustering algorithm goes the opposite way, by assuming as a starting point that all the drainage areas are one big cluster and then dividing (out) the most dissimilar ones into separate groups. Of significance is the similarity in the number of groups and the components of each group (i.e. which drainage areas are grouped together) produced by the different clustering methods, suggesting that the groupings are robust.

The bottom panel in each figure is a silhouette plot, which is used to identify the optimal number of groups. The general rule is to select the number of groups that maximises the silhouette width because groups are distinctive (far away from each other). The silhouette width ranges between –1 and 1, with 1 indicating good consistency within groups. As shown in Figure 21 and Figure 22, the optimal number of groups is 3, with the grouping arising from the divisive hierarchical clustering having marginally greater silhouette width.

The last section of this appendix (Section D.1) provides a summary of the statistical analyses used to relate the ecosystem response indicators to the resulting flow groups (clusters), and assess whether the differences in the mean condition or state of the ecosystem response indicators between the flow groups are significant.

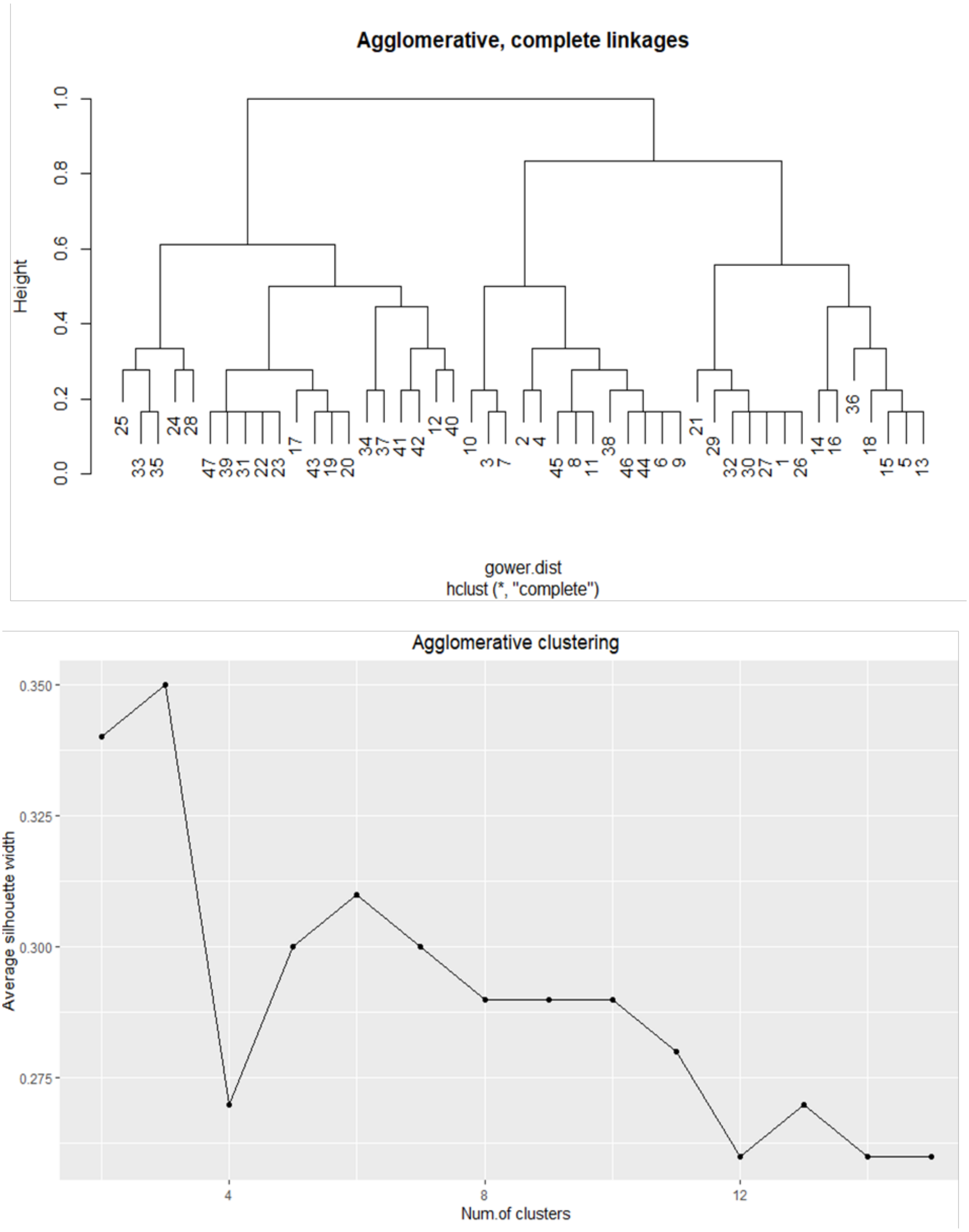

Figure 21 Dendrogram and silhouette plot resulting from the agglomerative hierarchical clustering of the flow related objectives for the 47 drainage areas in the Wianamatta–South Creek catchment

