Department of Planning and Environment

Wianamatta-South Creek stormwater management targets

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Cover photo: Staff inspecting dragonfly pond at The Ponds. Blacktown City Council

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Published by:

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Pre-editorial review version issued to stakeholders, April 2022. This version will be replaced on the website after it has undergone the required editorial and publishing process.

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1. 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 outlines the methods for developing new construction and operational phase stormwater quality and quantity (flow) targets for new developments in Wianamatta-South Creek. The new targets are presented as standard planning requirements for stormwater infrastructure in both the Western Sydney Aerotropolis Development Control Plan - Phase 2, and Mamre Rd Precinct Development Control Plan.

The new targets were specifically designed to achieve ambient water quality and stream flow objectives, which have been used as performance criteria for protecting and restoring the waterways, riparian corridors and other water dependent ecosystems in the Wianamatta-South Creek catchment (DPE 2022a, b). Collectively these environmental features make up the natural blue grid component of the Blue and Green Infrastructure Framework for the Western Parkland City (GSC, 2018; DPE 2022 b, d).

This document is technical in nature and provides information on the [1]MUSIC model set up and calibration for developing the stormwater management targets, the translation of the ambient waterway objectives into stormwater targets to apply at the development scale. The document discusses the use of flow percentiles for integrated management of stream bed and bank erosion and environmental flow requirements of waterways and water dependent ecosystems.

This document provides background for the NSW Government *Technical guidance for achieving Wianamatta-South Creek stormwater management targets* (DPE, 2022c). It is part of a technical series of documents that have been released by the NSW Government to support precinct planning in Western Sydney, see:

- *Mapping the natural blue grid elements of Wianamatta-South Creek: High ecological value waterways, riparian vegetation communities and other water dependent ecosystems* (DPE, 2022d)
- *Performance criteria for protecting and improving the blue grid in Wianamatta-South Creek: Water quality and flow related objectives for use as environmental standards in land use planning* (DPE, 2022a)
- *Review of water sensitive urban design strategies for Wianamatta-South Creek* (DPE, 2022e).

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[1] MUSIC (Model for Urban Stormwater Improvement Conceptualisation) is an industry standard and widely used tool for developing water sensitive urban design strategies – see https://ewater.org.au/products/music/

3. Background

For the past 15 years, the business-as-usual approach to managing stormwater in New South Wales (NSW) is to apply a ‘one size fits all’ set of post development pollutant load reduction targets (85% TSS, 65% TP, 45% TN). These targets have inarguably facilitated greater adoption of water sensitive urban design (WSUD) across NSW, and are easy to understand and readily applied by the stormwater industry. These targets originated in the need to reduce stormwater nutrient loads to Port Phillip Bay in Victoria in the late 1990s (Harris *et al*., 1996) and in understanding the cost-effectiveness of stormwater treatment systems. Soon after, the NSW Government recognised the pragmatic approach to setting the targets but also noted that they are ‘*generally insufficient to result in no environmental impacts*’ under a Greenfield development scenario (Figure 1, DECCW and SM-CMA, 2008). Consequently, the targets were recommended (to be used) as a *starting point* or *minimum* level of treatment for all developments, with requirements to consider the risks of impacts on community environmental values and uses of waterways before their adoption in local and state planning documents. This recommendation has been adopted in varying ways by local authorities. For example, the Wollongong City Council Development Control Plan specifies that the targets may be adjusted by the Council, particularly for developments located in sensitive catchments. Other Councils have two sets of targets, with the other set based on a Neutral or Beneficial Effect outcome (e.g. Mid-Coast Council), as done for high environmental value waterways in Sydney’s Drinking Water Catchments. Overall, however, the targets have been broadly applied without much consideration of risks associated with the differing sensitivities of waterways, the differing quality and quality of stormwater generated by different development types (residential versus industrial) and the differing development scenarios (Greenfield versus Re-development). Moreover, a growing body of contemporary literature indicates that the targets are ineffective in protecting freshwater ecosystems if other drivers of ecological health, such as stream flows and geomorphology, are not considered (Burns *et al*. 2012; Walsh *et al*. 2012; Fletcher *et al*., 2014; Walsh *et al*. 2016; Vietz *et al*., 2016; Kermode *et al*., 2020).

To support decisions on the extent of stormwater management required above the minimum level, the NSW Government released the ‘Risk-based framework for considering waterway health outcomes in strategic land use planning decisions’ (Dela-Cruz *et al*., 2017). The Risk-based Framework brings together the principles and strategies outlined in the National Water Quality Management Strategy, which the NSW Government adopted in 1992. It consists of five steps, aligned with the international standard for risk management and was designed as tool to support structured and transparent decision making. The Risk-based Framework has been identified as a key tool under the Marine Estate Management Strategy 2018-2028 to help drive improvements in stormwater management in NSW. It has also been embedded in regional plans, including the Greater Sydney Region Plan (GSC, 2018) and associated District Plans to address the cumulative impacts of urban development on receiving waterways.

In this document, we present the outcomes of our application of Steps 2 and 3 of the Risk-based Framework to generate a new set of stormwater quality and quantity (flow) targets for the Western Parkland City. This city is predominantly located in the Wianamatta-South Creek catchment, west of the Sydney Central Business District. It hosts Sydney’s second international airport and will be home to ~1.5 million people and support ~ 200,000 jobs. Urban planning for the city has been landscape led, with the waterways, riparian corridors and other water dependent ecosystems reconceptualised as essential city building infrastructure known as the blue grid (GSC, 2018; DPE 2022b). The new set of targets have been designed to achieve the performance criteria for the blue grid, which are established as ambient water quality and (stream) flow-related objectives in the Western Sydney Aerotropolis Precinct Plan (DPE, 2022a, b).

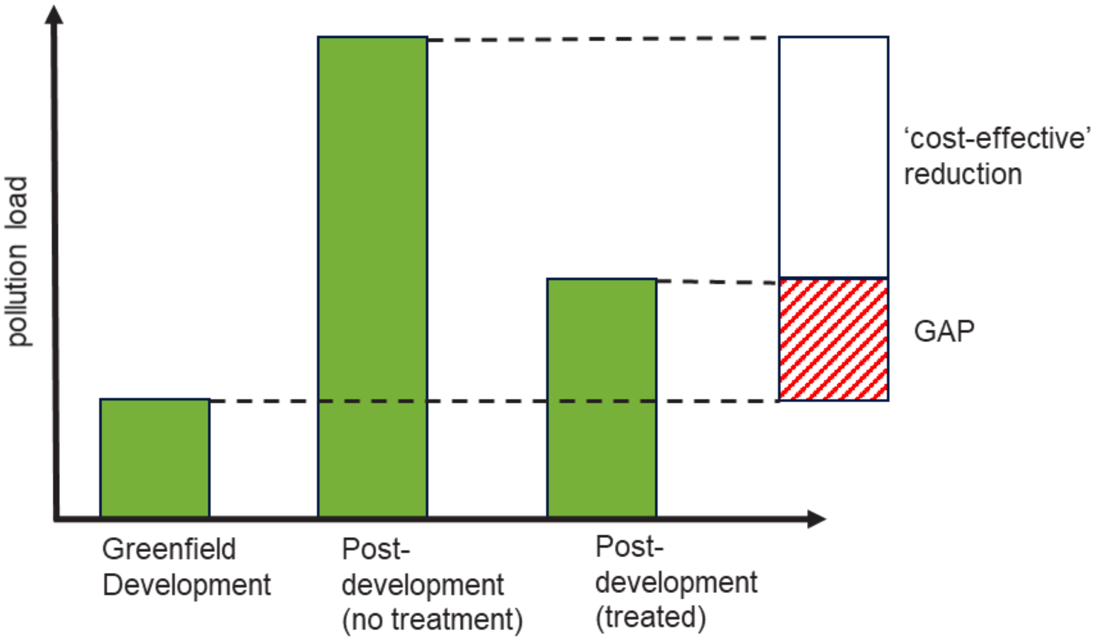


Figure 1 Starting point or minimum level of stormwater treatment for urban developments in NSW – originally based on assessments for Greenfield developments

3.1 Ambient water quality and (stream) flow-related objectives

Tables 1 and 2 provide the ambient water quality and (stream) flow-related objectives, which apply to all waterways in the Wianamatta-South catchment and should be used to inform stormwater and water sensitive urban design (WSUD) requirements. As indicated above, all new developments on land in the Western Sydney Aerotropolis precincts must show that they are achieving the objectives, as a mandatory requirement of the Precinct Plan.

The methods for deriving the objectives are presented in a companion study (DPE, 2022a). Generally, the water quality objectives are the in-stream or ambient concentrations of nutrients, sediments, salinity, pH and dissolved oxygen that are considered to be healthy for aquatic ecosystems. They were derived from an extensive database of field monitoring data using the referential approach methods outlined in the Australian Water Quality Guidelines 2018. The water quality objectives reflect inherent conditions such as soils and geology, and are consistent with the environmental standards that Councils in the area have already adopted for their state of environment reporting (e.g. BCC, 2021; LCC, 2021).

The flow-related objectives are the requirements of iconic and/or threatened species or communities and their associated habitats such as waterways and water dependent vegetation along the riparian corridors that make up the natural blue-grid. They were derived *via* an effects-based assessment that quantified the relationship between stream flows and the condition or health of the habitats. Streams flows were based on modelled data, calibrated against existing stream gauging stations. Habitat condition was based on field monitoring data. The specific numerical criterion selected for each flow-related objective was based on a 'tipping point' or threshold before the waterways, riparian corridors and groundwater dependent ecosystems are significantly impacted by stormwater discharges.

Table 1 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 2 Ambient stream flows to protect waterway and water dependent ecosystems in the Wianamatta-South Creek catchment

FLOW RELATED OBJECTIVES		
	1st and 2nd Order Streams **(CURRENT)**	≥ 3rd Order Streams **(TIPPING POINT)**
Median Daily Flow Volume (L/ha/day)	71.8 ± 22.0	1095.0 ± 157.3
Mean Daily Flow Volume (L/ha/day)	2351.1 ± 604.6	5542.2 ± 320.9
High Spell (L/ha/day) > 90th Percentile Daily Flow Volume	2048.4 ± 739.2	10091.7 ± 769.7
Freshes (L/ha/day) ≥ 75th and < 90th Percentile Daily Flow Volume	327.1 to 2048.4	2642.9 to 10091.7
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

4. Objectives and targets

There is a difference between the objectives for a waterway, and the stormwater management targets that the industry would use to design stormwater and WSUD infrastructure at the development scale:

- Waterway Objectives are recognised in the NSW Government Policy as the community environmental values and long-term goals for managing waterways. In this context, they are the environmental standards for delivering healthy waterways, riparian corridors and other water dependent ecosystems
- Stormwater Targets apply at the development scale to derive management strategies or options to ensure the waterway objectives are achieved – for example, a stormwater management target of 85% reduction in total suspended solid discharges from an urban development would contribute towards achieving an objective (e.g. Turbidity, 50 NTU) to have clear water (visibility) for swimming or for supporting particular aquatic habitat. The stormwater management targets that apply at the development scale generally relate to sizes of drainage areas above the 1st and 2nd order streams or smaller.

5. Approach to developing operational phase stormwater management targets

To translate the waterway objectives to stormwater targets, we developed calibrated MUSIC models for two drainage areas above two corresponding flow gauging stations (212048, 212320) within the vicinity of the Western Sydney Aerotropolis precincts (Figure 2). Both gauging stations are located within the main stem of Wianamatta-South Creek. The gauging station identified as 212048 is located at Great Western Highway, and the gauging station identified as 212320 is located at Elizabeth Drive.

We modelled the existing stream flows at the gauging stations and compared them to the stream flows under two post development scenarios that predominantly characterise the precincts in the Western Sydney Aerotropolis and Mamre Rd (DPIE, 2021; DPE, 2022b). A range of practically achievable water sensitive urban design (WSUD) strategies were subsequently designed, using the water quality and flow-related objectives as a benchmark for compliance (see DPE, 2022e). The range of WSUD strategies reflected differing approaches and costs of infrastructure delivery, which were identified through consultation with stakeholder and industry best practice. The final set of recommended stormwater management targets for Wianamatta-South Creek was based on the modelled flows and loads from the full range of WSUD strategies. The final set includes an explicit flow percentile target for managing stream bed and bank erosion, which was assessed against existing stream erosion indices.

The steps below outline the general method for developing the stormwater management targets:

1. Develop a calibrated MUSIC model, using local climate and existing/pre-development land use characteristics
2. Design a range of practical WSUD strategies, and assess their effectiveness in achieving the objectives using the calibrated MUSIC model
3. Develop operational phase stormwater management targets using the WSUD strategies that achieve the objectives:
    a. Flow targets - use ranges of flow percentiles based on the performance of the range of WSUD strategies

   b. Quality targets – assess the level of treatment of the WSUD strategies that achieved the flow objectives, and compare the resultant pollutant loads to a sustainable or total maximum annual load and adjust as needed (to meet the water quality objectives)

