Enhancing the Storm Water Treatment Performance of Constructed Wetlands and Bioretention Basins

by Isri Ronald Mangangka

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Contents

Abstract

Urbanisation leads to both quantitative and qualitative changes to storm water runoff. While the quantity changes have received much attention in the past, now the quality changes are beginning to receive significant attention. The quality changes are primarily due to a range of anthropogenic activities common to urban areas, which result in the generation of various types of pollutants. These pollutants accumulate on urban catchment surfaces and are eventually washed off by storm water runoff creating irreversible impacts on receiving water environments. In this context, structural storm water treatment measures are introduced, promoting pollutant removal through physical, chemical and biological processes. They also detain, retain and regulate storm water runoff to improve water quantity and quality characteristics.

Bioretention basins and constructed wetlands are among the most common storm water treatment systems, and their treatment performance is closely dependent on hydrologic and hydraulic characteristics. Consequently, the in-depth understanding of the role of hydrologic and hydraulic factors in bioretention basin and constructed wetland treatment performance is important for effective urban storm water design strategies. This research monograph presents the outcomes of a detailed investigation into the influence exerted by hydraulic and hydrologic factors on the treatment performance of bioretention basins and constructed wetlands.

In relation to bioretention basins, the research outcomes confirmed that the antecedent dry period is an important factor influencing pollutant removal efficiency. A relatively long antecedent dry period will result in comparatively low moisture content in the filter media, which can enhance the runoff retention capacity and consequently improve treatment performance. This implies that planting of vegetation with high evapotranspiration capacity would enhance treatment efficiency. Additionally, it was found that pollutant leaching influences bioretention basin treatment performance, particularly reducing the ability for nutrient removal. This highlights the importance of the selection of appropriate filter media and its timely replacement.

In the case of constructed wetlands, it was found that large and small rainfall events are subjected to different treatment. The pollutant load reductions in the initial sector of the runoff hydrograph from large rainfall events were relatively low due to the rapid mixing. This highlights the need to establish an inlet pond to initially intercept the flow entering the constructed wetland so that the inflow is stabilised. This is also supported by the fact that the initial sector of the runoff hydrograph generally carries higher pollutant loads, namely the first flush effect. Additionally, the provision of a bypass system is recommended to control the runoff to the constructed wetland. This will protect the treatment system from erosion damage resulting from high runoff rates.

This research monograph further showcases an innovative approach for using conceptual models to analyse storm water treatment system performance. The approach adopted has the capability to generate key hydraulic data for individual rainfall events in relation to the treatment systems investigated. This is a significant advancement from conventional approaches for the analysis of treatment system performance, which is based on the use of lumped parameters. The knowledge presented provides practical guidance and recommendations for improved urban storm water management to assist researchers, design engineers, decision-makers, urban planners and storm water quality model developers.

Chapter 1
Storm Water Treatment

Abstract Urbanisation leads to changes in storm water quantity and quality due to the increase in impervious surface areas. While the quantity changes include increase in runoff volume and peak flow and decrease in the time to the peak, the quality changes are primarily due to the fact that a diversity of anthropogenic activities contributes a range of pollutants to the urban environment. These pollutants are washed off by storm water runoff and transported to receiving waters. In this context, structural storm water treatment measures are commonly introduced to mitigate storm water quality degradation. This chapter presents reviews of typical structural storm water treatment systems used in urban areas, providing an overview of their design and the inherent treatment processes. The systems discussed include gross pollutant traps, vegetated swales/bioretention swales, detention/retention basins, infiltration systems, bioretention basins and constructed wetlands.

Keywords Urbanisation · Storm water treatment · Storm water quantity · Storm water quality

1.1 Overview

Impacts of urbanisation on the natural water cycle are clearly evident. Urbanisation results in the spread of impervious areas and a diversification of land use, with vegetated lands converted to impervious areas such as roofs, roads, driveways, car parks and other paved surfaces (Barron et al. 2011). These changes lead to both quantity and quality impacts on the water cycle, which are widely recognised as significant environmental threats (Liu and Qin 2009; Liu et al. 2015). While the quantity changes, such as increase in runoff volume and runoff peak and decrease in the time to the peak, have received much attention in the past, the quality changes are beginning to receive significant attention (Goonetilleke et al. 2005). The quality impacts are due to the fact that urban areas typically consist of residential, commercial and industrial land uses where anthropogenic activities typical to these areas generate a range of pollutants (Liu et al. 2012a). These pollutants are washed

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off by storm water runoff into receiving waters and create irreversible environmental impacts (Liu et al. 2012b). Community concerns regarding the importance of managing urban storm water pollution in order to protect the key environmental values of receiving waters has resulted in regulatory authorities being increasingly challenged to provide appropriate and prudent management of urbanisation impacts. Storm water treatment measures are among the most important components of storm water management.

Storm water treatment measures consist of non-structural and structural measures. Non-structural measures do not involve fixed permanent facilities, but entail regulations and/or economic instruments for changing stakeholder behaviour in relation to pollutant generation. Structural measures are treatment devices installed to capture or divert pollutants transported by storm water. Use of non-structural and structural measures in combination in storm water treatment is contextualised by using a range of terms across the world. In Australia, Water Sensitive Urban Design (WSUD) is the term commonly used to refer to the strategy to protect the urban water environment, while Low Impact Development (LID) is the term used widely in China. Best Management Practices (BMPs) is the term used in the United States. Sustainable Urban Drainage System (SUDs) and Storm water Quality Improvement Devices (SQIDs) are also terms used in a range of other countries to describe storm water management strategies.

Structural storm water treatment measures promote pollutant removal or mitigation through physical, chemical and biological processes, while also detaining or retaining polluted storm water to improve water quality. Figure 1.1 shows the common processes inherent in structural storm water treatment measures. They treat storm water runoff by preventing pollutant movement, removing pollutants and protecting and enhancing the environmental, social and economic values of receiving waterways. Selection of appropriate treatment measures depends on site

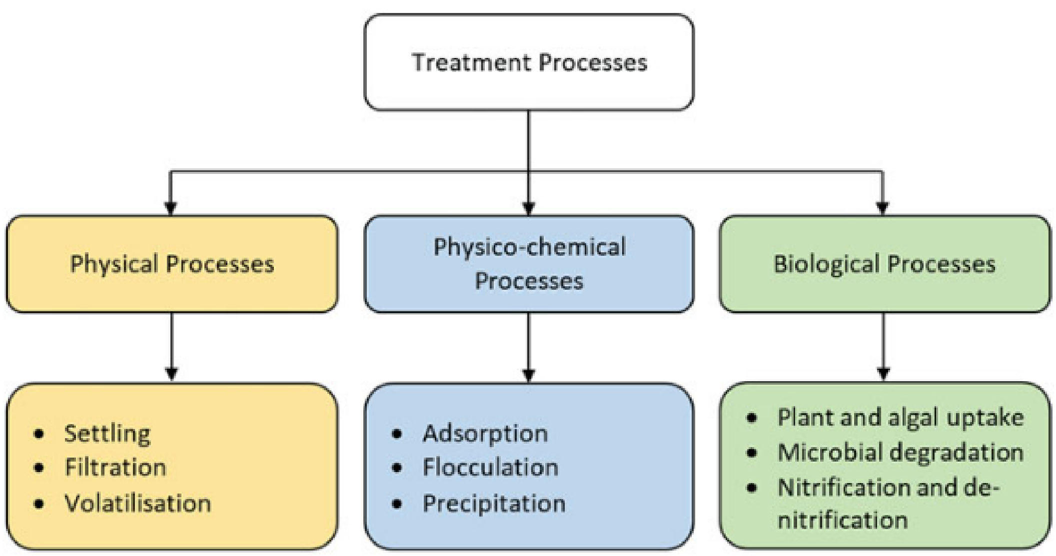

Fig. 1.1 Storm water treatment processes

conditions, target pollutants, local rainfall characteristics and catchment characteristics (Liu et al. 2013). The commonly used pollutant treatment measures are gross pollutant traps, vegetated swales (bioretention swales), detention/retention ponds (basins), infiltration systems, bioretention basins and constructed wetlands.

1.2 Common Structural Treatment Measures

1.2.1 Gross Pollutant Traps

Debris larger than 5 mm are defined as gross pollutants (Allison et al. 1997). Typically, gross pollutants include urban-derived litter and vegetation debris. These large pieces of urban debris get flushed from surfaces into the storm water system during rainfall events and can lead to poor waterway aesthetics and bad odours, and be a threat to aquatic biodiversity. Shaheen (1975) noted that 20 % of the weight of pollutants accumulated on road surfaces is litter. Additionally, organic matter such as leaves and grass clippings are primary litter on public roads. Madhani et al. (2009) found that organic matter accounts for 20–80 % of anthropogenic litter in Queensland, Australia. Due to their large size, gross pollutants are generally the most visible water pollution indicator to the community.

Gross pollutant traps (GPTs) are typically considered as a storm water pre-treatment measure. They play an important role in reducing the amount of urban derived gross pollutants exported to receiving waters. They also play a very important part in the treatment train (a series of measures combined in series for effective pollutant removal) by protecting downstream storm water treatment measures from clogging and malfunction. A number of different types of GPTs are used for storm water treatment. Each GPT has different design specifications with specific performance ability in trapping gross pollutants. Based on the way that GPTs operate, they can be classified into five types as given in Table 1.1 while Fig. 1.2 shows two typical GPT devices.

1.2.2 Vegetated Swales/Bioretention Swales

A vegetated swale or bioretention swale is an excavated trench filled with porous media (bioretention component) to create a broad, commonly parabolic or trapezoidal shallow channel (swale component) having vegetation cover on the side slopes and top layer. A vegetated swale or bioretention swale supports the achievement of storm water treatment objectives by disconnecting impervious areas from downstream waterways. The swale component promotes pre-treatment of storm water by removing coarse to medium sediments, whilst the bioretention

Table 1.1 GPTs devices and their characteristics

GPTs types	Typical devices	Comments
Drainage entrance treatment	• Grated entrance screens • Side entry pit traps (SEPTs) • Baffled pits	• Used at the entry point of the drainage system and traps gross pollutants from a catchment when water enters the drainage system
In-line screens	• Litter control devices (LCDs) • Release nets • Trash racks • Boom diversion systems • Return flow litter baskets	• Placed in the drainage channel to trap the gross pollutants present in the storm water runoff • Requires continuous monitoring and maintenance to remove the trapped gross pollutants
Self-cleaning screens	• Continuous deflective separation (CDS) • Downwardly inclined screens	• Improves the performance of in-line screens • Operates with a self-cleaning system
Floating traps	• Floating debris traps (FDTs) • Flexible floating booms	• Specifically used to trap floating gross pollutants
Sediment traps	• Sediment settling basins • Circular settling tanks • Hydrodynamic separators	• Commonly used at the downstream end of the drainage channel • Removes gross pollutants remaining in the storm water and prevents them from entering the storm water treatment facilities that follow

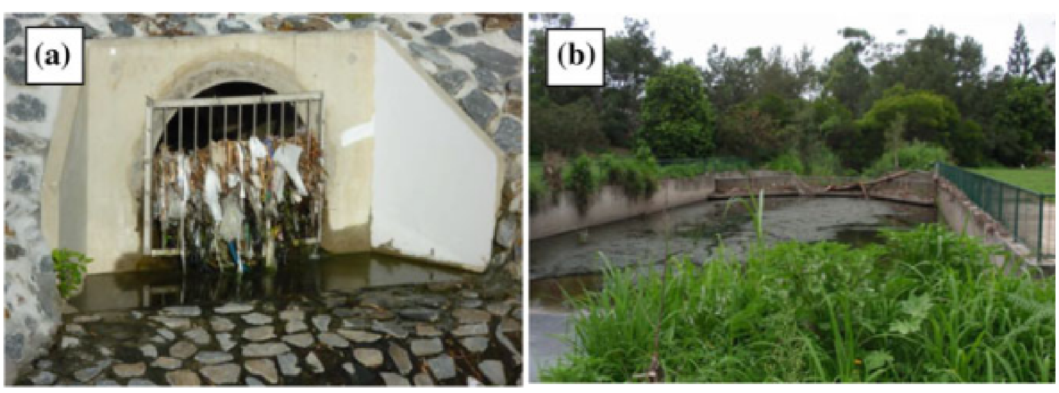

Fig. 1.2 Typical GPT devices. **a** Trash rack. **b** In-line screen

component removes finer particulates and associated pollutants through filtration, infiltration, adsorption and biological uptake. Figure 1.3 shows a typical road-side swale.

(a)

(b)

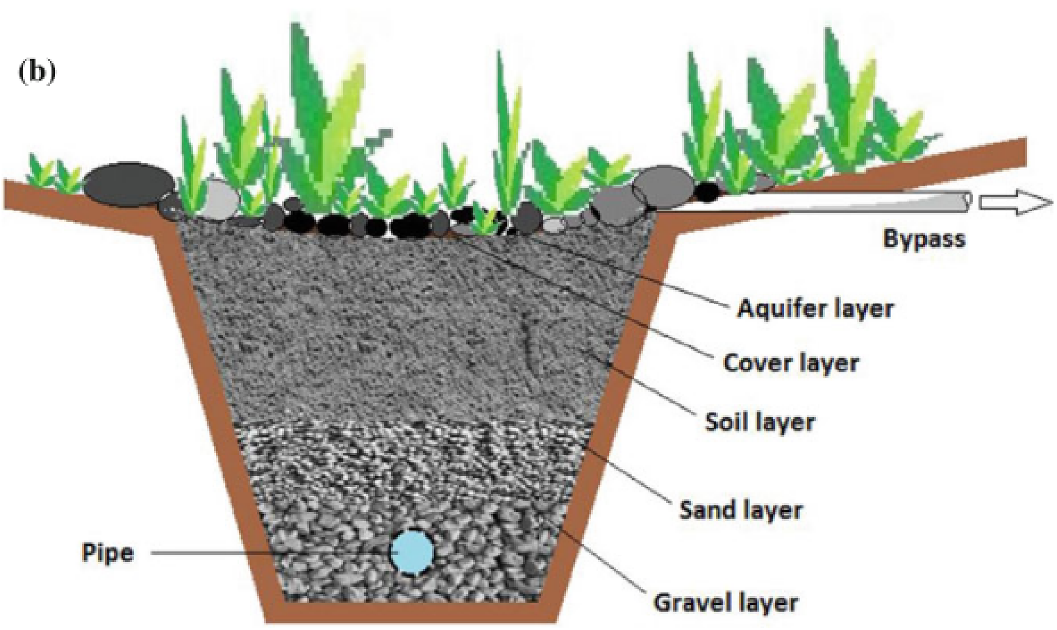

Fig. 1.3 A typical road side swale. **a** A road side swale. **b** Cross section

Vegetated swales or bioretention swales are typically used in road medians, verges, car park areas, and parks and recreation areas where flow velocities are low, as alternative to kerb and gutter arrangements. These treatment devices are commonly designed with side slopes no steeper than 3:1 and with longitudinal slopes of between 1 and 4 %, in which they can generate appropriate velocities promoting high infiltration. For slopes steeper than 4 %, check dams are typically constructed across the base, at intervals along the invert of the swale, to reduce flow velocities and to protect from erosion.

