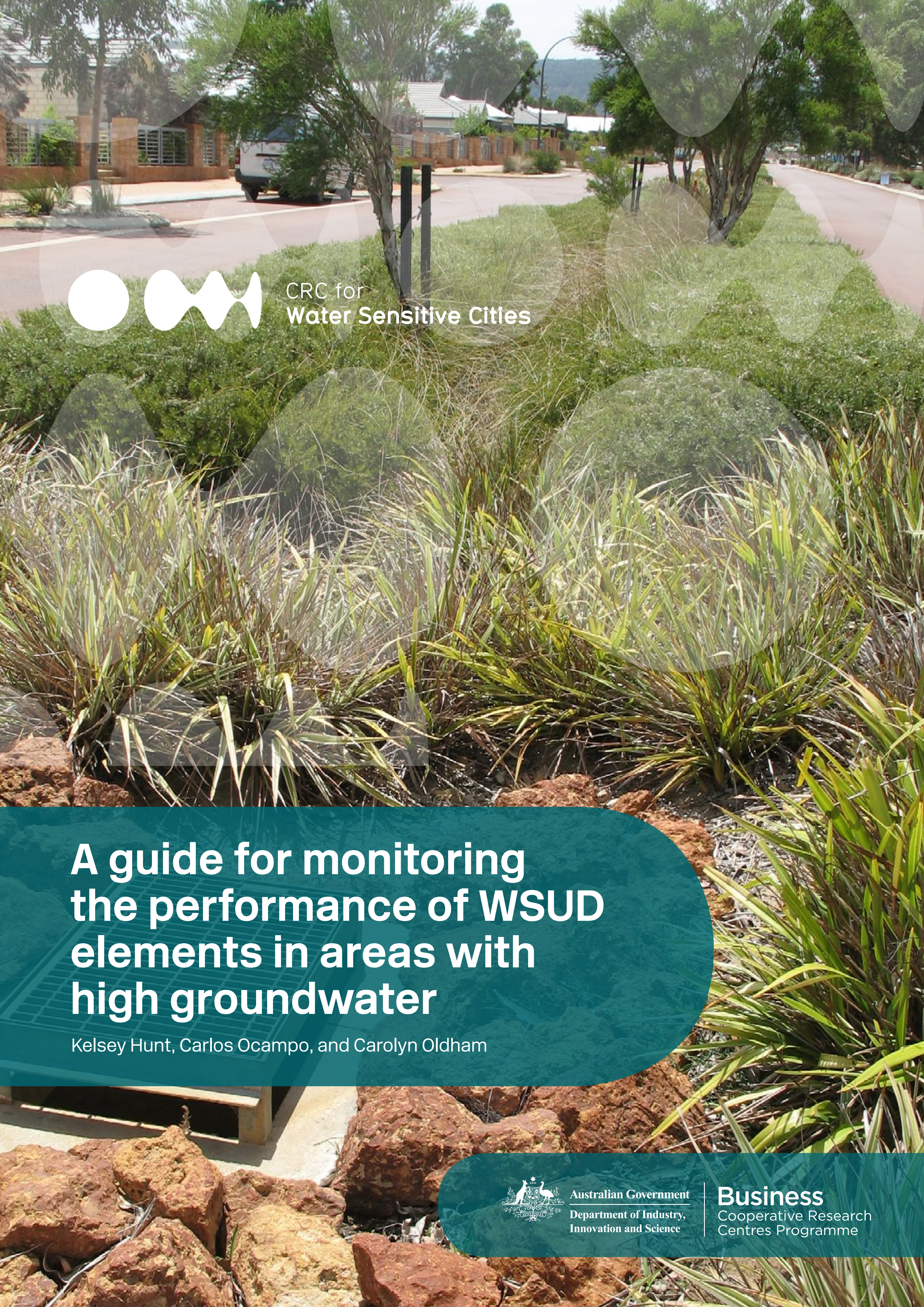

CRC for
Water Sensitive Cities

A guide for monitoring the performance of WSUD elements in areas with high groundwater

Kelsey Hunt, Carlos Ocampo, and Carolyn Oldham

Australian Government
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Business
Cooperative Research Centres Programme

A guide for monitoring the performance of WSUD elements in areas with high groundwater
Hydrology and nutrient transport processes in groundwater – surface water systems (Project B2.4)
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Authors

Kelsey Hunt, Carlos Ocampo, and Carolyn Oldham

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Cooperative Research Centre for Water Sensitive Cities

Level 1, 8 Scenic Blvd, Clayton Campus
Monash University
Clayton, VIC 3800

p. +61 3 9902 4985
e. admin@crcwsc.org.au
w. www.watersensitivecities.org.au

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Disclaimer

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1. Introduction

Water sensitive urban design (WSUD) is an approach for the planning and design of urban environments that is sensitive to water sustainability, resilience, and environmental protection. The approach integrates the urban water cycle (including potable water, wastewater, and stormwater) into built and natural landscapes to provide multiple benefits to society.

A WSUD element is a device, system or entire catchment designed in accordance with WSUD principles. WSUD elements are designed to manage urban stormwater and include vegetated swales, living streams, biofilters, constructed wetlands, infiltration basins, soakwells, litter and sediment traps, and rainwater storage and reuse systems. However, in areas with high groundwater, stormwater may be a combination of both surface water and groundwater, and both need to be managed concurrently. The high groundwater may be permanent, seasonally perched during the wet season, or temporarily perched by excessive rainfall events.

When a WSUD element is constructed in an area with high groundwater, nutrients and other pollutants in the groundwater may be mobilised and mix with surface water. This groundwater contribution to the water quality and flow through a WSUD element may reduce the effectiveness of the element in achieving its performance objectives.

Information about how different types of WSUD elements perform where there is interaction with high groundwater is critical to better understanding the function, efficiency, and design of elements under local conditions. The validation of WSUD element performance in areas with high groundwater is also important for the adoption of the technology.

This guide focuses on the quantitative monitoring of the nutrient removal performance of WSUD elements and presents an overview of monitoring and analysis techniques in areas where high groundwater may influence WSUD element performance. However, it should be noted that many WSUD elements are designed to meet multiple objectives, such as water quality improvement, flow attenuation, amenity, microclimate benefits, public health and safety, and ecological health. Those other objectives may be equally or more important to overall performance assessment.

General monitoring principles are outlined in Section 2, and detailed case studies are presented in Section 3 to provide examples of types of monitoring across a range of WSUD elements.

Organisations undertaking targeted and cost-effective monitoring of WSUD elements are encouraged to use the methodologies described in this report.

Further information about WSUD is available in the *Stormwater management manual for Western Australia* (DoW, 2004, 2007).

1.1 Target audience and application

The target audience for this guide includes state government agencies, local government authorities, land developers, consultants, and other stakeholders involved in the design, construction, operation, and monitoring of WSUD elements.

The guide is intended to be used where there is a willingness or need to understand the performance of a WSUD element in areas with high groundwater, or there is a requirement to monitor a WSUD element due to uncertainties about the element's design (for example, because of deviations from best practice design or because a new design approach or technique is being tested).

This guide should be used to optimise monitoring of WSUD elements where there is significant interaction with high groundwater, where pre-development site investigations identify groundwater within 2 metres of the ground surface or where groundwater is being managed or controlled.

1.2 Other relevant documents

Other relevant documents and standards should be consulted where guidance on the development of monitoring programs or general monitoring procedures is required.

All methods and equipment used in water sampling should meet the requirements of Australian/New Zealand AS/NZS 5667.1:1998: *Water quality sampling – guidance on the design of sampling programs, sampling techniques and the preservation and handling of samples*.

Specific advice on surface water and groundwater sampling is listed below. Many of the publications listed are from Western Australia because WSUD implementation in areas with high groundwater is an important issue in that state. Refer to relevant local guidelines where they are available.

- *Minimum construction requirements for water bores in Australia* (LWBC, 2003)
- *Groundwater sampling and analysis – a field guide* (Sundaram et al., 2009)
- *National industry guidelines for hydrometric monitoring* (BoM, 2013)
- *Water monitoring guidelines for better urban water management strategies and plans* (DoW, 2012)
- *Stormwater management manual for Western Australia* (DoW, 2004)
- *Stormwater management manual for Western Australia, Chapter 10 – performance monitoring and evaluation* (DoW, 2007)

- *Water resource considerations when controlling groundwater levels in urban development* (DoW, 2013)
- *Water quality monitoring program design: a guideline to the development of surface water quality monitoring programs* (DoW, 2008a)
- *Field sampling guidelines: a guideline for field sampling for surface water quality monitoring programs* (DoW, 2008b)
- *Surface water sampling methods and analysis – technical appendices: standard operating procedures for water sampling – methods and analysis* (DoW, 2008c)
- *Water quality protection note 30: groundwater monitoring bores* (DoW, 2006)
- *Operational policy no. 5.12 – hydrogeological reporting associated with a groundwater well licence* (DoW, 2009).

1.3 Assumptions

The guide presents techniques that are in use at the time of writing. New monitoring approaches and techniques may be developed as knowledge and technology in the area advance. However, the general monitoring requirements and analytical approaches are well established and are likely to remain relevant for the purposes of performance evaluation of WSUD elements.

1.4 Navigating this guide

The guide is designed to help you to:

- Set objectives – understanding what you are trying to show through your monitoring.
- Design a monitoring program that provides meaningful results in your context and for your WSUD design.
- Understand when to use a simple approach, and when a more complex design is appropriate.
- Analyse and communicate the results.

It is structured around a number of questions that help you achieve this:

1. How do I know what to monitor?	Go to section 2.1, 2.2, 2.3
2. How does my local context influence the monitoring program?	Go to section 2.5, 2.6
3. What monitoring technique should I use?	Go to section 2.4.1, 2.4.2, 2.6
4. What sampling design should I use?	Go to section 2.4.3, 2.4.4, 2.4.5, 2.4.6
5. How do I analyse the monitoring data?	Go to section 2.7
6. How do I report the findings?	Go to section 2.8
7. Can I see what others have done?	Go to Case Studies 1-6

2. Monitoring principles and approaches

2.1 Monitoring objectives

Identifying appropriate monitoring objectives for a WSUD element is the first step in designing an effective monitoring program. Monitoring objectives should be specific to the individual WSUD element and should be clear, concise, measureable, realistic, and results oriented.

The primary objective of monitoring a WSUD element is typically to assess its ability to attenuate stormflows and reduce nutrient concentrations and/or loads, measured against the design objectives for the element.

Some states, territories, catchments, and regions have defined performance targets or water quality objectives for nutrients. In the absence of defined local performance targets or water quality objectives, outflow concentrations of the WSUD element may be compared to the regional ecosystem trigger values cited in the *Australian and New Zealand guidelines for fresh and marine water quality* (ANZECC & ARMCANZ, 2000).

The objectives for the monitoring program should be determined in consultation with relevant stakeholders and approval authorities, and be in the context of any approved planning or environmental planning documents, such as an approved urban water management plan in Western Australia.

2.2 Where to monitor

While WSUD elements vary in their design and construction, most elements have one or more of the common water flow pathways shown in Figure 1. The selection of monitoring locations should consider each of the water flow pathways that are relevant to the WSUD element under investigation:

- 1a Controlled inflows (pipe/channel)
- 1b Controlled outflows (pipe/channel)
- 2 Uncontrolled surface inflows
- 3 Atmospheric exchange
- 4 Groundwater exchange
- 5 Storage.

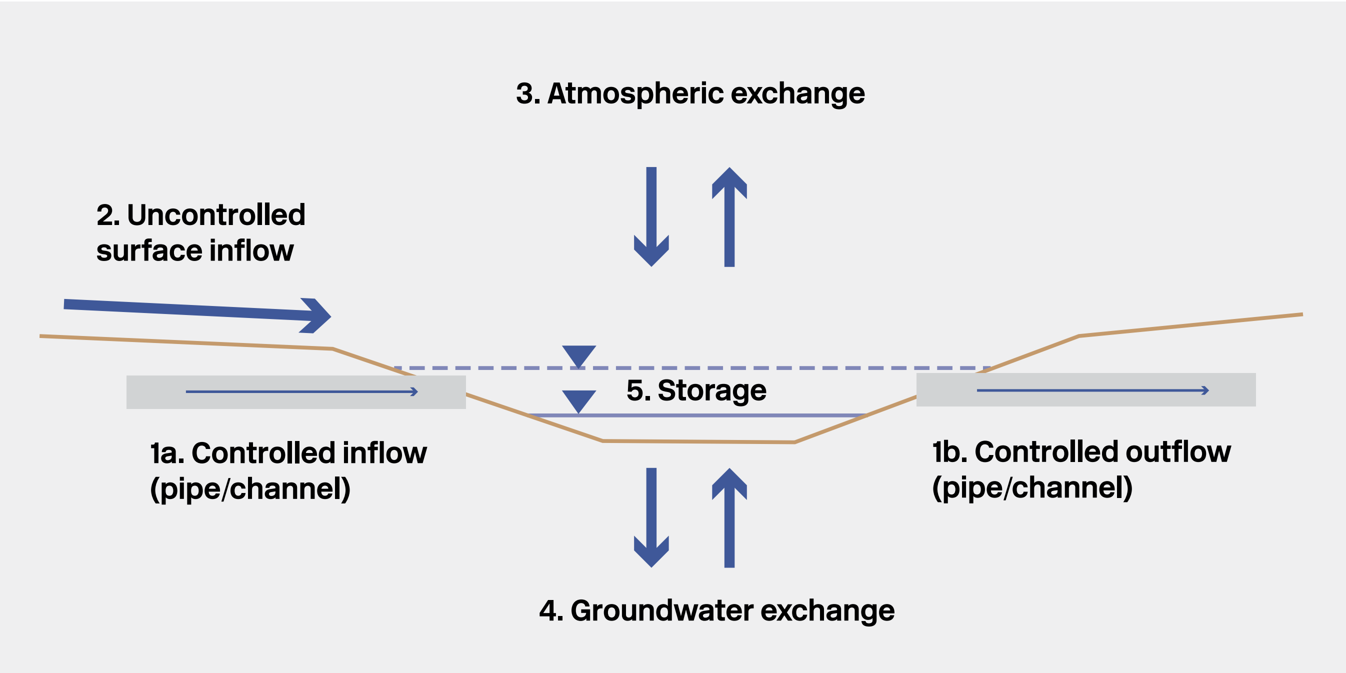


Figure 1: WSUD element flow pathways

Monitoring each location that is relevant to the element will enable the development of a quantitative water and nutrient balance.

Where multiple WSUD elements are installed in a treatment train, monitoring of individual elements should be completed to ensure that treatment efficiencies associated with one element are not attributed to another. For example, where a gross pollutant trap is installed in a treatment train upstream of a constructed wetland, the monitoring of the constructed wetland inflow location should occur downstream of the gross pollutant trap to ensure that the treatment efficiencies of the wetland itself are assessed.

Methods for quantifying the influence of vegetation on the water balance are not included in this guide. Where vegetation has a significant influence on the water balance of a WSUD element, additional calculations and monitoring approaches may be required, such as estimates or measurements of evapotranspiration (Barron et al., 2013).

2.3 What to monitor

2.3.1 Water quantity

Controlled inflows and outflows

All controlled inflows and outflows of a WSUD element should be monitored. In some WSUD elements, there are multiple surface water inflows and outflows, and it is important to monitor all of them in order to complete the water balance.

Where controlled inflows include subsoil drainage, the subsoil drain should also be monitored. During periods when the water table is below the level of the subsoil drain (that is, the controlled groundwater level, CGL), any subsurface inflows will carry infiltrated stormwater; at other times, the subsoil drain will carry intercepted groundwater.

Uncontrolled surface inflows

Some WSUD elements may be specifically designed to disperse uncontrolled surface inflows (as overland stormwater inflows) and attenuate peak flows. This slows down stormwater inflows and provides additional time for nutrient removal in the WSUD element. The magnitude of those inflows should be gauged, monitored or estimated where possible.

Atmospheric exchange

Atmospheric exchanges include rainfall and evaporation, and both are needed to complete the water balance. Rainfall data will also be needed to characterise storm event size and duration.

Groundwater exchange

In unlined WSUD elements, where infiltration is a key function of the element design, or where seasonal groundwater levels directly contribute a water source, groundwater monitoring should be undertaken to quantify volumes of groundwater entering or leaving the WSUD element.

Storage volume

The storage volume can include both surface storage and soil pore storage (temporary storage within the pore spaces of underlying soil/media). Changes in the storage volume during a monitoring period are an important component in the water balance of a WSUD element, and their quantification can be critical in interpreting monitoring data.

2.3.2 Water quality

When assessing the nutrient attenuation performance of a WSUD element, the following nutrients may be monitored:

- total nitrogen (TN)
- total phosphorus (TP)
- nutrient species: ammonium (NH_4^+), oxidised nitrogen (NO_x), dissolved organic nitrogen (DOrg-N) and filterable reactive phosphorus (FRP)

The monitored parameters should target the nutrients that the element was designed to treat. The nutrient speciation will provide a deeper understanding of the performance, as different WSUD elements are effective at removing different nutrient species. Nutrient speciation in groundwater is also typically different from that in surface water due to the different biogeochemical conditions.