4. Assess the adequacy of flow percentiles in mitigating stream erosion

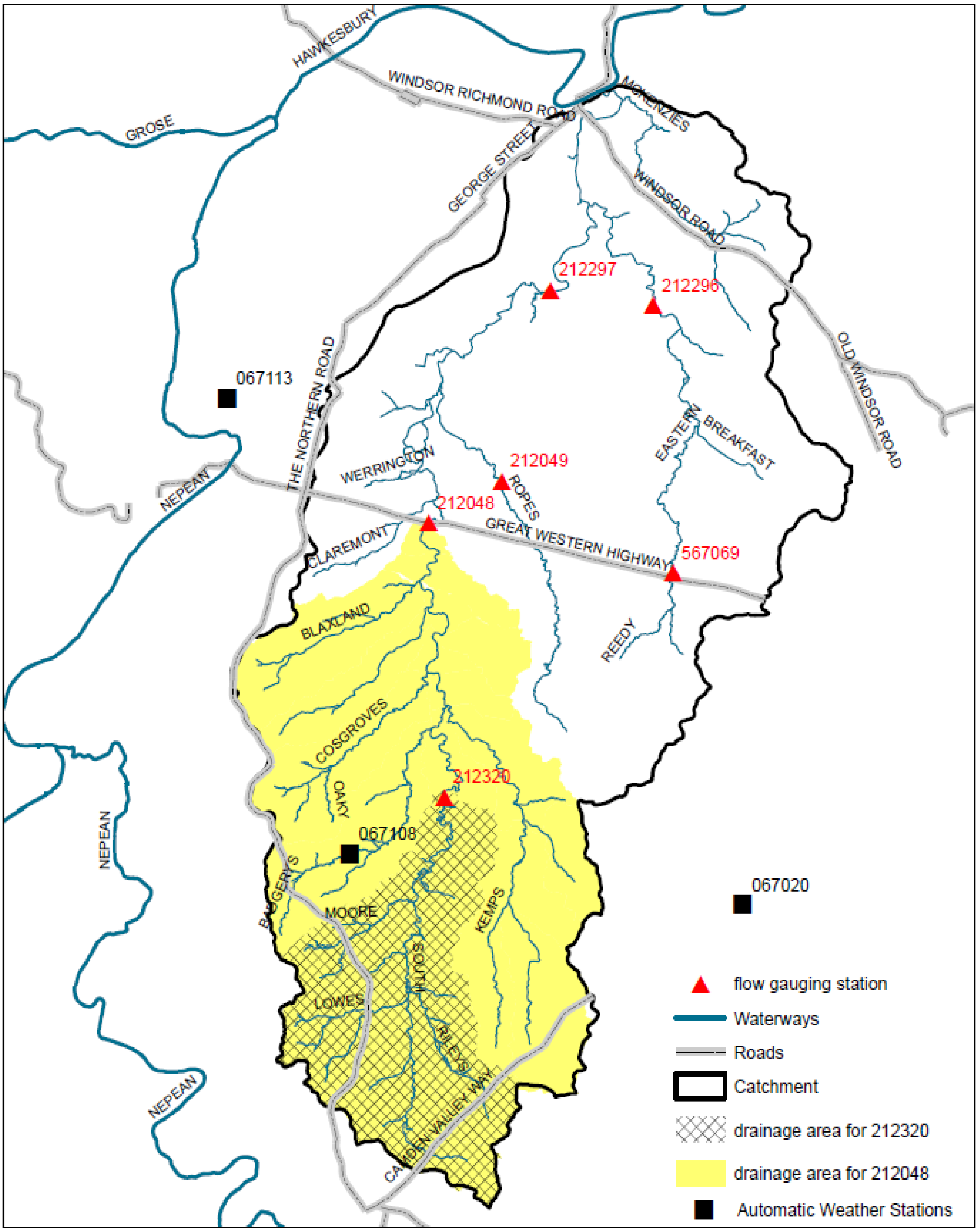


Figure 2 Drainage areas defining extent of calibrated MUSIC model, flow gauges and automatic weather stations.

6. MUSIC model development

MUSIC (Model for Urban Stormwater Improvement Conceptualisation) has become a widely adopted industry standard model for assessing compliance with stormwater management targets. It is for this reason that we used MUSIC to develop the operational phase stormwater quality and quantity (flow) targets for Wianamatta-South Creek. These targets are the ones that need to be achieved at the outlet of a development site, once the site has been fully developed (viz. ‘operational’).

The following sections outline the climate data used as input for MUSIC, the rationale for the parameters selected, the methods for calibration and results of testing or validating the (MUSIC) model performance.

6.1 Pluviograph data

A time series of 6-minute pluviograph data was required to adequately model the changes in surface runoff from new urban developments, as well as assess the effectiveness of proposed WSUD strategies in minimising the changes at the development scale.

A review of data from automatic weather stations within the Wianamatta-South Creek catchment showed the limited availability of a long time series of good quality data. The weather station identified as 067108 at Badgerys Creek was considered to provide the most geographically representative pluviograph data, but did not have enough sub-daily (6 min) data for use at the development scale. The data from this weather station was however used to validate the modelled outputs (see Section 6.7).

The review was extended to automatic weather stations outside of the Wianamatta-South Creek catchment, specifically focussing on the weather stations identified as 067020 at Liverpool (Michael Wended Centre) and 067113 at Penrith Lakes. These two weather stations had enough sub-daily (6 min) data for a period of > 5 years. To determine whether the rainfall falling outside of the Wianamatta-South Creek catchment is representative of the rainfall inside of the catchment, we compared a range of rainfall statistics among the weather stations (Table 3). This comparative analysis shows that the pluviograph data collected at the automatic weather station at Penrith Lakes appropriately represents rainfall within the Wianamatta-South Creek catchment and therefore adopted as the climate input for MUSIC.

Table 3 Rainfall statistics calculated from data collected at automatic weather stations

Statistic	Automatic Weather Stations		
	Badgerys Creek	Penrith Lakes	*Liverpool (Michael Wended Centre)
Mean annual rainfall (mm/y)	725	673	755
Highest annual rainfall (mm/y)	1094	1095	1044
Lowest annual rainfall (mm/y)	450	361	521
10th percentile of annual rainfall (mm/y)	531	467	648
Median annual rainfall (mm/y)	705	639	698
90th percentile of annual rainfall (mm/y)	950	935	996
Highest daily rainfall (mm)	139	200	135.8

Statistic	Automatic Weather Stations		
	Badgerys Creek	Penrith Lakes	*Liverpool (Michael Wended Centre)
Mean number of rainfall days (days)	130	113	114
Mean number of rainfall days > 1 mm (days)	71.08	66.4	81.55
Mean number of rainfall days > 10 mm (days)	21.48	19.6	22.27
Mean number of rainfall days > 25 mm (days)	7.04	6.28	7.09

* due to lack of recorded data, Liverpool statistics cover the period between 2002-2012, while statistics for the other two weather stations cover the period between 1996-2020.

6.2 Potential evapotranspiration data

The potential evapotranspiration (PET) data for MUSIC was sourced from the SILO Long Paddock database produced by the Queensland Government. The database provides daily meteorological datasets for a range of climate variables at 1 km spatial resolution. The Morton’s wet-environmental areal evapotranspiration for the Wianamatta-South Creek was extracted from the database and used as PET data for input to MUSIC. The monthly distribution of these data is presented in Table 4.

Table 4 Potential evapotranspiration data (PET)

Month	PET – mm/month
January	183
February	144
March	127
April	88
May	60
June	41
July	48
August	73
September	107
October	138
November	150
December	177
ANNUAL	1336

6.3 Time period

The period adopted for calibration of MUSIC is 2001-2007, simply due to the availability of fine scale/sub-daily (6 min timestep) pluviograph data required for this assessment.

6.4 Imperviousness

The imperviousness of the catchment plays an important role in the runoff characteristics, and is the parameter that MUSIC is most sensitive too. A spatial dataset of nominal impervious surfaces was sourced directly from the Department of Planning and Environment (Figure 3, Chirgwin and Dela-Cruz, 2022). This dataset was used to represent the existing total impervious area (TIA) in each of the two drainage areas. The TIA was then multiplied by 0.8 to derive effective impervious area (EIA, see BMT WBM, 2015) and used to parameterise MUSIC. Specifically, the adopted EIA of the drainage area above the flow gauging station identified as 212048 (Great Western Highway) is 8%, and the EIA of the drainage area above the flow gauging station identified as 212320 (Elizabeth Drive) is 10%.

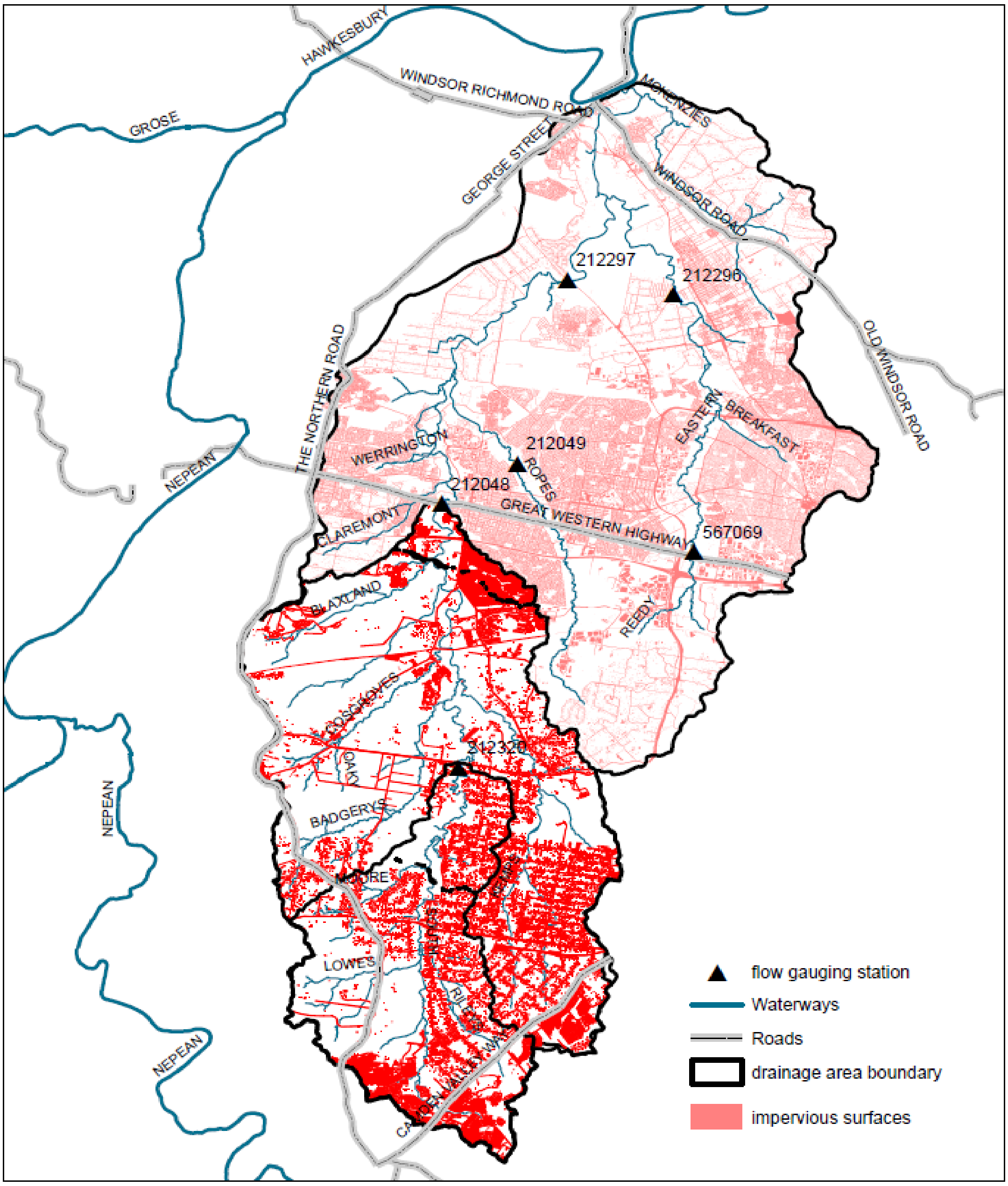


Figure 3 Nominal Impervious surfaces in the Wianamatta-South Creek catchment

6.5 Rainfall-runoff parameters

Translating rainfall to runoff in MUSIC requires specification of a suite of rainfall-runoff parameters. Table 5 shows the parameters that were used in MUSIC to develop the stormwater management targets. They represent parameters for existing/pre-development land uses.

As described in the next section, the parameters were derived from an iterative process using the rainfall-runoff parameters specified in the Penrith WSUD Technical Guidelines (PCC, 2015) as a starting point.

Table 5 Rainfall-runoff parameters for existing land use in the Wianamatta-South Creek catchment

Impervious Area Parameters	
Rainfall Threshold (mm)	2.5
Pervious Area Parameters	
Soil Storage Capacity (mm)	150
Initial Storage (% of capacity)	30
Field Capacity (mm)	130
Infiltration Capacity Coefficient – a	175
Infiltration Capacity Exponent – b	2.5
Groundwater Properties	
Initial depth (mm)	10
Daily Recharge Rate (%)	25
Daily Baseflow Rate (%)	1.4
Daily Deep Seepage Rate (%)	0.0

6.6 Stream routing

The Wianamatta-South Creek catchment is relatively elongated, with the length of ≥ 3rd order streams being relatively long. This means that flow leaving the 1st to 2nd order streams and associated upland drainage areas undergo significant routing, resulting in different hydrological characteristics as illustrated in Table 2.

To replicate routing within the main channel of the Wianamatta-South Creek catchment, we used the swale node in MUSIC, for model calibration. A standardised cross-section for a waterway was based on representative measurements of cross sections of creeks from within the catchment (DPE, 2022d). This approach to modelling ensured that:

- Nodes with the calibrated rainfall-runoff parameters generally replicate the hydrology of 1st and 2nd order streams (Table 2). Given the size of the upland drainage area of these streams, these nodes also replicate the typical hydrology at the development site scale
- Stream routing results in a hydrology that generally replicated the calibration sites and ≥ 3rd order streams.

6.7 Calibration

Model calibration is typically performed against observed/measured field data, in an attempt to replicate ‘real world’ conditions as accurately as possible. For this assessment however, MUSIC was calibrated against the modelled flow outputs of Sydney Water’s calibrated Source model (Sydney Water, 2021a). This is because the flow objectives were derived from the modelled outputs of the Source model (see DPE, 2022a), and also because of the longer time series of sub daily flows available (1998-2020) from the Source model. It is worth noting that 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, 2021a).

The selection of rainfall-runoff parameters was subsequently based on iterative MUSIC model runs using the Penrith City Council WSUD Technical Guidelines as a start. The parameters were adjusted until the MUSIC modelled flows represented the Source modelled flows at the downstream gauging stations (212048, 212320).

6.7.1 Statistical performance

The statistical performance of the rainfall-runoff parameterisation was assessed using the following criteria as set out by Moriasi *et al*. (2015), with model performance determined by the poorest performing of the criteria.