1.2.3 Detention/Retention Basins

Detention/retention ponds/basins are storm water facilities that provide storage for storm water runoff to be retained or detained. The key difference between retention and detention basins being that, in the case of detention basins, storm water is detained for a period of time and then slowly released into a waterway through a designed outlet. In the case of retention basins, storm water is retained and not released into a waterway. Detention/retention basins allow infiltration of storm water during the detention period. Therefore, these basins provide downstream protection and flood control by attenuating peak flow and reducing runoff volume.

The primary mechanism of pollutant removal in detention/retention basins is by the physical settling of suspended solids, which include particle-bound pollutants such as nutrients, heavy metals and hydrocarbons. However, a better result in improving storm water quality is achieved when these basins are combined with other storm water measures, forming a treatment train. Figure 1.4 provides a typical treatment train, where a detention basin is one of the devices employed. In combination with storm water wetlands, for instance, which will result in very fine and dissolved pollutants being removed by the wetland, whilst coarser sediments/solids will be trapped and remain in the basin, and accordingly, the wetland will be protected from damage. Furthermore, retention basins can also provide aesthetic and recreational benefits as well act as a water supply for irrigation or fire protection. Figure 1.5 provides the image of a retention basin.

1.2.4 Infiltration Systems

Infiltration systems capture storm water runoff and promote infiltration into surrounding soils. The primary focus of infiltration systems is managing storm water quantity by reducing storm water runoff volumes and peak flows. However, they also contribute to storm water quality improvement through infiltration of storm water into the subsurface soils. Storm water pre-treatment measures such as sedimentation basins and swale systems are required to be installed before infiltration systems. This is to avoid clogging of the infiltration system. Typical infiltration systems primarily include leaky wells/soakwells, infiltration trenches and porous/modular pavements. Figure 1.6 shows a typical infiltration system-infiltration trench.

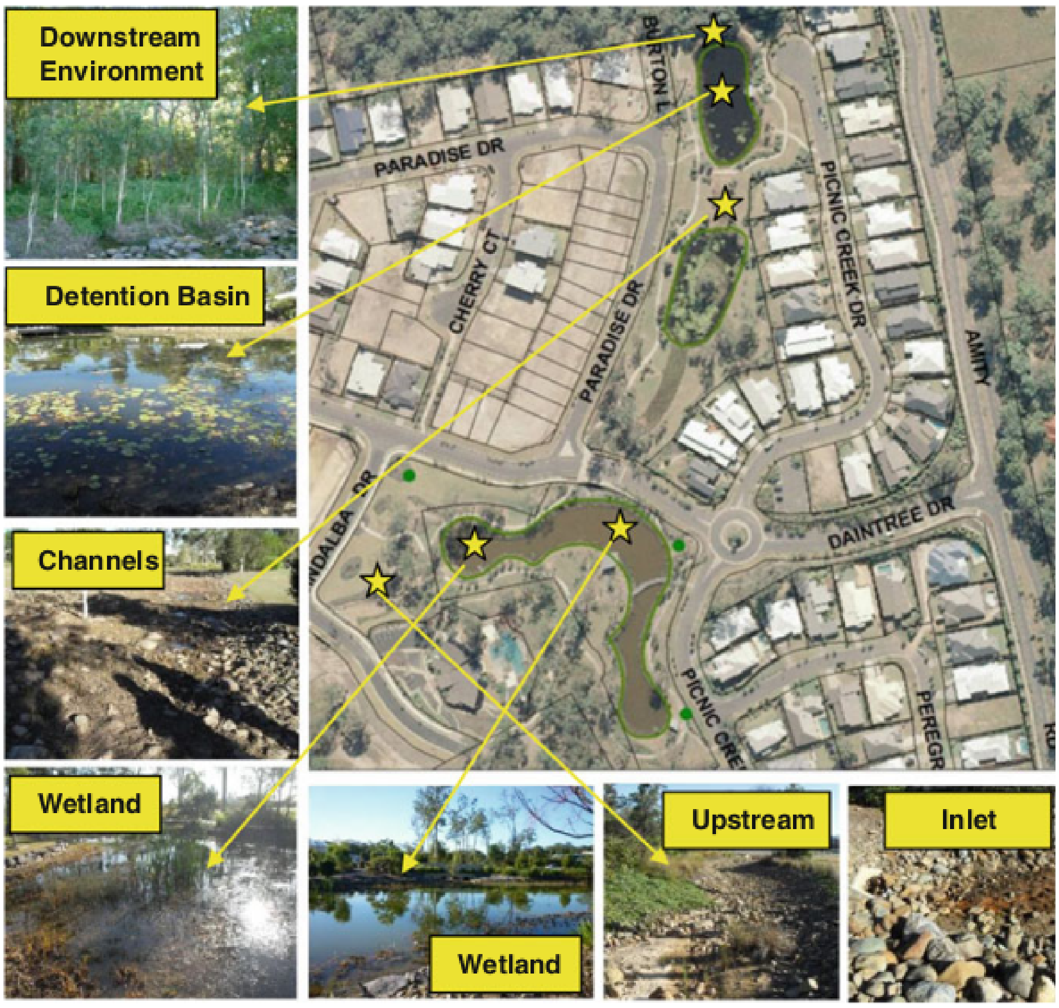

Fig. 1.4 A typical treatment train

Fig. 1.5 A typical retention basin

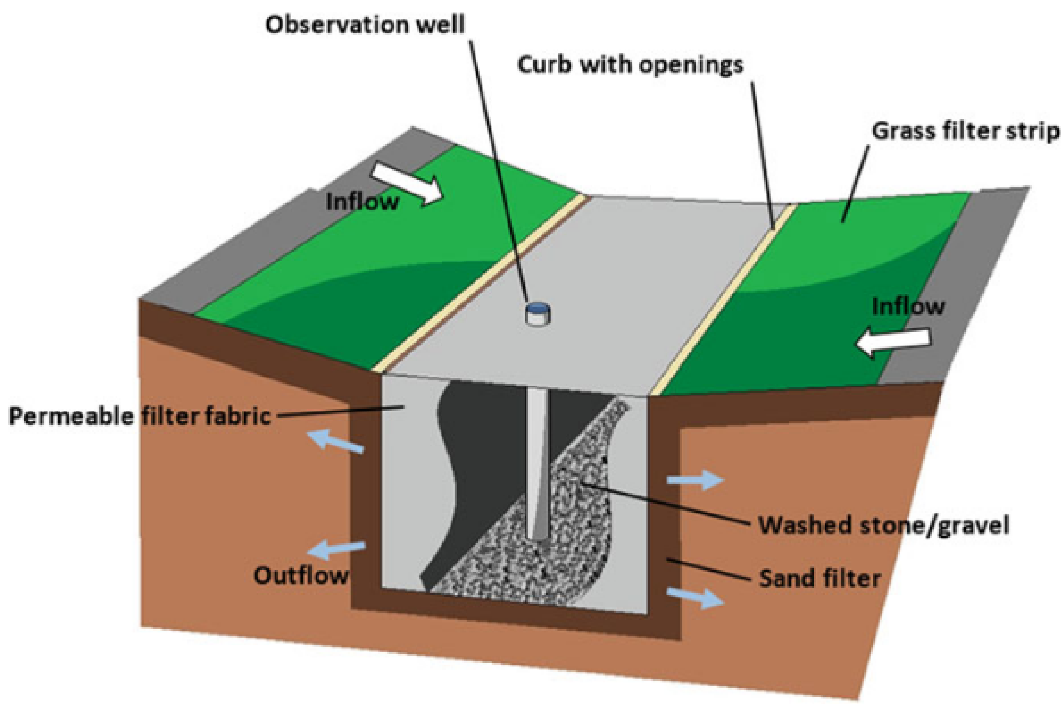

Fig. 1.6 Typical infiltration trench

1.2.5 Bioretention Basins

Bioretention basins are treatment devices that treat storm water runoff by passing through prescribed filter media with planted vegetation on the surface. Bioretention basins incorporate both vegetation and underlying filter media for removal of pollutants. The vegetation, which covers the system's surface, enhances the filtration process as well as maintains its porosity, while the filter media removes sediments and suspended solids when the storm water passes through.

Unlike bioretention swales, bioretention basins are not required to convey storm water runoff over the system surfaces, but the runoff is intended to pool on the surface, promoting infiltration and percolation through the filter media. However, excessive ponding of water can flow into overflow pits. The surfaces of bioretention basins are typically horizontal. Therefore, they are not subjected to high velocities that can dislodge collected pollutants or scour vegetation on the surface.

Bioretention media generally consist of three layers. These are the filter media layer, transition layer and drainage layer. The filter media is commonly either coarse sand (around 1 mm diameter) or fine gravel (2–5 mm). A drainage layer surrounds the perforated pipe. Below the filter media, a drainage layer is required to convey treated water from the base of the filter media to the perforated under-drain pipes, while a transition layer is required if fine gravel is used for filter media. This is to prevent migration of the filter media into the drainage layer and then into the perforated pipes. A bioretention basin and its cross section are shown in Fig. 1.7.

(a)

(b)

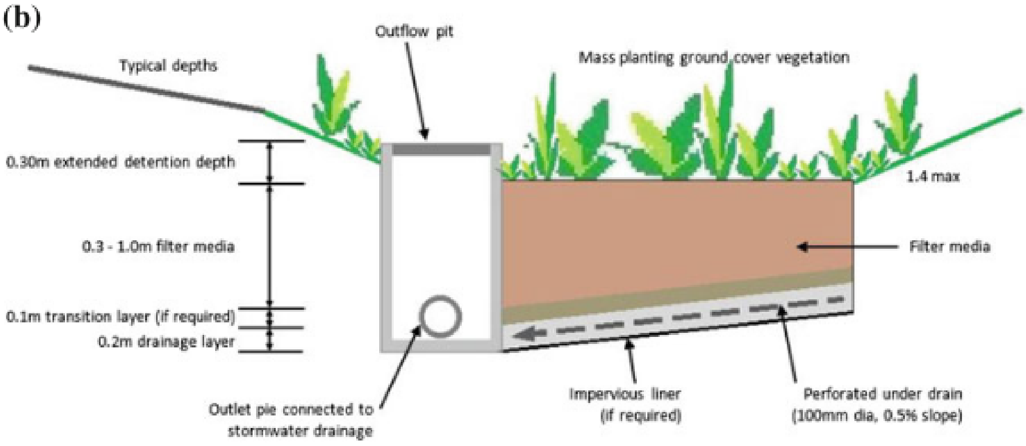

Fig. 1.7 A typical bioretention basin. **a** A bioretention basin. **b** Cross section

In the case of water quantity mitigation, bioretention basins use the replenishment of soil moisture deficit in the filter media and attenuate runoff peak discharge through detention/retention. Plant transpiration during preceding dry weather is a major contributor to the reduction in soil moisture in the filter media. Hunt et al. (2006) found that since runoff volume reductions by bioretention basins mainly depend on the moisture content in the filter media, the reductions can vary during different seasons from 46 % in winter to 93 % in summer.

The volume of water that can be retained in bioretention basins is mostly influenced by inflow characteristics. Bioretention basins are more effective in reducing peak runoff of small to medium storm events (Parker et al. 2009). The study undertaken by Hunt et al. (2008) found that for 16 storms with less than

42 mm of rainfall depth, their peak outflow reduced by at least 96.5 %, with a mean peak flow reduction of 99 %.

Bioretention basins provide flow retardation and are particularly efficient at removing nutrients. For example, Chen et al. (2013) noted that a bioretention basin can remove 56 % of influent total nitrogen concentration while Mangangka et al. (2015) found that the total phosphorus concentration can be removed by more than 50 %. However, it has also been noted that there can be elevated discharge of nutrients from bioretention basins. This is attributed to the leaching of native material, rather than failure to remove incoming pollutants (Hatt et al. 2008). Moreover, flushing and leaching of accumulated nutrients in bioretention basin filter media from previous rainfall events can be another possible reason for the increase in nutrient concentrations in the outflow (Mangangka et al. 2015).

The treatment performance of bioretention basins closely depends on a number of factors. The influential factors include vegetation type, hydraulic loading, detention time, hydraulic conductivity of the filter media and size ratio (the ratio of bioretention basin area to the catchment area). In-depth understanding of the relationship between these influential factors and treatment performance is critical in the design of effective bioretention basins.

1.2.6 Constructed Wetlands

Constructed wetlands are artificial, shallow and extensively vegetated water bodies. Constructed wetlands are primarily created for storm water pollutant removal. Improving landscape amenity and ensuring the availability of water for re-use are considered as supplementary benefits. A constructed wetland generally consists of an inlet zone, a macrophyte zone as the main area of the wetland, and a high flow bypass channel (see Fig. 1.8).

The inlet zone consists of a constructed sedimentation pond with a relatively deep open water body with edge and possibly submerged macrophytes. The pond is generally located upstream of the wetland, and commonly used as a pre-treatment device for coarse sediments and gross pollutants. The macrophyte zone is the main zone of the wetland system, comprising of a shallow water body with extensive emergent vegetation. There are some specific zones of vegetation throughout the wetland, where each zone is generally determined by the water depth. Figure 1.8 shows that constructed wetlands contain four vegetation zones including zones of shallow marsh vegetation, marsh vegetation, deep marsh vegetation and submerged vegetation. A constructed wetland also has an open water zone which promotes ultra violet exposure. Runoff flows entering the macrophyte zone are controlled at the inlet zone using a bypass system. This is to protect the macrophyte zone from scour, due to high flows. Unfortunately, this also reduces the treatment effectiveness of the wetland.

In terms of water quantity, constructed wetlands promote runoff volume and peak flow reduction through infiltration, evaporation and retention. The hydrologic

(a)

(b)

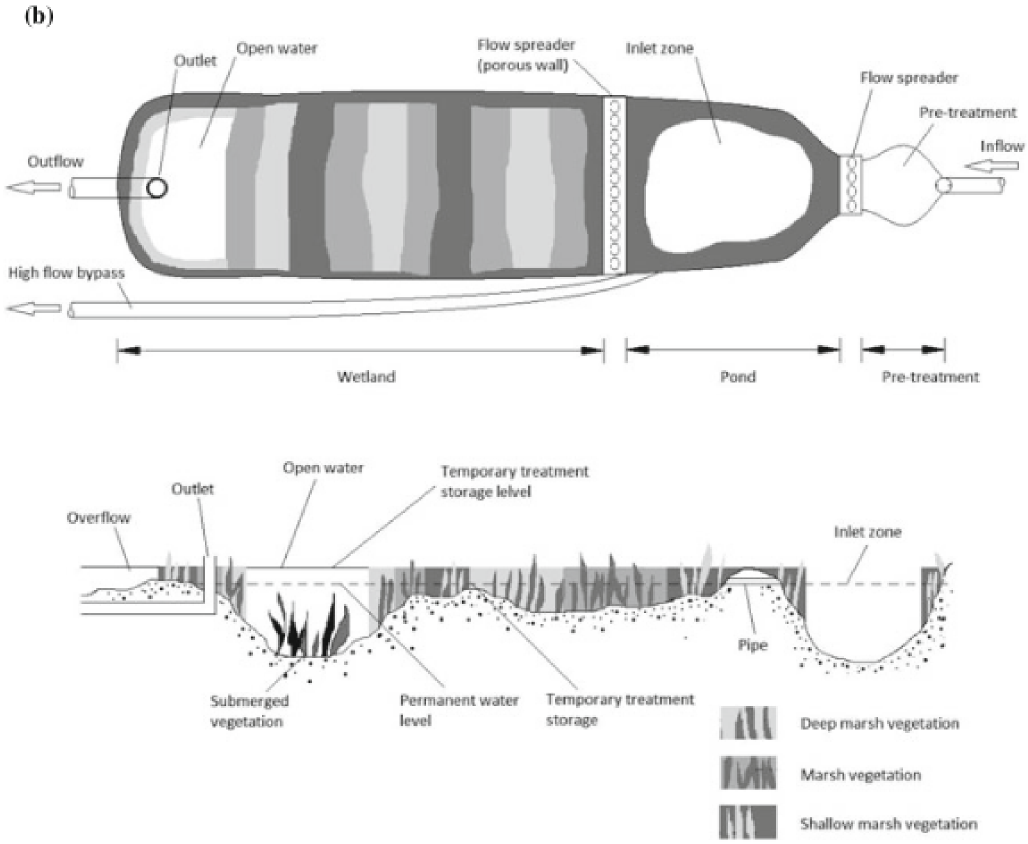

Fig. 1.8 Typical constructed wetland system. **a** A typical constructed wetland. **b** Structure of a constructed wetland system

effectiveness in retaining storm water is determined by the interaction between three factors, namely retention time, inflow characteristics and storage volume. Long retention time in the wetland system ensures significant reduction in runoff peak flow. However, due to saturated conditions in the wetland, less storm water percolates into the soil and hence would lead to only a low reduction in runoff volume. For instance, Parker et al. (2009) reported that a constructed storm water wetland investigated in South East Queensland, Australia, reduced runoff volume by only about 5 %.