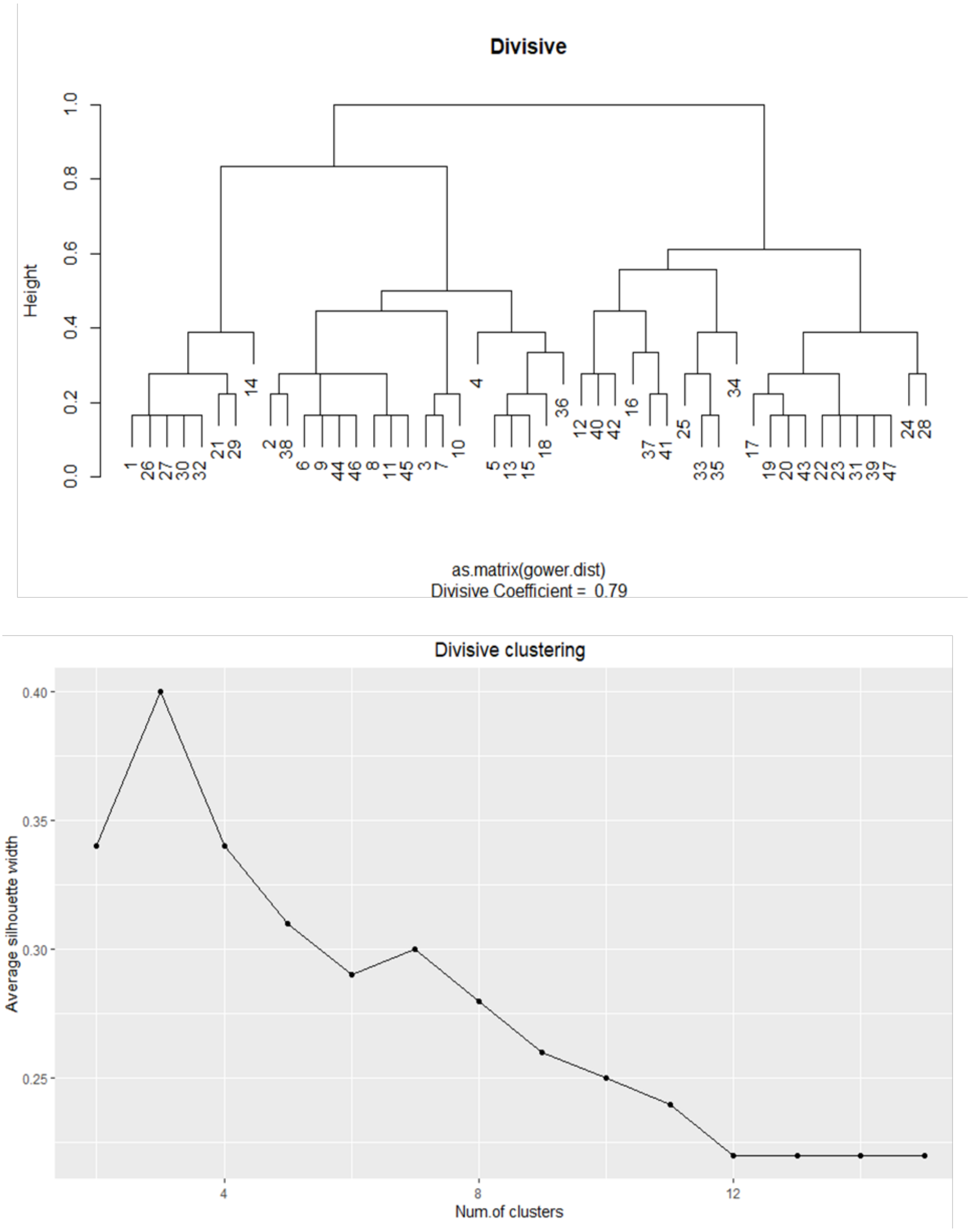

Figure 22 Dendrogram and silhouette plot resulting from the divisive hierarchical clustering of the flow related objectives for the 47 drainage areas in the Wianamatta–South Creek catchment

D.1 Statistical analysis to assess stressor–ecosystem response relationships

Figure 23 and Figure 24 shows the results of the non-parametric locally weighted smoothing (LOESS) used to identify the (non-linear) nature of the relationship between the flows and the condition of the riparian and instream habitats. The mean daily flow volume (MDF) was used as a surrogate stressor indicator to represent the other flow objectives, and the habitats used to represent the ecosystem response indicators. The LOESS shows an inflection point when the MDF is from 0.004–0.006 ML/ha/day for the riparian habitats (Figure 23), and from 0.002–0.004 ML/ha/day for the instream habitats (Figure 24).