Nash-Sutcliffe efficiency (NSE) coefficient

The NSE coefficient is used to assess the predictive power of hydrological models. An efficiency of 1 corresponds to a perfect match of modelled discharge to the observed data (Table 6). An efficiency of 0 indicates that the model predictions are only as accurate as the mean of the observed data. An efficiency of less than 0 occurs when the observed mean is a better predictor than the model. The NSE coefficient is calculated using the following equation:

$$\mathrm{NSE} \qquad 1-\frac{\sum_{i=1}^{n}\left(O_i-P_i\right)^2}{\sum_{i=1}^{n}\left(O_i-\bar{O}\right)^2}$$

Percent bias (PBIAS)

PBIAS is the average tendency of modelled data to be greater or less than the corresponding observed data. The closer the PBIAS value is to 0, the better the fit between modelled and observed data (Table 6). PBIAS is calculated using the following equation:

$$\mathrm{PBIAS} \qquad \frac{\sum_{i=1}^{n} O_i - P_i}{\sum_{i=1}^{n} O_i}\times 100$$

Root Mean Squared Error (RMSE) to observed data standard deviation ratio (RSR)

Standard Regression (R^2)

RMSE is a goodness-of-fit measure for the collinearity between the modelled and observed data. The closer the R^2 value is to 1, the more closely correlated the two sets of data (Table 6). R^2 is calculated using the following equation:

$$R^2 \qquad \left[\frac{\sum_{i=1}^{n}(O_i-\overline{O})(P_i-\overline{P})}{\sqrt{\sum_{i=1}^{n}(O_i-\overline{O})^2}\sqrt{\sum_{i=1}^{n}(P_i-\overline{P})^2}}\right]^2$$

Table 6 General performance criteria for assessing the calibration of hydrological models (based on monthly time step; adapted from Moriasi *et al.*, 2015)

Performance Criteria	PBIAS (stream flow)	NSE	R^2
Very good	PBIAS < ±5	0.80 < NSE ≤ 1	$0.85 < R^2 \leq 1$
Good	±5 ≤ PBIAS < ±10	0.70 < NSE ≤ 0.80	$0.75 < R^2 \leq 0.85$
Satisfactory	±10 ≤ PBIAS < ±15	0.5 < NSE ≤ 0.70	$0.60 < R^2 \leq 0.75$
Unsatisfactory	PBIAS ≥ ±15	NSE ≤ 0.5	$R^2 \leq 0.60$
Very good	PBIAS < ±5	0.80 < NSE ≤ 1	$0.85 < R^2 \leq 1$
Good	±5 ≤ PBIAS < ±10	0.70 < NSE ≤ 0.80	$0.75 < R^2 \leq 0.85$

Table 7 shows the statistical performance of the MUSIC models for the period between 2001-2007. Figure 4 shows flow duration curves based on the modelled flows from MUSIC, modelled flows Source and the observed flows at the gauging stations. Overall, the MUSIC model performance is rated as satisfactory using the performance criteria presented in Table 6.

Table 7 Statistical performance of MUSIC models, which were developed for the drainage areas above flow gauging stations in South Creek. MUSIC modelled outputs were compared with the Source modelled outputs.

Drainage area	PBIAS (stream flow)	NSE	R^2	Acceptance
212048 – South Creek at Great Western Highway	-12.2	0.61	0.66	Satisfactory
212320 – South Creek at Elizabeth Drive	0.9	0.58	0.63	Satisfactory

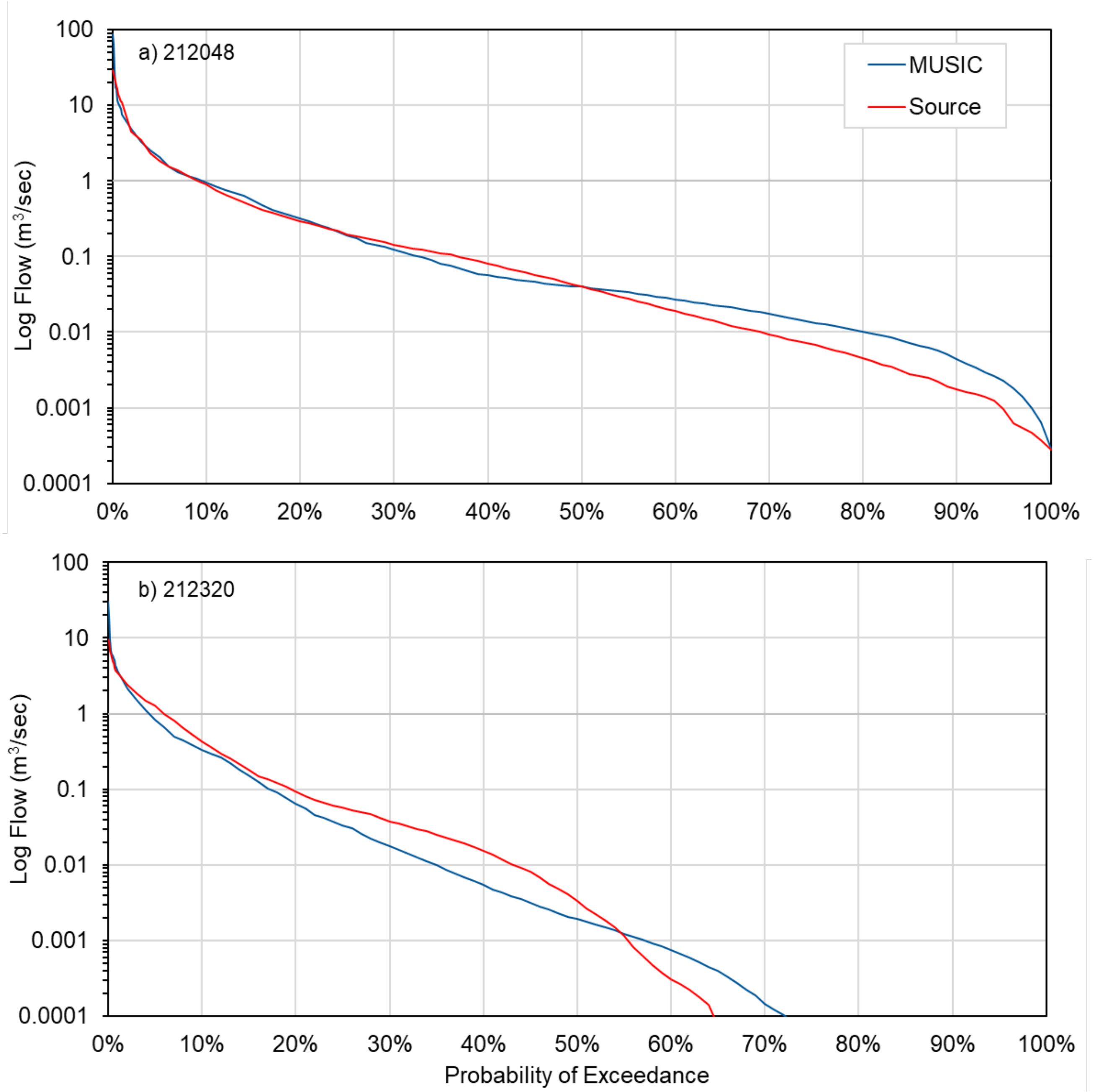


Figure 4 Flow duration curves based on the modelled flows from MUSIC and modelled flows Source at the gauging stations located in South Creek at Great Western Highway (a) and Elizabeth Drive (b).

6.8 Validation and recommended parameters

To further assess the robustness of the selected rainfall-runoff parameters, the MUSIC model outputs were validated/tested using independent daily rainfall data from the weather station at Badgerys Creek (067108). This exercise demonstrated an improved fit to the modelled output from Source (**Error! Reference source not found.**8), meaning that the rainfall-runoff parameters presented in Table 5 can be adopted more broadly across the Wianamatta-South Creek catchment. In addition, when using the recommended rainfall-runoff parameters, the existing 8% impervious coverage should be used as a guide to what is considered 'undeveloped' from a hydrologic assessment perspective.

Table 8 Statistical performance of MUSIC models using pluviography data from Badgerys Creek. Models were developed for the drainage areas above flow gauging stations in South Creek and tested against the modelled flows from Source.

Drainage area	PBIAS (stream flow)	NSE	R^2	Acceptance
212048 – South Creek at Great Western Highway	-0.9	0.67	0.66	Satisfactory
212320 – South Creek at Elizabeth Drive	10.2	0.74	0.75	Satisfactory

7. Operational phase stormwater quantity (flow) targets

To define the operational phase stormwater quantity targets, we used the calibrated MUSIC model to generate and compare flow duration curves for:

- existing/pre-development scenario
- unmitigated post development scenario, based on a large format industrial typology
- business as usual (BAU) scenario, based on applying the post development stormwater load reduction targets (85% TSS, 65% TP and 45% TN) to the large format industrial typology
- 16 WSUD strategies that achieve the flow-related objectives under a large format industrial typology

Table 9 provides a summary of the WSUD strategies, and a description on how the 16 strategies were selected is provided in a companion study (DPE, 2022e). Note a greater number of WSUD strategies was tested (> 50), but only those that were both relatively cost-effective in achieving the objectives and addressed stakeholder concerns were included in the shortlist of 16.

Figure 5 shows the flow duration curves for the first three scenarios listed above. It is clear from this analysis that unmitigated large industrial developments change all aspects of site hydrology when compared to the existing/pre-development scenario. In this specific example, mean annual runoff volume (MARV) increases from 0.7 ML/ha/y to 5 ML/ha/y for highly impervious sites. It is also clear from this analysis that the BAU scenario is unable to achieve the high spell, freshes and low spell flow objectives. The changes to the frequency and duration of flows are particularly significant in the 80-99th percentile range.

Table 9 Example WSUD strategies for Large Format Industrial (LFI) development

WSUD Strategy - LFI		Stormwater Infrastructure Requirements								
		Reduced site coverage	Tanks	Lot WSUD	Streetscape WSUD	Precinct WSUD (above 1% AEP)	Regional WSUD (maximise below 1% AEP)	Stormwater Quantity Detention	POS stormwater harvesting	Reticulated regional Stormwater Harvesting
A	Current Targets adopted by Local Government		✓	✓		✓		✓		
B1	Lot and streetscape	✓	✓	✓	✓			✓		
B2	Lot, streetscape and local irrigation	✓	✓	✓	✓			✓		
C1-a	Lot, local public open space and regional treatment (above 1% AEP)	✓	✓	✓	✓	✓		✓		
C1-b	Lot, local public open space and regional treatment (above 1% AEP)	✓	✓	✓	✓	✓		✓		
C2-a	Lot, local public open space and regional treatment (below 1% AEP)	✓	✓	✓	✓		✓	✓		
C2-b	Lot, local public open space and regional treatment (below 1% AEP)	✓	✓	✓	✓		✓	✓		
C3-a	Lot, local public open space and regional treatment and public open space irrigation (below 1% AEP)	✓	✓	✓	✓		✓	✓	✓	
C3-b	Lot, local public open space and regional treatment and public open space irrigation (below 1% AEP)	✓	✓	✓	✓		✓	✓	✓	
C4	Lot, local public open space and regional treatment and public open space irrigation (below 1% AEP)		✓	✓	✓		✓	✓	✓	
D1-a	Lots, regional treatment and reticulated stormwater reuse		✓	✓			✓	✓		✓
D1-b	Lots, regional treatment and reticulated stormwater reuse		✓				✓	✓		✓
D2-a	Regional treatment and reticulated stormwater reuse (no tanks)						✓	✓		✓
D2-b	Regional treatment and reticulated stormwater reuse (no tanks)						✓	✓		✓
D3-a	Lots and streetscape with regional treatment and reticulated stormwater reuse		✓	✓	✓		✓	✓		✓
D3-b	Lots and streetscape with regional treatment and reticulated stormwater reuse		✓	✓	✓		✓	✓		✓

*Differences between the ‘a’ and “b” options are different mixes of wetlands and bioretention systems for treatment (see DPE 2022d).

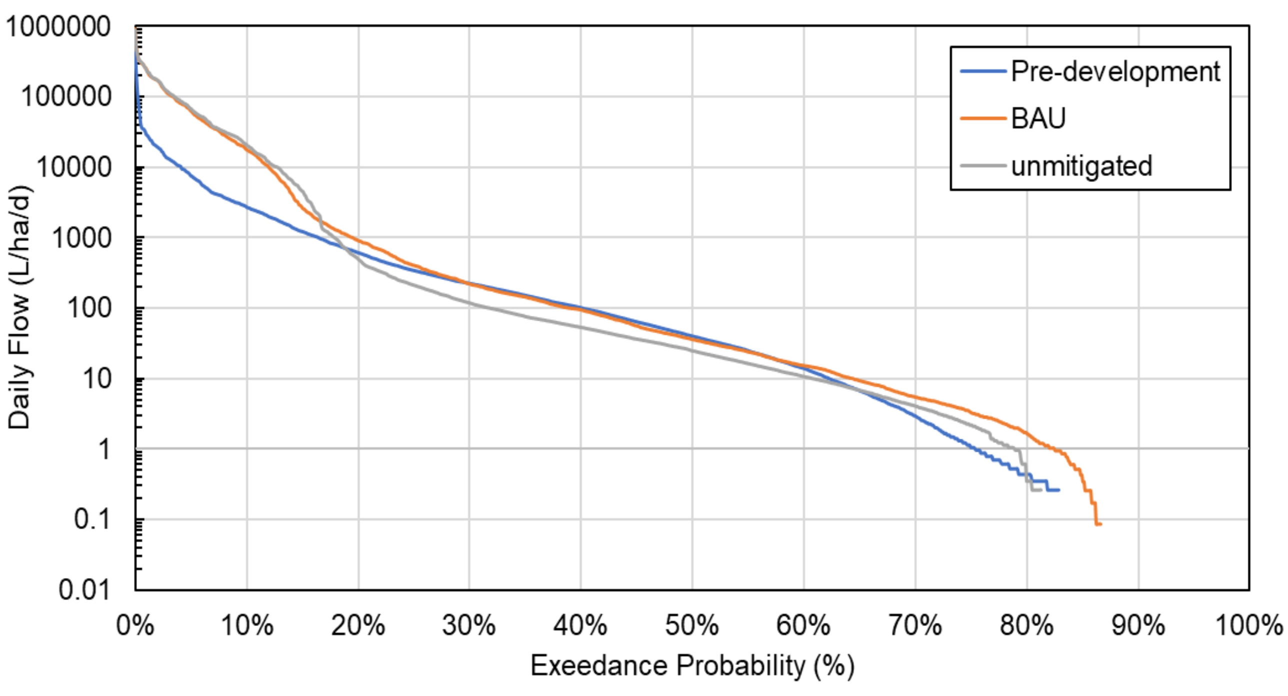


Figure 5 Flow duration curves based on the modelled flows for three scenarios i) existing/pre-development, ii) unmitigated large format industrial (LFI) development, iii) business as usual (BAU) approach to managing stormwater discharges.