In terms of water quality, constructed wetlands are termed as efficient storm water quality treatment devices, particularly when storm water contains high concentrations of dissolved pollutants that are difficult to remove by other storm water treatment devices. Pollutant removal in a constructed wetland is achieved by settling, vegetation uptake, adsorption, filtration and biological decomposition. Wetland vegetation enhances water quality by encouraging sedimentation, filtering of nutrients and other pollutants through roots, stems and leaves and promoting the growth of biofilms, which assimilate dissolved nutrients.

Storm water treatment processes are strongly dependent on rainfall characteristics, wetland design parameters, weather and seasons, pollutant loading rate and hydraulic retention time. Therefore, water quality improvement provided by constructed wetlands can be inconsistent and highly variable. For example, a constructed wetland designed as a 350 mm-depth horizontal subsurface flow showed a relatively high variability of concentration reduction rate of dissolved phosphorus (9.66–37.37 %) (Li et al. 2016). Sanchez et al. (2016) reported that the constructed wetland that they investigated had a better nitrogen removal performance in hot and dry summer. They attributed it to the higher transpiration water loss in summer that provided large volumes of replacement water into the microbes to process nitrogen.

1.3 Summary

Structural storm water treatment measures have been widely used to mitigate the changes to storm water quantity and quality due to urbanisation. Structural measures prevent, convey and collect pollutants, promote pollutant treatment through physical, chemical and biological processes taking place, and detain or retain storm water to improve water quality. Pollutant removal in these systems involves physical and biochemical processes achieved by settling, filtration, infiltration of particulate and in-bound pollutants and biological uptake.

This chapter has outlined the structure and functionality of six commonly used structural storm water treatment measures. Gross pollutant traps (GPTs) are primarily used for source, stream and downstream control for removal of items larger than 5 mm. Vegetated swales, or bioretention swales, are used for pollutant treatment while they convey storm water runoff. Retention basins remove pollutants by physical settling of suspended solids, which include particle-bound pollutants such as phosphorus and organic matter. Infiltration systems can remove sediments, which are finer particles including nutrients from polluted storm water via the processes of adsorption, filtration and infiltration.

Bioretention basins and constructed wetlands are among the most common storm water treatment systems. Bioretention basins treat storm water runoff by passing it through prescribed filter media with planted vegetation, while pollutant removal in a constructed wetland is achieved by settling, vegetation uptake, adsorption, filtration and biological decomposition. The pollutant removal performance of bioretention basins and constructed wetlands has been found to be variable with a range of factors including rainfall depth, rainfall intensity and antecedent dry days. This suggests that external factors such as hydrologic and hydraulic parameters play an influential role. Therefore, the in-depth understanding of the relationship between these influential factors and treatment performance is critical in the design of effective bioretention basins and constructed wetlands.

References

Allison R, Chiew F, McMahon TA, Stormwater gross pollutants (1997) Clayton, Victoria, Australia, CRC for Catchment Hydrology

Barron OV, Pollock D, Dawes W (2011) Evaluation of catchment contributing areas and storm runoff in flat terrain subject to urbanisation. Hydrol Earth Syst Sci 15:547–559

Chen XL, Peltier E, Sturm BSM, Young CB (2013) Nitrogen removal and nitrifying and denitrifying bacteria quantification in a stormwater bioretention system. Water Res 47 (4):1691–1700

Goonetilleke A, Thomas E, Ginn S, Gilbert D (2005) Understanding the role of land use in urban stormwater quality management. J Environ Manage 74:31–42

Hatt BE, Fletcher TD, Deletic A (2008) Hydraulic and pollutant removal performance of fine media stormwater filtration systems. Environ Sci Technol 42(7):2535–2541

Hunt WT, Smith AR, Sharkey JT (2006) Evaluating bioretention hydrology and nutrient removal at three field sites in North Carolina. J Irrig Drain Eng 132:600–608

Hunt WF, Smith JT, Jadlocki SJ, Hathaway JM, Eubanks PR (2008) Pollutant removal and peak flow mitigation by a bioretention cell in urban Charlotte, N.C. J Environ Eng 134(5):403–408

Li JK, Liang Z, Gao ZX, Li YJ (2016) Experiment and simulation of the purification effects of multi-level series constructed wetlands on urban surface runoff. Ecol Eng 91:74–84

Liu A, Egodawatta P, Goonetilleke A (2015) Role of rainfall and catchment characteristics on urban stormwater quality, 2015. Springer

Liu A, Egodawatta P, Guan YT, Goonetilleke A (2013) Influence of rainfall and catchment characteristics on urban stormwater quality. Sci Total Environ 444:255–262

Liu A, Goonetilleke A, Egodawatta P (2012a) Inadequacy of land use and impervious area fraction for determining urban stormwater quality. Water Resour Manage 26(8):2259–2265

Liu A, Goonetilleke A, Egodawatta P (2012b) Taxonomy for rainfall events based on pollutant wash-off potential in urban areas. Ecol Eng 47:110–114

Liu D, Qin C (2009) Influence on rainfall runoff due to urbanisation in Wuhan city of China. 2009 International Conference on Environmental Science and Information Application Technology. Wuhan, China, pp 182–184

Madhani JT, Dawes LA, Brown RJ (2009) A perspective on littering attitudes in Australia. J Soc Sustain Environ Eng 9(10):13–20

Mangangka IR, Liu A, Egodawatta P, Goonetilleke A (2015) Performance characterisation of a stormwater treatment bioretention basin. J Environ Manage 150:173–178

Parker N, Gardner T, Goonetilleke A, Egodawatta p, Giglio D (2009) Effectiveness of WSUD in the "real world". The 6th International Water Sensitive Urban Design Conference and the 3rd Hydropolis: Towards Water Sensitive Cities and Citizens, 2009. Perth, Australia

Sanchez CA, Childers DL, Turnbull L, Upham RF, Weller N (2016) Aridland constructed treatment wetlands II: Plant mediation of surface hydrology enhances nitrogen removal. Ecol Eng. doi:10.1016/j.ecoleng.2016.01.002

Shaheen DO (1975) Contributions of urban roadway usage to water pollution. US Environ Prot Agency, Washington DC

Chapter 2
Creating Conceptual Models of Treatment Systems

Abstract The chapter discusses two conceptual models developed for replicating bioretention basin and constructed wetland behaviour. This discussion firstly outlines the development processes adopted including the theory applied, mathematical equations used and assumptions made, and then presents the model calibration procedure indicating model accuracy. A range of hydraulic parameters were selected to replicate the processes in the two treatment systems. These parameters were selected based on their ability to facilitate the analysis of the relationships between hydrologic and hydraulic factors and system treatment performance.

Keywords Conceptual models · Hydraulic and hydrologic factors · Model calibration · Storm water quality · Storm water pollutant processes

2.1 Background

Although there are a range of treatment measures used, as discussed in Chap. 1, bioretention basins and constructed wetlands are among the most common systems for treating storm water. This is due to higher pollutant removal efficiency and ease of incorporating them into the surrounding landscape, compared to other measures. The treatment performance of these two devices is closely dependent on rainfall and storm water inflow and outflow characteristics (Mangangka et al. 2014a, b). This means that hydrologic and hydraulic factors play an essential role in driving the pollutant removal mechanisms within bioretention basins and constructed wetlands.

The review provided in Chap. 1 outlines the points of differences between bioretention basins and constructed wetlands, such as their layout and the treatment mechanism involved. Bioretention basins are provided with filter media and use filtration as the primary mechanism for pollutant removal, supported by plant uptake, adsorption and biotransformation, while constructed wetlands are typically a shallow, extensively vegetated water body with different zones to promote enhanced sedimentation, fine filtration and pollutant uptake processes to remove pollutants from storm water. Due to differences in pollutant removal mechanisms,

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hydrologic and hydraulic factors influencing their treatment performance are different.

Understanding the influence of hydrologic and hydraulic factors on the performance of bioretention basins and constructed wetlands is critical for effective urban storm water mitigation. However, developing such an understanding is difficult, due to practical limitations in the monitoring of governing hydrologic and hydraulic factors. Generally, field investigations monitor rainfall characteristics, and inflow and outflow data for treatment systems. The parameters related to the processes occurring within a system are not easy to monitor, such as average water depth and average retention time in the constructed wetland, and volume retained and contributed wetted area (representing the percentage of wetted area in the filter media) within the bioretention basin. However, these parameters can exert significant influence on pollutant removal efficiencies. This highlights the need for modelling approaches to estimate these factors and thereby investigate their influence on treatment performance. Since these factors are generally variable during a rainfall event, rather than representing long-term hydrologic and hydraulic characteristics, the modelling approach needs to be event-based and not based on a lumped modelling method, which is the conventional approach. This chapter discusses two conceptual models developed as part of a research investigation into the performance of a bioretention basin and a constructed wetland. The developed models were applied to generate a series of hydraulic factors that exert significant influence on the treatment performance of these two systems.

2.2 Study Sites

The study site was located at Coomera Waters, Gold Coast, Australia, which is a residential catchment (see Fig. 2.1a). A bioretention basin and a constructed wetland have been established to serve three different sub-catchments of the residential area as shown in Fig. 2.1b. The storm water runoff from Catchment A flows into the bioretention basin. After leaving the bioretention basin, the treated storm water enters the constructed wetland through the available drainage pipes. The storm water then receives further treatment in the constructed wetland, as part of the treatment train (a range of measures combined in series for effective pollutant removal). In addition to Catchment A, storm water from Catchment B and Catchment C also contribute to the constructed wetland. The characteristics of the three sub-catchments are summarised in Table 2.1.

The inlets and outlets of the bioretention basin and constructed wetland were monitored using automatic monitoring stations to record rainfall and runoff data and to capture storm water samples for water quality testing. Flow measurements were undertaken using calibrated V-notch weirs, and samples were collected by stage triggered, peristaltic pumping. Discrete storm water runoff samples were collected during rainfall events to investigate the variation in inflow and outflow water quality during a runoff event.

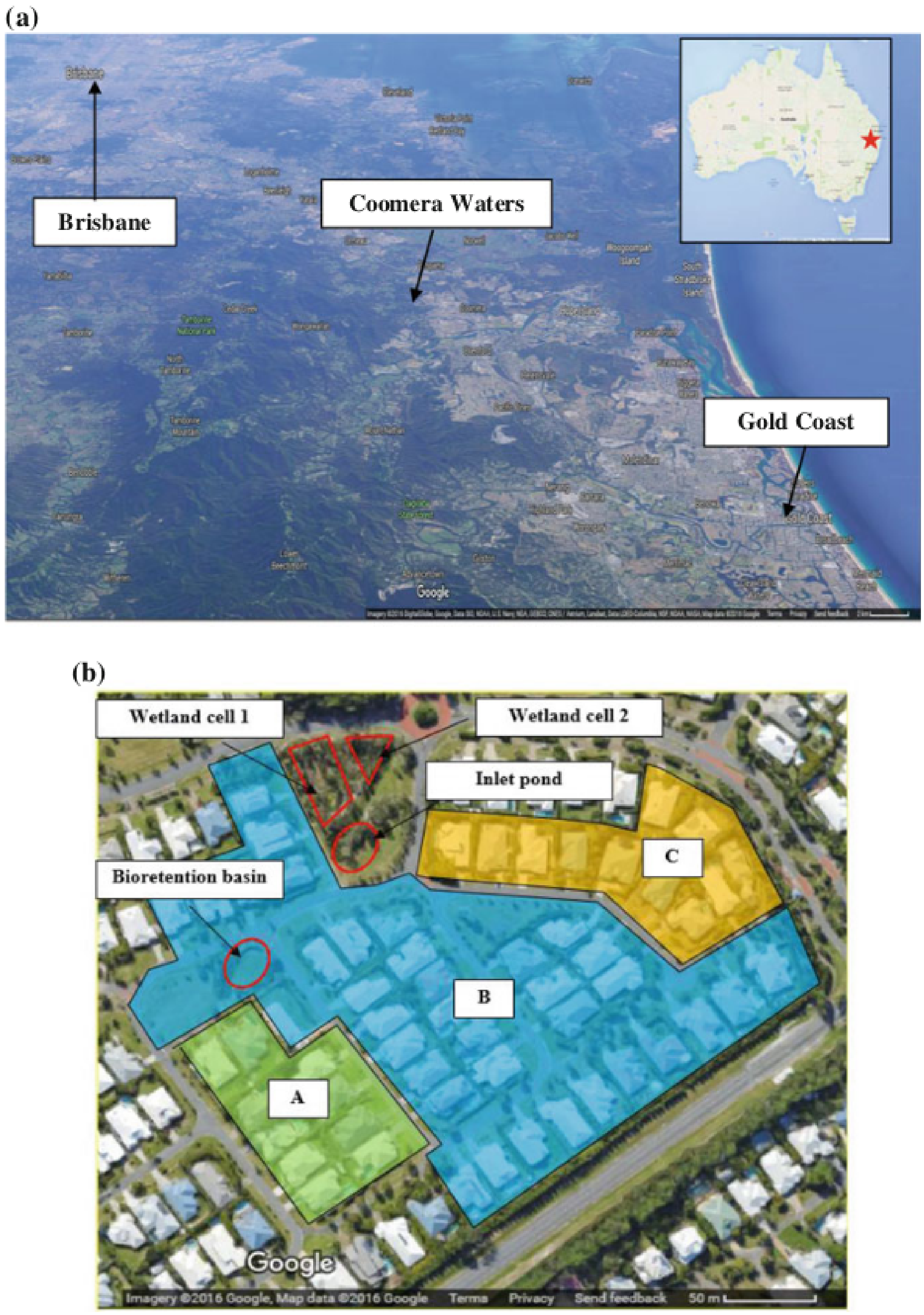


Fig. 2.1 Study sites. **a** Location of study sites. **b** Sub-catchments

Table 2.1 Sub-catchment characteristics of the study site

Characteristics	A	B	C
Area (m^2)	6530	44,470	10,500
Impervious area (m^2)	3402	21,348	4940
Impervious fraction (%)	52.1	48.0	47.0
Roof area (m^2)	2358	14,955	4586
Street area (m^2)	790	4868	44
Driveway area (m^2)	254	1462	310
Others (m^2)	0	63	0

2.3 Conceptual Model for a Bioretention Basin

2.3.1 Description of the Bioretention Basin

The bioretention basin has an extent of 248 m^2 area with a grass surface cover (see Fig. 2.2a). The size of the bioretention basin is approximately 3.8 % of the total contributing catchment area. Filter media of 0.8 m thickness promotes storm water treatment through infiltration (see Fig. 2.2b). The treated storm water, which infiltrates through the filter media, drains to the 0.2 m thick drainage layer underneath the filter media consisting of granular material. The bioretention basin also contains a network of perforated pipes in the drainage layer, which conveys infiltrated storm water to the invert of the outlet control pit. Perforated pipes are installed at the bottom of the drainage layer with 0.5 % slope. The top weir of the overflow control pit is designed 10 cm above the surface elevation. This allows storm water ponding up to 10 cm above the bed of the bioretention basin. The overflow control pit is utilised to be a bypass control. When the depth of storm water exceeds 10 cm, it bypasses into the pit and no treatment is provided.