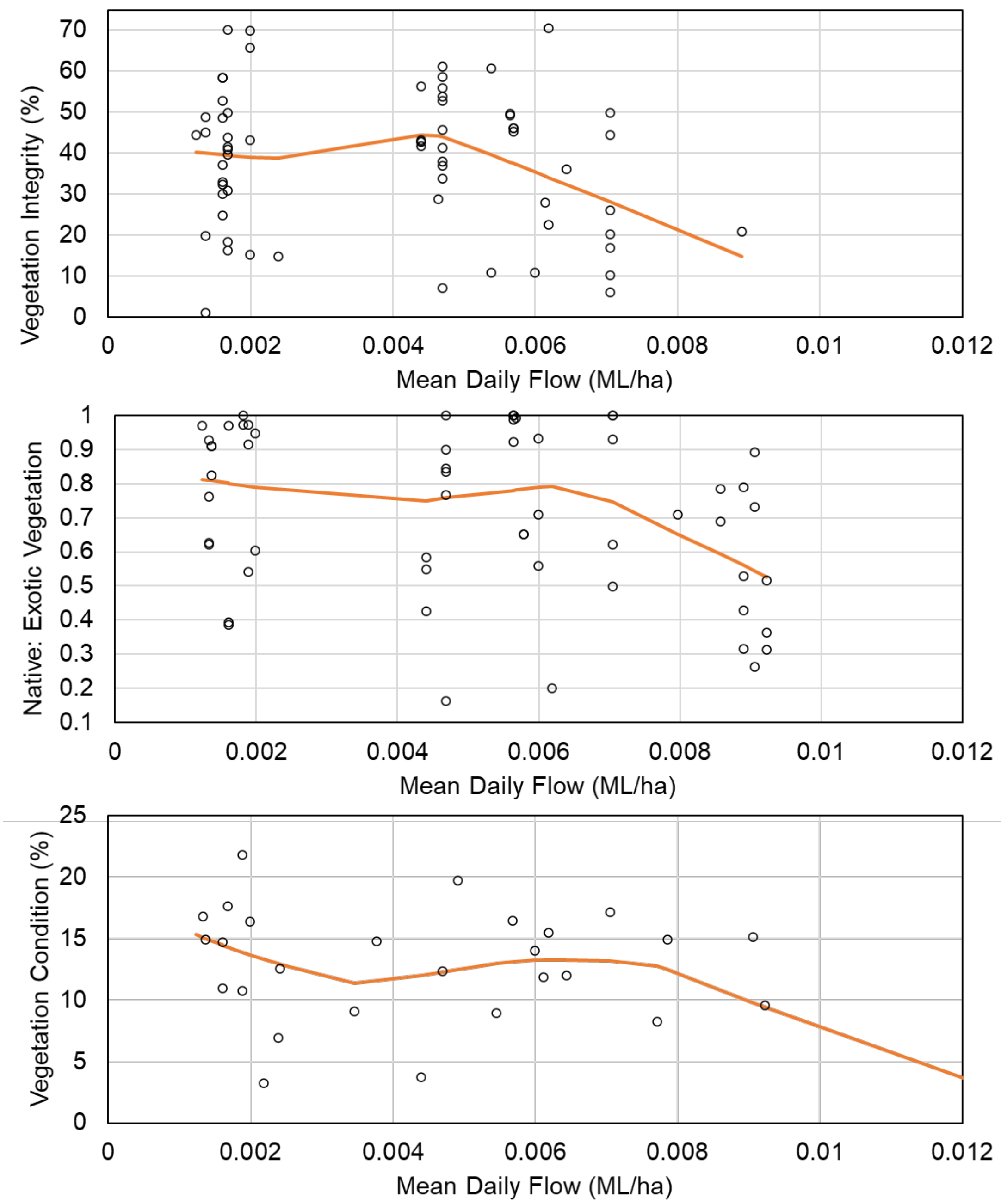

Figure 23 Non-parametric locally weighted smoothing to identify the nature of the relationship (orange line) between MDF and the condition of riparian vegetation habitats