The basic suite of physicochemical parameters – temperature, electrical conductivity (EC), pH and dissolved oxygen concentrations (DO) – should be monitored. These are easy to measure using a field probe and provide additional critical information on WSUD element performance. This data can also be useful in identifying causes of poor performance if an element fails to meet its design performance.

2.4 How to monitor

Water quantity and water quality parameters can be monitored through manual measurements (such as grab sampling or manual readings), automatic samplers or continuous measurements (such as loggers or sensors). The approach used will be determined by the available resources, the objectives of the monitoring, and the WSUD element's configuration and design.

Ongoing monitoring of a WSUD element should be considered during the design of the element to ensure effective and safe access to monitoring locations (see Section 2.5).

2.4.1 Water quantity

Controlled inflow/outflow

Common methods for obtaining flow measurements of controlled inflows and outflows, typically found in pipe/channel sections, are detailed below. For all methods, flow measurement locations should be selected to avoid variable backwater effects.

Water-level measurements

Water level measurement devices, such as staff gauges, water level data loggers, and float gauges, should be installed at a location with a well-defined cross-sectional area. Separate measurements of discharge velocity across a range of flow conditions must be related to water height to establish a stage–discharge table or curve. Once the stage–discharge relationship has been established, water levels can then be monitored and subsequently converted to discharge velocities. Weirs or flumes can be installed within a channel to create a well-defined channel geometry. Rating curves for standard weir and flume configurations are then used to convert water levels to discharges.

Theoretical equations can also be used to convert water-level measurements to discharge: for open channel flow, Manning's equation is used; for flow in pipes, Bernoulli's equation is used.

Manning's equation for open channel flow is:

$$Q = \frac{1}{n} \times A \times R^{2/3} \times S^{1/2} \tag{1}$$

where Q is the flow rate (m^3/s), n is Manning's roughness coefficient, S is the longitudinal slope (m/m), A is the cross-sectional area of flow (m^2), and R is the hydraulic radius (m), defined as A/P, where P is the wetted perimeter (m).

The discharge calculations using Manning's equation are significantly influenced by the roughness coefficient, which varies with flow depth, channel dimensions, and vegetation type. Manning's n values can be obtained from published tables (for example, Chow, 1959).

Where loggers are installed, it is recommended that they be programmed to record water levels at sufficiently frequent intervals to ensure that peak water levels are recorded in flash storm events. The logged interval can range from 2 minutes to 15 minutes, depending on the responsiveness of the catchment and the WSUD element's size (for example, the storage area).

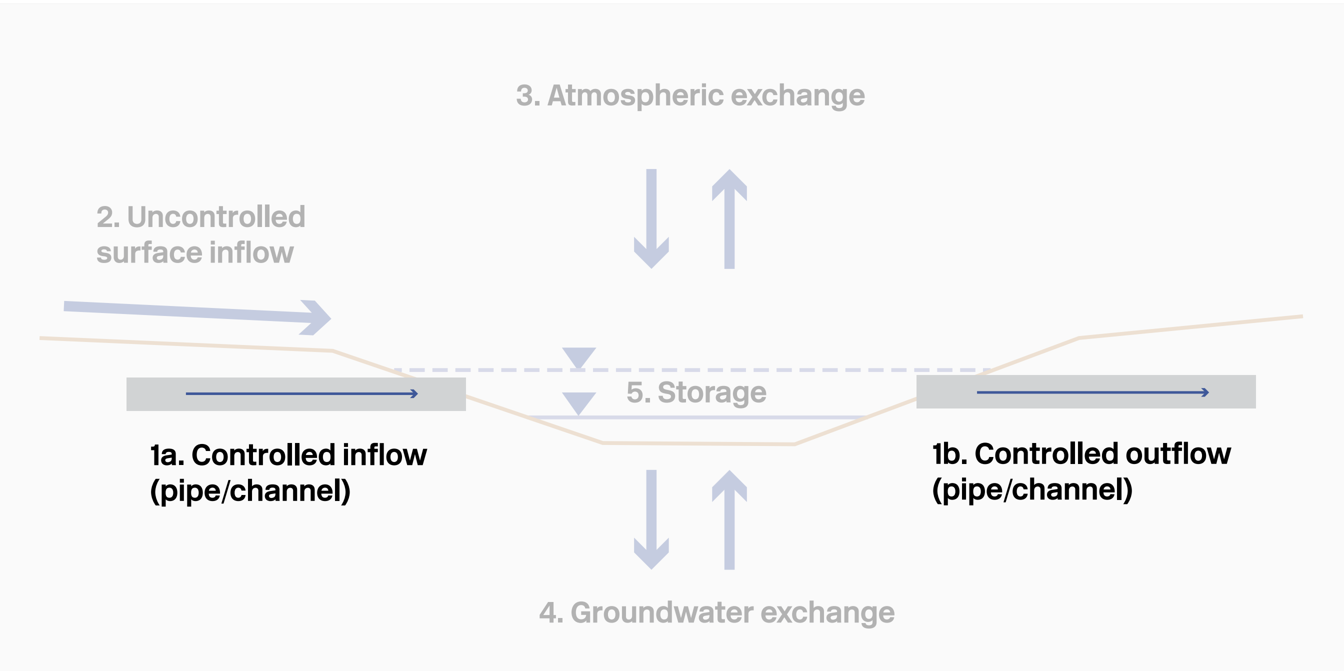


Figure 2: Controlled inflow/outflow

Where a staff gauge is used, cameras can be installed in situ and programmed to take multiple photographs of water levels on the gauge at specified intervals. The resulting water level data is converted to discharge using applicable theoretical equations or known stage–discharge relationships.

Refer to Case studies 3 and 4 in Section 3 for examples of the measurement of surface water quantity in open channels using loggers, and Case study 3 for an example of using in situ cameras to calculate discharge.

Bernouli's principle of conservation of energy and the concept of flow continuity can be used to compute pipe flow (turbulent flow). The friction loss (along the pipe length) and energy losses (created at the boundaries) need to be accounted for. Additional losses (at entrances and bends) need to also be considered in short pipes (such as culverts or drop inlets). Free flow discharge conditions in pipes are often found, and the velocity can be computed as:

$$v = \sqrt{\frac{2gH}{1 + K_m + K_p L}} \qquad (2)$$

where v is the velocity (m/s), g is the acceleration of gravity, H is the elevation head differential between inflow and outflow points (m), and K_m and K_p are the coefficients for minor losses and pipe friction losses along the pipe length, L. The discharge Q (m^3/s) can be computed using the continuity principle by multiplying v by the pipe area, A. Case study 2 presents an example for this computation. The discharge equation for exit conditions with no free flow is similar to the equation above, but with the introduction of the exit coefficient Kx with the losses.

The hydraulics of culvert flow with inlet and outlet controls (USBPR, 1965) can be used to compute flow rates, but additional considerations of the elevation of the tailwater in the outflow and the length of the pipe (culvert) are needed. Inlet control conditions are commonly observed in pits during peak flow conditions over a short period. Submerged outlet control in culverts flowing at full capacity is also commonly observed over the course of events. Although inlet control is assumed during the design of most WSUD systems that infiltrate water, such conditions change when the water table influences the water levels in the storage facilities. Monitoring water levels for inflow and surface storage areas is crucial to address flow conditions and determine the tailwater depth.

Direct velocity and discharge measurements

Direct velocity measurements within a pipe or channel section can be made using either a current meter or a simple float and stopwatch (for example, for surface velocity).

Ultrasonic (Doppler) sensors measure the mean velocity of a channel profile through the reflection of sound waves off particles and air bubbles in the flow. The sensors can be installed in either open channel or piped flow systems and can be mounted on the bottom or side of a channel section. Lack of seeding material (particles or bubbles) poses a limitation for this technique; such conditions can be found in outflows from bioretention systems (see Case study 4).

The velocity measurements can then be combined with cross-sectional area measurements to obtain the discharge using the equation:

$$Q = A_i V_i \qquad (3)$$

where Q is the flow rate (m^3/s), A_i is the cross-sectional area of the channel section (m^2) over period i, and V_i is the mean velocity of the channel section (m/s) over period i.

Discharge can also be estimated by directly measuring the time it takes to fill a vessel of known volume (such as a bucket of known volume) using the equation:

$$Q = \frac{Vol}{T} \qquad (4)$$

where Vol is the volume of the vessel (m^3) and T is the filling time.

Direct measurements are recommended for infrequent flow monitoring associated with non-storm events, and an average of multiple measurements should be used. Case Studies 3 and 4 present examples of direct flow measurements for outflows from subsoil pipes.

Uncontrolled surface inflow

WSUD elements may experience uncontrolled surface inflows, such as overland stormwater inflows (Figure 3). The element may be specifically designed to collect these flows, slow them down and possibly redirect them through additional treatment features, such as grassed swales. The flows may also be unintended (for example, due to earthwork batters).

Uncontrolled surface water inflows can be estimated by the following method:

1. Measure the contributing catchment area.

2. Estimate the runoff coefficient for the contributing catchment. The runoff coefficient is a function of rainfall intensity and frequency, and allowances should be made for expected losses through hydrological processes (such as interception or depression storages). Refer to Australian reference documents (for example, the Australian Rainfall and Runoff Tables) for runoff coefficients of similar surface types (such as road, grass, and bare earth).

3. Estimate the volume using the following equation:

$$Vol = ACR \qquad (5)$$

where A is the contributing catchment area (m^2), C is the runoff coefficient (as a function of rainfall intensity and frequency, with allowances for expected losses) and R is the total event rainfall (m).

Hydrological modelling software may be used to estimate uncontrolled surface inflows when they are expected to contribute a large proportion of the total inflows; this may occur, for example, when the catchment is predominantly impervious or very large.

Case study 3 provides an example of this method. Sheet flow from a paved road surface contributed to the inflows into a raingarden. Rainfall data from an on-site rain gauge and catchment physical parameters were used as inputs to a kinematic wave model to simulate rainfall-runoff transformation and routing of the uncontrolled surface inflow into the raingarden (Ocampo et al., 2016).

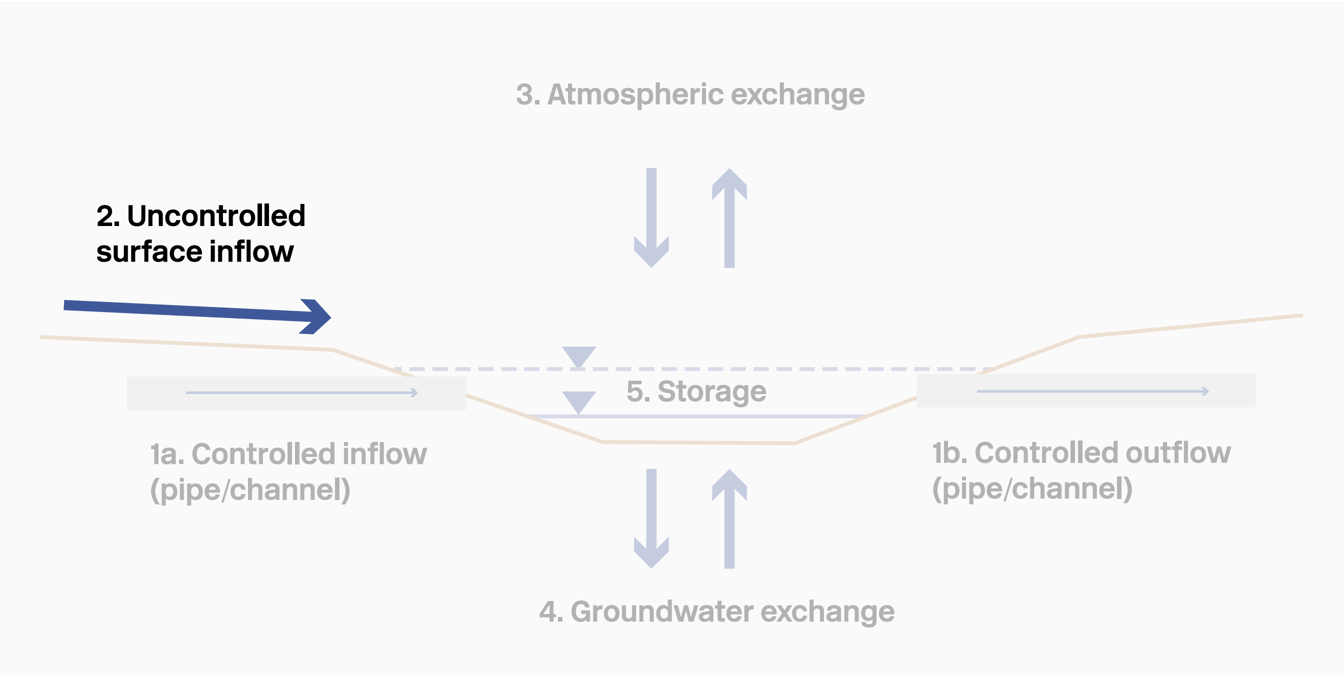


Figure 3: Uncontrolled surface inflow

Atmospheric exchange

The dominant atmospheric exchange (Figure 4) in Australia is rainfall. Rainfall can be highly variable over a small geographical area, so it is recommended that a tipping bucket rain gauge be installed on site. The selection of a site for meteorological installations should consider security. For example, public access should be restricted where possible, or gauges should be installed well above ground to reduce the chance of vandalism. Rain gauges in small catchments should ideally be located at the centroid of the catchment. Rain shadow effects from neighbouring buildings and other objects (such as trees) should also be considered when siting rain gauges.

Other meteorological data can also be important in assessments of WSUD element performance. Weather stations that monitor rainfall, air temperature, wind speed and direction, and barometric pressure are available. Stand-alone barometric pressure loggers may also be installed adjacent to a WSUD element to correct water-level data.

When the installation of a local rain gauge is not practical, data from a nearby Bureau of Meteorology station can be used, although this may increase the error associated with determining local rainfall inputs, especially over short time intervals. Evaporation data can also be obtained from nearby Bureau of Meteorology stations.

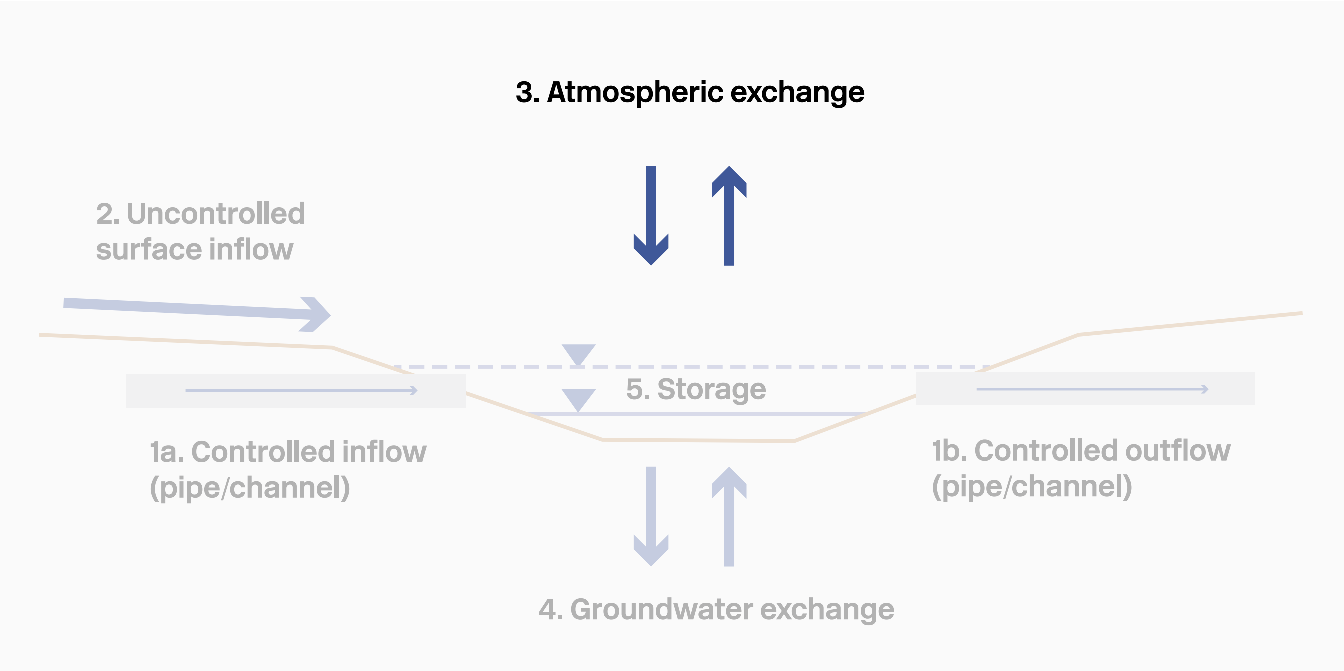


Figure 4: Atmospheric exchange

Groundwater exchange

Groundwater exchange with a WSUD element (Figure 5) is governed by the hydraulic gradient between the local water table and standing water levels in the WSUD element. Elements are therefore likely to experience variable groundwater exchange across different seasons and during storm events, and the exchange may be continuous or intermittent. Thus, the spatial and temporal variabilities of groundwater exchange need to be considered. The heterogeneity of local permeability (such as a combination of impervious banks and permeable media and base) will also affect groundwater exchange.