2.3.2 Model Set-up

2.3.2.1 Principles and Assumptions Adopted for the Model

Hydraulic characteristics of a bioretention basin are primarily based on infiltration and percolation processes of storm water through the filter media, and can be classified as typical subsurface flow. Subsurface flow can be best replicated by 3-dimensional flow models, which are very complex and often require numerical analysis. To reduce this complexity, a range of assumptions was made to convert a 3-dimensional flow system to a 1-dimensional flow system. For this purpose, the bioretention basin was divided into 10 equal zones in the conceptual model. The number of zones was determined based on a trial and error process. The storm water movement over the surface was conceptualised as typical surface flow from zone 1, where the inlet structure was located, to zone 10 where the outlet structure was

(a)

(b)

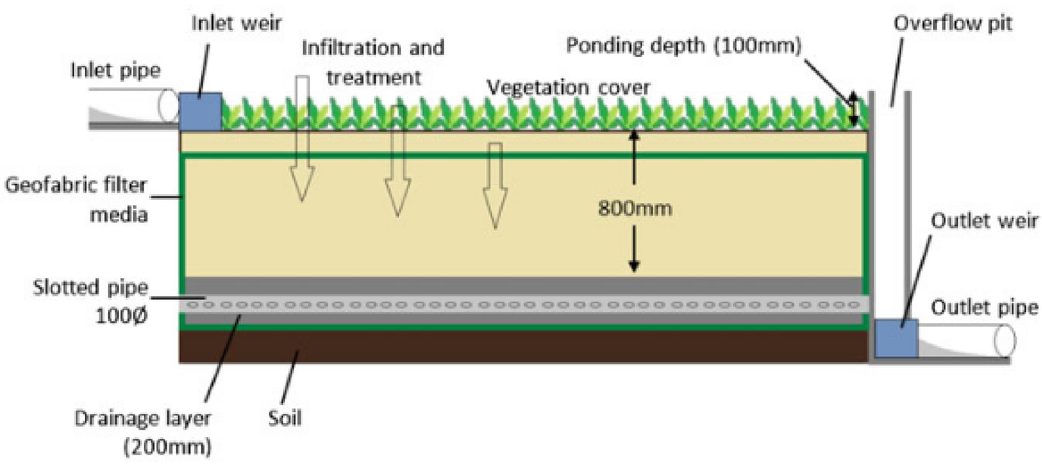


Fig. 2.2 The bioretention basin. **a** The bioretention basin at the site. **b** Cross-section

located. Each zone with 24.8 m^2 surface area was considered to be a soil column, in which a portion of water flows downwards to replicate the infiltration process. When the storm water flow on the surface of the assumed soil column exceeds the infiltration capacity of the soil, the excess runoff was assumed to be surface flow to the next zone. The storm water flow within the bioretention basin was modelled according to the processes described in the following steps, which were replicated by a range of mathematical equations as shown by the numbered labels given in Fig. 2.3.

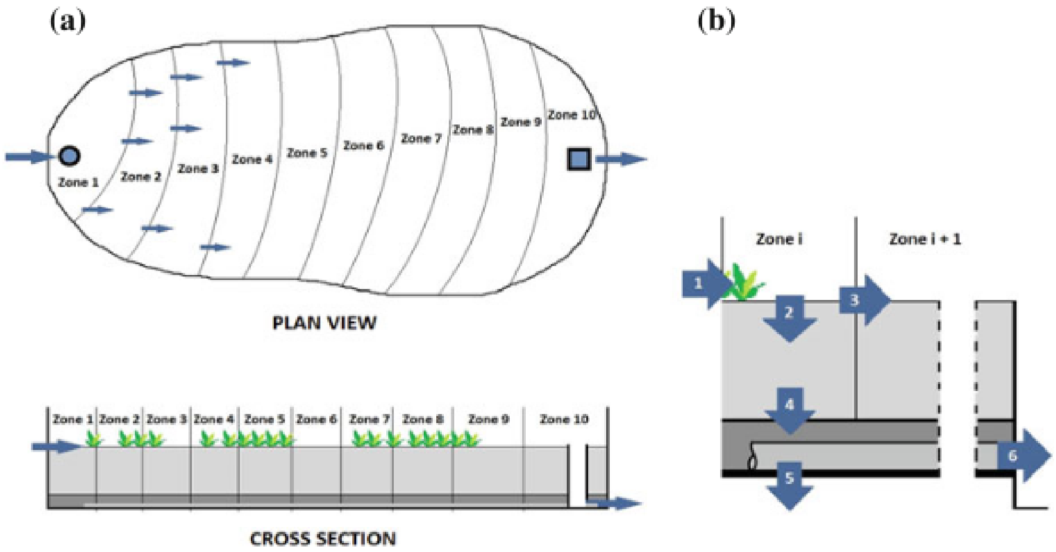


Fig. 2.3 Conceptual model for the bioretention basin. **a** Separation into 10 zones for model formulation. **b** Schematic of storm water flow

- Storm water runoff inflow (1) into the bioretention basin infiltrates into the soil column (2). This is replicated using an infiltration model;
- When the inflow rate is higher than the soil column's infiltration capacity, the excess runoff becomes surface flow to the next soil column (3);
- The infiltrated water percolates until it reaches the drainage layer where the storm water is temporarily stored (4);
- Part of the storm water stored in the drainage layer percolates to the original soil layer underneath (5);
- Through perforated pipes, storm water in the drainage layer flows to the outlet structure where the flow is monitored (6).

2.3.2.2 Modelling Water Flow

The soil column was considered as a system where water balance can be applied. This means that water entering (such as direct precipitation) and leaving (such as water losses due to percolation) the system were subjected to the water balance concept. In this way, cross interaction between an individual column and its surrounding columns were considered negligible. In the same way, any possible seepages from ground water and infiltration into the sidewalls were considered negligible. This was an acceptable assumption since the soil surrounding the system is silty clay with low infiltration rate. Adopting the water balance approach, the soil column was considered as a storage. The volume stored was considered as dependent on the volume of storm water entering and leaving the column. This action was replicated using a standard storage equation in the form of Eq. 2.1.

$$\Delta S = S_{t+\Delta t} - S_t = I \cdot \Delta t - O \cdot \Delta t \tag{2.1}$$

where:

ΔS Change in storage volume (m^3)
Δt Time interval (s)
S_t Storage volume (m^3) at the beginning of the time interval Δt
$S_{t+\Delta t}$ Volume (m^3) at the end of the time interval Δt
I Inflow discharge rate (m^3/s)
O Outflow discharge rate (m^3/s)

The inflow-outflow components considered in the model development are discussed below.

Direct Precipitation

Direct precipitation is rainfall that directly falls on the bioretention basin surface and the area surrounding the bioretention basin without entering a storm water inlet device. The amount of direct precipitation for a certain duration is considered as the rainfall depth for that duration, multiplied by the bioretention basin surface area. In the case where the rainfall falls on the surroundings of the bioretention basin area and the runoff produced does not flow through the inlet measurement device, but seeps through the bioretention basin, was estimated by applying a runoff coefficient. The initial runoff coefficient of 0.7 was considered appropriate to compensate for the loss of water due to interception and infiltration. However, this value was adjusted during model calibration.

Water loss due to Percolation

Since the type of soil underneath the bioretention basin is silty clay with a low permeability, a constant percolation rate of 1.8×10^{-6} m/h, as suggested by Lambe and Whitman (1969), was applied in the model throughout the bioretention basin area. However, during model calibration, this percolation rate was adjusted to improve the results.

Infiltration Process

The input to the system was considered as infiltration, while the output components of the system were percolation to the drainage layer underneath, and evapotranspiration. Infiltration was considered to be influenced by factors such as moisture content, porosity and hydraulic conductivity of the filter media, and surface conditions including vegetation cover. A range of equation formats are available to replicate the infiltration process, such as equations proposed by Horton (1933), Philip (1957) and Green and Ampt (1911). For this study, the Green-Ampt equation was adopted, due to its ability to incorporate filter media characteristics and the requirement of relatively less variables compared to the other models.

The principle of the Green-Ampt model is based on continuity and momentum. The conceptual format in which the Green-Ampt equation was applied in this study

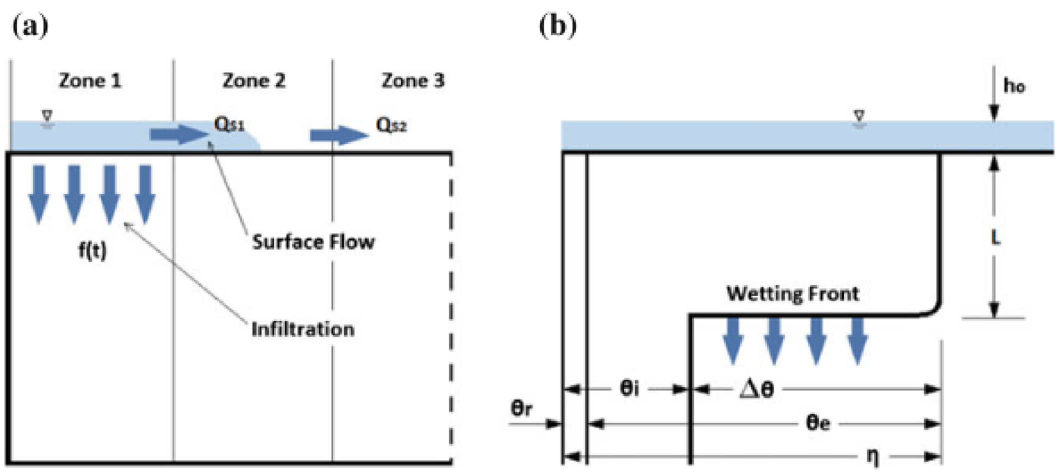


Fig. 2.4 Vertical soil column and Green-Ampt infiltration model

is presented in Fig. 2.4. Considering zone 1 as a vertical soil column (see Fig. 2.4a), the control volume was defined as the volume of the soil column from the surface to depth L (see Fig. 2.4b). As the wetting front progresses, the moisture content θ increases from the initial value θi to η (porosity). When θ equals η, the soil within the control volume is fully saturated. When L equals the thickness of the filter media (m), the whole filter media is considered fully saturated. In this condition, the wetting front passes through the whole filter media and reaches the drainage layer. For the subsequent subsurface flow, infiltration is replaced by percolation.

The developed model replicates the infiltration process in two phases. Phase I replicates the initiation of the infiltration process until it reaches the drainage layer. Phase II replicates the scenario where the infiltrated storm water contributes to the storage volume in the drainage layer. In this instance, the drainage layer was considered as a secondary storage. The storm water entering and leaving this secondary storage was also replicated using the water balance approach, with a standard storage equation in the form of Eq. 2.1.

Phase I

Initiation of Phase I occurs when the storm water from the catchment enters zone 1 or the excess surface flow enters the next zone. In scenarios where adequate flow of storm water is present, infiltration rate was considered as equivalent to infiltration rate capacity *F(t)* estimated using Eq. 2.2. In scenarios where inflow rate is less than the infiltration rate capacity of the soil column, the actual infiltration rate was considered as equal to the inflow rate. When the inflow rate is greater than the infiltration rate capacity, the actual infiltration rate is equal to the infiltration rate capacity while excess storm water flows to the next zone. The cumulative infiltration capacity estimation in the form of Eq. 2.2 requires an iterative approach to obtain the cumulative infiltration capacity *F(t)*.

$$F(t) = k_s \Delta t + \psi \Delta\theta \Delta ln\left(1 + \frac{F(t)}{\psi \Delta\theta}\right) \tag{2.2}$$

where:

F(t) Cumulative infiltration capacity (m)
k_s Hydraulic conductivity or saturated soil permeability coefficient (m/h)
t Time elapsed (h)
Ψ Wetting front soil suction head (m)
Δθ Difference between the initial water content and saturated water content or porosity (η)

Phase II

Phase II begins when the wetting front reaches the drainage layer and the storm water in the filter media starts draining to the drainage layer. The percolation of storm water from the filter media to the drainage layer was estimated based on two conditions. The first condition is when the filter media is still unsaturated while the second condition is when the filter media is fully saturated. The percolation rate in the second condition was replicated using the saturated coefficient of permeability k_s. Therefore, the volume of water that percolates during the modelling time interval Δt can be estimated in the form of Eq. 2.3.

$$V_{w\Delta t} = k_s \cdot \Delta t \times A \tag{2.3}$$

where:

$V_{w\Delta t}$ Volume of water percolating from filter media column (m^3)
k_s Hydraulic conductivity or saturated soil permeability coefficient (m/h)
Δt Time interval (h)
A Cross sectional area of the filter media column (m^2)

When the filter media is not in a fully saturated condition, the saturated soil permeability coefficient, k_s in Eq. 2.3 is replaced by k_w, which can be estimated using Eq. 2.4.

$$V_{w\Delta t} = k_w \cdot \Delta t \times A \tag{2.4}$$

where:

$V_{w\Delta t}$ Volume of water percolating from filter media column (m^3)
k_w Unsaturated soil permeability coefficient (m/h)
Δt Time interval (h)
A Cross sectional area of filter media column (m^2)

To obtain an accurate unsaturated soil permeability coefficient k_w, a field or laboratory experiment is required. However, Brooks and Corey (1964) have proposed an approximate method to obtain values for k_w, which is presented in Eq. 2.5.

$$k_w = k_s \times S_e^{\delta} \tag{2.5}$$

where:

k_w Unsaturated soil permeability coefficient (m/h)
k_s Saturated soil permeability coefficient (m/h)
S_e Effective saturation of soil
δ An empirical constant, expressed by $\delta = (2 + 3\lambda)/\lambda$, where λ is the pore size distribution index ($\lambda = 10$ which gives $\delta = 3.5$. This value was obtained from the calibration)

The effective saturation S_e is the ratio of the available moisture content $\theta - \theta_r$ to the maximum possible available moisture content $\eta - \theta_r$. It is written in the form of Eq. 2.6 (Chow et al. 1988).

$$S_e = \frac{\theta - \theta_r}{\eta - \theta_r} \tag{2.6}$$

where:

S_e Effective saturation of soil
θ Moisture content
θ_r The residual moisture content of soil after it has thoroughly drained
η Porosity

The maximum possible available moisture content is referred to as the effective porosity, reflected by $\eta - \theta_r = \theta_e$. The effective saturation, S_e was monitored during the modelling period to evaluate whether the filter media is in unsaturated or saturated condition. Once the value of S_e reaches 100 %, the filter media is considered to be saturated.