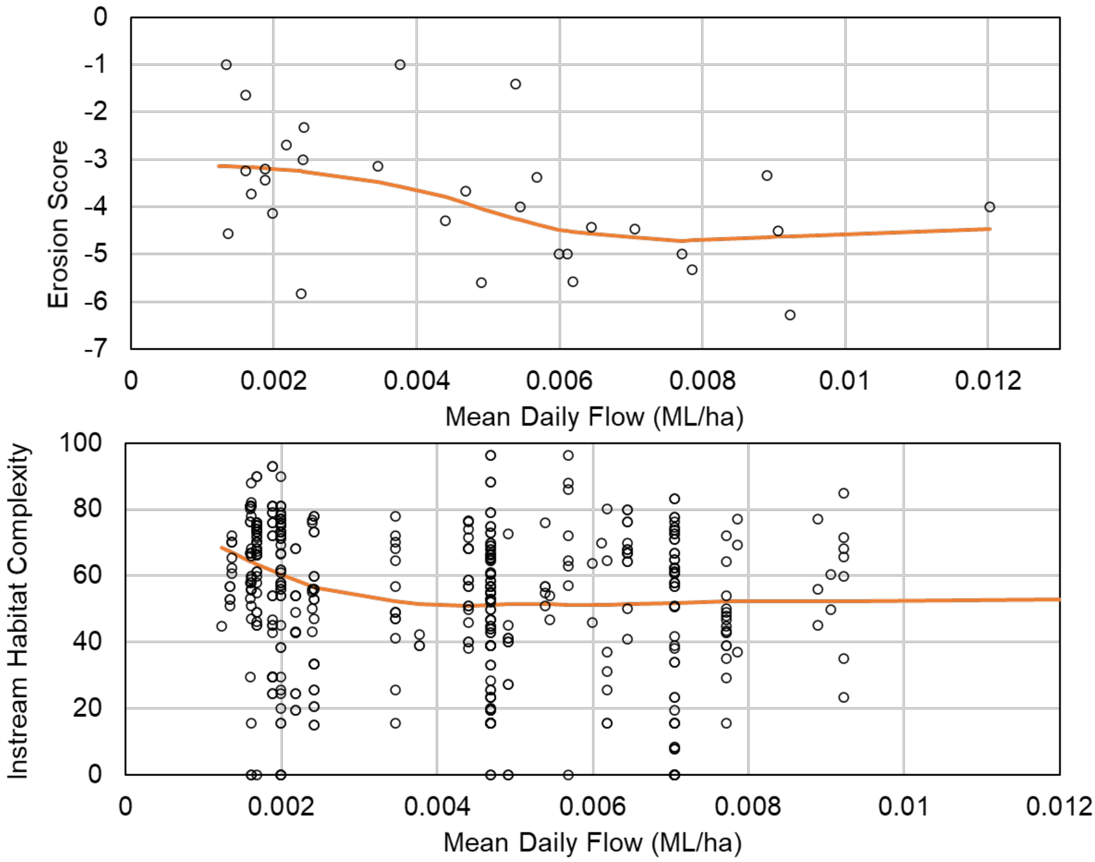

Figure 24 Non-parametric locally weighted smoothing to identify the nature of the relationship (orange line) between MDF and the condition of the stream bank and instream habitat

Table 10 and Table 11 provide the outputs of the ANOVA and Tukey's HSD, which showed that there are significant differences in the condition of stream bank and instream habitats between the groups. There are no significant differences in the condition of riparian vegetation.

Table 10 Outputs of one-way ANOVA with unequal variances used to test differences in the means of the condition of the riparian vegetation, stream bank and instream habitats between the 3 flow groups identified via divisive clustering

		SS	*df*	*MS*	*F*	*p-value*
Vegetation integrity	Between	191.8	2	95.9	0.3	ns* (0.73)
	Within	18,484.8	62	298.1		
	Total	18,676.6	64			
Native: exotic	Between	0.3	2	0.2	2.9	ns* (0.07)
	Within	3.0	54	0.1		
	Total	3.3	56			
Vegetation condition	Between	991.4	2	495.7	2.9	ns* (0.06)
	Within	81,422.8	477	170.7		
	Total	82,414.2	479			
Erosion	Between	73.8	2	36.9	4.1	<0.05
	Within	4,270.2	477	9.0		
	Total	4,344.0	479			
Instream habitat complexity	Between	11,693.2	2	5,846.6	12.1	<0.0001
	Within	229,821.8	477	481.8		
	Total	241,515.0	479			

* not significant

Table 11 Outputs of Tukey's HSD post hoc testing of mean differences in the condition of the stream bank and instream habitats between the 3 flow groups identified via divisive clustering

		BAU vs current	BAU vs tipping	Current vs tipping
Erosion	*Q stat*	3.9	3.1	2
	p-value	<0.05	ns* (0.07)	ns* (0.34)
Instream habitat complexity	*Q stat*	3.2	0.09	6.8
	p-value	ns* (0.06)	ns* (0.90)	<0.01

* not significant

Appendix E – Landscape features

Table 12 provides a summary of the datasets used to define the pressures and inherent landscape features of the Wianamatta–South Creek catchment that are shown in Figure 10, under Section 5.4.

Table 12 Pressures and inherent landscape features of the Wianamatta–South Creek catchment