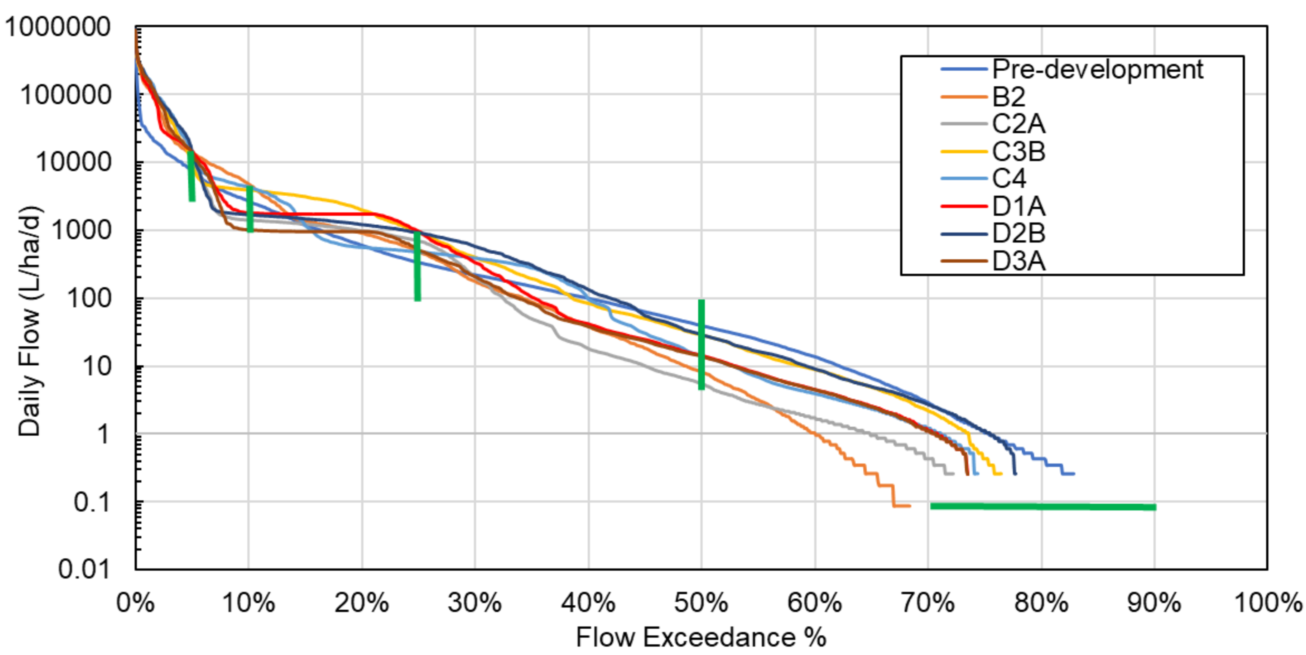


Figure 6 Flow duration curves based on the modelled flows for 16 water sensitive urban design strategies (see Table 9) that achieve stream flow-related objectives under a large format industrial typology. Green bars denote range in stormwater targets.

Figure 6 presents the flow duration curves for the existing/pre-development scenario and for the 16 WSUD strategies that achieve the flow-related objectives under a large format industrial typology. The recommended stormwater quantity (flow) targets are indicated by the green vertical bands, which span the full range of the flow duration curves.

The bands were defined as a result of the following considerations:

- A range or band is specified for the targets rather than a single number, in order to provide a level of flexibility in the selection of WSUD strategies for compliance under different typologies.
- The 95th percentile was added to explicitly account for stream erosion (Section 7).
- Ensuring alignment of stormwater quantity (flow) targets with the flow-related objectives for 1st-2nd order streams (Tables 10 and 11), which have upland drainage areas that are representative of the scale of development sites. A direct comparison of the recommended stormwater quantity (flow) targets with the ≥ 3rd order flow-related objectives is inappropriate at the development scale, due to in-stream routing as described in Section 6.6. When applying the targets across the whole catchment, the influence of in-stream routing within the main creek lines ensures the ≥ 3rd order stream flow-related objectives are achieved.

Generally, for development to achieve the flow-related objectives, it will be necessary to reduce the mean annual runoff volume from approximately 4-5 ML/ha/y to between 1.5-2.5 ML/ha/y. Our assessment of WSUD strategies showed that stormwater harvesting, and reuse systems are the most cost-effective option for achieving the objectives under a large format industrial typology (DPE 2022e), especially given the high variability of water demands from lot to lot. A large, reticulated stormwater reuse scheme could be used to distribute the harvested stormwater to industrial lots with high water demands, and more broadly provide opportunities for the harvested stormwater to be shared between drainage areas and precincts with different typologies and water needs.

Where a reticulated stormwater reuse scheme is not available, developing WSUD strategies for large formal industrial typologies becomes more difficult and expensive and can require larger land take. It is less difficult to develop complying WSUD strategies for high density residential typologies because of lower impervious cover, higher non-potable demands on allotments and potential applicability of green rooves. Strategies can be developed that do not result in a reduction in development yield for high density residential (see DPE 2022c, d).

Overall, our effects-based assessment of flow duration curves indicates that:

- It is not feasible to limit post development stormwater flow volumes to the existing mean annual flow volumes (~0.9ML/ha/y) for the Western Sydney Aerotropolis and Mamre Rd precincts.
- It is possible to limit post development stormwater flows volumes to approximately 1.5-2.5 ML/ha/y depending on the WSUD strategy adopted. The most feasible WSUD strategy includes large scale regional stormwater harvesting which is reticulated to all allotments for reuse to supply non-potable demands and all irrigation
- Replicating the existing flow duration curves (within some ranges) up to about the 96th percentile is generally possible, with flows above the 96th percentile mitigated to some extent but not to the pre-development flows
- To provide flexibility in compliance, the stormwater targets are defined as acceptable bands of percentiles that generally match the pre-development flow duration curve at the key percentiles (50%, 75%, 90%, 95%iles and cease to flow), which align with the flow-related objectives for protecting and restoring waterways in the Wianamatta-South Creek catchment

- Two options for the stormwater flow targets are presented in Table 10 and compared with the flow related objectives for 1st-2nd order streams. The comparison shows the direct relationship between targets and objectives
- Two options for the stormwater flow targets are provided based on feedback from stakeholders at the time of this study. Option 1 uses the mean annual runoff volume (MARV) for the 3rd order streams, and accompanying percentiles for the 1st-2nd order streams. The percentiles ensure the lower flow objectives (< 75th percentile) are achieved. A WSUD strategy that achieves only the MARV target of 2ML/ha/y can dry out the waterway. Option 2 uses the full suite of flow percentiles described above.

Table 10 Operational Phase Stormwater Quantity (Flow) Targets Option 1 - MARV

Parameter	Target	Flow objectives for 1-2 order streams
Mean Annual Runoff Volume (MARV)	≤ 2 ML/ha/y at the point of discharge to the local waterway	1.90 – 2.14 ML/ha/y[1]
90%ile flow	1000 to 5000 L/ha/day at the point of discharge to the local waterway	1309 to 2788 L/ha/day
50%ile flow	5 to 100 L/ha/day at the point of discharge to the local waterway	50 to 94 L/ha/day
10%ile flow	0 L/ha/day at the point of discharge to the local waterway	2% to 39% cease to flow[2]

Table 11 Operational Phase Stormwater Quantity (Flow) Targets Option 2 – flow percentiles

Parameter	Target	Flow objectives for 1-2 order streams
95%ile flow	3000 to 15000 L/ha/day at the point of discharge to the local waterway	-
90%ile flow	1000 to 5000 L/ha/day at the point of discharge to the local waterway	1309 to 2788 L/ha/day
75%ile flow	100 to 1000 L/ha/day at the point of discharge to the local waterway	327 to 2048 L/ha/day
50%ile flow	5 to 100 L/ha/day at the point of discharge to the local waterway	50 to 94 L/ha/day
Cease to flow	Cease to flow to be between 10% to 30% of the time	2% to 39%[2]

[1] denotes flow objective for ≥ 3rd order stream

[2] denotes low range cease to flow for 1st-2nd order streams, and high range cease to flow for ≥ 3rd order stream

7.1 Need for additional indices to mitigate stream bed and bank erosion

Stream bed and bank erosion is a well-established symptom of the urban stream syndrome (Paul and Meyer, 2001; Walsh *et al*., 2005; Tippler *et al*., 2012; Walsh *et al*., 2012; Vietz *et al*., 2014; Vietz *et al*., 2016). Two indices are typically used to mitigate erosion – the erosion potential index (EPI) and the stream erosion index (SEI). The following sections describes an investigation into the need to include either one of these indices in our suite of stormwater quantity (flow) targets.

7.1.1 Erosion potential index (EPI)

EPI is a measure of the change in excess shear stress or 'effective work' on a channel, resulting from changes in catchment hydrology following (for example) urban development. The EPI explicitly considers the magnitude and duration of flows above a threshold to estimate the time-integrated sediment transport and scour characteristics across a range of flows and time periods for different flow management scenarios. The continuous simulation EPI approach is considered to provide a realistic estimate of the effective work carried out on a channel by flow (Bledsloe, 2002).

The EPI approach has three main inputs:

- A calibrated continuous simulation hydrologic model (in this instance our calibrated MUSIC model) that produces long-term hydrographs for pre-development conditions and post-development conditions
- A hydraulic model (in this instance a 1d HEC-RAS model) that converts the hydrographs into time series of shear stress for the pre- and post-development scenarios
- A critical shear stress threshold below which significant sediment transport/channel erosion does not occur (in this instance determined through local assessments of sediment size)

A long-term time series of shear stress for the pre- and post-development scenarios is typically used to calculate the time-integrated total effective work. Figure 7 shows a schematic of the effective work for a single rain event.

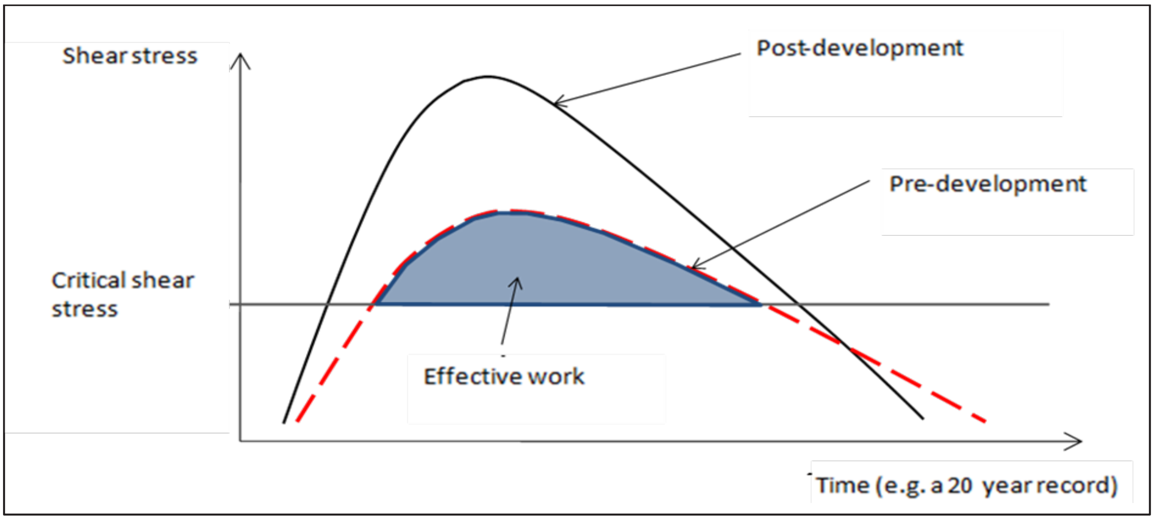


Figure 7 Difference in effective work for pre- and post-development scenarios.

The area under the shear stress curve above the critical shear stress threshold is defined as the *erosion potential* for that flow scenario. The ratio between post- and pre-development erosion potential is the erosion potential index:

$$EPI = \frac{EP_{post-development}}{EP_{pre-development}}$$

Where:

EPI is erosion potential index

$EP_{post\text{-}development}$ is erosion potential under post-development conditions

$EP_{pre\text{-}development}$ is erosion potential under pre-development conditions

An EPI equally 1 indicates there is no increase in effective work and there is unlikely to be a major change in channel trajectory resulting from the proposed development.

The EPI approach is most effectively applied to stream systems where a known threshold in the EPI has been defined, above which unacceptable channel change will occur.

Hydraulic model

For this investigation, the modelled flows from the calibrated MUSIC model were converted into a time series of estimated shear stress values using the HEC-RAS model developed for each study reach (Figure 8). The shear stress time series for the pre-development conditions and post-development conditions were used to compare the effect of unmitigated urban development on the erosion potential.

A one-dimensional hydraulic model (HEC-RAS) for Bardwell Gully, Badgerys Creek and South Creek was generated using LiDAR data sourced from Elvis (Geosciences Australia, 2021). There are four primary input variables required for HEC-RAS modelling:

- Channel geometry (LiDAR data, verified with site visits)
- Upstream and downstream boundary conditions (rating curve from gauge or slope)
- Hydraulic roughness (Manning’s n)
- Flow (from hydrologic analysis discussed above).

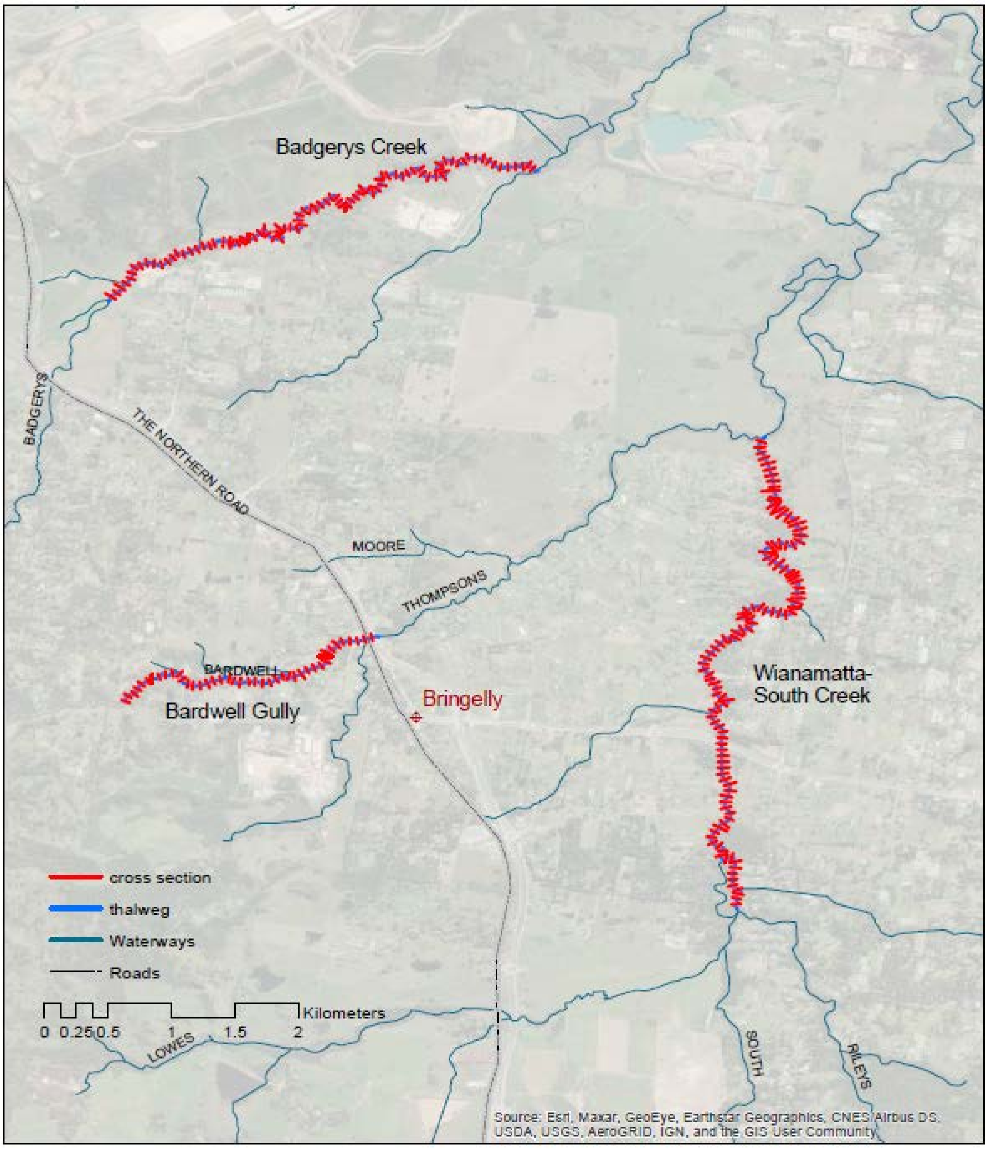
Table 12 lists the flow, boundary conditions and hydraulic roughness (Manning’s n) adopted for the hydraulic models for Bardwell Gully, Badgerys Creek and South Creek. Figure 8 shows the extent of the hydraulic model in the selected South Creek drainage area, including flowlines and cross sections used to create the model.