Overall, by using the equations discussed above, the infiltration process within the bioretention filter media was replicated. Since the processes are complex and correlated, a flowchart (see Fig. 2.5) was created to summarise the modelling process and equations used in each step.

2.3.2.3 Modelling the Flow Through Perforated Pipes to Outlet

Flow through the perforated pipes was modelled as flow in a circular open channel. Initially, this flow was assumed as laminar and later confirmed after calibration. The flow at the end of the perforated pipe near the outlet was also assumed as uniform and steady. This assumption was based on the fact that the longitudinal slope of the perforated pipe is very small (0.005). Manning's equation, in the form of Eq. 2.7, was used to simulate flow through the perforated pipes.

$$Q = \frac{k}{n} \times A \times R^{2/3} \times S^{1/2} \tag{2.7}$$

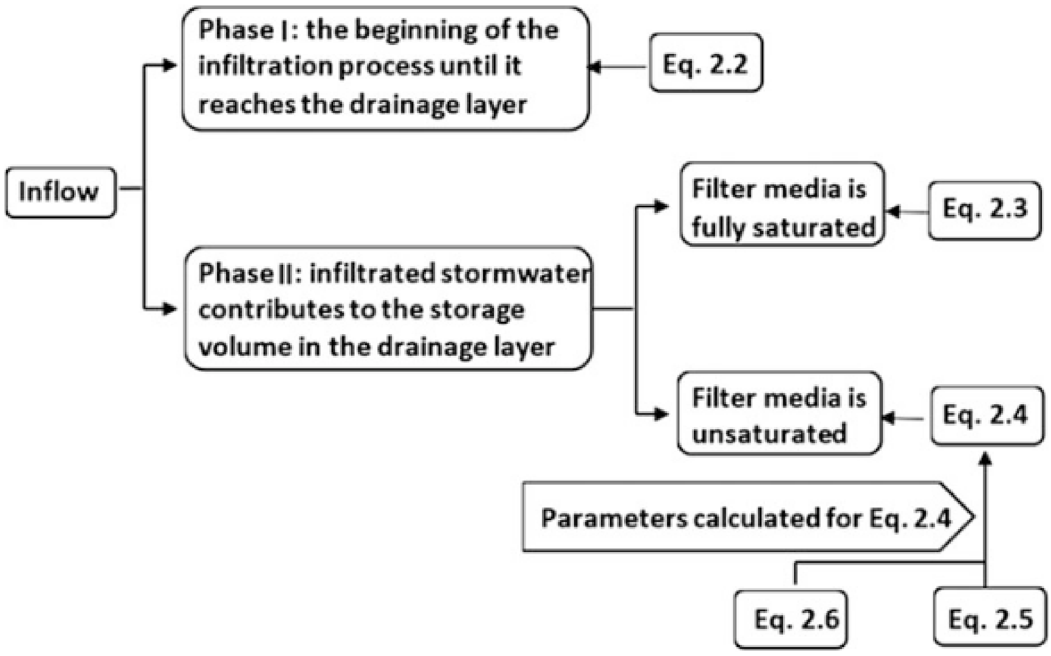


Fig. 2.5 The infiltration modelling process and equations used

where
Q Discharge (m^3/s)
k Conversion factor ($m^{1/3}/s$)
n Manning's coefficient
A Wetted cross sectional area of the circular pipe (m^2)
R Hydraulic radius of the wetted cross sectional area (m)
S Slope of the hydraulic grade line (equal to the longitudinal slope for uniform flow)

The internal surface of the perforated pipe was considered as rough, due to the presence of perforations. Therefore, the Manning's roughness coefficient in the range of 0.012–0.017 was initially used (Han 2008). The actual Manning's coefficient was obtained from calibration.

2.3.3 Model Calibration

Finalised model parameters were obtained by model calibration, which was undertaken by using a trial-and-error approach. The model parameters were changed until outputs reached visual fit to the measured outcomes. The model calibration was done using data from twelve rainfall events during the period April 2008 to March 2011. To assess the accuracy of the calibrated model, coefficient of determination (R^2) was used. R^2 typically demonstrates the 'goodness-of-fit' of models with respect to measured data. As such, the R^2 value is expected to be between 0 and 1 ($0 < R^2 < 1$). The higher the R^2 value, the better the model,

Table 2.2 The goodness-of-fit, coefficient of determination R^2

No.	Rainfall event	R^2
1	29-01-2008	0.89
2	03-02-2008	0.91
3	17-03-2008	0.92
4	18-04-2008	0.91
5	29-05-2008	0.92
6	22-01-2009	0.94
7	29-01-2010	0.98
8	18-04-2010	0.91
9	23-06-2010	0.92
10	19-07-2010	0.88
11	02-03-2011	0.93
12	29-03-2011	0.94
	Average	0.92

indicating that the model replicates reality closely. The R^2 value was calculated using Eq. 2.8.

$$R^2 = 1 - \frac{\sum_{i=1}^{n}(y_i - \hat{y}_i)^2}{\sum_{i=1}^{n}(y_i - \bar{y})^2} \tag{2.8}$$

where:

R^2 Coefficient of determination
y_i Measured value
$\hat{y}$ Modelled value
$\bar{y}$ Mean value

The R^2 values calculated for twelve monitored rainfall events are shown in Table 2.2. R^2 ranges from 0.88 to 0.98 with an average of 0.92. This range was considered satisfactory. This suggests that the approaches adopted in the model development are appropriate.

2.3.4 Generating Hydraulic Factors from the Model

The purpose of the developed conceptual model was to generate influential hydraulic factors for the analysis of water quality treatment performance. The selected hydraulic factors were, volume treated (VT), volume retained (VR), contributed wetted area (CA) and outflow peak (OP). The reasons for selecting these parameters are discussed below.

VT indicates the actual storm water quantity entering the treatment system, while VR is the volume retained within the system at the end of a storm event. VR is an important parameter influencing storm water treatment performance of bioretention

Table 2.3 Hydraulic factors generated from the bioretention basin model

No.	Rainfall events	Volume treated (m^3)	Outflow peak (L/s)	Contributing area (%)	Volume retained (m^3)
		VT	OP	CA	VR
B1	29-01-2008	54.65	1.528	70	31.33
B2	03-02-2008	87.73	3.417	100	22.00
B3	17-03-2008	31.03	1.342	50	23.23
B4	18-04-2008	51.69	1.258	40	24.81
B5	29-05-2008	112.26	1.877	100	48.86
B6	22-01-2009	79.06	3.032	70	38.47
B7	29-01-2010	70.56	1.550	100	49.51
B8	18-04-2010	49.33	1.458	40	20.38
B9	23-06-2010	8.70	0.522	10	6.03
B10	19-07-2010	31.87	0.933	50	28.41
B11	02-03-2011	28.88	1.595	40	23.20
B12	29-03-2011	38.82	1.303	60	31.17

basins (Jenkins et al. 2012). OP is the maximum outflow discharge recorded during a rainfall event, which was selected to investigate the influence of the rate of flow through filter media on treatment performance. Generally, a relatively smaller inflow volume might receive better treatment. On the other hand, a large runoff volume may flow through the treatment system at a relatively higher rate, resulting in little residence time for adequate treatment (Liu et al. 2013). CA represents the percentage of the wetted area of the bioretention filter media. This parameter is important for small events where the complete surface area of the system does not contribute to the treatment and hence could lead to a lower pollutant removal percentage (Mangangka et al. 2014a). The hydraulic factors generated from the conceptual model for the monitored twelve rainfall events are presented in Table 2.3. VT ranges from 8.70 to 87.73 m^3 while OP is from 0.522 to 3.417 L/s. CA is more than 40 % (except for the 23-06-2010 event). VR is from 6.03 to 49.51 m^3.

2.4 Conceptual Model for a Constructed Wetland

2.4.1 Description of the Constructed Wetland

The constructed wetland consisted of a sedimentation pond, two wetland cells and an overflow bypass system (see Fig. 2.6a). There were two pipes that conveyed storm water into the wetland from two separate sub-catchments (B and C in Fig. 2.1). The larger pipe (750 mm diameter) conveyed storm water from the larger sub-catchment (B), while the smaller pipe (300 mm diameter) conveyed storm water from the smaller sub-catchment (C). Consequently, two storm water monitoring stations were required for the wetland inlets. Storm water entering the constructed storm water wetland was pre-treated in the sedimentation pond prior to receiving further treatment in the wetland cells. A cell inlet control pit at the pond outlet ensures that the storm water enters the cells slowly, as high flow might disturb the cells and vegetation. Additionally, the maximum inflow rate that was allowed to enter the wetland cells was controlled by the bypass weir (see Fig. 2.6b). A 7 m wide bypass weir (broad crested) overflows when the water level is above its crest level and the storm water is discharged to the receiving water through the bypass channel without undergoing treatment. The bypass system was designed such that it activates only during large rainfall events and rest of the storm water is directed to wetland cells 1 and 2, respectively, for further treatment. Outflow from the constructed wetland system is via a PVC riser arrangement located at the downstream wetland cell (cell 2) (a detailed discussion is provided in Sect. 2.4.2.4). The PVC riser is designed to create high outflow rate when the water level of wetland is high. Outflow from the PVC riser flows though the outlet pipe to the wetland outlet station, where the flow can be measured and samples can be collected for laboratory testing. The layout of the constructed wetland is shown in Fig. 2.6.

2.4.2 Model Set-up

2.4.2.1 The Principles and Assumptions Adopted for the Model

The conceptual model for the constructed wetland was developed to represent water movement through the system. The basic concept incorporated in the model is the water balance approach. This considers the wetland components, including the inlet pond and its cells as storages interlinked via inlet/outlet structures. Water balance in each of these interlinked storages was replicated using a standard water balance equation, as shown in Eq. 2.1.

The inflow to the constructed wetland system comprises of inflow from inlet structures and direct precipitation to the wetland area and seepage from groundwater. Outflow from the wetland system comprises of outflow through the outlet structure, percolation and evapotranspiration. All inflow and outflow components mentioned above were included in the model developed. In this regard, inflow as seepage from the surrounding soil was considered negligible. The water flow within the wetland was replicated using the schematic shown in Fig. 2.7. Storm water entering the wetland system is through the inlet structure to the inlet pond (1). The water then flows to wetland cell 1 through a concrete pipe controlled by an inlet pit (2). High inflow creates high free surface elevation in the inlet pond leading to part of the inflow bypassing through a channel (3). The water from wetland cell 1 flows into wetland cell 2 through a 1 m wide channel (4), which is assumed as a broad crested weir. The water in wetland cell 2 leaves the wetland system through a PVC riser (outlet structure) (5).

Fig. 2.6 The constructed wetlands. **a** Aerial view of the constructed wetland. **b** The constructed wetlands at the site. **c** The bypass weir

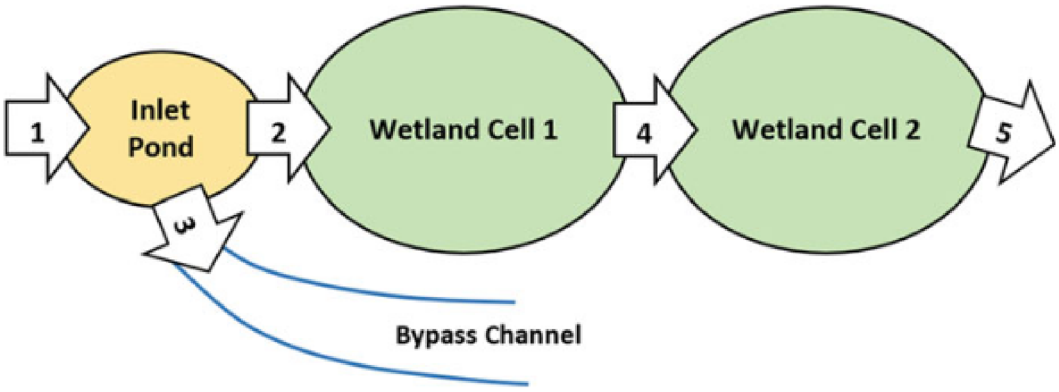


Fig. 2.7 The schematic of storm water flows in the wetland system

2.4.2.2 Generating the Volume Versus Depth Curve

Accurate estimation of storage volume played a pivotal part in the constructed wetland conceptual model. This was undertaken by developing volume versus depth curves for the inlet pond, wetland cell 1 and wetland cell 2, individually. For this purpose, the wetland contour map (see Fig. 2.8) was obtained by undertaking a bathymetry survey. Volume versus depth curves were developed based on the bathymetric contour map. The developed curves are provided in Appendix A.

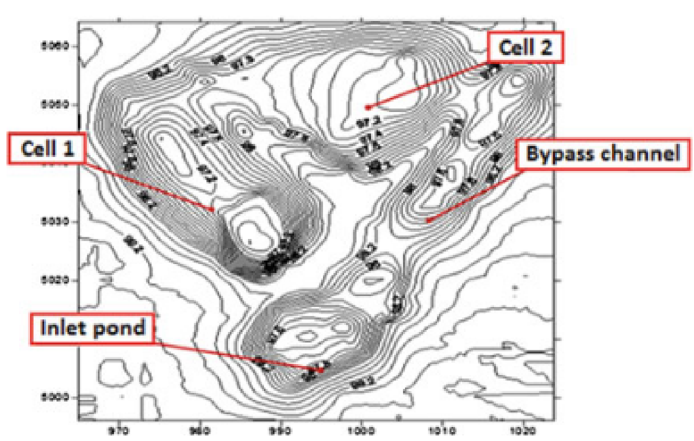
Water flows from inlet pond to cell 1, and from cell 1 to cell 2, were calculated based on the difference in free surface elevations. Free surface elevation in each storage device, therefore, acts as the control parameter in the model. Free surface elevation was obtained based on the volume versus depth relationships developed for each storage component.