Attribute	Description	Data source	Relevance
Land use	The NSW Landuse 2017 dataset captures how the landscape in NSW is being used for food production, forestry, nature conservation, infrastructure and urban development. It can be used to monitor changes in the landscape and identify impacts on biodiversity values and individual ecosystems. Land-use information uses the Australian Land Use and Management (ALUM) Classification Version 8 (ABARES 2016). In this study, each ALUM classification was broadly categorised into either 'Agriculture', 'Urban', 'Forest' or 'Not Assessed'.	NSW Landuse 2017 v1.2	Land use is a major factor influencing the health and condition of waterways. A higher prevalence of agricultural or urban land uses is generally correlated with poorer waterway health and condition.
Nominal imperviousness surfaces	Impervious surfaces capture areas that are not permeable to rain and runoff, such as roads and houses. Geoscape Buildings, which contains digital representation of buildings across Australia, was combined with ALUM classifications (ABARES 2016) of Airports (5.7.1), Roads (5.7.2), Railway (5.7.3), and Stormwater (6.4.3) from the NSW Landuse 2017 dataset to create an impervious surfaces dataset.	Geoscape Buildings NSW Landuse 2017 v1.2	Impervious surfaces are a driving force behind changes to catchment hydrology. A greater prevalence of impervious surfaces is associated with flashier hydrology, lower base flows, and increased channel incision.
Soil landscapes	Soil landscapes are areas of land that 'have recognisable and specifiable topographies and soils, that are capable of presentation on maps, and can be described by concise statements'. Six soil landscapes are mapped within the Western Sydney Aerotropolis area: Blacktown (bty), Luddenham (luz), Rickabys Creek (rcz), Picton variant a (pnza), South Creek (scy), Second Ponds Creek (spz).	Soil and Land Resources of the Hawkesbury-Nepean Catchment	Landscapes can be used to distinguish mappable areas of soils because similar causal factors are involved in the formation of both landscapes and soils. Similarly, constraints to rural and urban development of land are related to both landscape and soil limitations (see DPIE 2021c)

Attribute	Description	Data source	Relevance
Lithology	Lithology captures the underlying bedrock and was created by combining Penrith and Wollongong Geological Survey maps to cover the study area.	Penrith 1:100 000 Geological Map Wollongong Port Hacking 1:100 000 Geological Map	Lithology is one factor that influences water chemistry, with changes to area geology being reflected as changes to baseline water chemistry, including hardness, pH, and electrical conductivity.
Hydrogeological landscapes (HGL)	HGLs enable an understanding of how differences in salinity are expressed across the landscape and provide a tool to target a specific combination of land-use activities where they will provide the best salinity management outcomes. The Western Sydney HGLs that cover the Aerotropolis area are: Shale Plains, Upper South Creek, Mt Vernon, Mulgoa HGL, Greendale.	Western Sydney Hydrogeological Landscapes: May 2011 (First Edition)	When used for salinity management, HGLs describe the landscape impacts and hazards of salinity in an HGL unit. They consider risks associated with land salinity, instream salt load, and instream electrical conductivity, as well as the overall salinity hazard posed by the HGL unit (DPIE 2021d)
Water erosion	Water erosion hazard refers to the likelihood of soil detachment and movement under the effects of raindrop impact, initiation of runoff, and flowing water. The mapping is based on an 8-class system with values ranging between 1 and 8 that represent an increasing water erosion hazard.	Land and Soil Capability Mapping for NSW	The amount of water erosion is controlled by the slope gradient and length, erodibility of the soil, and the amount of vegetation cover on the landscape (OEH 2012).
Soil acidification	Soils vary considerably in their natural acidity status and in their buffering capacity to resist changes in pH. The climate imposes an acidification potential on the soil by providing a leaching regime than can drive acidifying processes, especially nitrate leaching, but also by increasing plant growth and the plant related acidifying processes such as nitrogen fixation. The mapping is based on an 8-class system with values ranging between 1 and 8 that represent an increasing soil acidification hazard.	Land and Soil Capability Mapping for NSW	Soil acidification impacts on vegetation include direct impact on biological and plant growth systems, increased presence of some toxic elements, including aluminium at pHCaCl levels below 4, reduction in availability of some plant nutrients. The resulting poor plant growth means increased potential for soil erosion and increased recharge into groundwater systems leading to increased salinity hazard reduced biodiversity.

E.1 Statistical analyses to assess pressure–stressor relationships

This section of Appendix E provides the outputs of the statistical analyses used to assess the relationships between the pressures and the mean daily flow volume (MDF). The MDF was used as a representative surrogate for the spatial variability of all other flow objectives described in Section 5.3 and Appendix C.

Non-parametric locally weighted smoothing (LOESS) was specifically used to identify the relationship between the MDF and the percentage of dominant land uses and percentage imperviousness in the Wianamatta–South Creek catchment. The mean differences between the percentage of dominant land uses and imperviousness of each of the 3 flow groups were assessed via a one-way ANOVA with unequal sample sizes and post hoc Tukey's HSD test. The independent variable was the flow group and the dependent variable the percentage areas of agricultural, urban, native vegetation and imperviousness.

As shown in Figure 25, the highest MDF occur in drainage areas with the greatest percentage of urban land and imperviousness. Lowest MDF occur in drainage areas with the lowest percentage of urban land and imperviousness but greatest percentage of agricultural land. There is a clear inflection point when the MDF is from 0.004–0.006 ML/ha/day.

Table 13 and Table 14 provide the outputs of the ANOVA and Tukey's HSD, which showed that there are significant differences in the percentage of urban and agricultural land and imperviousness between the groups. Both the LOESS and ANOVA showed there are no differences in the percentage of remnant native vegetation (viz. 'forested').