Table 12 Hydraulic parameters adopted in HEC-RAS modelling

	Parameter	Bardwell Gully	Badgerys Creek	South Creek
Manning's roughness[1]	Left overbank	0.065	0.065	0.065
	Channel	0.065	0.065	0.065
	Right overbank	0.065	0.065	0.065
Boundary conditions[2]	Downstream slope	0.01	0.004	0.002
	Upstream slope	0.01	0.004	0.002

[1] Based on report authors industry experience, and informed by aerial imagery and recommended roughness coefficients (Chow, 1956)

[2] Based on upstream and downstream slope respectively, working off $1m^2$ 2011 LiDAR (Geosciences Australia, 2021)



Source: Esri, Maxar, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

Figure 8 Extent of the hydraulic models created for the EPI assessment

Critical bed-shear stress

Erosion potential can be undertaken at any location where there is a known (or estimated) relationship between flow and shear stress. Flow data for each reach was sourced from the calibrated MUSIC model, at the upstream extent of each modelled creek. The flow series were converted to a continuous series of shear stresses in each reach using the HEC-RAS model.

Shear stress is the force exerted by flow on the channel boundary. Once a critical value is reached the channel boundary may begin to erode. Given the saline/sodic nature of the soils in Wianamatta-South Creek catchment it is expected that any change in EPI may cause creek erosion. There are already many sections of waterways within the catchment that have undergone geomorphic change as a result of the change in use from forest to grazing, agriculture and peri-urban (see DPE 2022a, d).

For this investigation, we assessed the potential critical bed-shear stress from the sediment size distribution of soil samples which we collected from the bed, toe and top of bank of waterways at 20 locations within the Wianamatta-South Creek catchment (Appendix 1). The soil samples collected from the bed and toe at 12 locations had sediment sizes characteristic of a clay/silt/sand mix (< 0.06 mm). The soil samples collected from the remaining 8 locations had sediment sizes characteristic of gravel (> 2 mm) in the bed of the waterway, and sand (0.06 – 2 mm) along the toe. As shown in Table 13, soil samples characteristic of a clay/silt/sand mix have a very low critical bed-shear stress of 0.08 – 0.11 N/m^2, indicating that the waterways within the Wianamatta-South Creek catchment are susceptible to erosion even under very low flow conditions.

Table 13 Soil classification and corresponding critical bed-shear stress based on sediment size

Soil classification based on Sediment Size	Sediment Size (mm)	Critical bed-shear stress for surface erosion (N/m^2)
Clay	<0.002	0.03
Clay-Silt-Sand	0.002 - 0.075	0.08
Sand	0.075 - 0.15	0.11
Sand	0.15 - 0.3	0.145
Sand	0.3 - 0.425	0.194
Sand	0.425 - 0.6	0.27
Sand	0.6 - 1.18	0.47
Sand-Gravel	1.18 - 2.36	1.3
Gravel	2.36 - 4.75	2.7
Gravel-Cobbles	4.75 - 9.5	5.7
Cobbles	9.5 - 19	12.2
Cobbles	19 - 37.5	25.9
Cobbles	37.5 - 75	53.8

Effectiveness of WSUD strategies in mitigating erosion

The EPI was estimated for the existing/pre-development scenario, and two post development scenarios for large format industrial areas differing by the WSUD strategy adopted, i.e.

- Post development that incorporates wetland treatment, with local stormwater harvesting for irrigation and a low flow discharge out of the wetland of 0.2 L/s to replicate existing/pre-development low flows. Refer to Option C2 in Table 9.
- Post development that incorporates wetland and bioretention treatment, and stormwater harvesting from the wetland. Refer to Option D2 in Table 9.

The estimated EPI for Bardwell Gully, Badgerys Creek and South Creek for selected range of critical bed-shear stresses are presented in Table 14. The range includes the 0.08 and 0.11 N/m^2 critical bed-shear stress characteristic of soils made of a clay/silt/sand mix, and several other critical bed-shear stresses to encompass the full range of flow volumes recommended as flow objectives for Wianamatta-South Creek (see Table 2, Figures 4, 5).

Based on the critical bed-shear stresses of 0.08 and 0.11 N/m^2, the EPI for the post development scenario that incorporates wetland treatment with local harvesting (Option C2, Table 9) ranges between 1.1 and 1.3. Typically, a 10% increase in EPI poses a risk of erosion (Alluvium, 2021) suggesting that under this post development scenario, the three creeks are at their threshold for erosion of the bed and toe. By comparison, the EPI for the post development scenario that incorporates wetland and bioretention treatment and stormwater harvesting from the wetland (Option D2, Table 9) is less than 1.1 for all creeks. These results suggests that under this post development scenario, creek erosion is unlikely to occur.

Overall, this investigation showed similar results to those identified *via* the flow duration curve analyses of WSUD strategies. Significant changes to the EPI occur at and above the 75th percentile flows, which require the removal of flows *via* evaporation or stormwater harvesting. Attempting to reduce flows to existing levels (MARV 0.7-0.9 ML/ha), may not be feasible. The similarity in results indicates that a separate EPI target is not warranted as the range of percentiles provided in Tables 10 and 11 adequately manage for erosion up to the 96th percentile.

Limitations

This investigation serves the purpose of informing whether a separate EPI should be added to the suite of stormwater quantity (flow) targets for Wianamatta-South Creek. It is limited to a high-level understanding of active geomorphic processes within the study area, and does not consider changes to sediment supply due to urbanisation (which may impact channel erosion processes further). An assessment of the risks of channel erosion in the Wianamatta-South Creek catchment would require more detailed geomorphic, geotechnical, hydrologic and hydraulic assessment.

Table 14 Results for the EPI analysis at three key reaches within the Wianamatta-South Creek catchment

					Existing/Pre-development		Post-development Option C2			Post-development Option D2		
	Flow Threshold (m^3/s)	Flow Threshold (m^3/s/ha)	Flow Threshold (L/d/ha)	Shear Stress Threshold (N/m^2)	Σ of shear stress > threshold	Number of events >threshold	Σ of shear stress > threshold	Number of events >threshold	EPI	Σ of shear stress > threshold	Number of events >threshold	EPI
Bardwell Gully	0.00001 - 0.0001	3.7 E-8 - 3.7 E-7	3.2 – 32	0.08	2,360,598	427,022	3,008,767	375,319	1.27	1,262,794	328,909	0.53
	0.00001 - 0.0001	3.7 E-8 - 3.7 E-7	3.2 – 32	0.11	2,347,787	427,022	2,997,507	375,319	1.28	1,252,927	328,909	0.53
	0.00001 - 0.0001	3.7 E-8 - 3.7 E-7	3.2 - 32	0.5	2,181,249	427,022	2,851,133	375,319	1.31	1,124,652	328,909	0.52
	0.0001 - 0.0002	3.7 E-7 - 7.4 E-7	32 - 64	1	1,997,633	356,887	2,682,670	330,282	1.34	981,541	278,837	0.49
	0.0003 - 0.0004	1.1 E-6 - 1.5 E-6	95 - 130	5	781,909	242,283	1,454,782	282,749	1.86	467,795	81,240	0.60
	0.0044 - 0.01	1.6 E-5 - 3.7 E-5	1,382 - 3,197	10	170,389	46,052	353,109	103,106	2.07	301,784	25,745	1.77
	0.02 - 0.03	7.4 E-5 - 1.1 E-4	6,394 - 9,504	15	62,904	14,119	209,535	17,733	3.33	178,584	23,248	2.84
	0.11 - 0.12	4.1 E-4 - 4.5 E-4	35,424 - 38,880	20	24,621	3,537	138,014	11,807	5.61	90,233	12,168	3.66
Badgerys Creek	0.00001 - 0.0001	1.7 E-9 - 1.7 E-8	0.2 - 1.5	0.08	2,412,128	493,799	2,665,797	444,377	1.11	1,519,678	403,350	0.63
	0.00001 - 0.0001	1.7 E-9 - 1.7 E-8	0.2 - 1.5	0.11	2,397,314	493,799	2,652,466	444,377	1.11	1,507,578	403,350	0.63
	0.0001 - 0.0002	1.7 E-7 - 3.4 E-7	15 - 29	0.5	2,219,430	435,009	2,494,437	383,266	1.12	1,366,519	338,358	0.62
	0.0001 - 0.0002	1.7 E-7 - 3.4 E-7	15 - 29	1	2,001,925	435,009	2,302,804	383,266	1.15	1,197,340	338,358	0.60
	0.0009 - 0.001	1.5 E-6 - 1.7 E-6	130 - 147	5	544,295	251,028	939,922	286,332	1.73	430,899	69,834	0.79
	0.02 - 0.03	3.4 E-5 - 5.1 E-5	2,938 - 4,406	10	154,608	24,138	292,880	23,102	1.89	285,774	25,208	1.85
	0.1 - 0.11	1.7 E-4 - 1.9 E-4	14,688 - 16,416	15	70,554	11,306	200,605	15,500	2.84	170,086	20,515	2.41
	0.24 - 0.25	4.1 E-4 - 4.3 E-4	35,424 - 37,152	20	29,746	5,064	131,361	11,996	4.42	84,031	12,885	2.82
South Creek	0.00001 - 0.0001	1.9 E-9 - 1.9 E-8	0.2 - 1.6	0.08	3,261,920	618,293	3,944,675	596,261	1.21	1,820,567	602,508	0.56
	0.00001 - 0.0001	1.9 E-9 - 1.9 E-8	0.2 - 1.6	0.11	3,243,371	618,293	3,926,787	596,261	1.21	1,802,492	602,508	0.56
	0.0001 - 0.0002	1.9 E-8 - 3.9 E-8	1.6 - 3.4	0.5	3,011,508	585,353	3,706,812	551,616	1.23	1,579,766	558,979	0.52
	0.0001 - 0.0002	1.9 E-8 - 3.9 E-8	1.6 - 3.4	1	2,718,832	585,353	3,431,004	551,616	1.26	1,300,276	558,979	0.48
	0.008 - 0.009	1.6 E-6 - 1.8 E-6	138 - 156	5	895,708	263,842	1,744,574	282,371	1.95	193,419	59,908	0.22
	0.08 - 0.09	1.6 E-5 - 1.8 E-5	1,382 - 1,555	10	289,125	66,138	631,822	183,416	2.19	120,131	8,611	0.42
	0.28 - 0.29	5.5 E-5 - 5.7 E-5	4,752 - 4,925	15	68,297	28,785	102,959	23,517	1.51	78,122	8,153	1.14
	9.9 - 10	1.9 E-3 - 2.0 E-3	164,160 - 172,800	20	11,219	1,725	47,312	5,845	4.22	49,070	4,379	4.37

7.1.2 Stream Erosion Index (SEI)

The purpose of the SEI is to manage the volume and duration of stormwater flows entering local waterways to protect the geomorphic values of those waterways (PCC, 2013). It is widely used in the Development Controls Plans (DCP) of local authorities within the Wianamatta-South Creek catchment. Part J of Blacktown City Council's DCP and associated 2020 WSUD developer handbook - MUSIC modelling and design guide defines SEI as:

'*Sum of the post development volume of mean annual stormwater flows greater than the stream-forming flow (or critical flow) divided by the sum of the pre-development (for the catchment under natural conditions) volume of mean annual stormwater flows greater than the 'stream-forming flow*'.

Critical flow is the flow threshold below which minimal erosion is expected to occur within a waterway. This has been estimated as a percentage of the pre-development 2-year ARI flow (Earth Tech, 2005). For Western Sydney 25% of the 2-year ARI flow is generally applied by local authorities.

The calculation is similar to EPI, however the threshold for the calculation is defined by an estimated flow rate based on a simple rational method which is assumed to be the 'critical flow' above which erosion occurs downstream. By comparison, the EPI approach more accurately defines the critical bed-shear stress for a particular waterway and then uses this to underpin the calculation.

Local authorities in the Wianamatta-South Creek catchment typically require a SEI of < 3.5 (e.g. PCC, 2013; PCC, 2015). This means the volume of flow above a critical flow for a development can increase by a maximum of 3.5 times post development. Similar to the EPI, any change in SEI above 1 has a high risk of causing channel erosion, noting that the soils are inherently saline and sodic and many waterways have already undergone geomorphic change as a result of historic land use change.

Effectiveness of SEI in mitigating erosion

For this investigation, we used the calibrated MUSIC model to calculate the SEI for:

- development areas of 10ha and 100ha, and assumed BAU stormwater management consisting of 85%, 65%, 45% reduction in TSS, TP and TN respectively, and use of storage to reduce flows to achieve an SEI of 2 and 3.5
- development areas of 10ha and 100ha, with WSUD strategies (Option C2 and D2, Table 9) designed to achieve the new stormwater quantity (flow) targets derived using the flow duration method

Figure 9 presents the flow duration curve for a large format industrial typology complying with BAU stormwater management and Figure 10 presents the same information for a high-density residential typology. These flow duration curves explicitly demonstrate that the SEI focusses on the high flows (i.e. 98th percentile and upwards) and ignores the remainder of the flow duration curve. BAU approaches to comply with the SEI simply transfer flow from one part of the curve (above the 96%ile) to another part of the curve (80%ile to 90%ile). This has the potential to impact the other flow objectives that need to be achieved.