2.4.2.3 Flow Through Wetland Cells and Bypass

Water flow from inlet pond to cell 1

Storm water flow from inlet pond to wetland cell 1 is through a pit and pipe arrangement. The concrete pipe discharging water from pit to cell 1 has a diameter

Fig. 2.8 The wetland contour map



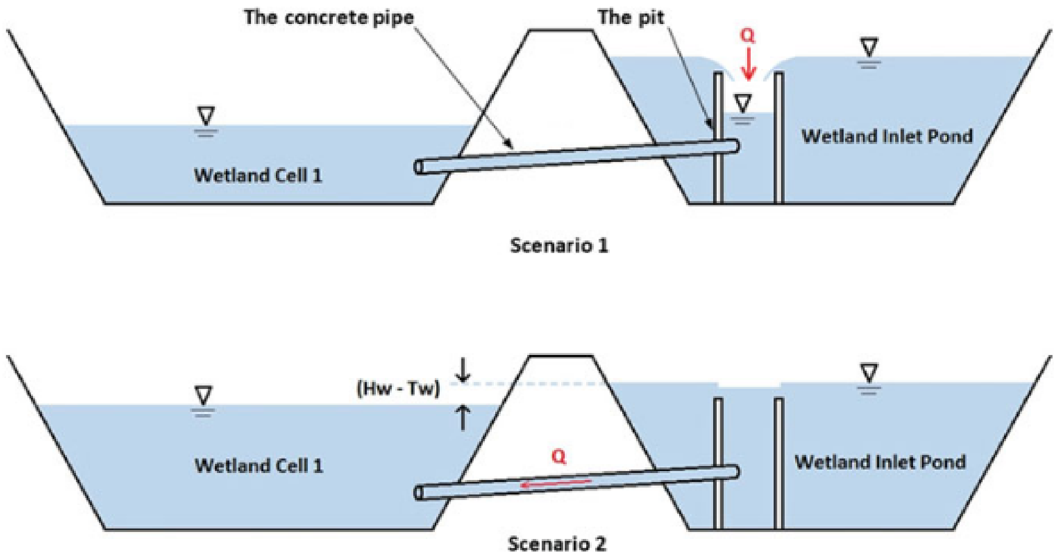


Fig. 2.9 Flow from wetland inlet pond to wetland cell 1

of 350 mm. This pipe is typically submerged, below the free surface level of the pit and wetland cell 1 (see Fig. 2.9). The pit has 15 cm thick concrete walls with length and width of 1.90 m and 1.00 m, respectively. Based on this configuration, the flow from the inlet pond to the wetland cell 1 was modelled for two different scenarios (see Fig. 2.9) and the governing scenario was taken into account. The first scenario was when the free surface elevation in the wetland cell 1 is relatively low and the flow from inlet pond to cell 1 is controlled by the flow entering the pit. Under this scenario, the pipe is assumed to have adequate capacity to convey the flow. The second scenario is when the free water surface elevation in wetland cell 1 is above a threshold and the resulting backwater influences the water level in the inlet pond. Under the second scenario, flow from inlet pond to cell 1 was modelled by estimating the discharge capacity through the pipe.

For scenario 1, water entering the pit was assumed as flow through a broad-crested weir. The weir width was taken as the inner perimeter of the pit. According to Gerhart and Gross (1985), the discharge through a broad-crested weir can be expressed in the form of Eq. 2.9.

$$Q = Cd\left(\frac{2}{3}\right)\sqrt{2g}LH^{3/2} \tag{2.9}$$

where:

Q Discharge (m^3/s)

Cd Discharge coefficient ($\frac{1}{\sqrt{3}}$ was used as an initial estimate while value used during simulations was obtained using a calibration process)

g Acceleration due to gravity (m/s^2)

L Weir width (m)

H Head above the weir crest (m)

For scenario 2, flow through the pipe is the governing scenario. In this regard, the flow velocity through the pipe is relatively low and hence entry loss and frictional head loss was considered insignificant. Therefore, the simplified flow equation as shown in Eq. 2.10 was used to replicate the flow scenario. In Eq. 2.10, discharge coefficient (Cd) was used to compensate other minor losses.

$$Q = CdA\sqrt{2g(Hw - Tw)} \tag{2.10}$$

where:
Q Discharge (m3/s)
Cd Discharge coefficient (0.6 was used as an initial estimate and value used during simulations was obtained using a calibration process)
A Cross section area of the inner pipe (m^2)
g Acceleration due to gravity (m/s^2)
Hw Head water (water elevation in the pond) (m)
Tw Tail water (water elevation in the wetland cell 1) (m)

Water Flow from Cell 1 to Cell 2 The flow of water from cell 1 to cell 2 was considered as the flow through a broad-crested weir and Eq. 2.9 was used for flow estimation. The weir width (L) was estimated based on the opening shown in the bathymetric survey and the head (H) was the height of free water surface elevation in cell 1 from the crest. However, when the water level in cell 2 rose above the weir crest, then the difference in the surface water elevation between cell 1 and cell 2 was assumed as the head (H).

Water Bypass Bypass from the detention pond is over a 7 m wide broad-crested weir. It was designed to bypass excess water above the crest of the weir to flow across to the bypass channel. The model adopted an equation similar to Eq. 2.9 to replicate the bypass flow.

2.4.2.4 Modelling the Outlet

Retention time in a wetland is significantly influenced by the outlet structure. For example, Konyha et al. (1995) in their study found that an orifice outlet structure would provide longer retention time than a weir outlet structure. Wong et al. (1999) reported different performances of outlet structures and suggested that a riser outlet gives the best performance. The monitored wetland in this study utilises a PVC riser outlet, which consists of a number of 20 mm diameter slots as shown in Fig. 2.10.

Two scenarios were used to model this outlet using the conceptual model. In the first scenario, when a slot is fully submerged, the flow was assumed as flow through a small orifice as shown in Fig. 2.11. Flow through a fully submerged orifice was calculated using Eq. 2.11.

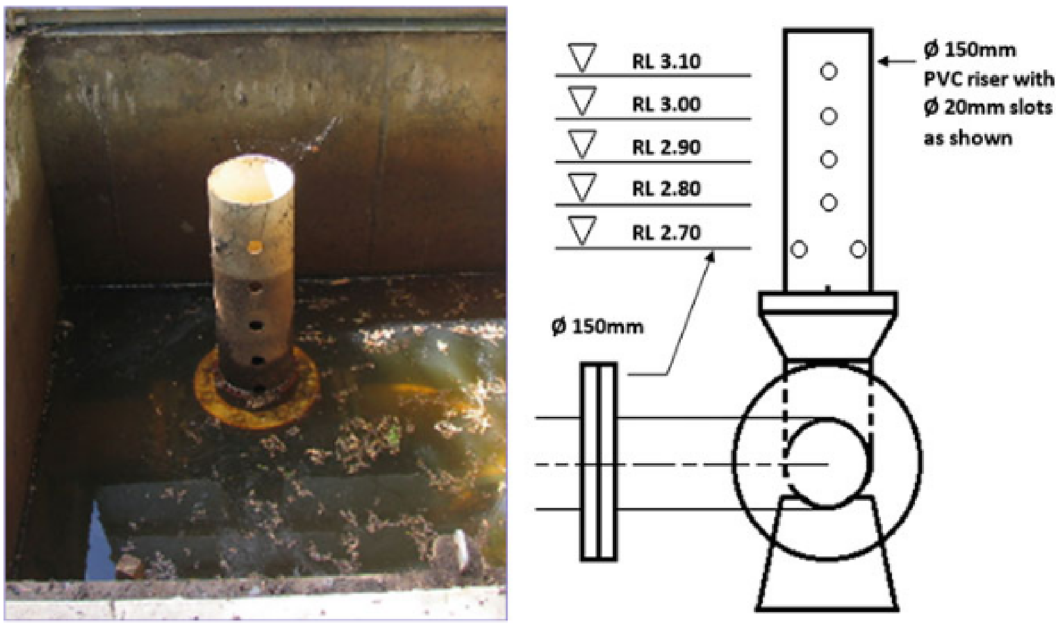


Fig. 2.10 The configuration of the PVC riser

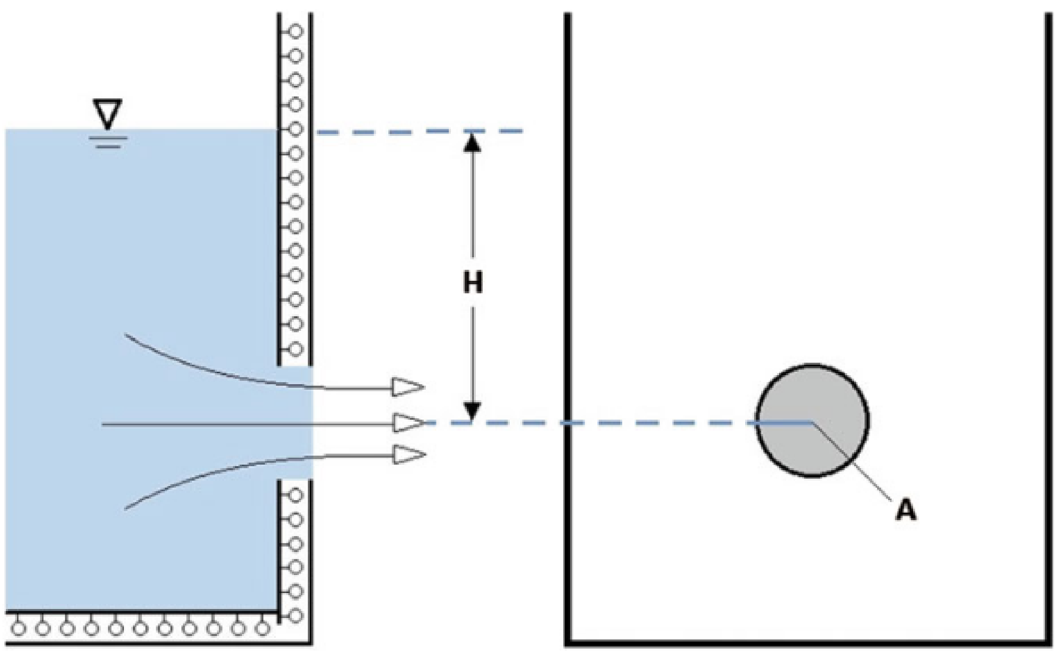


Fig. 2.11 Flow through a small orifice

$$Q = CdA\sqrt{(2gH)} \tag{2.11}$$

where
Q Discharge (m^3/s)
Cd Discharge coefficient

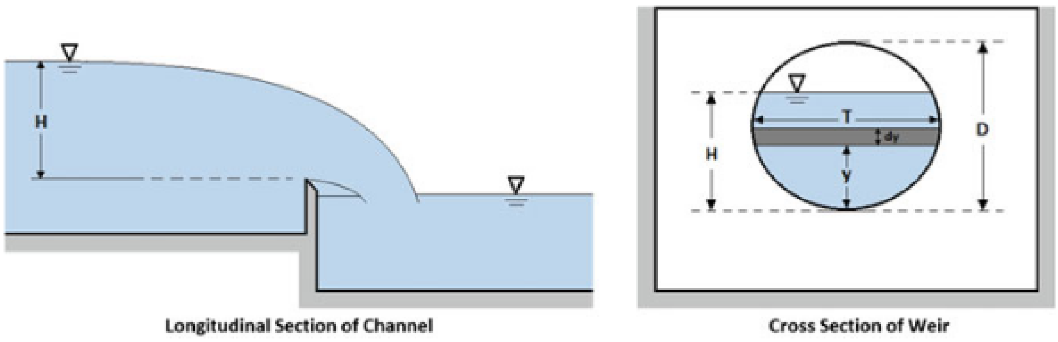


Fig. 2.12 Flow through a circular sharp-crested weir

A Cross section area of the slot (m^2)
g Acceleration due to gravity (m/s^2)
H Head from the centre of the slot (m)

In the second scenario, when a slot is partially filled, flow was calculated, considering it operates as a circular sharp-crested weir (Fig. 2.12). In this regard, the equation form proposed by researchers such as Greve (1932) and Stevens (1957) was used for this model. They have expressed discharge through a circular sharp-crested weir as shown in Eq. 2.12.

$$Q = 0.3926Cd\sqrt{2g}H^{3/2}D\eta^{1/2}(\sqrt{1-0.2200\eta}+\sqrt{1-0.7730\eta}) \qquad (2.12)$$

where
Cd The discharge coefficient
g The acceleration due to gravity (m/s^2)
H Flow depth above the weir crest (m)
D The diameter of circular weir (m)
h The filling ratio (= H/D)

Researchers have noted a diverse range of experimental values for discharge coefficient (Cd) in Eq. 2.12. For this study, the equation presented by Vatankhah (2010) was used to estimate Cd (Eq. 2.13). However, the value obtained using Eq. 2.13 was only used as an initial value. The actual Cd value was obtained during the calibration process.

$$Cd = \frac{0.728 + 0.240\eta}{1 + 0.668\sqrt{\eta}} \qquad (2.13)$$

In summary, the equations discussed above describe processes of water flow from the inlet pond (including bypass) to the outlet. Similar to the bioretention basin model, the processes involved are complex and correlated. Therefore, a

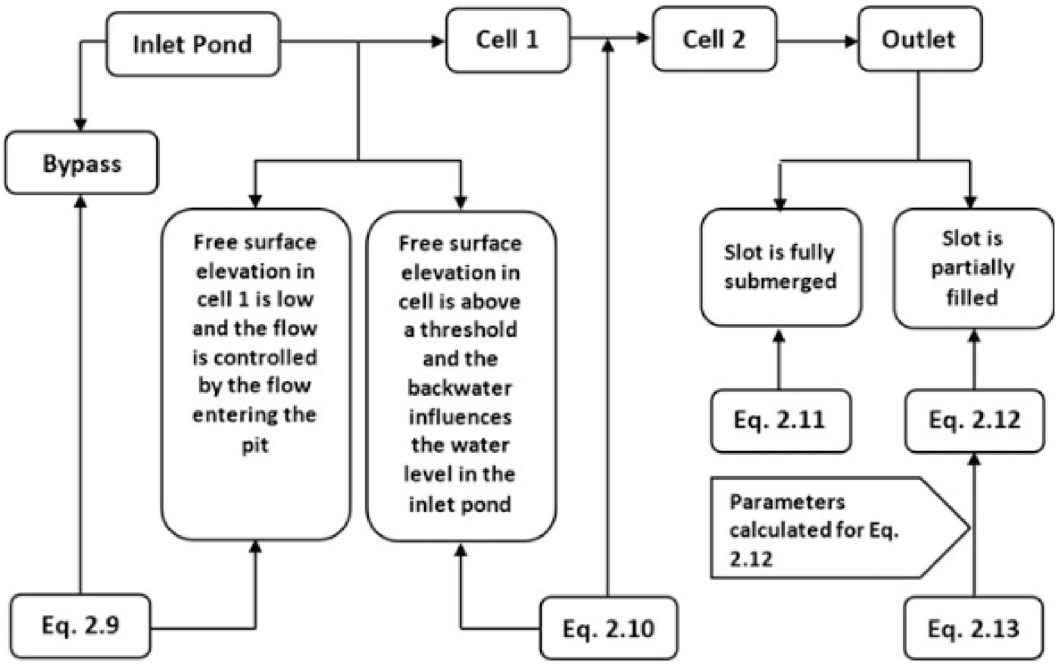


Fig. 2.13 Wetland modelling process and equations used

schematic (see Fig. 2.13) has been created to illustrate the modelling process and equations used in each step.

2.4.2.5 Percolation, Evapotranspiration and Direct Precipitation

Percolation and evapotranspiration are two important factors influencing the constructed wetland water balance. A range of methods are available to estimate percolation rates. However, in the model developed, a constant percolation rate was used to ensure simplicity of the model. Initial percolation rate was selected based on the soil bed characteristics. The monitored wetland bed consisted of silty clay soil and approximate percolation rate was estimated as 5×10^{-4} m/h (Rawls et al. 1983). The actual percolation rate was obtained during model calibration. A range of methods are available to estimate evapotranspiration. For the developed wetland conceptual model, a constant daily evapotranspiration rate obtained from the Bureau of Meteorology Australia (2011) was used to ensure simplicity.