A summary of common techniques used to measure groundwater exchange is provided below. Where more certainty in estimates of groundwater exchange is required, a combination of techniques should be used.

Hydraulic method

A mapping of water table heights around the WSUD element is required. Water levels in groundwater observation bores sited upstream and downstream of the element should be monitored over the seasons. The standing water level within the WSUD element should also be monitored over the seasons, and over storm events. Once the relative heights of the water table and the standing water levels are determined, the hydraulic gradient can be calculated, and groundwater fluxes into and out of the element can be estimated using the standard Darcy's Law (see below).

Where high groundwater conditions have not been clearly defined, groundwater exchange locations should be monitored at three locations spaced around the WSUD element to quantify the water table gradient (groundwater flow direction) and potential groundwater interaction with the element.

Groundwater levels in observation bores can be measured periodically using a groundwater dip meter or continuously logged in situ using water-level data loggers that can be programmed to measure the water level at a specific frequency. In high groundwater areas, it is recommended that loggers be set to log at 15-minute intervals.

Groundwater observation bores, the WSUD element and other features of the element (such as controlled inflow and outflow locations, and subsoil drains) should be surveyed to the Australian Height Datum (AHD) or local height datum.

It is recommended that supporting information on hydraulic conductivity relevant to the local aquifer around the element be assessed (for example, using observation bore pumping or slug tests), as site works and variable fill can result in hydraulic conductivity values that vary from averaged values for local soils.

The groundwater contribution to the WSUD element can be estimated using Darcy's Law, which is expressed as:

$$Q = KA\frac{(h_1 - h_2)}{L} \tag{6}$$

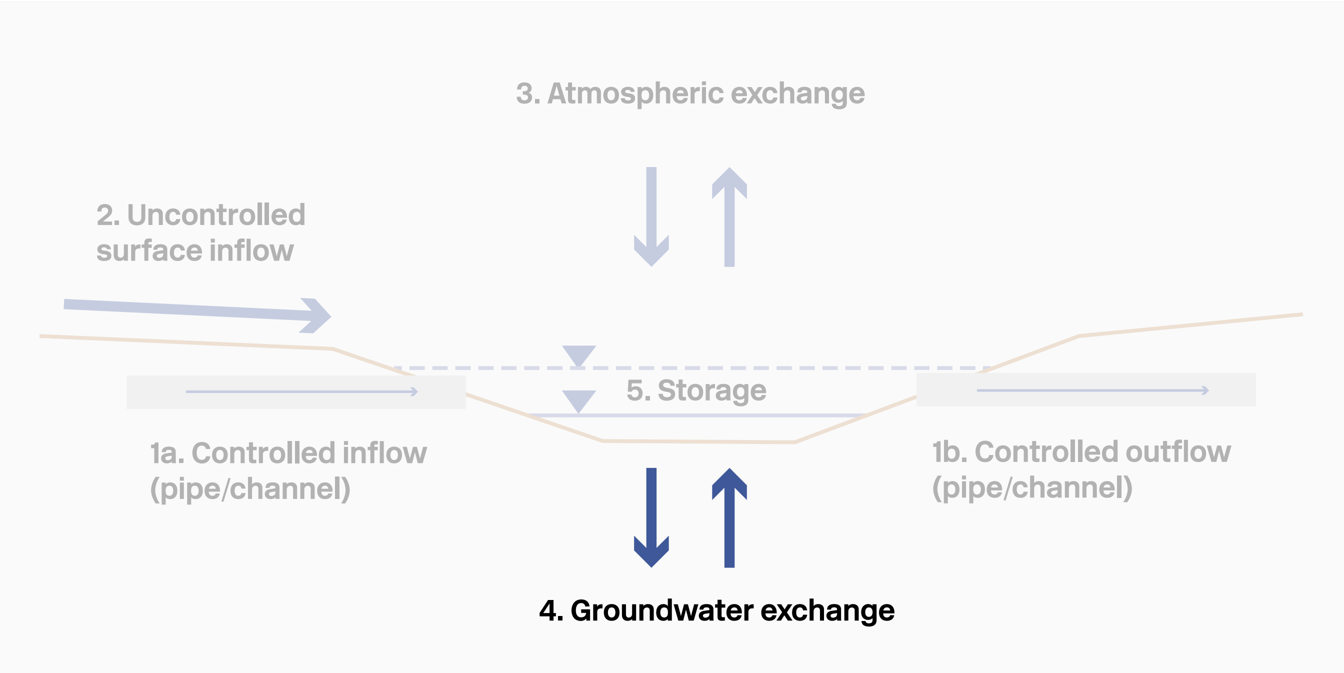


Figure 5: Groundwater exchange

where *Q* is the flow through a vertical plane associated with the WSUD element (m^3/day), *K* is the hydraulic conductivity of the superficial aquifer media (m/day), *A* is the cross-sectional area through which groundwater must pass to enter or leave the WSUD element (m^2), defined as *a x b*, where *a* is the length of the WSUD element along the groundwater interface and *b* is the effective thickness of the aquifer, h_1 is the water level in the groundwater bore of interest (m AHD), h_2 is the standing water height in the WSUD element (m AHD) and *L* is the distance between the groundwater bore and the WSUD element (m).

The effective thickness of the aquifer *(b)* can be one of the more difficult parameters to determine (Rosenberry et al., 2008). For WSUD elements such as basins, wetlands, and swales, *b* can be estimated from the geometry of the groundwater capture zone (Townley et al., 1993). Following this approach, most WSUD elements would exhibit 2a/B < 1, where *B* is the aquifer thickness (m); *b* can then be derived using regime plots (Townley et al., 1993). Local aquifer properties and conditions should be used when determining the effective aquifer thickness for a WSUD element.

Key sources of error when using the hydraulic method are related to the typically poor physical characterisation of the aquifer properties that affect flow (the local hydraulic conductivity, *K*, and the effective thickness of the aquifer, *b*) (Rosenberry et al., 2008).

Water balance

Where all other inflows and outflows have been quantified, the groundwater exchange component can be estimated from the WSUD element water balance.

The water balance can be expressed as:

$$\sum V_{in} - \sum V_{out} = \Delta S \qquad (7)$$

where ΣV_{in} is the sum of all the inflow volumes over a period of time Δt (m^3), ΣV_{out} is the sum of all the outflow volumes over a period of time Δt (m^3), and ΔS is the change in volume of water stored in the WSUD element over a period of time Δt (m^3).

Conservative and passive environmental tracers

The contribution of groundwater to a WSUD element can also be estimated by monitoring conservative environmental tracers (such as natural salt concentrations) in the contributing water sources (for example, surface water and groundwater). This approach can be used only when there is a significant difference in tracer concentrations between the contributing water sources, and the groundwater concentration is stable.

Tracer concentrations in the contributing water sources are monitored along with any changes in tracer concentration within the WSUD element. A tracer mass balance can then be used to quantify groundwater exchange.

Case study 1 provides an example of this technique, using the conservative tracer electrical conductivity (EC) converted to salinity (ppt). Estimates of the groundwater contribution to a living stream are derived using the following equation:

$$Q_G K_G = Q_{out} K_{out} - Q_{in} K_{in} \qquad (8)$$

where Q_G, Q_{out}, and Qin are the flow rates of groundwater, other outflows, and other inflows, respectively (m^3), and K_G, K_{out}, and K_{in} are the salinities of groundwater, outflows, and inflows, respectively.

Heat exchange

Where the temperature difference between groundwater and surface water sources to a WSUD element are sufficiently large, temperature profiles can be used to estimate the groundwater contribution to the element (Kalbus et al., 2006).

The use of heat as a tracer of groundwater exchange involves time-series monitoring of temperature in both the groundwater source and the WSUD element. Mohamed et al. (2013) described an approach to quantify groundwater exchange to a surface channel in Western Australia using a combination of temperature sensors installed in the channel bed and bank, and in the surface water, and a one-dimensional heat transport model. The groundwater exchange was verified with hydrometric data using water-level sensors in bores and monitoring of the water level in an open channel.

An overview of the use of temperature as a tracer of groundwater exchange with surface water systems is given by Constantz et al. (2008).

Storage

The volume of standing water stored in a WSUD element (Figure 6) can be estimated by measuring surface water height. The height is converted to volume using a previously established volume–height curve for the element (Figure 7). Surface water heights can be measured periodically using a staff gauge or continuously measured in situ using water-level sensors, such as pressure sensors, ultrasonic or bubbler methods; the sensors can be programmed to measure and record the water level at a specific frequency (see the section above on monitoring water level). For subsurface storage, such as in permeable soil/media, the storage volume can be estimated based on porosity parameters and water saturation sensors.

Case Studies 2 and 3 provide examples of estimating the change in WSUD element storage volume by monitoring surface water levels.

2.4.2 Water quality

Surface water

Surface water quality monitoring should where possible be conducted at the same location used for surface water flow measurements. Water quality monitoring locations should be selected to be representative of the water source they are assumed to represent (such as inflow), and samples should be collected from a well-mixed zone. For example, if a sample is to be representative of inflows to a constructed wetland, it should be collected from the inflow channel and not within the wetland, which contains water from other sources as well.

Discrete grab sampling is considered best suited for base or seasonal flow conditions. Grab sampling does not generally provide sufficient temporal resolution to estimate event mean concentrations (EMCs) for a storm event, or to capture intra-storm variability; grab sampling during a storm event can be challenging (because of safety issues and the time of occurrence) and resource intensive.

Where laboratory analysis of water is required, discrete or composite samples can be collected, either manually or by autosamplers. Sensors are also available for many water quality parameters and may be deployed for continuous monitoring and logging.

When a design storm event is being monitored and multiple samples are needed to characterise the entire storm hydrograph, automatic sampling should be used. The selection of autosampler model should accommodate the frequency of sampling required for monitoring.

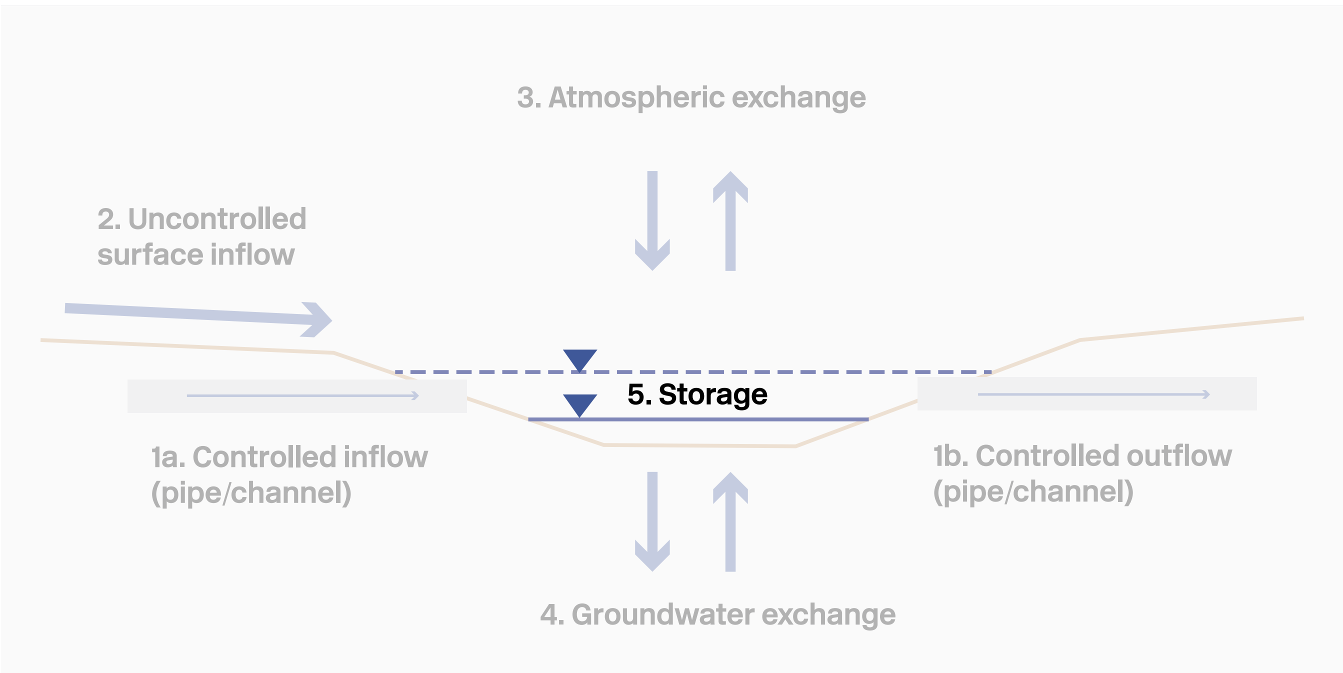


Figure 6: Storage

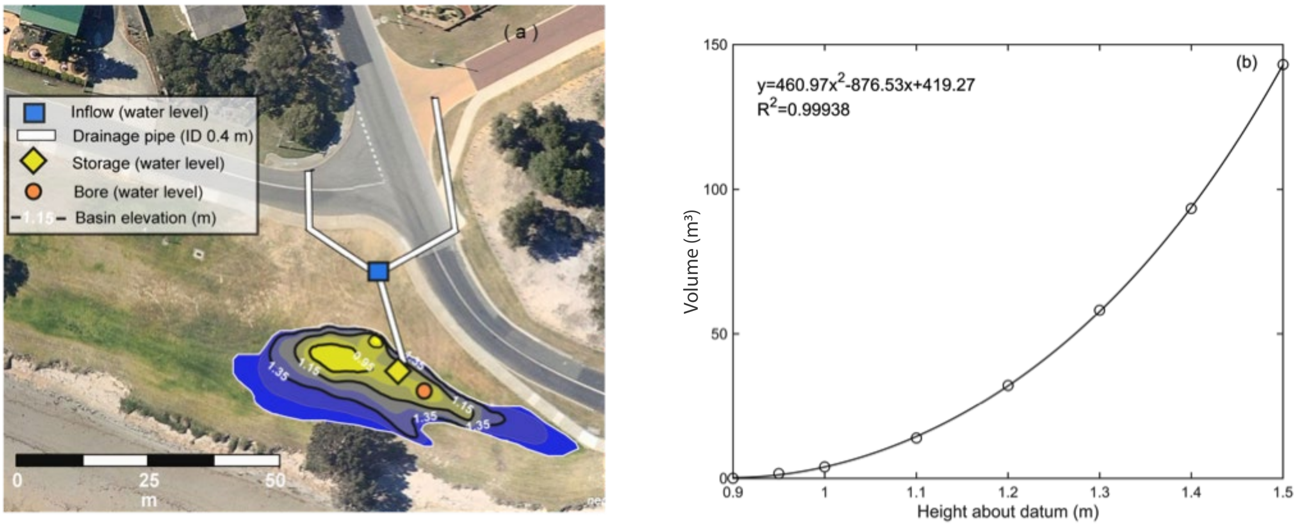


Figure 7: Example volume–height curve derived from basin topography
a) basin topography of a shallow depth infiltration area
b) derived volume-height curve (modified from Woods, 2014)

For example, an autosampler that samples at 10-minute intervals may not be suitable for sampling rapid flow changes on the rising limb of the hydrograph for a small catchment with a short time of concentration.

Composite sampling can be a more cost-effective approach for estimating EMCs and nutrient loads across a storm event. A composite sample is made up of a number of individual samples collected at regular time intervals (for example, between 5 and 30 minutes) or flow-based intervals during an event (such as after approximately 100 L, depending on the size of the targeted storms) and combined to form a single sample that is considered representative of the event stormwater quality. Case studies 5 and 6 provide examples of these techniques. Automatic sampling equipment that can be programmed to sample the first flush of a storm event, as well as to collect a composite sample for the remainder of the event hydrograph, is also available (Global Water, 2016); Case studies 3 and 4 provide examples of the use of two-bottle autosamplers.

Groundwater

For WSUD elements with potential inflow from high groundwater, or where soil amendment is used around subsoil drainage to treat intercepted groundwater, groundwater sampling should be completed from at least one groundwater bore sited upstream of the WSUD element in order to characterise background groundwater. Where a WSUD element infiltrates to groundwater, a groundwater bore sited downstream of the element should also be sampled for quality.