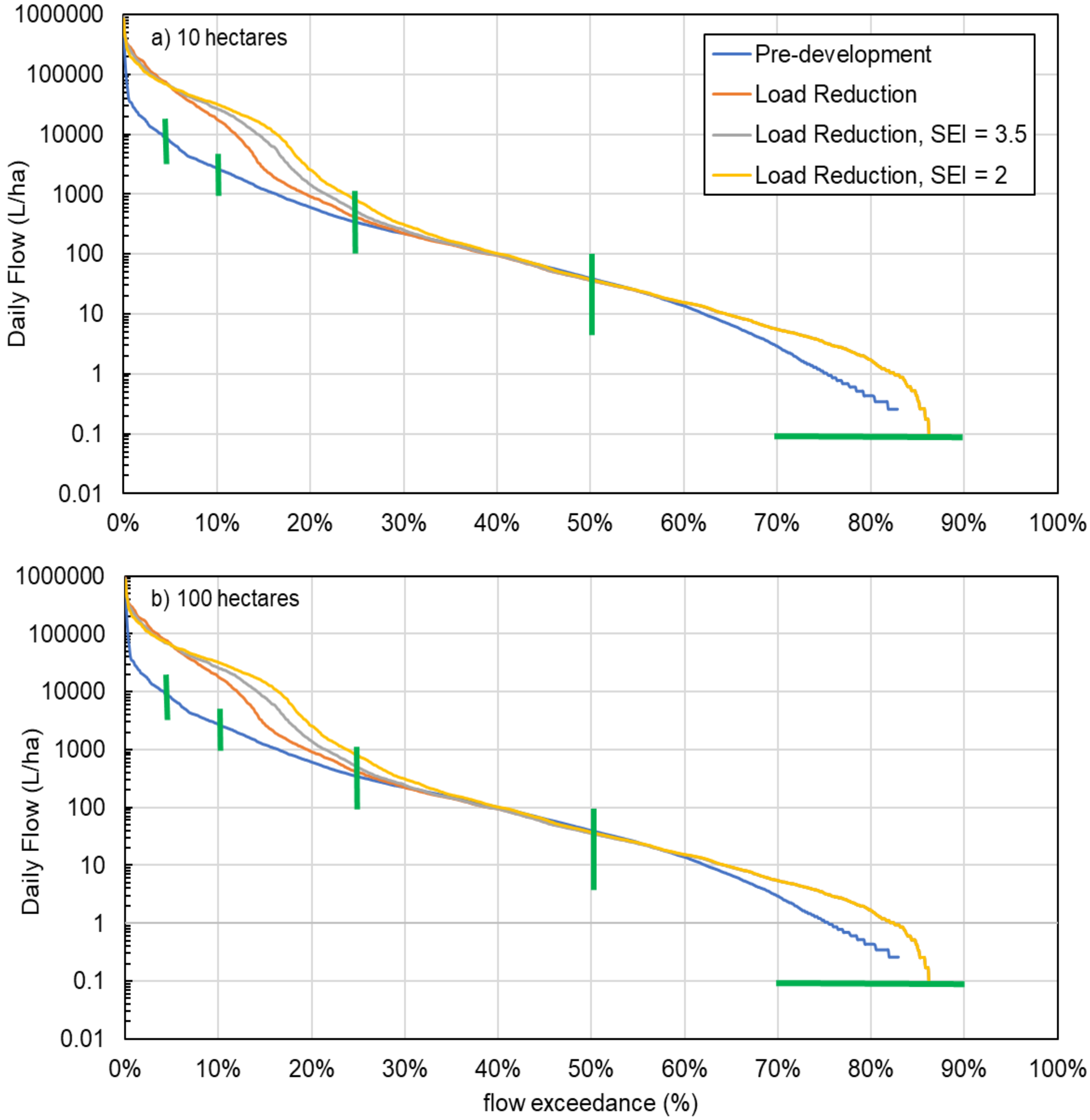


Figure 9 Daily flow duration curves for large format industrial development delivering business as usual stormwater management reliant on load reduction targets and the stream erosion index (SEI)

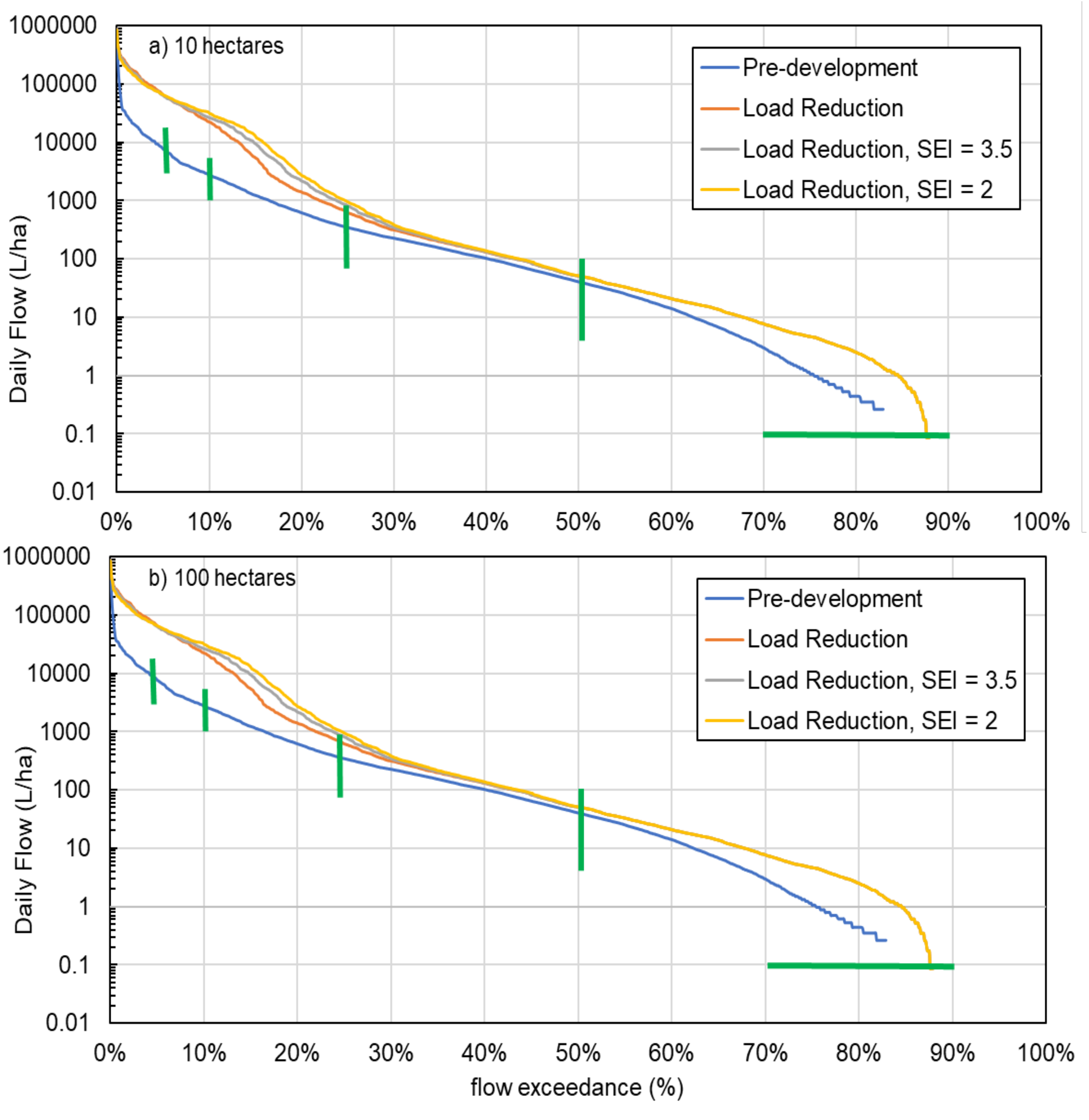


Figure 10 Daily flow duration curves for high density residential development delivering business as usual stormwater management reliant on load reduction targets and the stream erosion index (SEI)

Table 14 provides a summary of the SEI for WSUD strategies (Options C2 and D2) which achieve the recommended stormwater quality and flow targets for Wianamatta-South Creek. The results clearly show that the WSUD strategies deliver a significant improvement in SEI compared to BAU, even without dedicated storages for reducing flows below a 'critical flow'. All the SEI values for the WSUD strategies are <3.5 and they achieve the full suite of flow targets.

Overall, this investigation shows that there is no need to include the SEI with the suite of stormwater quantity (flow) targets proposed for Wianamatta-South Creek catchment. Moreover, if the SEI is applied independent of other flow percentiles, there is a high risk that the flow outcomes for the waterway will be impacted because the general approach to achieving the SEI is to transfer the excess stormwater from one part of the flow duration curve to another.

Table 14 Stream Erosion Index for water sensitive urban design (WSUD) strategies that achieve flow objectives for Wianamatta-South Creek, compared to the business as usual (BAU) strategy

Typology	WSUD strategy	**Development area (ha)**	
		10	100
Large Format Industrial	BAU	6.78	6.71
	*Option C	2.05	2.25
	*Option D	3.03	2.94
High Density Residential	BAU	5.86	5.79
	*Option C	1.97	2.16
	*Option D	3.29	3.52

* refer to Table 9

8. Operational Phase Stormwater Quality Targets

To define the operational phase stormwater quality targets, we calculated a sustainable or total maximum annual load export per hectare as a benchmark for achievement of the water quality objectives (see ANZECC & ARMCANZ, 2000). This was based on multiplying the mean annual runoff volume for ≥3rd order streams (i.e. MARV = 2 ML/ha/y flow objective) by the ambient water quality objectives for TSS, TP and TN:

- TSS load = 37 mg/L x 2 ML/ha/y = 74 kg/ha/y
- TP load = 0.14 mg/L x 2 ML/ha/y = 0.28 kg/ha/y
- TN load = 1.72 mg/L x 2 ML/ha/y = 3.44 kg/ha/y

These exports are characteristic of those within nearby rural residential and non-dairy grazing areas of the Hawkesbury-Nepean (Table 15), and are up to 29 times lower than the exports from market gardens, horticultural and turf farms in the Wianamatta-South Creek catchment (Haine *et al*., 2011).

Table 15 Total nitrogen (TN) and total phosphorus (TP) exports from dominant types of agricultural land uses either within or immediately downstream of the Wianamatta-South Creek catchment (data adapted from Haine *et al*., 2011)

Land use	TN (hg/ha/y)	TP (kg/ha/y)
Field Vegetables	122.2	21.9
Turf	52.5	20.3
Cropping	13.5	3.2
Dairy Grazing	4.4	2.9
Rural Residential	4.2	0.8
Non-Dairy Grazing	2.4	0.3
Tree & Shrub Cover	1.2	0.0

The calibrated MUSIC model was used to assess the feasibility of achieving the sustainable/total maximum annual load exports for the large format industrial and high-density residential typologies. A select number of WSUD strategies identified in Table 9 was used in the assessment and compared with BAU stormwater quality management, based on 85%, 65% and 45% post development load reductions of TSS, TP and TN respectively. The key findings of this analysis are summarised in Figure 11. They indicate that:

- BAU stormwater quality management is likely to result in a worsening of loads entering the waterways compared to the proposed sustainable/total maximum annual loads and existing/pre-development loads from grazing and rural residential areas
- Post development reductions of 90%, 80% and 65% for TSS, TP and TN, respectively are optimal as they contribute towards achieving the water quality objective – noting that instream attenuation processes are not accounted for in MUSIC.

The stormwater quality targets are expressed as percentage reductions of loads compared to development with no stormwater treatment measures implemented. This is consistent with how current (BAU) stormwater quality targets are expressed. However, for development areas that have a high proportion of pervious cover (either with the use of green rooves or by adopting greater levels of landscaped areas), alternative stormwater quality targets can be adopted based on exports per hectare.

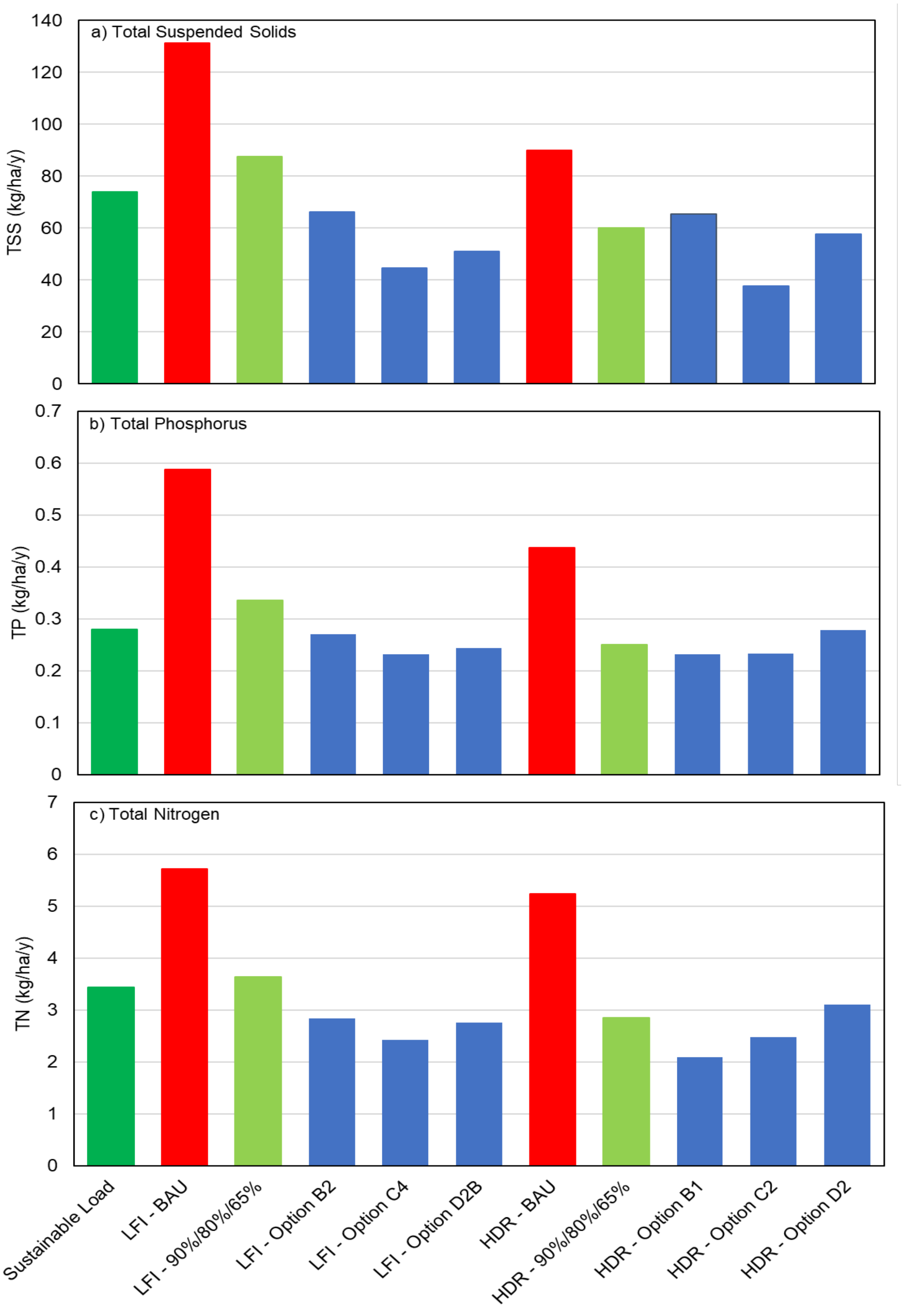


Figure 11 Sediment (a) and nutrient (b, c) load exports of different WSUD strategies (blue bars) compared to the sustainable load (dark green), business as usual (BAU, red bars) and recommended/target load (light green bars) exports.