Direct precipitation into the wetland perimeter is also an important input to assess the water balance for the wetland. Two components, namely, rainfall falling directly on wetland surface water area and rainfall falling in the wetland perimeter with no contribution to the piped flow network, were considered. The calculations were the same as the direct precipitation in the case of the bioretention basin (see Sect. 2.3.2.2).

2.4.3 Model Calibration

Final parameters were obtained by model calibration. The calibration undertaken was similar to the calibration steps adopted for the bioretention basin conceptual model. The model calibration was done using data from eleven rainfall events during April 2008 to March 2011. The coefficient of determination (R^2) estimated, based on all measured and simulated hydrographs, is shown in Table 2.4. As evident from Table 2.4, R^2 values for the eleven rainfall events range from 0.80 to 0.97. This is considered satisfactory, suggesting that the approach used to develop the model is appropriate.

2.4.4 Generating Hydraulic Factors from the Model

The purpose of the wetland conceptual model was to generate the influential hydraulic factors for the analysis of water quality treatment performance. The selected influential hydraulic factors were outflow volume (OV), outflow average discharge (OQ), average water depth in the wetland (AD), average retention time (RT) and outflow peak (OP). The reasons for selecting these parameters are discussed below.

OQ values represented the outflow characteristics, while OP was the maximum outflow discharge recorded during the runoff event. OQ, OV and OP reflect how much volume goes through the constructed wetland and hence could receive treatment (Mangangka et al. 2014b). AD influences the wetland environment, such as light penetration and dissolved oxygen concentration, and hence would play an important role in treatment performance of plants and microorganisms (Paudel et al. 2013). RT is a critical parameter, as it represents the time period in which the storm water receives treatment in the wetland system. Generally, a longer RT leads to better treatment (Elliott and Trowsdale 2007). Event-based hydraulic factors

Table 2.4 The goodness-of-fit, coefficient of determination R^2

No.	Rainfall event	R^2
1	05-04-2008	0.80
2	18-04-2008	0.93
3	29-05-2008	0.89
4	11-02-2009	0.95
5	04-03-2009	0.85
6	29-01-2010	0.90
7	18-04-2010	0.96
8	23-06-2010	0.89
9	19-07-2010	0.89
10	02-03-2011	0.97
11	29-03-2011	0.86
	Average	0.90

Table 2.5 Hydraulic factors generated from the wetland conceptual model

No.	Rainfall event	Average retention time	Outflow peak	Average outflow discharge	Outflow volume	Average depth of water
		(day)	(L/s)	(L/s)	(m^3)	(m)
		RT	OP	OQ	OV	AD
W1	05-04-2008	2.98	1.163	0.642	98	0.350
W2	18-04-2008	2.56	2.319	1.197	493	0.465
W3	29-05-2008	2.37	2.696	1.564	524	0.539
W4	11-02-2009	3.97	1.071	0.302	168	0.250
W5	04-03-2009	4.31	0.753	0.282	44	0.270
W6	29-01-2010	2.48	2.477	1.255	594	0.452
W7	18-04-2010	3.15	1.768	0.883	383	0.403
W8	23-06-2010	4.24	0.969	0.398	93	0.283
W9	19-07-2010	2.97	1.513	0.637	228	0.327
W10	02-03-2011	1.92	2.536	1.358	251	0.497
W11	29-03-2011	2.22	2.242	1.101	255	0.443

obtained from the conceptual model are presented in Table 2.5. RT ranges from 1.92 to 4.31 days while AD is below 0.5 m (except for 29-05-2008 event). The ranges for OP, OQ and OV values are 0.753–2.696 L/s, 0.398–1.564 L/s and 44–594 m^3, respectively.

2.5 Summary

Due to the fact that a number of important hydraulic factors which influence the treatment performance of bioretention basins and constructed wetlands are difficult to directly monitor, two conceptual models were developed using mathematical relationships underpinned by fundamental hydraulic theory. These two models demonstrated satisfactory performance as evident from the statistical analysis undertaken, and were found to be capable of generating the required hydraulic parameters. The parameters generated by conceptual models for the bioretention basin were; volume treated, outflow peak, contributing area and volume retained, while the parameters generated for the constructed wetlands were average retention time, outflow peak, average outflow discharge, outflow volume and average depth of water.

This showcases an innovative approach in using conceptual models to generate influential hydraulic factors, which in turn can be used to analyse storm water treatment system performance. Additionally, the approach adopted has the capability to generate key hydraulic data for individual rainfall event rather than using long-term rainfall characteristics. This is a significant advancement from conventional approaches for the analysis of treatment system performance, which is based on the use of lumped parameters.

References

Australia B (2011) Recent Evapotranspiration. Retrieved 21 May 2011, from http://www.bom.gov.au/watl/eto/

Brooks RJ, Corey AT (1964) Hydraulic properties of porous medium, Colorado State University (Fort Collins)

Chow VT, Maidment DR, Mays LW (1988) Applied hydrology. McGraw-Hill Inc, New York

Elliott AH, Trowsdale SA (2007) A review of models for low impact urban stormwater drainage. Environ Model Softw 22:394–405

Gerhart PM, Gross RJ (1985) Fundamentals of fluid mechanics. Reading Addison-Wesley, Massachusetts

Green WH, Ampt GA (1911) Studies on soil physics, part I, the flow of air and water through soils. J Agric Sci 4:1–24

Greve FV (1932) Flow of water through circular, parabolic and triangular vertical notch weirs. Eng Buletin, Purdue Univ 40(2):37–60

Han D (2008) Concise Hydraulics. Ventus Publishing

Horton RE (1933) The role of infiltration in the hydrologic cycle. Trans Am Geophys Union 14:446–460

Jenkins GA, Greenway M, Polson C (2012) The impact of water reuse on the hydrology and ecology of a constructed stormwater wetland and its catchment. Ecol Eng 47:308–315

Konyha KD, Shaw DT, Weiler KW (1995) Hydrologic design of a wetland: advantages of continuous modeling. Ecol Eng 4(2):99–116

Lambe TW, Whitman RV (1969) Soil mechanics. Wiley, New York

Liu A, Guan YT, Egodawatta P, Goonetilleke A (2013) Selecting rainfall events for effective Water Sensitive Urban Design (WSUD) implementation. The 16th International Conference on Diffuse Pollution and Eutrophication. Beijing, China

Mangangka IR, Liu A, Egodawatta P, Goonetilleke A (2014a) Performance characterisation of a stormwater treatment bioretention basin. J Environ Manage 150:173–178

Mangangka IR, Liu A, Egodawatta P, Goonetilleke A (2014b) Sectional analysis of stormwater treatment performance of a constructed wetland. Ecol Eng 77:172–179

Paudel R, Grace KA, Galloway S, Zamorano M, Jawitz JW (2013) Effects of hydraulic resistance by vegetation on stage dynamics of a stormwater treatment wetland. J Hydrol 484:74–85

Philip JR (1957) The theory of infiltration: 1. The infiltration equation and its solution. Soil Sci 83 (5):345–357

Rawls WJ, Brakensiek DL, Miller N (1983) Green-ampt infiltration parameters from soils data. J Hydraul Eng 109(1):62–70

Stevens JC (1957) Flow through circular weirs. J Hydraul Eng 83(6):1455-1451–1455-1424

Vatankhah AR (2010) Flow measurement using circular sharp-crested weirs. Flow Meas Instrum 21(2):118–122

Wong THF, Breen PF, Somes NLG, Lloyd SD (1999) Managing urban stormwater using constructed wetlands, 1999. Cooperative Research Centre (CRC) for Catchment Hydrology and Department of Civil Engineering, Monash University

Chapter 3
Assessing Bioretention Basin Treatment Performance

Abstract This chapter investigates the influence of hydrologic/hydraulic factors on the treatment performance of a bioretention basin using parameters generated by the conceptual model discussed in Chap. 2. The study outcomes showed that antecedent dry period is an important factor influencing pollutant removal efficiency. A long antecedent dry period will result in relatively low moisture content in the filter media which can enhance the runoff retention capacity and consequently improve treatment performance. This implies that planting vegetation with a high evapotranspiration capacity would enhance treatment efficiency. Additionally, it was found that pollutant leaching influences bioretention basin treatment performance, particularly reducing the ability for nutrient removal. This highlights the importance of the selection of appropriate filter media and its timely replacement.

Keywords Bioretention basin · Antecedent dry period · Treatment performance · Pollutant leaching · Storm water quality

3.1 Background

As discussed in Chap. 1, bioretention basins are among the most commonly used storm water treatment measures. In bioretention basins, filtration is the main treatment mechanism, supported by evapotranspiration, absorption and biotransformation. Bioretention basins can also provide storm water quantity mitigation by attenuating peak runoff and reduction in runoff volume through detention and retention (Davis et al. 2006).

The effective design of a bioretention basin is closely dependent on the in-depth understanding of the influence of hydrologic and hydraulic factors on treatment performance. This is because these factors play an important role in influencing pollutant removal processes of a bioretention basin. The influential factors include rainfall characteristics and inflow and outflow parameters.

This chapter investigates the treatment performance of a bioretention basin by relating its performance to hydraulic and hydrologic factors. The hydrologic factors

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were obtained from a field monitoring program (see Sect. 2.2 in Chap. 2) while hydraulic factors were generated by the conceptual model discussed in Chap. 2. The study outcomes are expected to contribute to a greater understanding of the treatment performance of bioretention basins and in turn enable improved design and operation and maintenance of these systems.

3.2 Hydrologic/Hydraulic Factors Selection

Twelve monitored rainfall events were selected for the analysis. The selected rainfall events were less than one year average recurrence interval (ARI). This ARI range is used for most urban storm water treatment system designs (Dunstone and Graham 2005), due to their relatively more frequent occurrence and responsibility for a high fraction of annual runoff volume from catchments (Liu et al. 2013a, b). Additionally, the twelve rainfall events accommodated the mid-range of the rainfall depth (4.8–52.0 mm) typical to the study area (Liu et al. 2012). An appropriate number of storm water runoff samples had been captured by the installed automatic sampler for all 12 events.

In addition, hydraulic factors as identified in Chap. 2 and three hydrologic factors were also selected for the assessment. The characteristics of the rainfall events were considered as the hydrologic factors and included rainfall depth (RD), antecedent dry period (AD) and average rainfall intensity (RI) (see Table 3.1). RD is directly related to the runoff volume generated by a catchment. AD can generally reflect the amount of pollutants available for wash-off with storm water runoff. As a number of previous researchers have noted (such as Vaze and Chiew 2002; Deletic and Orr 2005), a longer antecedent dry period can lead to relatively higher pollutant build-up load on the catchment surfaces. RI is an important factor influencing peak runoff and pollutant wash-off from catchments. High RI can result in high rain drop kinetic energy and lead to a high fraction of pollutant wash-off from urban surfaces (Kleinman et al. 2006; Brodie and Rosewell 2007; Liu et al. 2012, 2013a). As discussed in Chap. 2, hydraulic factors selected for the assessment were; volume treated (VT), volume retained (VR), contributed wetted area (CA) and outflow peak (OP), and are listed in Table 3.1.

From the seven hydraulic and hydrologic factors selected, the most critical factors for influencing treatment performance were selected for detailed assessment. The selection of hydrologic and hydraulic factors was undertaken by using PROMETHEE, which is a multi criteria decision making method (Khalil et al. 2004; Liu et al. 2015), and the Pearson correlation analysis. Detailed information regarding the PROMETHEE method and Pearson correlation analysis is provided in Appendix B. This selection was to prevent too many correlating parameters overshadowing critical relationships between hydrologic and hydraulic factors and treatment performance of the bioretention basin (Egodawatta et al. 2006).

Outcomes of the PROMETHEE analysis are presented in Table 3.2. The φ net value is the net ranking flow where a higher φ net value of an object indicates the

Table 3.1 Hydrologic/hydraulic factors for the bioretention basin analysis

Rainfall no.	Rainfall depth (mm)	Rainfall intensity (mm/h)	Antecedent dry period (day)	Volume treated (m^3)[a]	Outflow peak (L/s)[a]	Contributing area (%)[a]	Volume retained (m^3)[a]
	RD	RI	AD	VT	OP	CA	VR
B1	20.6	7.36	8.51	54.65	1.528	70	31.33
B2	52.0	14.86	3.05	87.73	3.417	100	22.00
B3	12.0	5.45	6.60	31.03	1.342	50	23.23
B4	18.4	3.91	6.83	51.69	1.258	40	24.81
B5	44.6	5.95	10.48	112.26	1.877	100	48.86
B6	51.8	8.22	13.05	79.06	3.032	70	38.47
B7	25.8	4.69	10.36	70.56	1.550	100	49.51
B8	19.4	8.08	4.24	49.33	1.458	40	20.38
B9	4.80	2.53	4.56	8.70	0.522	10	6.03
B10	9.60	8.73	10.50	31.87	0.933	50	28.41
B11	20.2	8.78	5.88	28.88	1.595	40	23.20
B12	12.6	6.63	13.07	38.82	1.303	60	31.17

[a]generated from the wetland conceptual model

Table 3.2 Rainfall event PROMETHEE ranking of the bioretention basin

Ranking	Rainfall events	φ value	Rainfall depth (mm)
1	B6	0.2955	51.8
2	B5	0.2926	44.6
3	B2	0.2712	52.0
4	B7	0.1507	25.8
5	B1	0.0141	20.6
6	B12	−0.0117	12.6
7	B10	−0.0801	9.60
8	B11	−0.1089	20.2
9	B8	−0.1246	19.4
10	B4	−0.1324	18.4
11	B3	−0.1526	12.0
12	B9	−0.4139	4.80

higher position in the rank order. It can be noted that the higher ranked objects are those rainfall events with higher rainfall depths. For example, three top ranked events (B6, B5 and B2) have the highest rainfall depths (51.8, 44.6 and 52.0 mm) among the twelve monitored events. In contrast, the bottom ranked event has the lowest rainfall depth (B9, 4.8 mm). This fact can also be supported by the GAIA biplot (Fig. 3.1). Detailed information regarding the GAIA biplot is provided in Appendix B. The decision axis Pi points to the events with high rainfall depths (B5 and B6), while the lowest rainfall depth event (B9) is located opposite to the

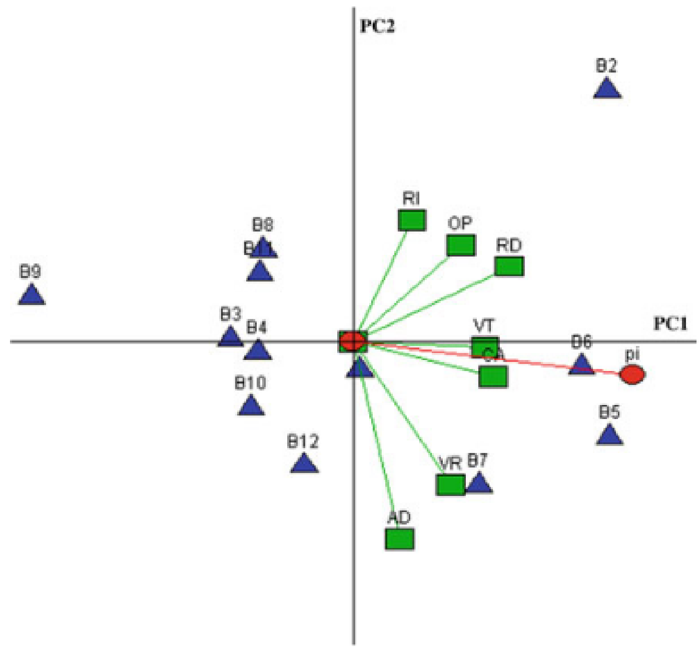

Fig. 3.1 GAIA biplot for factor selection (Δ = 87.16 %)

direction of the Pi axis. This suggests that rainfall depth is an important factor among the hydraulic parameters and hence could be critical to the overall hydraulic performance of the bioretention basin. Additionally, RD shows a close relationship with OP, VT and CA, since the RD vector forms acute angles with the OP, VT and CA vectors. This means that RD can be a representative factor for OP, VT and CA. RI indicates the capacity of the rainfall for detaching pollutants from catchment surfaces and hence should be selected for the detailed analysis. It is also noted in Fig. 3.1 that AD and VR are located far from other hydrologic and hydraulic factors. This means that AD and VR are relatively independent from other hydrologic/hydraulic factors. AD is dry days between consecutive rainfall events while VR is the volume retained in the bioretention basin.