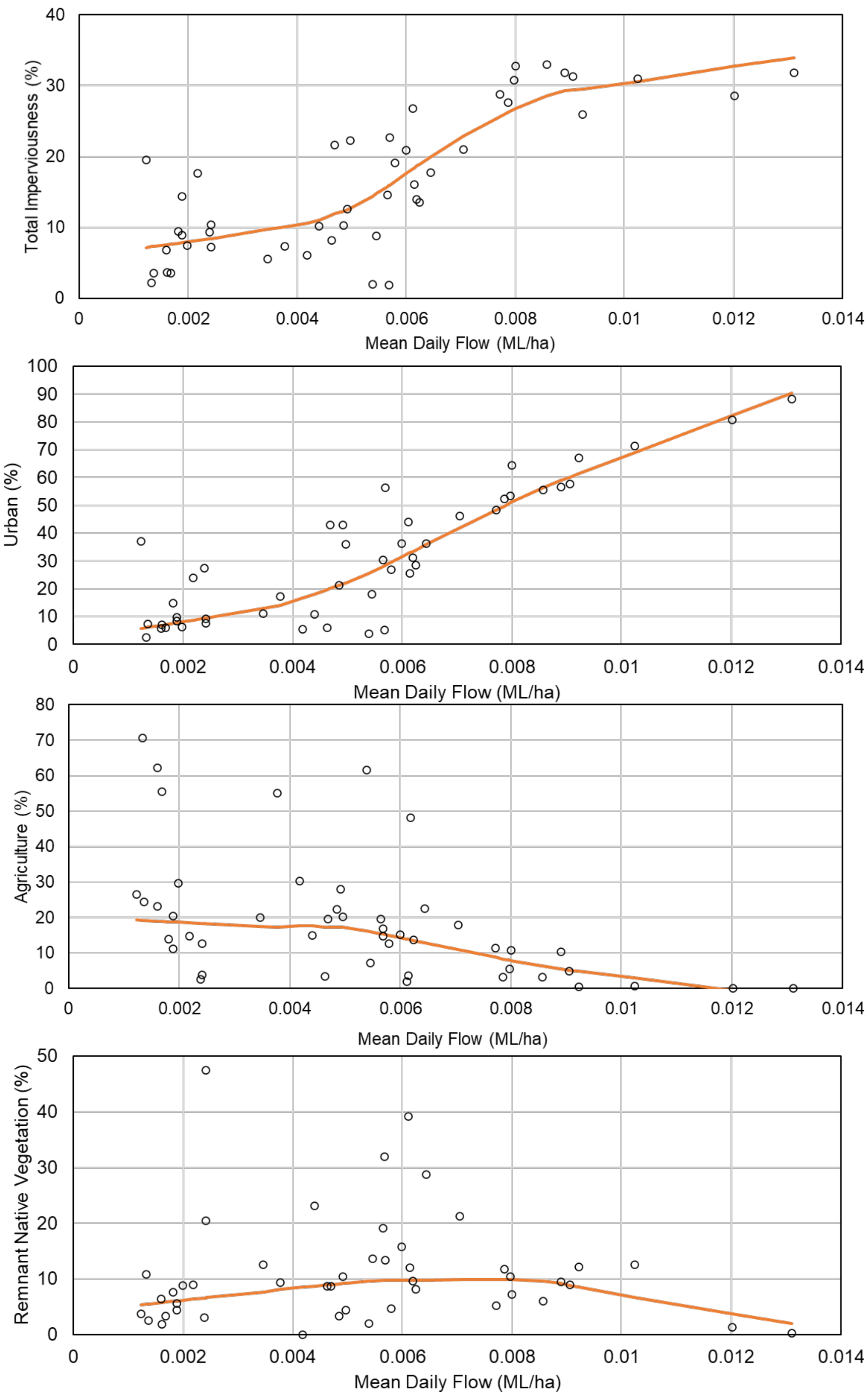

Figure 25 Non-parametric locally weighted smoothing to identify the nature of the relationship (orange line) between MDF and the percentage imperviousness and dominant land use

Table 13 Outputs of one-way ANOVA with unequal variances used to test differences in the means of the percentage of dominant land uses and imperviousness between the 3 flow groups identified via divisive clustering

		SS	*df*	*MS*	*F*	*p-value*
Imperviousness	Between	1,795.1	2	897.6	14.3	<0.0001
	Within	2,753.5	44	62.6		
	Total	4,548.7	46			
Urban	Between	12,069.3	2	6,034.7	21.2	<0.0001
	Within	12,511.4	44	284.3		
	Total	24,580.7	46			
Agriculture	Between	3,332.9	2	1,666.5	6.6	<0.01
	Within	11,114.6	44	252.6		
	Total	14,447.5	46			
Remnant native vegetation	Between	204.4	2	102.2	1.1	ns* (0.35)
	Within	4,231.7	44	96.2		
	Total	4,436.1	46			

* not significant

Table 14 Outputs of Tukey's HSD post hoc testing of mean differences in percentage of dominant land uses and imperviousness of the 3 flow groups identified via divisive clustering