9. Construction Phase Stormwater Quality Targets

Management of construction phase stormwater quality in NSW generally follows the design requirements outlined in Managing Urban Stormwater: Soils and Construction – Blue Book. The Blue Book covers erosion control and drainage suitably when considered with IECA (2008). However, the design of sediment controls (i.e. sediment basins) results in treating only of approximately 40%-55% of flows from construction and building sites, which presents a high risk to achieving the ambient water quality objectives in Wianamatta-South Creek.

Traditional sediment basins are classified into either Type C, Type D or Type F, corresponding to the target sediment type i.e. coarse-grained, dispersive or fine-grained, respectively. The Type C basin is rarely used because they do not target fine or dispersive sediment. Type D and F basins are sized using the same criteria, essentially to capture runoff generated from a certain amount of rainfall. Both types of basins operate as batch systems, meaning that once the rainfall event has ceased, the basins are left to settle until the desired TSS concentration (50 mg/L) in the basin water column is achieved. For the Type D basin, settling is done through chemical flocculation whereas for the Type D basin, setting is done by gravity alone. Once settled, the basin is dewatered (emptied), with the entire process of settlement and dewatering required to occur within a 5-day period after rainfall. Both flocculation and dewatering procedures are undertaken manually at virtually all construction sites.

It should be noted that only the volume of water contained within the Type D or F basin at the end of the rainfall event is treated to the design standard (50mg/L). During rainfall periods which exceed the design rainfall volume, the basin will be full and any additional runoff entering the basin typically flows through the basin and discharges over a high-flow weir without being treated to the design standard. Continuous time series modelling indicates that Type D basins treat only 40%-55% of flow volumes from construction and building sites in Western Sydney.

While full treatment to the design discharge standard is not achieved for those flows which exceed the basin volume, a portion of the sediment load will still be removed as coarser sediments settle rapidly as they pass through the sediment basin. There is no reduction of dispersive sediment during these overflow events.

A relatively recent innovation in sediment basin design is High Efficiency Sediment (HES) basins – described in IECA (2018) as Type-B and Type-A. These basins operate as continuous flow systems, with on-going addition of flocculant and release of treated water throughout the runoff event. This continuous treatment process means that a much greater volume of runoff is treated compared to a similar sized batch system.

Given the significant treatment benefits associated with HES basins compared to traditional sediment basins, HES basins are now encouraged in Queensland and are also proposed in this study to protect the highly valued waterways and water dependent ecosystems in Wianamatta-South Creek catchment – especially given the marginal changes in BAU practice required.

9.1 Derivation of construction phase stormwater quality targets

Hydrologic effectiveness curves show the percentage of annual runoff volume that is treated through a stormwater treatment measure (Figures 12,13). They illustrate how varying sediment basin volumes/standards affect the percentage of annual average runoff that is captured and treated.

Hydrologic modelling was undertaken using the calibrated MUSIC parameters. Curves were derived for Type D basin for the current maximum permitted emptying/dewatering time of 5 days (Figure 12). A curve was then developed for a Type B basin designed using HES basin technology (Figure 13). Generally, MUSIC was used to determine the daily surface runoff volumes from a typical construction site to a sediment basin. The MUSIC model outcomes were exported into MS EXCEL to develop a spreadsheet water-balance model of the basin and then operational rules for the basin, such as flocculation and dewatering, were applied. These rules represent how Type F and Type D basins function based on the required management regime, as follows:

- Basin fills to the design volume if not emptied, with basin volume accumulating on successive days in which emptying does not occur
- Basin is emptied only after 5 days of no inflow of surface flows. Basin volume emptied is assumed to have been treated to the design discharge standard of 50mg/L TSS
- Once the basin is full, additional runoff is assumed to overtop the basin spillway without being treated to the design discharge standard

The spreadsheet model was then run several times based on a range of basin sizes to derive the percentage of runoff volume able to be treated to the design discharge standard. The final curves were derived for a range of impervious values which represent the range of conditions which may be experienced during different stages of construction.

For the scenario using the HES basin (Figure 13), the same MUSIC model as used with the exception that the flows were exported at 6-minute time-steps. These flows were used as input to the spreadsheet model, where they were used in combination with a nominated basin volume to derive the instantaneous residence time at each time-step. The residence times derived were then compared to the critical residence time value of 1 hour which has been nominated by flocculant manufacturers as the expected contact time required to get effective settling (IECA, 2018).

All flows having a residence time of greater than 1 hour were identified as being effectively treated, while flows having a lower residence time were identified as being untreated. The total flow volumes were then summed into ‘treated’ and ‘untreated’ categories and the resulting hydrologic effectiveness estimate obtained.

9.2 Effectiveness of HES basins

The 5 day 85th percentile rainfall depth, and settling volume of 193 m^3/ha was used as a benchmark for comparison of hydrologic effectiveness curves derived for traditional batch (Type D) sediment basins. This benchmark is used by Penrith City Council. The resulting hydrologic effectiveness curves for traditional batch (Type-D) sediment basins are shown in Figure 12 for a range of imperviousness. The level of treatment from BAU practices is between 41-55% of the average annual runoff volume, for typical levels of imperviousness experienced during construction (i.e. traditional batch sediment basin treated 41-55% of average annual runoff with the remainder bypassing untreated).

For a HES Type-B sediment basin, the required size of the settling zone can be estimated for an assumed time of concentration, using the procedures outlined in Best Practice Erosion and Sediment Control (IECA, 2018). This yields an indicative Type-B settling zone size of 148-223m^3/ha depending on time of concentration and coefficient of runoff assumptions. The current basin sizing standard for Type-D basins (196m^3/ha) falls squarely within this range. The results of the hydrologic effectiveness modelling for the HES Type-B basin are presented in Figure 13. The level of treatment achieved through operating basins as is around 80%, irrespective of the level of imperviousness. In other words, by continuing to create sediment basins to the current size but by augmenting them with high-efficiency features (i.e. auto-dosing, forebays and level spreaders), the proportion of runoff which can be treated by the sediment basins is approximately doubled. Note that the HES basins should be designed on the basis of the final level of imperviousness for the development site to cater for all phases of the development construction (i.e. earthworks, civil works, landscape works and building construction).

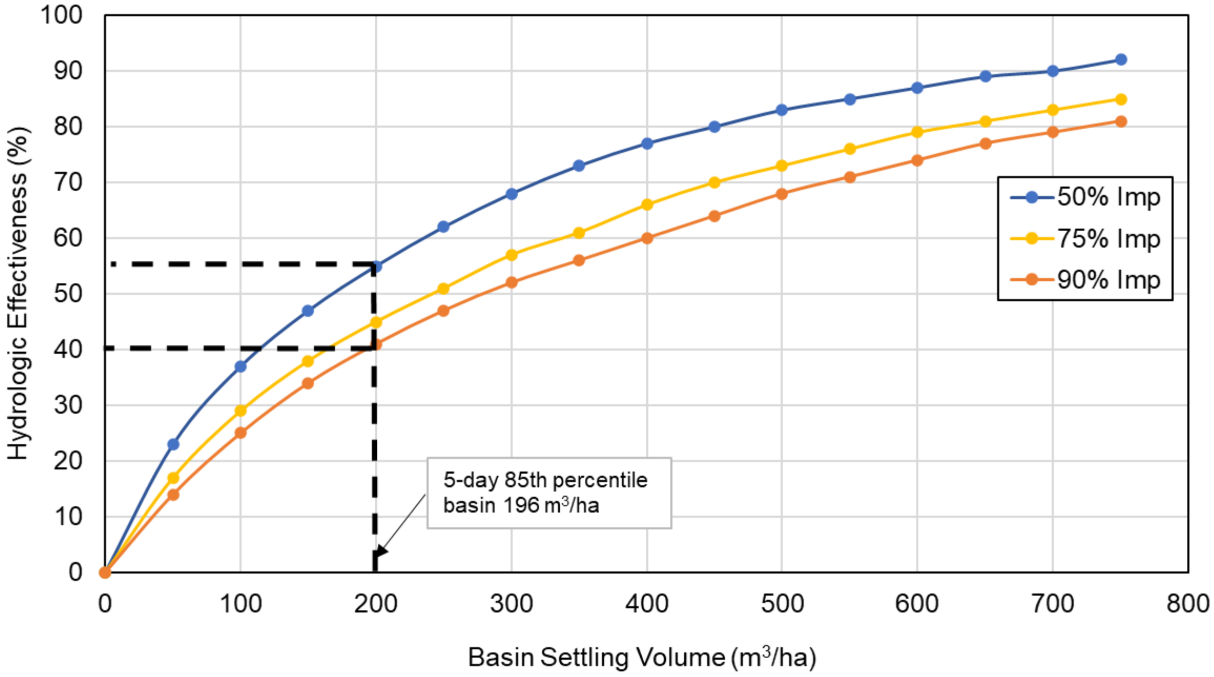


Figure 12 Hydrologic effectiveness curves for Type D sediment basins, under a range of site imperviousness (imp)

Type D Basin. Photo: Design Flow Consulting

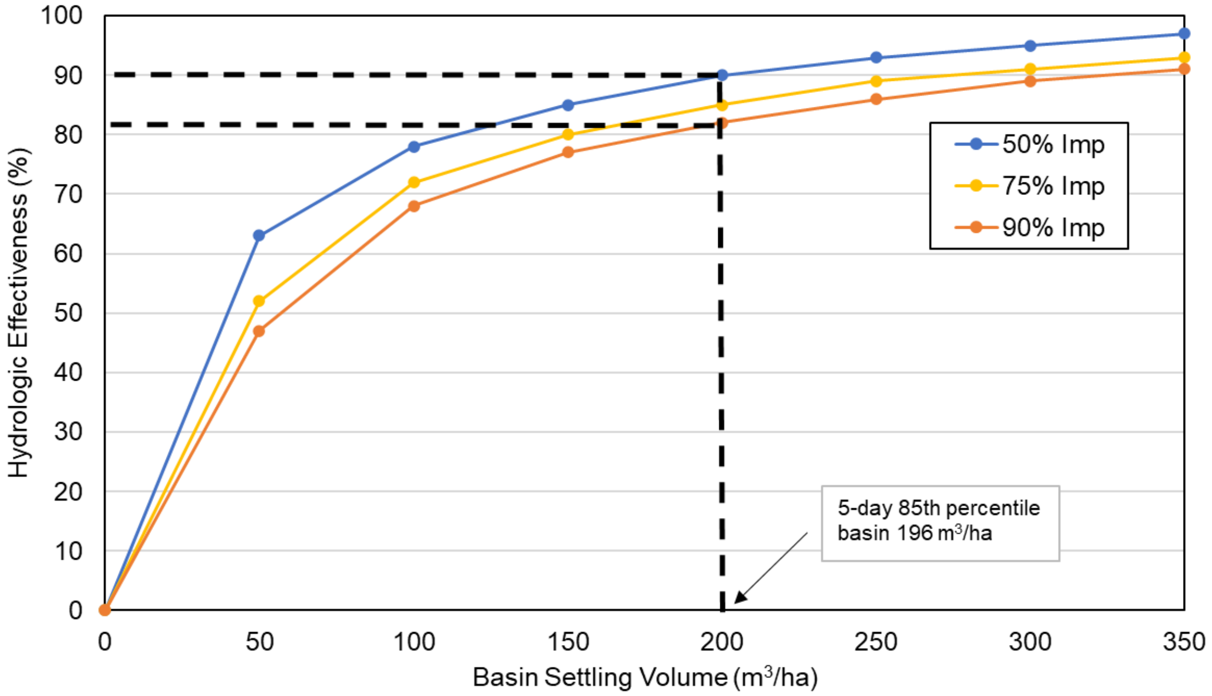


Figure 13 Hydrologic effectiveness curves for high efficiency sediment basins, under a range of site imperviousness (imp)

High Efficiency Basin. Photo: Design Flow Consulting

10. Recommended Stormwater Management Targets

This section provides summary tables (Tables 16 to 20) of the stormwater management targets recommended for the Wianamatta-South Creek catchment. The targets have already been adopted in the Western Sydney Aerotropolis - Phase 2 and Mamre Rd Precinct Development Controls Plans (DCPs). They have also been used as benchmarks for achievement of the ambient water quality and flow objectives in Sydney Water's stormwater and water cycle management studies for the area (Sydney Water 2020; Sydney Water 2021b). Further instruction on how the targets should be used and where they apply is provided in the DCPs and the NSW Government '*Technical guidance for achieving Wianamatta-South Creek stormwater management targets*' (DPE, 2022b).

Generally, the operational phase stormwater management targets need to be achieved at the outlet of a development site during the operational phase i.e. once the site has been developed.

There are two options of operational phase targets provided for stormwater quality and two for stormwater quantity (flow). The two options are intended to provide flexibility in demonstrating compliance with the targets (see DPE 2022c), and were a direct request of the water professionals or practitioners who were representing large landowners in Wianamatta-South Creek at the time of this present study. One option for stormwater quality and one option of stormwater quantity must be met to demonstrate compliance with the waterway objectives.

For stormwater quality targets, most development will likely adopt Option 1, which is based on annual load reduction targets (Table 16). If a development incorporates significant areas of pervious space (e.g. by adopting green rooves), then a proponent may prefer to use Option 2 which is based on allowable loads (Table 17).