2.4.3 Timing and frequency

WSUD elements are often designed to promote the biological attenuation of nutrients and pollutant removal. WSUD element treatment performance should be analysed after the element has become established (for example, after the designed vegetation coverage has been established) and the WSUD design performance is expected. Monitoring treatment performance should continue until urban development within the contributing catchment has been completed and design conditions have been achieved.

The frequency and timing of monitoring should be selected to ensure that they cover the critical flow conditions that affect the water quantity and water quality of the WSUD element, including design storm events, seasonally variable flow conditions, and groundwater interactions.

Where a WSUD element has been designed to target nutrient attenuation in baseflow, monitoring to quantify design performance must be undertaken during baseflow conditions, and care must be taken to avoid sampling during a storm event or the recession period of a storm event. The time to return to baseflow conditions following storm events will vary between catchments. As a rule of thumb, baseflow sampling should not be undertaken within 72 hours of a significant rainfall event (>15 mm of rainfall).

WSUD elements targeting nutrient attenuation are usually designed to treat the first flush and small storm event runoff (runoff generated by the first 15 mm of rainfall); monitoring of nutrient attenuation performance must therefore be undertaken over the design storm event. The frequency of water sampling must capture changes during storm events, and thus the entire hydrograph should be monitored (that is, the rising limb, peak flow, and falling limb) to ensure that the data collected is representative of the event.

Where a WSUD element is designed to attenuate stormwater flows, it is important to consider the flow regime (the shape and duration of the hydrograph) of the monitoring locations and collect samples at time intervals that span the residence time of the WSUD element.

For example, Figure 8 shows hypothetical hydrographs for a WSUD element showing the different periods of flow and water quality sampling required to quantify nutrient concentrations of upstream and downstream sampling locations (Shuster et al., 2007). In this example, sampling at the same time interval at the inflow and outflow sampling locations enables a representative sampling of the outflow; however, it misses the peak of the inflow. A cost-effective two-bottle autosampler can overcome this limitation at inflow stations for a time to peak of less than 10 minutes, as the first-flush bottle ensures sampling coverage until it is full (~6–7 minutes between triggering, purging, and sample collection).

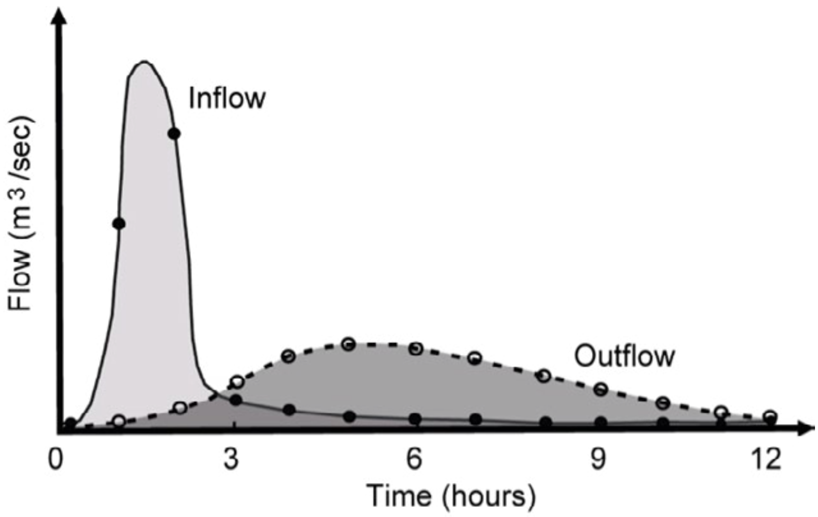


Figure 8: Hypothetical WSUD element inflow and outflow hydrographs (from Shuster et al., 2007)

It is important to recognise that, on top of practical challenges in sampling the rapid response of inflows and the timing of the occurrence of events (midnight and early morning), there is the potential for the outflow to contain contributions of water from sources other than the inflow event. Biofilters with a saturated zone can store water for up to five weeks (Shuster et al., 2007), and it is important to know whether the sample taken is old stored water (from a previous storm event) or treated water from the current storm. For example, Figure 9 shows how a two-bottle autosampler can be used to characterise outflow water from a bioretention basin and to identify old stored water from the first-flush bottle.

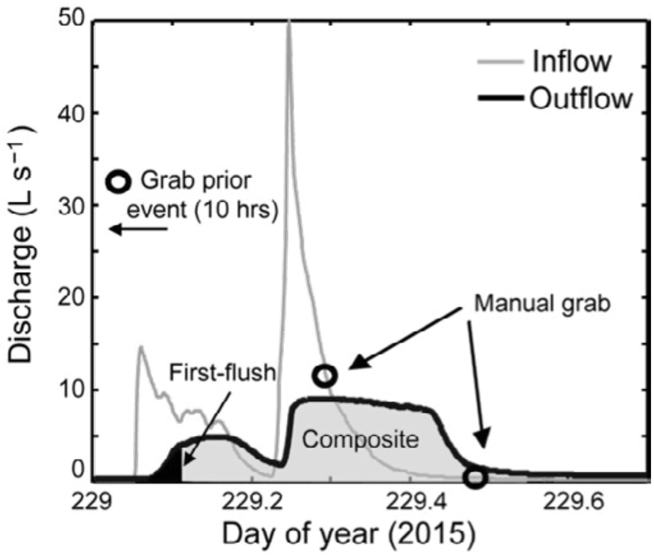


Figure 9: Two-bottle sampling strategy for a bioretention basin outflow (Case study 4)Note that the timing of the event is 1:20 a.m. on 31 July. Manual grab samples (prior, after peak, and recession) characterised the inflow hydrograph.

For elements designed to treat groundwater entering subsoil drains, monitoring intervals must reflect the seasonal interaction between groundwater and the element. Where this is continuous, quarterly monitoring can provide a broad pattern of seasonal variation in groundwater quality. Where interaction is seasonal, monitoring should be scheduled to encompass the re-wetting phase as the water table is rising, peak groundwater levels, and the ongoing interactions as the water table declines again at the end of the wet season. Case study 4 provides an example of an element interacting with groundwater over event and seasonal scales.

In situ concentrations (such as of dissolved oxygen) or passive tracers (such as EC) should be measured at a frequency and for a duration that matches the hydrological dynamics. As an example, in Case studies 5 and 6 DO concentrations in groundwater were measured monthly to capture seasonal dynamics. Daily measurements of DO concentrations in inflows were used to identify event-scale inputs from the catchment, and hourly measurements of DO concentrations were needed to understand the effects of respiration and photosynthesis diurnal cycles on nutrient concentrations. In Case study 4, EC was used as a passive tracer to explore hydrological dynamics across multiple timescales. In all cases, the sampling regime must be designed to align with the monitoring objectives.

2.4.4 Number of monitoring events

DoW (2007) recommends at least three monitoring events for each flow condition (such as the design storm event) to provide the minimum data needed for assessing statistical differences. Timing of monitoring should consider the potential seasonal groundwater interaction with the WSUD element.

Where baseflow is the critical flow condition, monthly sampling would be sufficient to characterise seasonal baseflow characteristics (that is, low and high groundwater contributions). Additional monitoring will be likely to be required where there are significant issues in the receiving water body, limited pre-installation data to characterise site surface water and groundwater, or uncertainties about the WSUD element design (such as when a new element design approach is being tested).

2.4.5 Number of samples

The number of samples collected during each monitoring event will be based on the critical flow conditions for the site. Baseflow or seasonal monitoring can comprise a single grab sample from each of the monitoring locations for each monitoring event.

Where the critical flow event is a storm, a number of samples may be needed to fully characterise the hydrograph of surface water inflow and outflow locations. For a storm event, a minimum of three samples should be obtained from each controlled inflow and controlled outflow monitoring location across the hydrograph, including at least one sample on the rising limb, one near the peak, and one on the falling limb. Where EMCs are to be calculated for an individual event, at least five samples (by automatic or manual collection) are required for each sample location (such as inflow and outflow). Alternatively, a composite sample can be collected over the event (see Section 2.4.2). At least one surface standing water sample and one groundwater sample should also be collected during storm event monitoring.

2.4.6 Quality control

Water quantity

Where instrumentation is used to continuously monitor the quantity of surface water and groundwater (as either water level or water flow), periodic calibration checks of the instrumentation should be performed. For flow monitoring equipment, periodic discharge measurements should be completed. Where water-level loggers are deployed, manual water level measurements should be recorded before removing loggers to correct for any change in water level following the reinstatement of the logger.

Water quality

Quality control water samples should be collected to identify any contamination associated with sample collection, transport, and laboratory techniques, and to ensure data integrity. Quality control samples include replicate samples and field blanks:

- *Replicate samples:* Two or more samples should be taken from the same site at the same time to establish the reproducibility of sampling. Replicate sampling will highlight the variability in the sampling method or natural variability in the environment. It is recommended that one replicate sample be taken for every 10 samples collected during the monitoring program.
- *Field blanks:* Field blanks contain deionised water that is exposed to the sampling environment at each sampling site and handled in the same manner as the real sample (for example, preserved or filtered). The blanks quantify any contamination that may result from the handling technique and from exposure to the atmosphere. One field blank should be collected during each monitoring event.

Where a water quality sensor is deployed, periodic calibration checks of the sensor should be performed.

Maintenance

The maintenance of monitoring equipment is important to maintain the accuracy and completeness of the data collected. Where monitoring equipment is installed in situ, the data should be regularly downloaded to verify it, to check battery levels and to check that the equipment is functioning as expected. For in situ monitoring, periodic field testing and calibration of equipment should be conducted throughout the monitoring program. Periodic maintenance visits should also check for obstructions to monitoring equipment.

It is important to keep accurate records of WSUD element maintenance activities, such as variations in inlet or outlet weir height, or the removal of sediment or vegetation. These activities may affect water level, water quality or performance within the element.

2.5 Design of WSUD elements

It is important to consider the monitoring requirements early in the design of the WSUD element to facilitate ease of monitoring and access and to ensure safety. Where possible, the design of the WSUD element should be undertaken in consultation with those who will be monitoring the element.

Key considerations in the design and construction of WSUD elements that directly affect the way they can be monitored include the following:

- *Access and safety considerations* – The inflow and/or outflow of WSUD elements (pits, pipes, culverts, channels, weirs) should be designed to facilitate monitoring. For example:
  - Where inflow and outflow areas are piped, pit lids that are large enough to enable access for monitoring should be installed.
  - Pit lids should be designed with safety and ease of removal in mind, and should be lockable to prevent public access.
  - Inflow and outflow channels should be designed with safe access and exit points.
- *Measurement considerations* – The design should consider all water sources that will potentially influence the WSUD element, such as surface water runoff, piped inflow, and groundwater. For example:
  - Where possible, consolidate multiple piped inflows and outflows into a single piped flow to simplify monitoring requirements.
  - Where automatic samplers may be installed, the inflow and outflow design should consider the incorporation of pits to accommodate the monitoring equipment and minimise vandalism.
  - Design flow control sections, such as weirs, into the inlet and outlet structures. The design of sections should ensure free flow conditions without backwater effects.
  - Where subsoil drainage is proposed to intercept seasonal groundwater, consider the requirements for monitoring groundwater interaction with subsoil drains. In particular, include access pits to monitor and sample drain flows at junction points, and provide access to outlet points.

2.6 WSUD element monitoring summary

Table 1 summarises the performance monitoring requirements for WSUD elements in areas with high groundwater where the uncertainty of the system's performance may pose risks to the receiving environment.

As noted in Section 2.4.4, additional monitoring events may be required when there are significant issues in the receiving water body, there is limited pre-installation data so that the site surface water and groundwater are poorly characterised, or there are uncertainties about the WSUD element design, such as when a new element design approach is being tested.

A reduced, but robust, monitoring program may be applied where the implementation of a WSUD element is considered to have a low level of risk to the receiving environment. A site with a low level of risk is considered to have the following characteristics:

- Sufficient data has been collected to appropriately characterise pre-installation surface water and groundwater.
- The site is not located within the catchment of a sensitive receiving environment.
- The WSUD element uses a standard design with proven nutrient treatment performance under similar hydrological and hydrogeological conditions.

Table 1: Performance monitoring requirements for higher risk WSUD elements in areas with high groundwater

WSUD element	When to monitor			Where to monitor	What to monitor	How to monitor
	Critical flow conditions	Minimum number of monitoring events[1]	Number of samples[2] (per monitoring event)			
Biofilters, bioretention systems, raingardens	Design storm event	3 events/ year (x 3 years)	Multiple[3]	Controlled inflow and outflow Uncontrolled surface water inflow Atmospheric exchange Groundwater exchange Storage	*Water quantity (flow)* *Water quality (laboratory):* nitrogen[4], phosphorus[5] *Water quality (in situ):* temperature, pH, electrical conductivity, dissolved oxygen	*Water quantity:* Surface water or groundwater level (manual measurements or pressure sensor), with discharge calculated through stage–discharge relationship or theoretical equations; velocity sensors or direct measurement (e.g. filling a vessel of known volume) combined with cross-sectional measurements; monitoring of conservative tracers in water sources and calculation through mass balance; calculation of runoff from uncontrolled surface inflows; hydrological modelling (uncontrolled surface inflows) or numerical modelling (groundwater exchange); rainfall volume using rain gauge. *Water quality (laboratory):* manual grab sample or automatic sampling (discrete or composite) *Water quality (in situ):* manual measurement or continuous measurement (water quality sensor).
Constructed wetland	Design storm event	3 events/ year (x 3 years)	Multiple[3]			
	Baseflow	Monthly (x 3 years)	One			
Dry or ephemeral detention areas	Design storm event	3 events/ year (x 3 years)	Multiple[3]			
Infiltration basins or trenches	Design storm event	3 events/ year (x 3 years)	Multiple[3]			
Living stream	Design storm event	3 events/ year (x 3 years)	Multiple[3]			
	Baseflow	Monthly (x 3 years)	One			
Swales and buffer strips	Design storm event	3 events/ year (x 3 years)	Multiple[3]			

1. *Timing of events should consider seasonal groundwater interaction with the WSUD element.*
2. *Excluding quality assurance samples.*
3. *A minimum of three samples should be obtained from each monitoring location across the hydrograph (at least one sample on the rising limb, one near the peak, and one on the falling limb), or a composite sample over the event should be obtained.*
4. *Nitrogen: Total nitrogen (TN), ammonia (NH_3), nitrate (NO_3), nitrite (NO_2), dissolved organic nitrogen (DOrg-N)*
5. *Phosphorus: Total phosphorus, filterable reactive phosphorus (FRP).*

2.7 Data analysis and interpretation

Suitable methods of data analysis that enable the evaluation of the performance of the WSUD element against the monitoring objectives should be used. Consistent approaches to the analysis of WSUD element performance are important to allow comparisons of different types of element, particularly in areas with high groundwater.

2.7.1 Chemical mass balance

The determination of both a water and a chemical mass balance for the site is recommended to identify the flow contributions and chemical loads from all input sources (surface water and groundwater). The chemical mass balance uses the water balance Equation 7 and measured chemical concentrations to evaluate chemical load attenuation by the WSUD element:

$$\sum C_{in} V_{in} - \sum C_{out} V_{out} = C_s \Delta S \qquad (9)$$

where C_{in} is the chemical concentration in the inflow averaged over a period of time Δt (mg/L), C_{out} is the chemical concentration in the outflow averaged over a period of time Δt (mg/L), and C_s is the chemical concentration in the standing water storage averaged over a period of time Δt (mg/L). V_{in} is the inflow volume over some period of time Δt (L), V_{out} is the outflow volume over a period of time Δt (L), and ΔS is the change in storage volume of the WSUD element over time Δt (L). The product of C and V is the chemical load (mg) entering or exiting the WSUD element over time Δt. $\Sigma C_{in} V_{in}$ is therefore the sum of all inflowing chemical loads, and $\Sigma C_{out} V_{out}$ is the sum of all outflowing chemical loads over time Δt.

2.7.2 Evaluation of WSUD element nutrientattenuation performance

The *Stormwater management manual for Western Australia* (DoW 2004, 2007) recommends an approach to evaluate the pollutant removal efficiency of structural WSUD elements based on *Urban stormwater BMP performance monitoring* (USEPA 2002). Further methods, statistical approaches, and limitations are discussed in USEPA (2009).

Event mean concentration

The event mean concentration (EMC) is defined as the average concentration of a pollutant over the period of an event discharge at a monitoring location. The EMC is calculated using all data available for each monitoring location, such as inflow and outflow, and for each monitoring event, which may be a storm event or other flow condition (for example, baseflow or seasonal flow).

The EMC is a statistical parameter to represent the flow proportional average pollutant concentration during a monitoring event and is calculated as:

$$EMC = \frac{\sum V_i C_i}{\sum V_i} \qquad (10)$$

where V_i is the flow volume and C_i is the pollutant concentration over period *i*. This method assumes that during each monitoring event a number of water samples are collected at the same time that flow rate is measured.