		BAU vs current	BAU vs tipping	Current vs tipping
Impervious	*Q stat*	7.6	5.3	3.8
	p-value	<0.01	<0.01	<0.05
Urban	*Q stat*	9.2	6.5	4.6
	p-value	<0.01	<0.01	<0.01
Agriculture	*Q stat*	5.1	3.4	2.8
	p-value	<0.01	ns* (0.05)	ns* (0.13)

* not significant

Appendix F – Stakeholder feedback on performance criteria

Ahead of the public exhibition of performance criteria in the draft Aerotropolis Precinct Plan, we conducted a series of workshops with state and local governments, industry practitioners and academia, as a requirement for setting objectives under the Risk-based Framework and the Australian Water Quality Guidelines (Commonwealth of Australia 2018).

Table 15 provides a summary of targeted consultation with subject matter experts prior to a broader stakeholder workshop. Table 16 provides a summary of the feedback of the broader workshop, which was held on 19 October 2020 and convened by an independent chair. There were 57 participants of this workshop, with representatives from the following:

- Western Sydney Planning Partnership
- DPIE – Environment, Energy and Science Group
- DPIE – Place Design and Public Spaces
- DPIE – Water
- Department of Primary Industries – Fisheries
- Infrastructure NSW
- NSW Environment Protection Authority
- Greater Sydney Commission
- WaterNSW
- Sydney Water
- Penrith City Council
- Liverpool City Council
- Alluvium Consulting
- CTENVIRONMENTAL
- Aurecon

The purpose of the broader workshop was to seek feedback and endorsement on the performance criteria (objectives) and the stormwater and WSUD strategies for achieving them in the Aerotropolis. The latter strategies were developed by Sydney Water, who was responsible for developing the integrated water cycle management plan for the Aerotropolis. The workshop was designed to support EES in identifying what is needed for them to finalise their advice to Western Sydney Planning Partnership Office for final endorsement and inclusion of the performance criteria in the final Aerotropolis Precinct Plan.

Overall, the participants supported the science that informed the objectives and the objectives themselves; however, they highlighted 4 key issues with delivery:

1. costs for achieving the objectives and ongoing maintenance of infrastructure
2. governance in ongoing management of waterways and stormwater and WSUD infrastructure
3. consideration of impacts of achieving objectives on flood behaviour
4. technical capacity of state and local governments to assess compliance with objectives, and for the urban development industry to provide solutions.

In direct response to this feedback, EHG commissioned a technical guide for stakeholders to demonstrate compliance with the objectives in the most cost-effective manner (DPE 2022d). While the guide does not resolve issues related to funding or governance, it provides a range of WSUD strategies for achieving the performance criteria. The recommended strategy is via regional reticulated stormwater harvesting as it is the most cost effective and achieves the Parkland Vision (DPE 2022c). A staged strategy is also provided to allow time for development of relevant policy and/or legislative settings for regional infrastructure delivery.

Table 15 Feedback arising from targeted consultation with subject matter experts

Subject matter experts	Feedback
DPIE – EES (Science, Economics and Insights Division – Water, Wetlands and Coasts Science Branch) who undertake similar work for estuaries	• Recognised the complexity and challenges • Agreed and supported methods for deriving objectives, and robustness of analysis – recommended that the flow ecology relationship focus on a tipping point • Concern that the WQOs are too lenient – raised an issue that setting objectives that are less stringent upstream compared to downstream is problematic and non-intuitive, but conceded that the soils, geology, other landscape hazards and low flows in the South Creek catchment would lead to this outcome. If feasible (i.e. opportunity to access sites), they recommended that we undertake soil sampling, and extend to leachate analysis to justify the WQOs being proposed
Independent external reviewer (academia) – national expert on urban waterway health management and green infrastructure	• Recognised the complexity and challenges • Agreed and supported methods for deriving objectives, and robustness of analysis • Concern that environmental outcomes will be hampered by who will fund and be the ongoing managers of the infrastructure and ongoing maintenance
Independent external reviewer (industry) – national expert on stormwater and flow modelling, and who provides expert advice to the Independent Planning Assessment Committee	• Agreed and supported how we have used the Sydney Water modelled flows, and in particular how we have accounted for the uncertainty in the modelled data • Identified that cease to flow components are important for Wianamatta–South Creek, and these can be used as a surrogate for baseflows and low spells in absence of better data
DPIE – Water – Water Science	• Raised significant concerns that flow objectives are being developed, because these will have implications for water sharing plans. It was agreed that there is a need to change the terminology to note the distinction • Highlighted that they needed more time to 'digest' the information and assess potential conflicts. It was agreed that DPIE – Water would review this document prior to public release
Infrastructure NSW	• Concerned about the ability of industry to achieve the 0.9 ML/ha/year for 1st–2nd order streams, without significant impact on land availability and costs; however, agreed with approach to limit to these sensitive streams • Indicated that types of flow objectives used in water sharing plans have a different intent to those being used in this study