Differences between the two options for the stormwater quantity (flow) targets are mainly related to the extent of post-processing of results generated from the industry standard model MUSIC (DPE, 2022c). Option 1 allows results to be directly extracted from MUSIC and compared with the targets (Table 18). Option 2 requires flow data to be extracted from MUSIC and a flow duration curve to be developed (Table 19). The proponent is free to select whichever option suits their WSUD strategy best, noting that:

- Option 1 stormwater quantity (flow) targets are based around limiting the mean annual runoff volume (MARV) from a development site as well as ensuring there is suitable low flow regime in the streams.
- Option 2 stormwater quantity (flow) targets are based on preserving key percentiles of a flow duration curve.
- Compliance with the flow percentiles is demonstrated when the stormwater volume discharges at the outlet of a development site is between the upper and lower bands/ranges specified for the flow percentile

Compliance with the construction phase stormwater quality targets apply to development sites > 2,500m^2 (Table 20), and were designed to strengthen existing requirements in the Managing Urban Stormwater - Soils and Construction (The Blue Book). It is ideal for independent audits to be undertaken by a Certified Professional in Erosion and Sediment Control to certify that the management of the site complies with these targets, or where not in compliance, specific advice is provided to the proponent to achieve compliance. Further technical guidance on achieving the construction phase targets is provided in DPE (2022c).

Table 16 Operational Phase Stormwater Quality Targets Option 1 – annual load reduction

Parameter	Target - reduction in mean annual load from unmitigated development
Gross Pollutants (anthropogenic litter >5mm and coarse sediment >1mm)	90%
Total Suspended Solids (TSS)	90%
Text Total Phosphorus (TP)	80%
Total Nitrogen (TN)	65%

Table 17 Operational Phase Stormwater Quality Targets Option 2 – allowable loads

Parameter	Target - allowable mean annual load from development
Gross Pollutants (anthropogenic litter >5mm and coarse sediment >1mm)	< 16 kg/ha/y
Total Suspended Solids (TSS)	< 80 kg/ha/y
Text Total Phosphorus (TP)	< 0.3 kg/ha/y
Total Nitrogen (TN)	< 3.5 kg/ha/y

Table 18 Operational Phase Stormwater Quantity (Flow) Targets Option 1 - MARV

Parameter	Target
Mean Annual Runoff Volume (MARV)	≤ 2 ML/ha/y at the point of discharge to the local waterway
90%ile flow	1000 to 5000 L/ha/day at the point of discharge to the local waterway
50%ile flow	5 to 100 L/ha/day at the point of discharge to the local waterway
10%ile flow	0 L/ha/day at the point of discharge to the local waterway

Table 19 Operational Phase Stormwater Quantity (Flow) Targets Option 2 – flow percentiles

Parameter	Target
95%ile flow	3000 to 15000 L/ha/day at the point of discharge to the local waterway
90%ile flow	1000 to 5000 L/ha/day at the point of discharge to the local waterway
75%ile flow	100 to 1000 L/ha/day at the point of discharge to the local waterway
50%ile flow	5 to 100 L/ha/day at the point of discharge to the local waterway
Cease to flow	Cease to flow to be between 10% to 30% of the time

Table 20 Construction Phase Stormwater Quality Targets

Parameter	Target (reduction in mean annual load from unmitigated development)
Total suspended solids (TSS) and pH	All exposed areas greater than 2500 m^2 are to be provided with sediment controls which are designed, implemented and maintained to a standard that would achieve at least 80% of the average annual runoff volume of the contributing catchment (i.e. 80% hydrological effectiveness) to 50mg/L Total Suspended Solids (TSS) or less, and pH in the range (6.5–8.5) No release of coarse sediment is permitted for any construction or building site. Sites less than 2,500m^2 are required to comply with the requirements of Managing Urban Stormwater - Soils and Construction (The Blue Book)
Oil, litter and waste contaminants	No release of oil, litter or waste contaminants
Stabilisation	Prior to completion of works for the development, and prior to removal of sediment controls, all site surfaces are to be effectively stabilised including all drainage systems. An effectively stabilised surface is defined as one that does not or is not likely to result in visible evidence of soil loss caused by sheet, rill or gully erosion or lead to sedimentation water contamination.

11. Acknowledgements

This project was delivered by the following team:

- Design Flow Consulting Pty Ltd – Robin Allison and Shaun Leinster who undertook the feasibility assessment, including extensive consultation with stakeholders, developing WSUD strategies, MUSIC modelling and associated life cycle costings, and preparing the draft versions of this document
- Alluvium Australia Consulting – Tony Weber and Adyn de Groot who developed the calibrated MUSIC model and delivered the Erosion Potential Index investigation
- Environment and Heritage Group of DPE – Marnie Stewart, Susan Harrison, Trish Harrup and Jocelyn Dela-Cruz who were involved in extensive consultation with stakeholders, including responding to industry queries and state significant development submissions. Jocelyn Dela-Cruz was responsible for the overall management and delivery of the project, analysis of data from soils samples, and helped with finalising the document.
- CT Environmental – Carl Tippler and Ben Green who collected the soil samples, and analysed the resulting data

The project team are grateful to Peter Mehl, Director at J. Wyndam Prince who reviewed the MUSIC modelling, WSUD strategies and the draft versions of the document to ensure the models and targets were robust, practical and locally specific to the catchment. Chris Avis from Infrastructure & Development Consulting (idc), and Mark Liebman from the Sustainability Workshop, also reviewed this document and provided key inputs to some of the modelling assumptions and strategies.

DPE Planning Teams for Western Sydney, especially Melissa Rassack and Jane Grose who supported this work through their consultation with developers and landowners, informing the WSUD strategies and integrating the outputs of this project into relevant planning documents.

Sydney Water who kindly provided access to their MUSIC models and data during the early stages of this project. We especially thank Dan Cunningham, Phillip Birtles and Peter Gillam (contractor Aurecon).

This project was funded by the NSW Government under the Marine Estate Management Strategy 2018-2028. The ten-year Strategy was developed by the NSW Marine Estate Management Authority to coordinate the management of the marine estate.

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13. Appendix 1

Sediment samples (upper 10 cm) were collected from the bed and toe of waterways at 20 locations in the Wianamatta-South Creek catchment (Figure 14), and sent to the NATA accredited commercial testing laboratory Australian Laboratory Services (ALS) Smithfield for analysis of particle size distribution and soil classification.

Sample locations were randomly selected however samples were collected from the outside edge of the creek where the risk of erosion is greatest.

As shown in Table 12, under Section 7.1, particle size was used to classify sediment into sand, silt, clay, gravel and cobbles and derive the corresponding critical bed-shear stress.

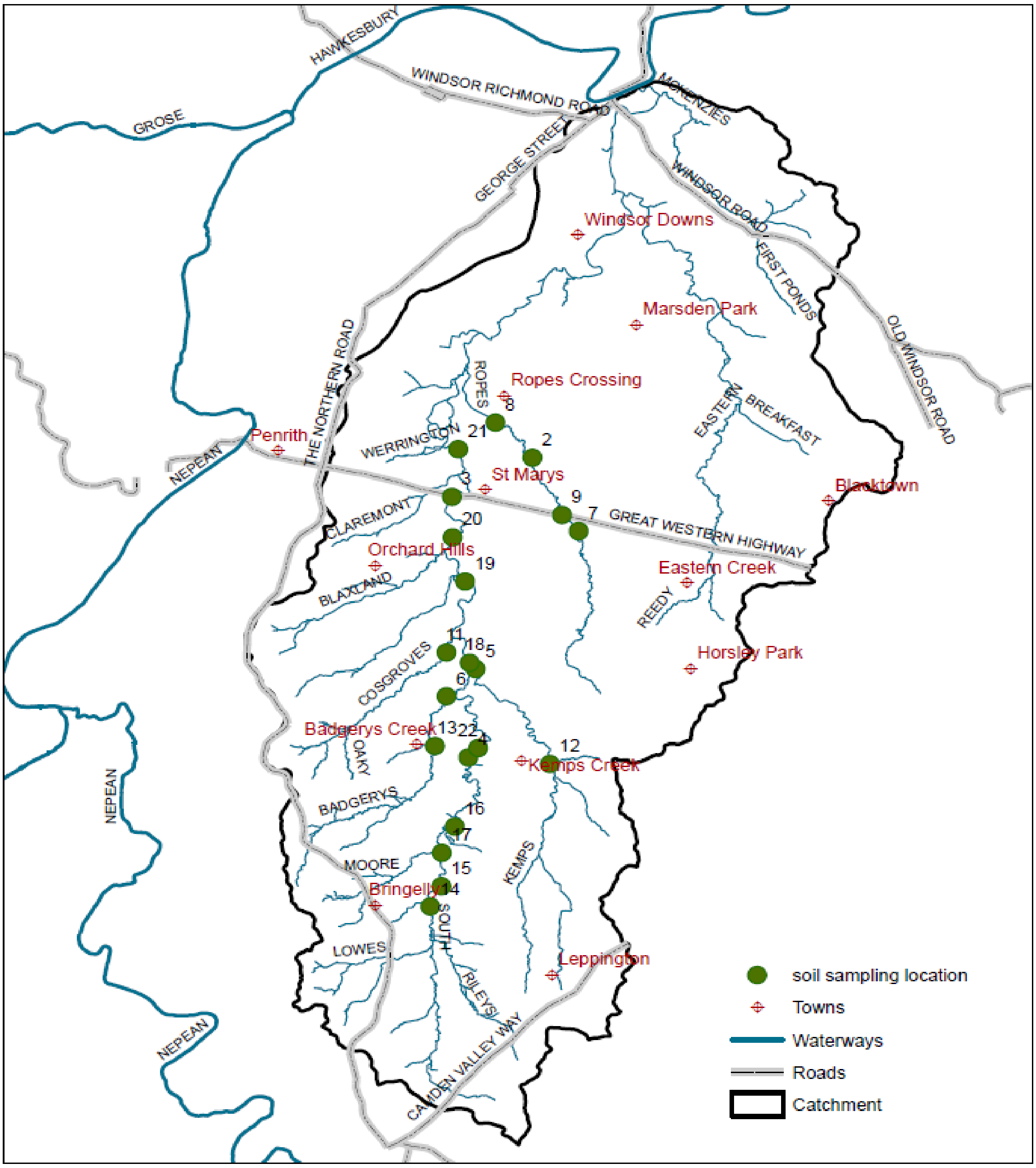

Figure 14 Soil sampling locations within the Wianamatta-South Creek catchment

A Principal Component Analysis (PCA) was used to summarise the results of the laboratory analysis, specifically using the percentage of each sediment size class that is present in the sample. Figure 15 shows a biplot of the PCA outputs, which is used to identify any similarities in samples and any key trends based on the groupings of the samples within the biplot. The arrows provide an explanation for the groupings. For example, samples that are located in the upper right-hand side of the biplot have relatively greater composition of silt and clay. Samples located in lower right-hand side are predominantly sandy and those located on the left-hand side of the biplot are characteristic of gravel. Using Table 12, it is clear that the samples located on the right-hand side of the biplot have lower critical bed-shear stress, and hence more susceptible to erosion than those on the right.

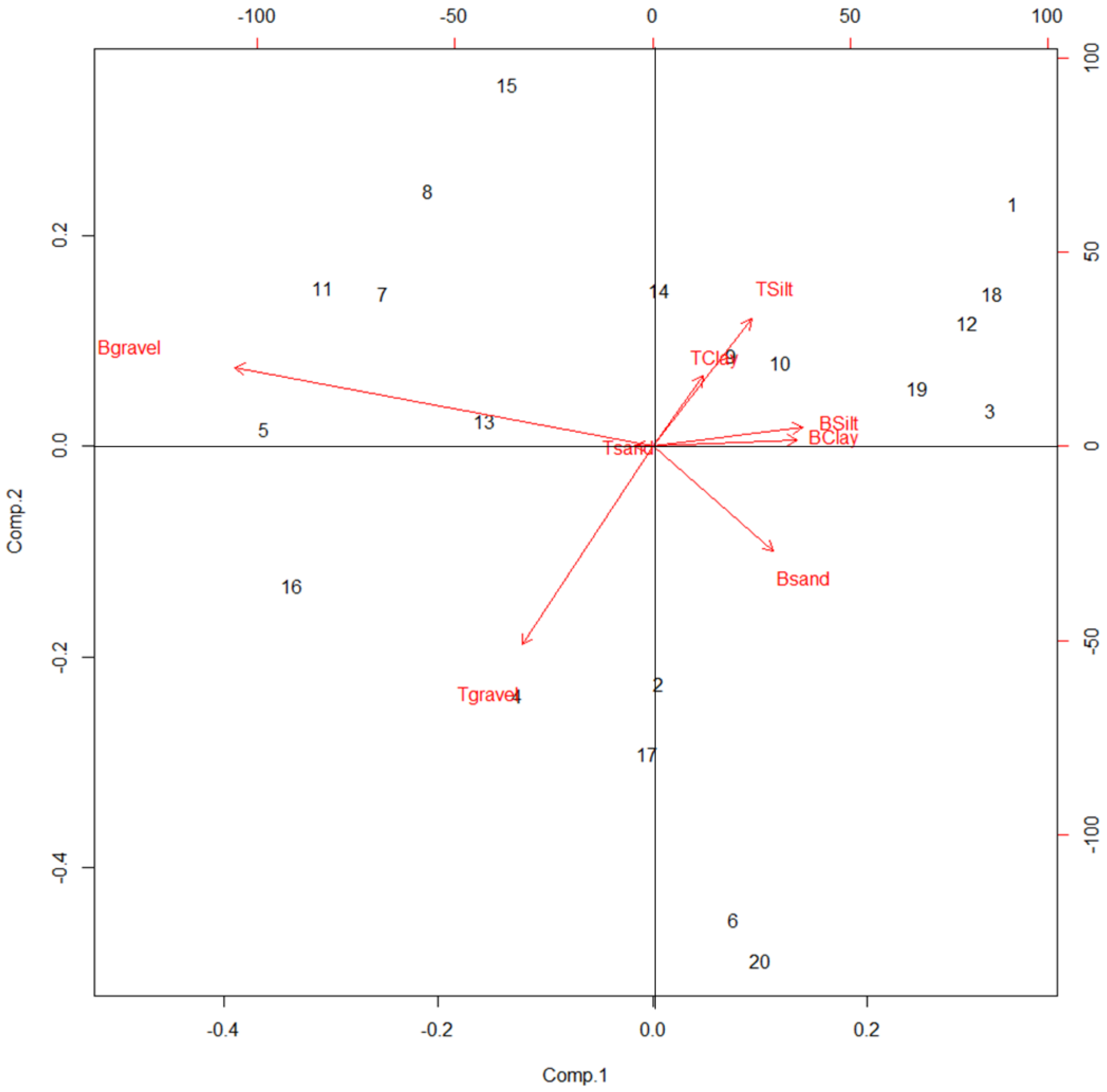

Figure 15 Biplot of summarising a Principal Component Analysis of the percentage of sediment size classes in soil samples collected from the bed (B) and toe (T) of waterways in the Wianamatta-South Creek catchment