As discussed in Section 2.4.5, monthly measurements of concentrations and flows are appropriate for WSUD elements designed to treat baseflows. For WSUD elements designed to treat storm events, a minimum of three water samples and flow rate measurements should be taken from each monitoring location across the hydrograph (at least one sample on the rising limb, one near the peak and one on the falling limb); alternatively, a composite sample can be collected over the event by an automatic water sampler triggered by flow sensors.

EMCs of storm event data

Where storm events have been monitored, it is recommended that the EMCj be separately estimated for each monitored stormwater event j, as per the recommendation in USEPA (2002).

USEPA (2002) also recommends the calculation of the log-normal mean EMC (luEMC) to allow for normalisation of the data for statistical purposes. The luEMC can be calculated using the logarithmic transformation of each EMC:

$$luEMC = \frac{\sum Log(EMC_j)}{m} \qquad (11)$$

where *m* is the number of stormwater events that were monitored. For the set of storm events under consideration, the statistical difference in the *luEMC* between the inflow and outflow data can then be determined.

Efficiency ratio

The efficiency ratio (ER) is an estimate of the reduction in EMC between the inflows and outflows of a WSUD element for each monitoring event.

For seasonal datasets or individual storm events, the ER is defined as:

$$ER = \frac{EMC_{in} - EMC_{out}}{EMC_{in}} \qquad (12)$$

where EMC_{in} is the mean EMC for all inflows (if there are more than one), and EMC_{out} is the mean EMC for all outflows. This approach gives the removal efficiency for the monitored event so that the impact of different flow conditions can be quantified.

A log-normal ER (*luER*) can also be calculated for a number of monitored stormwater events based on the *luEMC*:

$$luER = \frac{luEMC_{in} - luEMC_{out}}{luEMC_{in}} \qquad (13)$$

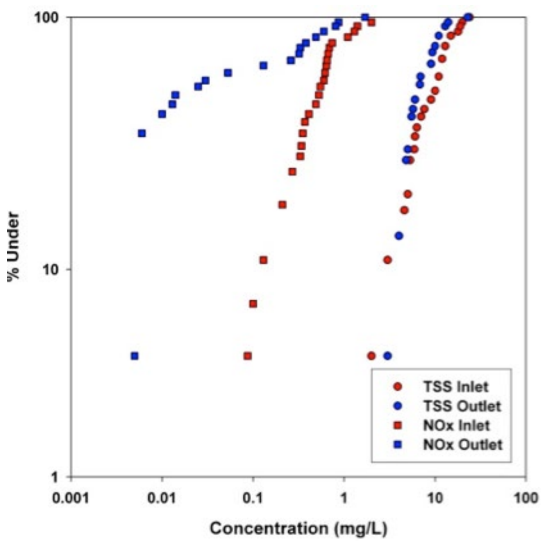
An assessment of the statistics of EMC data is needed to determine whether *luER* is a reasonable performance measure for a particular water quality parameter.

Effluent probability method

Another method to quantify the effectiveness of a WSUD element in attenuating nutrients uses effluent probability. To do this:

1. Determine whether the WSUD element is providing nutrient treatment by ascertaining whether the inflow and outflow luEMC are statistically different for the flow condition/s of interest.

2. Examine a cumulative distribution function of the inflow and outflow water quality on a log-normal probability plot, with the concentration on the x-axis and the percentage of measurements that are under a particular concentration on the y-axis (see example Figure 10). The differences between the inflow and outflow at different concentrations will indicate both the level of treatment that the WSUD element is providing and the difference in effectiveness at different inflow nutrient concentrations.



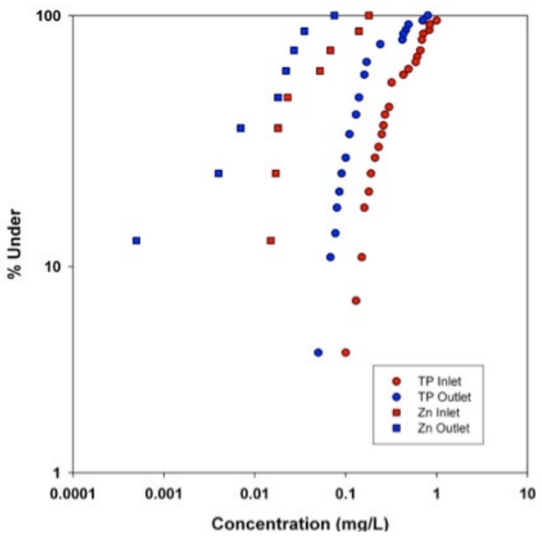


Figure 10: Example of effluent probability method plots of monthly Liege Street constructed wetland data for total suspended solids, NOx, TP and zinc (from Case study 6, GHD, 2007)

Additional data presentation approaches

Data plots

Initial graphical representation of the data can provide important information, for example:

- *Time series plots* showing inflow and outflow sample concentrations across the monitoring period provide an indication of the number of samples collected and the relative difference between inflow and outflow concentrations.

- *Box plots* can be used to display the central tendency and spread of data. Inflow and outflow measurements can be summarised in side-by-side box plots.

Standardised delta concentration

Where incomplete flow data limits the calculation of the EMC for different flow conditions, the concentrations of nutrients measured through sampling inflows and outflows can be useful as a first-pass assessment of WSUD element performance. The reduction in nutrient concentrations between the element inflow and outflow can be estimated by calculating the standardised delta concentration:

$$SDC = \frac{C_{in} - C_{out}}{C_{in}} \quad (14)$$

The standardised delta concentration is only an indicative value; for example, decreases in concentration can be caused by dilution by ungauged sources, rather than attenuation of nutrient loads. This approach can be used in conjunction with a conservative tracer (such as electrical conductivity) to assess ungauged water source contributions.

2.8 Review and reporting

2.8.1 Review

The data collected and the subsequent performance assessment of a WSUD element should be reviewed after the first year of monitoring and, after consultation with relevant stakeholders and regulatory agencies, the program should be adjusted if required.

Periodic review of results should be completed throughout the monitoring program. Regular review of the data in consultation with the regulatory agencies will assist in improving data collection processes to better meet the objectives of the monitoring program.

If the review of monitoring data identifies any source of significant environmental risk or concern, the proponent should immediately consult with the relevant regulatory agency.

2.8.2 Reporting

The reporting of the performance of the WSUD element should be completed in accordance with the reporting timeframes defined in any approved planning or environmental planning documents, such as an approved urban water management plan in Western Australia. Reporting should:

- provide an overview of the monitoring program and summarise previous reporting, such as pre-development monitoring
- summarise the WSUD element design and construction, including “as constructed” drawings with survey information such as the Australian Height Datum (AHD) or local height datum
- outline objectives for monitoring
- provide detail of the monitoring program design (monitoring locations, frequency, duration and timing of monitoring, parameters, methods)
- discuss the results, including data analysis and interpretation of the data, in the context of the monitoring program’s objectives
- outline conclusions and recommendations.

3 Case studies

The case studies in this section present examples of the monitoring and analysis undertaken to enable water and nutrient mass balance estimation and performance evaluation for different WSUD elements in areas with high groundwater. Because Western Australia has been the focus of recent investigations into the performance of WSUD elements in areas with high groundwater, the case studies are from that state. However, the approaches outlined in the case studies are relevant to any site affected by groundwater.

The case studies were selected because they each demonstrate the application of one or more of the recommended monitoring techniques for WSUD elements. Collectively, they demonstrate the range of monitoring approaches and how the monitoring requirements for a WSUD element are dependent on the element design objectives, monitoring objectives, and site-specific characteristics. They also demonstrate the range of the analyses used to quantify the performance of a WSUD element.

Case study 1: Bannister Creek living stream, Lynwood

Identification of groundwater flow contribution using passive tracers

Case study 2: Coodanup infiltration basin, Mandurah

Water balance and nutrient mass balance

Case study 3: The Glades raingarden, Byford

Water balance and nutrient mass balance

Case study 4: The Glades bioretention basin, Byford

Water balance and nutrient mass balance

Case study 5: Anvil Way living stream, Welshpool

Water balance and nutrient mass balance

Case study 6: Liege Street constructed wetland, Cannington

Water balance and nutrient mass balance

Case study 1: Bannister Creek living stream, Lynwood

WSUD element characteristics

WSUD element: Retrofitted living stream

Performance assessment: Quantify groundwater contribution to living stream to assess its impact on water and nutrient mass balances.

Overview

Bannister Creek is one of the main tributaries of the Canning River. It was originally a series of wetlands but was modified into a main drain in 1979. Waterway health deteriorated due to erosion, pollution, altered hydrology, and loss of riparian vegetation. The aim of the living stream project was to transform a straight section of drain into an ecologically healthy living stream while maintaining the function of the waterway to convey floodwaters from the approximately 23 km^2 urban and industrial catchment into the Canning River. As the creek is within a recreational reserve, enhancement of the creek's aesthetics was also an objective.

The site is in an area of sandy soils overlying clayey swamp flats that experiences a seasonally high water table. However, the groundwater contribution to surface flows in the creek had not been quantified. Understanding the groundwater contribution is essential to evaluate its role in the water balance, the nutrient balance, and the performance of the WSUD element.

The retrofit of the drainage channel was designed to mimic the natural creek's morphology and vegetation. It comprised several pool–riffle sequences, foreshore restoration, the establishment of fringing native vegetation for the biofiltration of pollutants, aesthetic improvement, and habitat creation.

The living stream was designed to:

- reduce flow velocity while maintaining stormwater conveyance
- stabilise banks and the streambed in order to reduce erosion
- reduce the export of nutrients and other pollutants
- increase habitat and biodiversity values and enhance amenity.

Monitoring objective

The monitoring of the Bannister Creek living stream has included water quality sampling, stream flow measurements, fauna surveys, visual observations, photographic records, social surveys, and analysis of property prices in the vicinity of the project site.

This case study focuses on targeted monitoring conducted along a 700 m reach of the living stream where there was an observed increase in electrical conductivity (EC), suggesting that the stream intercepts groundwater.

The monitoring objective of the targeted study was to quantify the groundwater contribution to surface water flows under baseflow conditions, in order to assess its role in the water balance and nutrient removal performance of the living stream.

Details of the monitoring and data analysis are in Li (2015).

Methods

EC was used as a passive tracer to quantify the groundwater contribution. EC was converted to salinity and then used to close a simple salt balance along the reach of the living stream (see Figure 11).

EC was measured at regularly spaced intervals along the reach and at a minor drainage inflow during seasonal baseflow conditions. The groundwater EC in the catchment is reasonably stable (around 1,550 uS/cm) and approximately twice the surface water EC. The marked difference and stability in the EC signatures of the two water sources, and the ease (and low cost) of their measurement, make EC an ideal tracer for quantifying the groundwater discharge along reaches of the living stream. A monitored reach can be used as a control volume for the calculation of water, salt and nutrient mass balances. Discharge rates were also measured at a gauging station downstream of the living stream (Table 2).

Table 2: Bannister Creek living stream monitoring program

Monitoring location	Parameter	Equipment	Frequency
Outflow of living stream section	Surface water discharge	Department of Water gauging station	Continuous
Groundwater bores (12 bores)	Groundwater EC	Hydrolab MS5 multi-parameter probe	Single measurement to confirm groundwater EC
Living stream segments (control volumes)	Surface water EC	Hydrolab MS5 multi-parameter probe	Single measurement at each segment during monitoring event
Minor drainage inflow	Surface water EC	Hydrolab MS5 multi-parameter probe	Single measurement during monitoring event

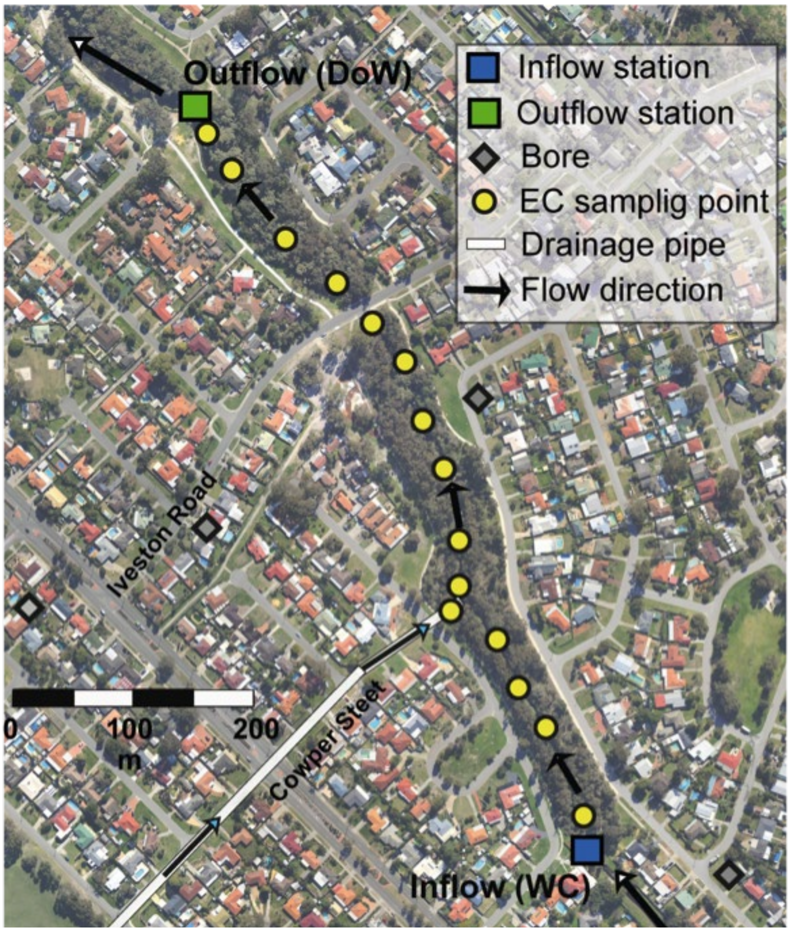


Figure 11: Bannister Creek living stream monitoring. Yellow pins indicate sampling locations.

Performance assessment

A salt mass balance was calculated using the salinity of groundwater and of living stream surface water as water source end members, along with the flow measured at the gauging stations:

$$Q_G K_G = Q_{out} K_{out} - Q_{in} K_{in} \qquad (15)$$

where Q_G is the net groundwater discharge into the control volume, K_G is the groundwater salinity, Q_{out} is the discharge out of the control volume, Kout is the salinity of outflowing stream water, Q_{in} is the surface water discharge into the control volume, and K_{in} is the salinity of inflowing stream water.

The salt mass balance showed that groundwater discharges to the living stream ranged from 0.1 L/s to 10 L/s. This section of the living stream is a net gaining stream and receives groundwater contributions under a range of baseflow conditions. Decreases in salinity were observed across some segments of the living stream on some monitoring occasions, suggesting the possible injection of freshwater to the stream from garden irrigation.

Successes

The study used simple, cost-effective and readily available tools to identify groundwater source contributions that had previously been unaccounted for in assessments of the water quality of the living stream.

Lessons learnt

Where groundwater inflow is suspected to be contributing to the discharge of a WSUD element such as a living stream, a conservative tracer such as EC can be used to quantify the groundwater contribution.

Case study 2: Coodanup infiltration basin, Mandurah

WSUD element characteristics

WSUD element: Infiltration basin

Performance assessment: Water balance and nutrient mass balance to assess how groundwater interception affects volume and nutrient load attenuation performance.

Overview

The Coodanup infiltration basin is located within a medium-density residential area in Mandurah and receives stormwater from a 27 ha residential catchment. The management of nutrients within the catchment of the Peel Inlet is a key concern due to historical water quality issues and algal blooms in the Peel–Harvey estuarine system. Infiltration basins are widely used in the city of Mandurah to reduce direct stormwater runoff and nutrient input to the Peel Inlet; however, there have been minimal assessments of how the basins perform, and whether their performance varies seasonally.

Piped stormwater inflow is delivered to the surface of the infiltration basin. The sump has a base surface area of approximately 1,400 m^2 and a storage volume of approximately 1,404 m^3.

The infiltration basin was designed to:

- provide storage and on-site infiltration of stormwater runoff
- reduce nutrient inputs to the Peel Inlet.

Monitoring objectives

The primary objectives of the monitoring program were:

- to assess how the infiltration basin interacts with high groundwater
- to assess seasonal and event changes in nutrient reduction performance

Methods

Water and nutrient fluxes at the basin inflow, storage, and outflow (groundwater) were monitored. Monitoring was undertaken over a three-month winter period (July to September 2014), which included three storm events.

The key design features of the infiltration basin, including monitoring locations, are shown in Figure 12. The monitoring program is summarised in Table 3.