Table 16 Feedback arising from a large stakeholder workshop held in October 2020

Stakeholder	Feedback
Penrith City Council	• Consideration must be given to how EES's work correlates to tree canopy cover targets, and how WSUD elements (to achieve the objectives) in the public domain can be used most effectively to care for trees and other green infrastructure • Not all council staff were able to attend the early part of the workshop, but council has discussed this work before with the project team in previous consultation • This work is supported in principle but noting that (in achieving the objectives) councils are not responsible for maintaining assets in industrial areas • Reservations are to do with costs (e.g. street trees) for maintenance and ownership (e.g. wetlands in open space) of infrastructure required to achieve objectives • Need clarity on integration of this work with flooding • Overall great work on waterway management but still need to better understand funding (including long-term renewal) and governance issues. Also need to consider cost–benefits, etc.
NSW Environment Protection Authority	• Impacts on flood behaviour need to be considered in regard to the vegetation and the associated tipping points and recommendations for 1st and 2nd order streams • Presentations insightful, lots of information to unpack this issue • Key pieces needed include engagement, with a good communication strategy on Parkland Vision. Needs to be a story about transition, and how we move to this approach to bring everyone along • Costs and practicality and what it means for house prices, buildings and land take. Economic piece is critical to define what are the bottom line costs for achieving the objectives – affordability is important • Adaptive pathway – EPA thought the WSUD scenarios to demonstrate how the objectives could be achieved were 'black and white', i.e. more scenarios are needed • Governance needs to be clarified on how to move to this approach • How can this work be integrated into BASIX? • The work needs to include the role of treated water from the Sydney Water Factory and reuse options as they will compete with some of the solutions discussed today. As well it will also inform the design of the new plant. Needs some discussion and the contribution of the treated water to flow if needed • This is really vital work and discussion – our challenge is the how and who to get this through and integrated. Without it, we cannot get the blue and green corridors with integrity for future despite the high-level objectives in all other plans
Western Sydney Planning Partnership Office	• The Western Sydney Street Design Guidelines include WSUD as a requirement in all local streets. Part of the solution for achieving the objectives should include trees

Stakeholder	Feedback
Infrastructure NSW	• Presentations insightful • Costs for achieving objectives are around 50–70% greater than current costs, plus land take for wetlands at 5% of catchment, street trees, stormwater harvesting, etc. How do we look at implementability? – current WSUD approach hard to construct and maintain but expecting more now • Building capacity for industry – how to get industry to adopt approach and get expertise to show compliance against new objectives • Flooding work needs to be integrated, because there will also be land take of detention basins – need to avoid double up • We are still a way from meeting the outcomes of the Risk-based Framework (OEH 2017) which calls for a 'Strategic Impact Assessment' of any proposed measures to 'assess the feasibility in achieving the options', to ensure that the selected management responses are reasonable, practical and cost effective
WaterNSW	• Warragamba pipeline is at risk of being knocked off anchor block through flood events. There needs to be a balance between flood detention versus water retention issue • Pre and post development flows objectives need to be included in development control plans to manage them • Modelling – assumptions for permeability are critical. How can we make sure that permeability presented today (to achieve objectives) is incorporated into the development control plan?
DPIE – Water	• Interactions with *Water Management Act 2000* need to be considered in context of how solutions to achieve objectives work with floodplain harvesting and existing farm dams • No comment on objectives without understanding the methods on how they were developed. There is other work going on around the state on environmental watering requirements and there needs to be consistency
Sydney Water	• Integration of this work with flood management is underway • Clear about the governance and sustainable funding for infrastructure – there are processes in play and it's important to get that right (e.g. previous work of Infrastructure NSW) • When it comes to development, we need to be clear what we are asking of them to make sure the options are clear to everyone. So, guidance on achieving the objectives needs to be clear • Sydney Water encountered major challenges with land acquisition for stormwater and flooding in Rouse Hill. The planning work will need to understand 'highest and best use' for land to be acquired for public purposes, to achieve the objectives. The importance of land costs needs to be recognised • Development industry are happy to deliver to new approach/differently but need regulatory framework; the biggest issue is that the new approach has to be done from first development, otherwise there is a precedent that is set; applies to funding question; needs the right planning control

Stakeholder	Feedback
Aurecon	• Our consultation with Urban Development Industry Association (UDIA), big developers, are not opposed to healthy waterways and don't mind spending money but what they don't like/shy away from is the uncertainty of approvals. Time is money, they need assurance for their approvals. Has to be simple – no harder than what is currently happening, processes need to be seamless • Spending thousands on stormwater management measures that don't achieve what we want (like business-as-usual) is not reasonable, practical and cost effective. Sustainable funding and catchment wide coordination is essential
DPIE – EES	• Western Sydney Planning Partnership need to resolve the relationship between this work and objectives in engineering design guidelines • Funding and governance mechanisms for delivery are critical to achieving the objectives and hence vision for the Western Parkland City • Given development has already started, when finalising this work, there needs to be a consideration of timeline. This work needs to be included as early as possible