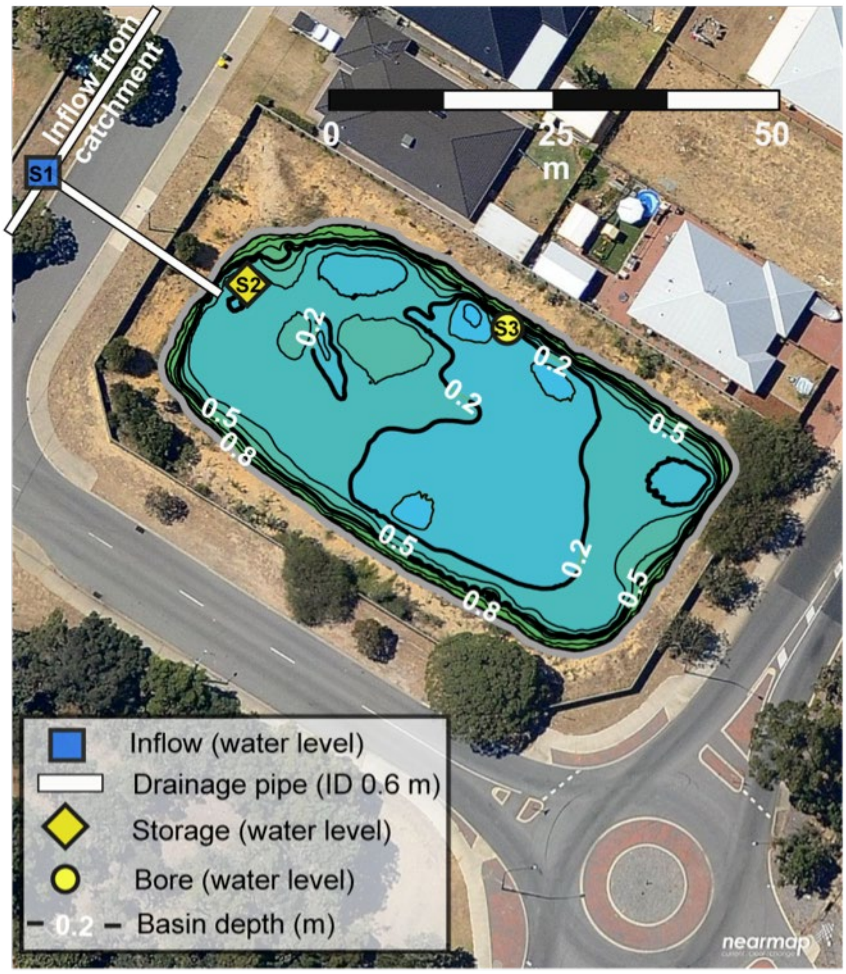


Figure 12: Coodanup infiltration basin monitoring

Table 3: Coodanup infiltration basin monitoring program

Monitoring location	Parameter	Equipment	Frequency
Outflow – groundwater bore (Figure 12, location s3)	Groundwater quantity (groundwater level)	Capacitance probe	15 minutes
	Groundwater quality (nutrients1)	Submersible pump used to collect sample following purging of three bore volumes	Event-based grab samples
	Groundwater quality (in situ physicochemical2)	Multi-parameter probe	Event-based
Inflow – inlet manhole (Figure 12, location s1)	Surface water quantity (water level)	Capacitance probe	15 minutes
	Surface water quality (nutrients[1])	Manual vacuum pump	Event-based grab samples
	Surface water quality (in situ physicochemical[2])	Multi-parameter probe	Event-based
Storage (Figure 12, location s2)	Surface water quantity (water level)	Capacitance probe	15 minutes
	Volume	Water level depth Basin survey	Event-based
	Surface water quality (nutrients[1])	Submersible pump attached to extendable rod	Event-based grab samples
	Surface water quality (in situ physicochemical[2])	Multi-parameter probe	Event-based
Weather station	Rainfall, barometric pressure	Bureau of Meteorology Mandurah weather station (009977)	Five minutes

1. *Nutrients: total nitrogen, nitrate, ammonia, total phosphorus, filterable reactive phosphorus.*
2. *In situ physicochemical: electrical conductivity, pH, temperature, dissolved oxygen*

Performance assessment

The study used a first-order mass balance to assess surface water and groundwater inflows and outflows from the system, where the inflows were taken as surface runoff from the catchment into the basin, the storage was standing water in the basin and the outflow (infiltration to groundwater) was the difference between inflow and storage volumes.

A water balance was approximated for the basin using the following equation:

$$S_{i+1} - S_i = \frac{Q_{in_i} + Q_{in_{i+1}}}{2}\Delta t - \frac{Q_{out_i} + Q_{out_{i+1}}}{2}\Delta t \quad (16)$$

where *S* is the storage volume of the basin (m^3), Q_{in} is inflow discharge (m^3/s), Q_{out} is outflow discharge (m^3/s), and Δt is the period of time between *i* and *i + 1* (s).

Storage, *S*, was calculated using volume–height curves derived from the basin topography. *A* bathymetric contour map of the basin was generated using a basin survey, water-level measurements, and satellite photography (Figure 12).

Inflow discharge to the basin, Q_{in}, was calculated using Manning's equation for open channel flow in a partially full pipe, in which the flow depends on the tailwater elevation and head loss:

$$Q_{in} = A\sqrt{\frac{2g\Delta h}{2gn^2L / R_h{}^{4/3} + k_e + 1}} \quad (17)$$

where *A* is the pipe cross-sectional area (m^2), *g* is gravity (m/s^2), Δh is the difference between the water height (AHD) at S1 and the water height (AHD) in the storage (m), *n* is Manning's roughness coefficient, *L* is the pipe length (m), R_h is the hydraulic radius (A/P), *P* is the wetted perimeter (m), and k_e is the entrance loss coefficient.

A nutrient mass balance was then calculated for the basin:

$$\Delta M = \sum Q_{in} C_{in} \Delta t - \sum Q_{out} C_{out} \Delta t \quad (18)$$

where ΔM is the change in mass (kg) over a time period Δt (s), C_{in} is the nutrient concentration in the inflows (kg/m^3), and C_{out} is the nutrient concentration in the outflows (kg/m^3).

Further details on the monitoring of the sump, the results, and the conclusions are in Woods (2014).

Successes

The water depths required for calculating the sump water balance were monitored using affordable and readily available equipment (capacitance probes) retrofitted into an existing drainage design, and applying a theoretical equation.

Through the completion of the water and nutrient mass balances, the study confirmed that a high water table limited the rate of infiltration in the sump, reduced the thickness of the unsaturated zone between the basin and the water table, and therefore reduced nutrient load attenuation.

Lessons learnt

The study also collected EC and temperature data during water quality sampling events with the intention of using those parameters as conservative tracers to characterise interaction between surface water and groundwater; however, the frequency of the EC and temperature data collection was insufficient for those purposes. When monitoring aims to use temperature (or EC) as a conservative tracer, it is recommended that the sensors be installed in situ and set to record at a sufficiently high frequency to capture the hydrological dynamics.

Case study 3: The Glades raingarden, Byford

WSUD element characteristics

WSUD element: Raingarden

Performance assessment: Water and nutrient mass balances to assess ability to reduce storm flows and attenuate nutrient loads.

Overview

The Glades is a residential development located approximately 2 km south-west of the Byford town centre in Perth, Western Australia. The raingardens are part of a train of structural controls designed to treat stormwater before discharging it into a tributary of Cardup Brook, which discharges into the Peel-Harvey Estuary.

The raingardens (BF1 and BF2, Figure 13) are vegetated basins situated in a median strip with flush kerbing, receiving sheet runoff directly from the paved road surface (Figure 14). Outflow from the raingardens is via slotted subsurface pipes that discharge to a pit joining the main drainage pipe of the area and connected to a downstream bioretention basin.

Figure 13: The Glades raingardens (BF1 and BF2) and bioretention basin (BF4; Case study 4) Raingarden BF1 is the focus of this case study.

Figure 14: Raingarden containing a vegetated basin and flush kerb for sheet inflow Arrows indicate flow direction.

The superficial aquifer in this region, referred to as the Byford Area, has a maximum thickness of 20 m and consists of clayey sediments of the Guildford formation. The duplex soils associated with the Guildford formation, including hardpan layers, result in the seasonal formation of a shallow perched water table.

Gingin loam was used as the raingarden medium (0.55 m deep), and local clay was used to create a natural lining. The treated effluent is collected by a 0.15 m diameter slotted PVC pipe located at the base of the raingardens (JDA, 2009) and then discharged into a pit joining the main drainage pipe of the area.

The raingardens were designed to:

- reduce storm flows from small rainfall events (up to 1-year ARI , 1-hour duration)
- reduce nutrient input to the Peel–Harvey Estuary.

Monitoring objective

The primary objectives of the monitoring program were:

- to assess the hydrological performance of the raingarden (BF1) under different conditions
- to determine whether groundwater had an effect on the raingarden's performance
- to quantify the reduction in nutrient concentrations between the raingarden inlet and outlet.

Methods

Water and nutrient mass balances of raingarden BF1 were monitored over 18 storm events between July and December 2015. Events of different magnitude were targeted to collect sufficient hydrological and water quality data to enable an assessment of the raingarden's performance.

Continuous hydrological monitoring stations were installed at five surface water sites. The monitoring undertaken at each station is outlined in Table 4. Theoretical rating equations were developed for each station based on hydraulic conditions and the geometry of the pits and pipes. Opportunistic volumetric discharge measurements at the BF1 outflow (using a stopwatch and flexible buckets) were used to verify and adjust the theoretical rating for low flows. This data was then used to compute the inflows and outflows for the raingarden for each rainfall event and to estimate groundwater interaction. Groundwater showed a distinct EC signature, so continuous EC readings were used to identify groundwater inflows.

At BF1 inflow (BF1IN), water sampling was done using surface water runoff traps. Three were placed at even spacing along the raingarden's length. Each trap consisted of a shallow well with a mesh covering slots in the upper portion of the pipe, allowing surface flow to enter, and a lid to seal the sample. The traps collected water from events capable of developing surface runoff with sufficient depth to reach the opening; this was estimated during the field trial to be at flow discharge rates of 4 L/s. Sampling represented high

Table 4: The Glades raingarden monitoring program

Component	Parameter	Equipment	Frequency	Sites
Surface water				
Water quality	Nutrients (TN, TP, NOx-N, DOrgN, NH4-N, FRP), total suspended solids (TSS), dissolved oxygen, pH	In situ parameters: Multi-parameter probe (YSI Pro Plus and Hydrolab MS5) Laboratory samples: Surface water runoff traps (BF1IN) Automatic sampler (Model WS750, Global Water Inc.) (BF1OUT)	Event-based sampling	BF1IN, BF1OUT
	Temperature, electrical conductivity	CTD (conductivity, temperature, depth) sensor (YSI 650 LS, Solinst)	Continuous (2–10 minute intervals)	BF1
Hydrology	Water level	CTD (conductivity, temperature, depth) sensor Digital still camera (BF1OUT)	Continuous (2–10 minute intervals)	BF1OUT
	Total rain (mm)	Rainfall–runoff modelling for inflow (BF1 IN)	Continuous (2 minute intervals)	BF1IN
Groundwater				
Water quality	Nutrients (TN, TP, NOx-N, DOrgN, NH4-N, FRP), total suspended solids (TSS), dissolved oxygen, pH	Multi-parameter probe (in situ parameters) (Hydrolab MS5) Low flow pump used to collect sample following purging of three bore volumes	Sporadic (fortnightly)	BGB1, BGB2
Hydrology	Water level	Capacitance probes (ODYSSEY loggers)	Continuous (15 minute intervals)	BGB1, BGB2
Rainfall				
Hydrology	Total rain (mm)	Tipping bucket rain gauge (RIMCO) linked to datalogger with 3G telemetry (Neon-Unidata)	Continuous (2 minute intervals)	BSUMP

flow rates, as water was expected to infiltrate into the media under low flow rates. Samples were collected immediately after an event using a small diameter plastic bailer.

The BF1 outflow (BF1OUT, via its subsoil pipe) was sampled using an automatic sampler (Model WS750, Global Water Inc.) inside a rugged case and attached to the pit ladder. This sampler had two peristaltic pumps that could be independently triggered, two 4 L containers for water samples, a water sensor to trigger the sampler, and two intake hoses.

The first bottle was triggered to fill as soon as flow commenced and thus captured the “first flush”. The second bottle collected a composite sample made up of 100 mL collected every 5 minutes, to cover a 3-hour, 10-minute period until the bottle was filled. The composite sample bottle could also collect multiple events if the first event finished and the bottle was only partially filled. Additional manual grab samples were also collected if the outflow was active during field visits.

A detailed description of the design features and monitoring design is in Ocampo et al. (2016).

Performance assessment

Stormwater runoff into the raingarden was from sheet flow (uncontrolled surface inflow) from the paved road catchment. Rainfall data obtained from the site rain gauge and catchment physical parameters were used as inputs to a kinematic wave model to simulate rainfall–runoff transformation and routing of the uncontrolled surface inflow to the raingarden. The model’s performance was tested against instantaneous peak flow discharge obtained using the Rational Method and design parameters (time of concentration and rainfall intensity).

Raingarden outflow was documented using still photographs taken at the raingarden outlet, and flow width, depth, and time for rainfall events was extracted using photo-editing software. Flow discharge was computed using Manning’s equation and critical depth formula for a circular pipe for comparison; field checks of estimated flow rates were completed on four site visits using volumetric discharge measurements.

Raingarden outflow hydrographs for ungauged events were obtained using a simple water balance model following Burns et al. (2015), and the water balance was tested against the 18 measured outflow hydrographs before being used to predict outflow hydrographs.

The interaction of groundwater with the raingarden was assessed using a combination of measured groundwater levels and construction specifications. The high water table did not directly interact with the raingarden; however, it did intercept the subsurface drainage downstream of the raingarden system, and hydrometric data indicated a continuous baseflow discharge to the downstream bioretention basin.

Nutrient removal efficiency calculations were completed by first determining the event mean concentration (EMC) at the inflow and outflow of the raingarden, and then using the EMC to calculate the change in nutrient load from inflow to outflow to assess nutrient removal efficiency.

Successes

Careful quantification of the water balance demonstrated that, on average, the raingarden reduced peak storm flows by 89%. The water balance also demonstrated that the water table did not intercept the raingarden; however, infiltration rates from the raingarden were reduced when the water table was elevated.

Monitoring of both discharge and nutrient concentrations at the inlet and outlet of the raingarden enabled the calculation of nutrient load reduction. The raingarden was highly effective at TP load reduction (up to 90%) and very good at TN load reduction (on average 72%).

Limitations in the water sample collection at the raingarden inflow and outflow stations made it difficult to calculate EMCs. Instead, the arithmetic mean concentration was estimated using three grab samples for BF1 inflow and using time-weighted composite samples for BF1 outflow.

Lessons learnt

The study found that the nutrient loads estimated using concentrations in a first-flush water sample were up to 25% different from nutrient loads estimated using concentrations in a time-weighted composite sample. The difference was particularly marked early in the season. It was more notable for larger storm events, when the first-flush bottle was unable to capture the extended flow conditions.

This finding has important implications for monitoring and brings into question the validity of considering concentrations from single-bottle sampling at the outflow at the beginning of an event to be representative of mean concentrations throughout the event.

Case study 4: The Glades bioretention basin, Byford

WSUD element characteristics

WSUD element: Bioretention basin

Performance assessment: Water balance and nutrient mass balance to determine the impact of a high water table on WSUD element performance.

Overview

The Glades bioretention basin receives stormwater runoff from a 9.24 ha catchment of The Glades residential development in Byford, Western Australia. Pre-development monitoring identified the presence of a seasonal perched water table above a local hardpan layer within the soil profile. Due to the low infiltration capacity of the local soils, on-site infiltration at the lot scale was not considered viable. Stormwater quantity and quality treatment was undertaken at the neighbourhood catchment scale through the construction of a bioretention basin. Sand fill was imported to the site to provide sufficient groundwater clearance for construction, and subsoil drains were installed to manage the local perched groundwater.

The bioretention basin was designed according to the most recent guidelines (FAWB, 2009; Payne et al., 2015) as much as was practicable, but with a few differences, such as no transition or drainage layers around the basin media. Instead, a homogenous medium of Gingin loam was used, along with a slotted underpipe. The local Gingin loam has been found to meet the requirements for biofilter media according to FAWB (2009) and demonstrated good efficiency in contaminant removal (Seah, 2011). The bioretention basin was completed in 2010, and was therefore five years old at the time of the assessment, with mature, established vegetation.

Water quality monitoring completed prior to development found that average concentrations of nutrients in surface water were generally below the appropriate guideline values; however, the average concentrations of total nitrogen and total phosphorus in groundwater exceeded the guideline values. It was therefore likely that nutrient attenuation performance might be compromised when groundwater intercepted the bioretention basin.

The key objective of the bioretention basin design was to treat storm event runoff and reduce the concentration of common urban pollutants in the basin outflow for small storm event runoff (1-year, 1-hour ARI design storm event, runoff generated by the first 16.9 mm of rainfall) (JDA, 2009).

Monitoring objective

The objectives of the monitoring program were to:

- develop water and nutrient mass balances for the bioretention basin
- assess the contribution of high groundwater to the bioretention basin during stormwater runoff events
- assess the impact of high groundwater on the nutrient attenuation performance of the bioretention basin.

Methods

Water discharge and nutrient concentrations at the inflows (Figure 15, BF4IN) and outflows (BF4OUT) to the basin were monitored over a 12-month period to allow the calculation of water and nutrient mass balances.

The key design features of the bioretention basin, including monitoring locations, are shown in Figure 15. The monitoring program is summarised in Table 5.

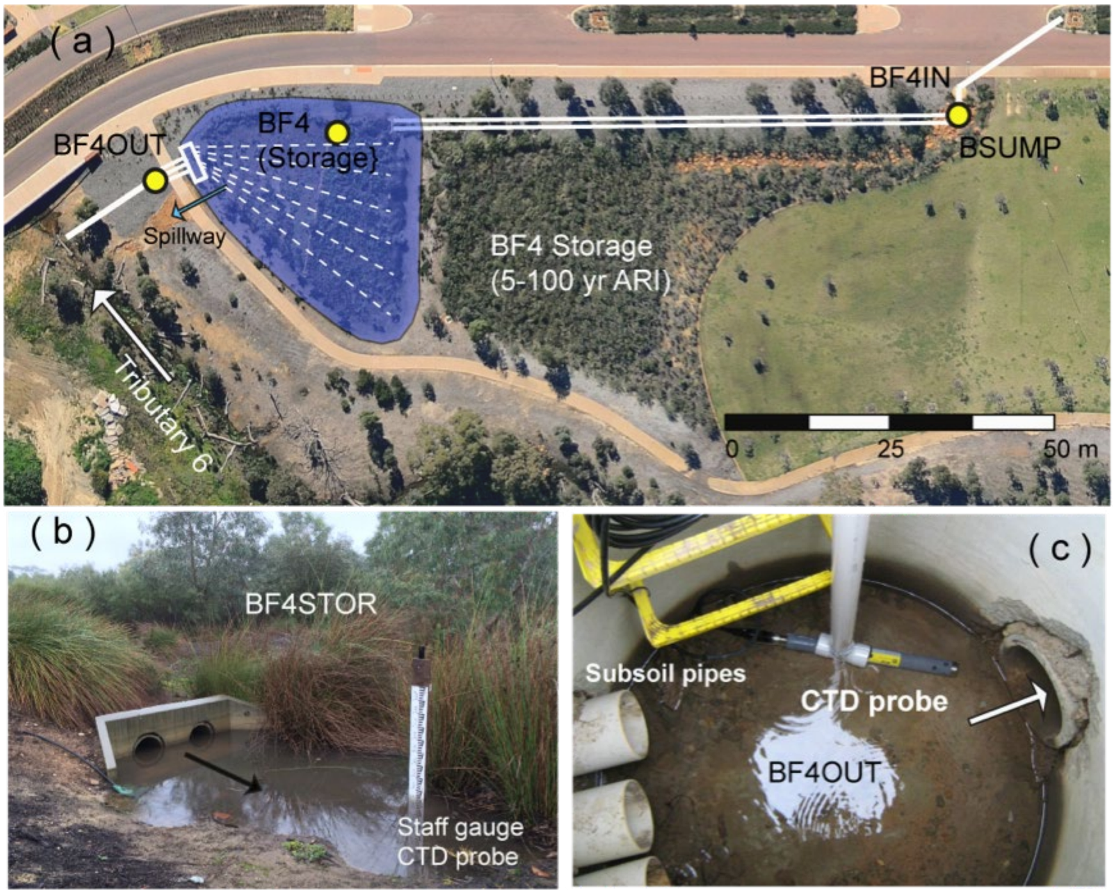


Figure 15: Bioretention basin drainage components and selected monitoring points
a) plan view showing inflow and outflow locations (yellow dots)
b) inflow to the basin storage area for treatment
c) effluent from the filter media flows into the discharge pipe to Tributary 6 of the Cardup Brook
Arrows indicate flow direction.

Table 5: The Glades bioretention basin monitoring program

Component	Parameter	Equipment	Frequency
Inflow to basin (BF4IN)	Surface water quantity (water level, electrical conductivity and temperature)	Water-level logger (YSI 600 LS CTD)	2–5 minutes
Basin storage (BF4STOR)	Surface water inlet quantity (water level)	Staff gauge Water-level logger (Solinist LTC Junior)	10–15 minutes
Outflow of basin (BF4 chamber)	Surface water and subsoil outlet quantity (water level, electrical conductivity and temperature)	Water level logger (YSI 600 LS CTD)	2–5 minutes
Outflow to creek (225 mm pipe)	Surface water outlet quantity	Staff gauge	Ad hoc manual readings
Groundwater bore	Groundwater quantity (water level)	Capacitance probe (ODYSSEY)	15 minutes
Inlet to element (BF4 Inlet)	Nutrients1	Manual grab samples	Event-based grab samples
Outlet to element (BF4 Outlet)	Nutrients1	Autosampler	Storm event samples Composite samples

1 Nutrients: total nitrogen, total oxidised nitrogen, total phosphorus, filterable reactive phosphorus.

Theoretical rating equations were developed based on hydraulic conditions and the geometry of the pits and pipes. Opportunistic volumetric discharge measurements along the pipe network (using a stopwatch and flexible buckets) were used to verify and adjust the theoretical rating. This was done at the BF4 outflow station for low, mid and high flow conditions. The data was then used to compute the inflows and outflows for the bioretention basin for each rainfall event, and also to estimate groundwater interaction.

Groundwater showed a distinct EC signature, so continuous EC readings were used to identify the two different water sources entering the bioretention basin (high groundwater and stormwater inflow). A two-component mixing model was used to calculate the groundwater contribution (Sklash & Farvolden, 1979).

The configuration of the pit was controlled by its hydraulic functioning, and that configuration together with public access issues made the implementation of an automatic sampling system difficult at the BF4 inflow station. Consequently, manual grab samples were collected to characterise water inflow to the bioretention basin. Grab samples were collected before, during and after a flow event; the timing of sampling was informed by Bureau of Meteorology forecasts and telemetry water-level data that indicated high flow conditions. Finally, 1–2 grab samples were collected within 12 hours after the event, ensuring that the recession period of the hydrograph was captured.

An automatic water sampler was used to sample the bioretention basin outflow (BF4 OUT). The first bottle collected 4 L of the first-flush runoff out of the bioretention basin filter media, while the second bottle collected a composite sample (150 mL every 30 minutes to 1.5 hours, depending on the season) over the duration of the event.

Performance assessment

The water balance model used the following input parameters:

- *Soil storage:* Permeable layer storage was estimated based on permeable soil parameters and the surface area and depth of the storage.
- *Basin storage:* Any changes in surface water storage in the basin were estimated using the water level measured in the basin and a topographic model of the basin.
- *Outputs:* Flow discharge into the brook was estimated using Manning's equation and water-level readings at the BF4 outlet.

The water balance model assumed that any differences between model outputs (which neglected groundwater) and the recorded outflow (at the BF4 outlet) were indicative of the groundwater contribution to the outflow. The water balance model was calibrated using storm events when the high groundwater level was lower than the basin subsoil drainage (Sidoti 2015).

The model was then used to calculate the storm event outflow when high groundwater intersected the subsoil drains. In these instances, the model could not account for nearly 18% of the measured outflow, indicating significant groundwater contribution to the bioretention outflow via the subsoil drainage pipes.

Further information about the monitoring program and hydrological function and nutrient attenuation performance of the Glades bioretention basin is in Ocampo et al. (2016). Further detail on the water balance modelling is in Sidoti (2015).

Successes

The detailed water balance demonstrated that groundwater contributed on average 20% of the outflow as the water table rose over the season. As in the raingarden (Case study 3), the rising water table also affected infiltration rates.

The nutrient mass balances demonstrated that groundwater interception affected nutrient load attenuation. However, the inflowing groundwater nutrient concentrations varied seasonally; sometimes, the groundwater diluted surface water nutrients; at other times, groundwater nutrient concentrations were high and thus groundwater inputs increased the nutrient load being discharged. Overall, the bioretention basin reduced nutrient loads to 30%–40% for both TN and TP.

Lessons learnt

The collection of water samples at the inlet and outlet took into account the residence time of the water flow through the basin. Inflow and outflow hydrographs in bioretention basins are quite different, as the outflow is generally highly attenuated.

Consideration should always be given to installing automatic sampling equipment for the inflow station that can capture the rapid response and the peak of the inflow. In this case study, outflow monitoring using a two-bottle autosampler allowed sampling of the initial rising of the hydrograph (first flush) and the longer recession period of the outflow (composite sample).

Case study 5: Anvil Way living stream, Welshpool

WSUD element characteristics

WSUD element: Constructed living stream

Performance assessment: Water balance and nutrient mass balances to assess changes in nutrient attenuation performance since construction.

Overview

The Anvil Way living stream is a compensation basin that was retrofitted as a living stream to treat low flows from a subcatchment of the Mills Street Main Drain catchment in Welshpool, Western Australia.

The Mills Street Main Drain has a catchment that drains almost 12 km^2 of residential and industrial land before discharging into the Canning River. The Mills Street catchment was identified in the Swan Canning Cleanup Program Action Plan (SRT, 1999) as a priority catchment for improved water management due to the export of nutrients and contaminants (SRT, 2008).

The area contributing to the Anvil Way living stream ranges between 1.8 km^2 and 3.6 km^2, depending on hydraulic connection with the upstream compensation basin network. The living stream was designed to maintain the hydrological capacity of the drainage network, improve the quality of urban stormwater runoff, reduce nutrients entering the Canning River, and enhance the habitat and ecological value of the site.

Monitoring objectives

The objectives of the monitoring program included:

- evaluating nutrient attenuation performance under different hydrological conditions (baseflow, rising limb, and falling limb of various storm events)

- evaluating whether the nutrient concentrations in the outflowing water were meeting the Healthy River Action Plan targets (TN <1 mg/L and TP <0.1 mg/L).

Methods

Baseline monitoring commenced in 2004; the discharge and water quality of the major surface water inflows and outflows were measured, along with adjacent groundwater levels and water quality.

Surface flows were monitored at the inflow (Starflow ultrasonic instrument) and outflow (a float well sensor located upstream of a variable height weir). Superficial groundwater levels were measured on a monthly basis from four bores, all located within 200 m of the living stream.

Surface water and groundwater samples were generally collected manually on a monthly basis to provide a simple continuous monitoring record. Dissolved oxygen measurements have been recorded at the inflow monthly since 2004. Total nitrogen (TN), total oxidised nitrogen (NOx-N), ammonia (NH3-N), total Kjeldahl nitrogen (TKN), total filterable nitrogen (TFN), dissolved organic nitrogen (DOrg-N), total phosphorus (TP), and filterable reactive phosphorus (FRP) were measured to determine whether the living stream was meeting its objective of improving water quality and reducing nutrient concentrations under low flow conditions. The key design features of the living stream, including monitoring locations, are shown in Figure 16. The monitoring program is summarised in Table 6.

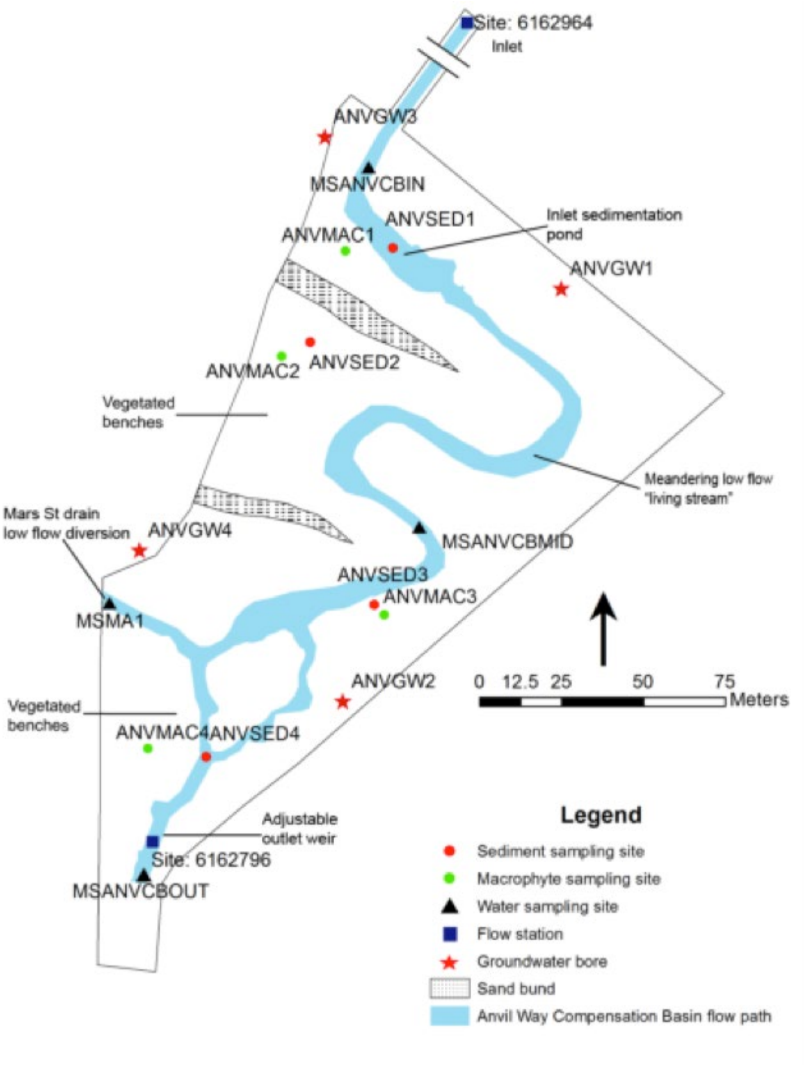


Figure 16: Anvil Way living stream

Table 6: Anvil Way living stream monitoring program

Monitoring location	Parameter	Equipment	Frequency
Surface water inflow at Orrong Road	Water level and velocity	Starflow ultrasonic Doppler	5 minutes
Surface water outflow	Water level	Variable height weir	
Float well sensor	5 minutes		
Groundwater bores	Groundwater level	Manual dip	Monthly
Routine surface water quality sampling locations (inflow, outflow), groundwater bores	Nutrients1 Dissolved oxygen	Manual grab samples	Variable, but generally monthly
Welshpool Depot (WIN 509359)	Rainfall/meteorology	Tipping bucket	5 minutes

1 Nutrients: total nitrogen, total oxidised nitrogen, ammonia, total Kjeldahl nitrogen, dissolved organic nitrogen, total phosphorus, filterable reactive phosphorus.

Performance assessment

The measurement of water levels (at the inflow and outflow) and velocity (at the inflow) was used to establish a water balance for the system, identify dominant hydrological fluxes, and assess ungauged water sources. A detailed water balance was completed for 28 individual rainfall events, and the volumetric contribution of the ungauged areas was found to be large (40%–80%) for small, frequent rainfall events (<1-year ARI), particularly in spring and summer. This was attributed to two possible sources: an ungauged piped inlet (Mars Street drain) and groundwater discharging into the stream.

The study concluded that groundwater level data for low flow (baseflow) conditions was not of a suitable quality for directly assessing the groundwater contribution. The provisional nature of the rating curve at the inflow and outflow stations, and the resultant manipulation and editing of the water stage for low flow conditions, did not allow the estimation of water balances. Given that discharge into the living stream from high groundwater was identified as a potential ungauged source under high antecedent wetness, further analysis and data are needed to quantify the groundwater discharge contribution.

The water quality dynamics under low and high flow conditions were assessed, accounting for changes in flow conditions before and after the construction of the living stream. Due to the incompleteness of the flow records at the inflow, event mean concentrations could not be calculated. Instead, an estimation of the standardised delta concentration was used to indicate performance, and loads were estimated where possible after the construction of the living stream and the improved measurement of flows became possible.

The water quality analysis found that TN in the outflowing waters complied with the Healthy Rivers Action Plan targets on most sampling occasions; however, the living stream failed to reduce TP below the target values. The TN and TP standardised delta concentrations were improved following restoration, suggesting that the living stream features (vegetation, meandering path, increase in low flow retention time) are useful in reducing the concentration of particulate organic matter.

A detailed description of the monitoring program, the approach used to assess the water balance, and the results of a performance assessment of the living stream is in Ruibal Conti et al. (2015).

Successes

The manual monthly measurement of surface water (inflow and outflow) and groundwater dissolved oxygen and nutrient concentrations over a long period enabled an assessment of changes in performance under different baseflow conditions across the seasons. The analyses of nutrient concentrations concluded that quantifying the influence of seasonal hydrology and storm events on water source contributions was important, and that changes in those water source contributions could affect water quality.

Lessons learnt

The ungauged inputs to the system limited the ability to assess the performance of the living stream. The water contribution from the ungauged Mars Street drain was deemed to be significant during storm events, particularly small, frequent rainfall events (<1-year ARI). Flow and water quality monitoring of this additional input was a key recommendation.

Changes in the location of monitoring stations and sampling frequency during the program introduced uncertainty into the analysis. It was recommended that a relatively simple long-term monitoring program be continued as consistently as possible, and that issues related to intensive event sampling be addressed separately.

The long-term monitoring of dissolved oxygen concentrations was critical for the interpretation of the variable performance of the WSUD element.

Finally, the preliminary nature of the rating curves for the inflow and outflow stations limited the use of the flow data; additional independent discharge measurements and point velocity measurements were recommended to reduce uncertainties in the flow records.

Case study 6: Liege Street constructed wetland, Cannington

WSUD element characteristics

WSUD element: Constructed wetland

Performance assessment: Estimation of water and nutrient mass balances to determine the attenuation of storm flows and nutrient discharges.

Overview

The Liege Street wetland was constructed at the outlet of the Liege Street and Cockram Street main drains in the city of Canning, Western Australia. The constructed wetland discharges into the Canning River above the Kent Street weir. The wetland was primarily designed to attenuate nutrients and improve the water quality of outflows during summer baseflow conditions and autumn first-flush events (GHD 2007).

Monitoring objectives

The objectives of the monitoring program were to:

- establish a water balance for the wetland to determine its hydrological performance
- evaluate the performance of the wetland in reducing nutrient concentrations in the surface water outflow to below Healthy River Action Plan targets for TN and TP
- establish nutrient mass balances to determine whether the wetland was attenuating nutrients.

Methods

The water discharge and water quality of the major inflows and outflow of the constructed wetland were measured, along with adjacent groundwater levels and quality.

Two surface water inflow stations were equipped with Starflow ultrasonic instruments, and the outflow station was equipped with a water-level logger located upstream of a variable height weir. Groundwater levels were measured on a monthly basis.

Surface water and groundwater quality samples were collected manually, generally on a monthly basis. Additional storm event samples were collected automatically using a load measurement unit. The water samples were analysed for total nitrogen (TN), total oxidised nitrogen (NOx-N), ammonia (NH3-N), total phosphorus (TP), and filterable reactive phosphorus (FRP).

The key design features of the constructed wetland, including monitoring locations, are shown in Figure 17. The monitoring program is summarised in Table 7.

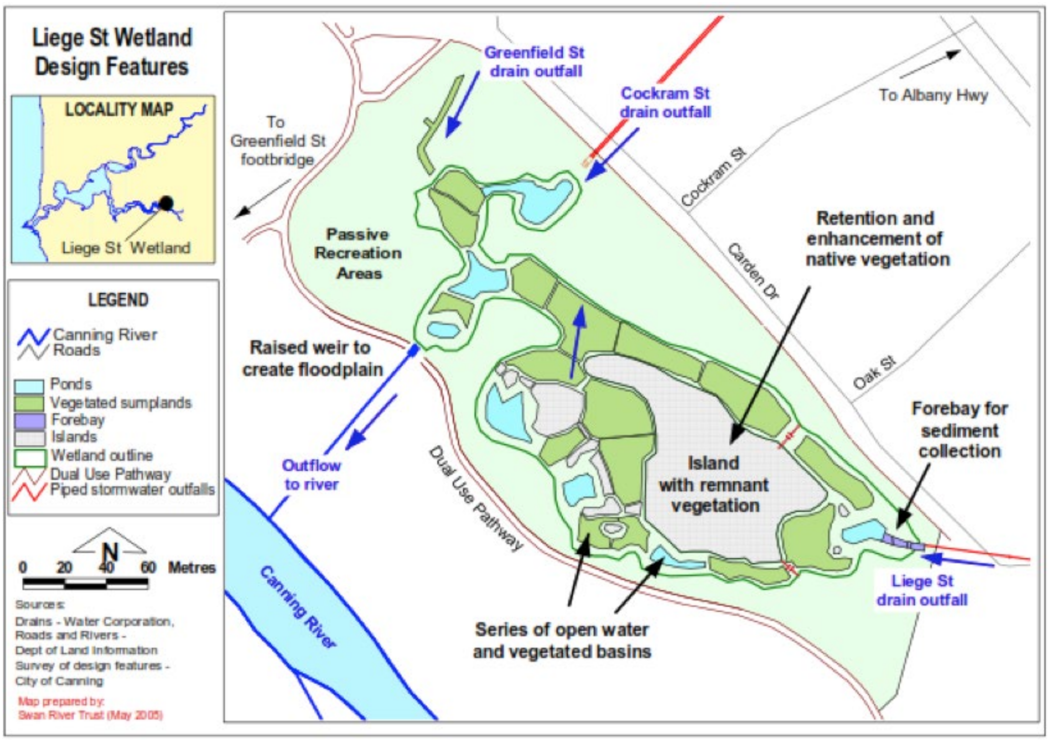


Figure 17: Liege Street constructed wetland

Table 7: Liege Street constructed wetland monitoring program

Monitoring location	Parameter	Equipment	Frequency
Liege Street Main Drain inflow – surface water	Surface water quantity (flows)	Starflow ultrasonic Doppler flow and depth instrument	Continuous
	Surface water quality (nutrients[1], total suspended solids (TSS), physicochemical parameters)	Manual grab sample	Monthly
	Surface water quality (TN, TP, TSS)	Load measurement unit autosampler	6–10 times/ storm event
Cockram Street inflow – surface water	Surface water quantity (flows)	Starflow ultrasonic Doppler flow and depth instrument	Continuous
	Surface water quality (nutrients[1], TSS, physicochemical parameters)	Manual grab sample	Monthly
	Surface water quality (TN, TP, TSS)	Load measurement unit autosampler	6–10 times/ storm event
Inflow –groundwater bore	Groundwater quantity (groundwater level)	Manual dip	Monthly to July 2005 then quarterly until 2015
	Groundwater quality (nutrients[1], TSS, physicochemical parameters)	Manual grab sample collected following purging of three bore volumes	
Outflow – surface water	Surface water quantity (flows)	Weir, water-level logger	Continuous
	Surface water quality (nutrients[1], physicochemical parameters)	Manual grab sample	Monthly
	Surface water quality (TN, TP, TSS)	Load measurement unit	6–10 times / week or storm event
Weather station	Rainfall	Bureau of Meteorology Perth Airport weather station (009021)	Daily

1 Nutrients: total nitrogen, total oxidised nitrogen (NOx-N), ammonia (NH3-N), total phosphorus, filterable reactive phosphorus (FRP).

Performance assessment

The study assessed the performance of the constructed wetland for the period from 1 January 2005 to 31 December 2006. A water balance model was used to identify the dominant hydrological fluxes. The water balance showed that the inflows were greater than expected, and this was attributed to higher baseflows. The study noted that, while the wetland interacts with the local unconfined aquifer, the direct groundwater contribution to the wetland was assumed to be negligible due to a number of factors, including local silty clay soils and the small size of the wetland compared to the contributing catchment.

Initial assessments of the wetland's performance identified the percentage exceedance of the median TN and TP concentrations, on an annual basis and under summer baseflow conditions, over the Healthy River Action Plan short- and long-term nutrient targets. During baseflow conditions, the calculation of standardised delta concentrations, as shown Equation 14, indicated a 45% reduction of median TP concentrations and a 29% reduction of median TN concentrations.

An attempt was made to use the water samples collected by the load measurement unit at the major inflow and outflow to assess the wetland's nutrient attenuation performance during storm events. However, those events sometimes triggered inflows equivalent to the total volume of the wetland in less than 1 hour. To accurately calculate a nutrient mass balance for the wetland, monitoring is therefore needed at a frequency of 1 hour or less, and concurrently at all inflows and the outflow. The load measurement unit sampling was not coordinated, and, as a consequence, events were only partially covered for nutrient data and nutrient mass balances could not be accurately calculated.

As an alternative, EMCs (Equation 10) were estimated from the load measurement unit data at the inflows and outflow, and nutrient mass balances for the storm events were calculated using the EMCs. The mean log-normal transformation of the event data suggested that little or no water quality improvement occurred in the wetland.

Nutrient mass budgets under baseflow conditions were estimated for TN and TP using log-normal mean concentrations, assuming zero treatment by the wetland during event flows. The nutrient mass budget showed that the wetland removed approximately 11% of TN load and 21% of TP load.

Successes

While the wetland's nutrient attenuation performance under event flow conditions could not be estimated, the regular sampling of the inflows and outflows enabled an assessment under baseflow conditions.

Lessons learnt

The inflow monitoring locations were located within the wetland near the inlet, resulting in poor characterisation of the inflow water quality, particularly under summer baseflow conditions. It was recommended that the monitoring locations be moved just upstream of the wetland to improve inflow water quality characterisation.

4 References

ANZECC & ARMCANZ (Australian and New Zealand Environment and Conservation Council and Agriculture and Resource Management Council of Australia and New Zealand) (2000). Australian and New Zealand guidelines for fresh and marine water quality, ANZECC and ARMCANZ, Canberra, 1–103.

Barron, O. V., A. D. Barr, and M. J Donn (2013). Evolution of nutrient export under urban development in areas affected by shallow watertable. Science of the Total Environment, 443:491–504.

BoM (Bureau of Meteorology) (2013). *National industry guidelines for hydrometric monitoring*. BoM, Commonwealth of Australia.

Burns, M. J., T. D. Fletcher, C. J. Walsh, A. R. Ladson, and B. E. Hatt (2015). Flow-regime management at the urban land-parcel scale: test of feasibility. *Journal of Hydrologic Engineering* (ASCE) 04015037. DOI: 10.1061/(ASCE)HE.1943-5584.0001002.

Chow, V. T. (1959). *Open channel hydraulics*, McGraw-Hill, New York.

Constantz, J. E., R. G. Niswonger, and A. E. Stewart (2008). Analysis of temperature gradients to determine stream exchanges with ground water. In: D. O. Rosenberry and J. W. LaBaugh (eds), Field techniques for estimating water fluxes between surface water and ground water, US Geological Survey Techniques and Methods 4-D2, p. 128.

DoW (Department of Water) (2004). Stormwater management manual for Western Australia – performance monitoring and evaluation. Department of Water, Perth, Western Australia

DoW (Department of Water) (2007). Stormwater management manual for Western Australia – performance monitoring and evaluation, Chapter 10, https://www.water.wa.gov.au/__data/assets/pdf_file/0020/4772/44217.pdf, accessed September 2016.

DoW (Department of Water) (2006). Water quality protection note 30: groundwater monitoring bores, https://www.water.wa.gov.au/__data/assets/pdf_file/0010/4033/59685.pdf, accessed September 2016.

DoW (Department of Water) (2008a). Water quality monitoring program design: a guideline to the development of surface water quality monitoring programs, https://www.water.wa.gov.au/__data/assets/pdf_file/0018/2934/87153.pdf, accessed September 2016.

DoW (Department of Water) (2008b). Field sampling guidelines: a guideline for field sampling for surface water quality monitoring programs, https://www.water.wa.gov.au/__data/assets/pdf_file/0020/2936/87154.pdf, accessed September 2016.

DoW (Department of Water) (2008c). Surface water sampling methods and analysis – technical appendices: standard operating procedures for water sampling – methods and analysis, https://www.water.wa.gov.au/__data/assets/pdf_file/0019/2935/87152.pdf, accessed September 2016.

DoW (Department of Water) (2009). Operational policy no. 5.12 – hydrogeological reporting associated with a groundwater well licence, https://www.water.wa.gov.au/__data/assets/pdf_file/0003/1659/89953.pdf, accessed September 2016.

DoW (Department of Water) (2012). Water monitoring guidelines for better urban water management strategies and plans, https://www.water.wa.gov.au/__data/assets/pdf_file/0012/3630/104023.pdf, accessed September 2016.

DoW (Department of Water) (2013). Water resource considerations when controlling groundwater levels in urban development, https://www.water.wa.gov.au/__data/assets/pdf_file/0012/1722/104909.pdf, accessed September 2016.

FAWB (Facility for Advancing Water Biofiltration (2009). Adoption guidelines for stormwater biofiltration systems, Monash University, June 2009.

GHD (2007). Liege Street Wetland performance report 2005–2006. Prepared for Swan River Trust.

Global Water (2016). Global Water instrumentation 2010–2012 resources book. Chapter 3: Sampling, p. 12, accessed from http:/www.globalw.com/downloads/Catalog/Sampling.pdf.

JDA (2009). The Glades at Byford Local Water Management Strategy (LMWS), unpublished report prepared for LWP Property Group Ltd, June 2009.

Kalbus, E., F. Reinstorf, and M. Schirmer (2006). Measuring methods for groundwater, surface water and their interactions; a review. *Hydrology and Earth System Sciences*, 10:873–887.

Land and Water Biodiversity Committee (2003). Minimum construction requirements for water bores in Australia.

Li, Q. (2015). Groundwater – surface water interactions at Bannister Creek, Masters thesis, University of Western Australia.

Mohamed, H., C. J. Ocampo, and K. Smettem (2013). Seasonal changes to hyporheic zone water exchange in a coastal plain drain. Proceedings of 2013 IAHR World Congress.

Ocampo, C., B. Rennie, and C. Oldham (2016). Performance of two urban stormwater biofilters in a high groundwater region of Perth Region, Western Australia, Cooperative Research Centre for Water Sensitive Cities, Australia.

Payne, E., B. Hatt, A. Deletic, M. Dobbie, D. McCarthy, and G. Chandrasena (2015). Adoption guidelines for stormwater biofiltration systems, Cooperative Research Centre for Water Sensitive Cities, Melbourne.

Rosenberry, D. O., J. W. LaBaugh, and R. J. Hunt (2008). Use of monitoring wells, portable piezometers, and seepage meters to quantify flow between surface and ground water. In: D. O. Rosenberry and J. W. LaBaugh, (eds), *Field techniques for estimating water fluxes between surface water and ground water*, U.S. Geological Survey Techniques and Methods 4-D2, p. 128.

Ruibal Conti, A., C. Ocampo, T. Adyel, M. Hipsey, and C. Oldham (2015). Performance assessment of the Anvil Way Compensation Basin living stream: 2004–2013, Cooperative Research Centre for Water Sensitive Cities, Australia.

Seah, T. T. T. (2011). A preliminary investigation of readily available local soils that are suitable filter media for biofiltration systems in Western Australia, Honours thesis, University of Western Australia, accessed at http://www.web.uwa.edu.au/__data/assets/pdf_file/0008/1835486/Seah-T-thesis-2011.pdf.

Shuster, W., T. D. Fletcher, and A. Deletic (2007). Stormwater. In T. D. Fletcher and A. Deletic (eds), Data requirements for integrated urban water management. Taylor & Francis, Paris.

Sidoti, D. (2015). Water sensitive urban designs: the effectiveness of bio-retention basins in areas of significant groundwater interference, Masters thesis, University of Western Australia.

Sklash, M. G. and R. N. Farvolden (1979). The role of groundwater in storm runoff. *Journal of Hydrology*, 34:45–65.

SRT (Swan River Trust) (1999). Swan–Canning Cleanup Program Action Plan: an action plan to clean up the Swan–Canning rivers and estuary. Swan River Trust / Water and Rivers Commission, East Perth, Western Australia.

SRT (Swan River Trust) (2008). Healthy Rivers Action Plan. Swan River Trust, East Perth, Western Australia.

Sundaram, B., A. Feitz, P. D. Caritat, A. Plazinska, R. Brodie, J. Coram, and T. Ransley (2009). Groundwater sampling and analysis – a field guide. *Geoscience Australia*, Record, 27:95.

Townley, L.R., J. V. Turner, A. D. Barr, M. G. Trefry, K. D. Wright, V. Gailitis, C. J. Harris, and C.D. Johnston (1993). Wetlands of the Swan Coastal Plain, Volume 3: Interaction between lakes, wetlands and unconfined aquifers, CSIRO Division of Water Resources, Western Australia.

USBPR (United States Bureau of Public Roads) (1965). Hydraulic charts for the selection of highway culverts, Hydraulic Engineering Circular no. 5, US Department of Commerce, Washington DC.

USEPA (United States Environmental Protection Agency) (2002). Urban stormwater BMP performance monitoring: a guidance manual for meeting the national stormwater BMP database requirements, USEPA and American Society of Civil Engineers, USA.

USEPA (United States Environmental Protection Agency) (2009). Urban stormwater BMP performance monitoring: a guidance manual for meeting the national stormwater BMP database requirements – update. Geosyntec Consultants and Wright Water Engineers.

Woods, P. (2014). The effectiveness of infiltration basins in areas with significant groundwater – surface water interactions, Honours thesis, University of Western Australia.

Cooperative Research Centre for Water Sensitive Cities

Level 1, 8 Scenic Boulevard
Monash University
Clayton VIC 3800

info@crcwsc.org.au

www.watersensitivecities.org.au