For confirmation of the relationships between these factors, the Pearson correlation matrix was created (Table 3.3). It is evident that VT, OP and CA have very close correlations with RD, as the coefficients are 0.887, 0.931 and 0.739, respectively. This is in agreement with the observations from the GAIA biplot (Fig. 3.1). This essentially confirms that high rainfall depth (RD) leads to high storm water volume entering the bioretention basin, high outflow peak and a large filter media wetted area. RI is an independent factor, since it shows a relatively weak relationship with the other factors except with OP (0.738). AD is an independent factor by its definition since it represents the dry period prior to rainfall occurrence. VR is an important hydraulic factor for most storm water treatment devices. Therefore, considering the correlations and PROMETHEE and GAIA results, RD, VR, RI and AD were eventually selected for further analysis.

Table 3.3 Pearson correlation matrix for hydrologic and hydraulic factors

	RD	RI	AD	VT	OP	CA	VR
RD	1						
RI	0.56	1					
AD	0.125	-0.211	1				
VT	0.887**	0.355	0.249	1			
OP	0.931**	0.738**	0.017	0.720**	1		
CA	0.739**	0.428	0.331	0.871**	0.659*	1	
VR	0.495	-0.018	0.714**	0.723**	0.309	0.793**	1

*Correlation is significant at the 0.05 level (2-tailed)
**Correlation is significant at the 0.01 level (2-tailed)

3.3 Relationship Between Water Quality Treatment and Hydrologic/Hydraulic Factors

As discussed in Chap. 2, the bioretention basin was monitored for rainfall-runoff characteristics and storm water samples were collected from each event for quality analysis. The samples collected were tested for total nitrogen (TN), nitrate (NO_3^-), nitrite (NO_2^-), ammonium (NH_4^+), total phosphorus (TP), phosphate (PO_4^{3-}) and total suspended solids (TSS), which can be considered as the primary storm water pollutants (Liu et al. 2013a; Miguntanna et al. 2013). Based on the outcomes of the laboratory testing, pollutant event mean concentrations (EMC) at the inlet and outlet were determined for each rainfall event. EMCs were obtained by dividing the total inflow and outflow pollutant loads by the total inflow and outflow volumes. Sample testing was undertaken according to test methods specified in Standard Methods for the Examination of Water and Wastewater (APHA 2005). Sample collection, transport and storage complied with Australia New Zealand Standards, AS/NZS 5667.1:1998 (AS/NZS 1998).

Principal Component Analysis (PCA) was used to investigate the relationships between the treatment performance and hydrologic and hydraulic factors. PCA is an effective technique to explore correlations among variables and objects (Kokot et al. 1998). For performing PCA, objects were the 12 rainfall events while the variables were the percentages of the TSS, TP, TN, NH_4^+, NO_3^-, NO_2^- and PO_4^{3-} EMC reductions and RI, RD, VR and AD. Figure 3.2 shows the resulting PCA biplots. A detailed discussion of the PCA method is provided in Appendix B.

As seen in Fig. 3.2, the pollutant EMC reduction vectors are divided into two groups. TSS, TP, PO_4^{3-}, NO_2^- and NH_4^+ EMC reduction vectors are projected on the positive PC1 axis along with AD and VR vectors, while NO_3^- and TN vectors are projected on the negative PC1 axis. This implies that the influence exerted by AD and VR are different on the two groups of pollutant EMC reduction vectors, namely (TSS, TP, PO_4^{3-}, NO_2^- and NH_4^+) and (NO_3^- and TN). AD and VR are relatively the more important factors influencing treatment performance,

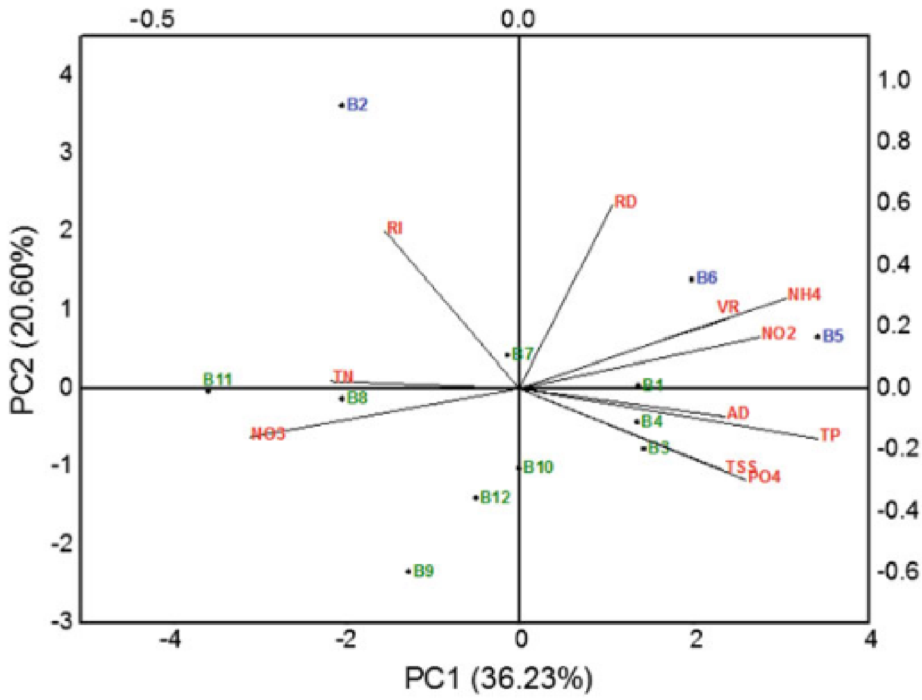

Fig. 3.2 PCA biplot of pollutant EMC reduction in bioretention basin. *Note* Events with *blue label* (B2, B5 and B6) have high rainfall depth values and are ranked top in PROMETHEE results (Table 3.2) while events with *green labels* are the rest

particularly for TSS, TP, PO_4^{3-}, NO_2^- EMC reductions. Additionally, these observations show that the EMC removal characteristics of the different nitrogen species are also different. This is evident due to the differences in orientation of the vectors representing (NO_2^- and NH_4^+) and (NO_3^- and TN). However, RD and RI do not show a close relationship with any of the pollutant EMC reduction vectors.

The close correlation between AD and TSS, TP and PO_4^{3-} EMC reduction vectors means that solids and phosphorus reduces in the bioretention basin with the increase in the antecedent dry period. Relatively long AD commonly leads to high pollutant build-up loads, particularly for particulate pollutants such as phosphorus (Vaze and Chiew 2002). Additionally, the average size of particulate pollutants received by a bioretention basin can also be expected to increase with the increase in AD (Egodawatta and Goonetilleke 2006). High particulate input load would enhance solids and phosphorus removal as phosphorus is primarily present in particulate form (Miguntanna et al. 2013). This can be supported by the fact that relatively larger particle sizes are more easily removed by storm water treatment systems (Hsieh and Davis 2005).

In the case of the differing removal characteristics of different nitrogen species, Fig. 3.2 shows that there is a strong positive correlation of AD and VR with NO_2^- and NH_4^+ EMC reduction percentages and negative correlation with NO_3^- and TN. This suggests that a longer dry period and the resulting higher volume retention capacity increases NO_2^- and NH_4^+ removal, but decreases NO_3^- removal. The possible reason is that a longer antecedent dry period allows NH_4^+ and NO_2^- oxidation, thus reducing their concentrations, and increases NO_3^- concentration. As Davis et al. (2009) have noted, exposure of NH_4^+ and NO_2^- to the atmosphere during the dry period can lead to nitrification due to relatively abundant oxygen content, resulting in excess NO_3^- washout during subsequent events. This implies that nitrification occurs in the bioretention basin during the dry period.

The fact that particulate (TSS and phosphorus) and dissolved pollutants (nitrogen) show different removal characteristics in the bioretention basin can be attributed to different treatment mechanisms. Particulate pollutants would be primarily removed by filtration, while dissolved pollutants would be primarily removed by biochemical processes such as denitrification.

Additionally, except for NO_2^- and NH_4^+ vectors, the other pollutant EMC reduction vectors point towards medium and low rainfall depth events. This means that the bioretention basin would have a relatively lower capacity for treating high rainfall depth events. This highlights the fact that the treatment of events with high rainfall depth may not be technically feasible in a bioretention basin. Treatment of large events would also not be economically feasible due to relatively high land and cost requirements.

3.4 Analysis of Water Quality Treatment Performance

As discussed above, antecedent dry period and resulting volume retained would exert influence on the water quality treatment performance of bioretention basins. Most of the pollutant EMC reduction percentages (TSS, TP, PO_4^{3-}, NO_2^- and NH_4^+) are related to antecedent dry period and resulting volume retained (see Fig. 3.2). Therefore, a data matrix on water quality treatment performance (EMC reduction percentages) was prepared, based on the antecedent dry period as shown in Table 3.4.

It can be noted that the mean pollutant EMC reduction percentages for rainfall events occurring after a relatively long dry period (>6 days) are generally higher than the corresponding values for rainfall events after a relatively shorter dry period (<6 days) except for TN EMC and NO_3^- EMC reduction percentages. This confirms the important role played by the antecedent dry period, which results in drying of the filter media and increased volume being retained, thereby influencing the bioretention basin treatment performance. Additionally, the data presented in Table 3.4 also support the fact that nitrification occurs in the bioretention basin. A longer antecedent dry period allows NH_4^+ oxidation, which increases the NO_3^- load and consequently reduces the overall NO_3^- removal percentage.

As the study outcomes confirm that longer dry periods and resulting lower filter media moisture content can enhance the treatment capacity of bioretention systems

Table 3.4 Pollutant EMC reduction data (%)

Dry period	Rainfall no.	TSS	NH_4^+	NO_2^-	NO_3^-	TN	PO_4^{3-}	TP
Long dry period (>6 days)	B1	18.09	61.73	6.85	−87.50	−17.73	66.42	58.54
	B3	43.91	92.56	38.99	−51.16	−48.69	67.97	32.72
	B4	74.03	71.73	16.23	−112.57	−70.34	−38.74	1.73
	B5	66.54	71.05	9.57	−145.10	−63.04	49.47	55.82
	B6	36.39	61.47	−39.39	−98.14	−82.55	26.17	18.10
	B7	3.87	−15.52	68.69	39.79	19.71	−38.49	27.63
	B10	44.99	−41.25	−63.65	−69.99	−10.29	70.38	9.54
	B12	21.36	−44.06	−123.02	50.49	−71.14	57.84	5.74
	Mean	38.65	32.21	−10.72	−59.27	−43.01	32.63	26.23
	Standard deviation	22.46	52.36	57.51	65.72	33.87	43.20	20.40
Short dry period (<6 days)	B2	3.23	64.40	−36.36	−57.30	−31.04	−69.23	−58.09
	B8	14.26	−69.38	−47.59	0.24	−49.83	−0.73	−31.30
	B9	50.26	−37.78	−102.00	−36.06	−41.66	24.38	−13.88
	B11	25.30	−74.94	−186.18	40.11	20.58	−101.63	−21.31
	Mean	23.26	−29.42	−93.03	−13.25	−25.49	−36.80	−31.15
	Standard deviation	17.43	55.99	59.23	37.05	27.42	50.74	16.74

by retaining a higher storm water volume, the presence of vegetation would further contribute to enhancing the treatment performance (Davis et al. 2009). Vegetation will reduce the filter media moisture during dry periods due to evapotranspiration, as well as increase the filter media porosity. This means that appropriate planting, particularly vegetation species with high evapotranspiration capacity, can enhance the treatment capacity of bioretention basins.

It is noteworthy that Table 3.4 also shows negative values for pollutant reduction percentages, particularly for nitrogen and phosphorus. This implies the possibility of nutrient leaching from filter media. Nutrient leaching can be attributed to the flushing of runoff retained in the filter media from the preceding rainfall events, which could have contained elevated concentrations. Furthermore, nutrients present in the bioretention filter media itself could also contribute to pollutant leaching (Davis 2007; Dietz and Clausen 2005). This means that the increase in pollutant retention in the filter media, in the long term can potentially cause pollutant export. This highlights the importance of timely replacement of filter media in order to reduce nutrient accumulation and for the selection of appropriate filter media to enhance nutrient sorption.

3.5 Conclusions

This chapter discussed the treatment performance of a bioretention basin and its relationship with hydrologic/hydraulic factors. It is noted that the antecedent dry period plays an important role in influencing treatment performance of a bioretention basin. A long antecedent dry period will result in relatively low moisture content in the filter media which can enhance the runoff retention capacity and consequently improve treatment performance. In this context, planting of appropriate vegetation, particularly vegetation with a high evapotranspiration capacity would enhance treatment efficiency. Additionally, it is concluded that the bioretention basin has a relatively lower ability for treating events with high rainfall depth. This phenomenon should be taken into consideration in the design. This is also supported by the possible land and cost savings.

Furthermore, the research outcomes show that nitrification occurs within a bioretention basin, leading to high nitrite and ammonium nitrogen reduction, but lower nitrate removal. Additionally, the outcomes also show that pollutant leaching influences bioretention basin treatment performance, particularly reducing nutrient removal. This highlights the importance of the selection of appropriate filter media and its timely replacement.

References

APHA (2005) Standard methods for the examination of water and wastewater. American Public Health Association, Washington DC
AS/NZS (1998) Water quality–sampling-guidance on the design of sampling programs, sampling techniques and the preservation and handing of samples. Australian Standards
Brodie I, Rosewell C (2007) Theoretical relationships between rainfall intensity and kinetic energy variants associated with stomwater particle wash-off. J Hydrol 340(1–2):40–47
Davis AP (2007) Field performance of bioretention: Water quality. Environ Eng Sci 248: 1048–1063
Davis AP, Hunt WF, Traver RG, Clar M (2009) Bioretention technology: Overview of current practice and future needs. J Environ Eng 135(3):109–117
Davis AP, Shokouhian M, Sharma H, Minami C (2006) Water quality improvement through bioretention media: nitrogen and phosphorus removal. Water Environ Res 78:2177–2185
Deletic A, Orr DW (2005) Pollution buildup on road surfaces. J Environ Eng 131(1):49–59
Dietz ME, Clausen JC (2005) A field evaluation of rain garden flow and pollutant treatment. Water Air Soil Poll 167(1–4):123–138
Dunstone G, Graham H (2005) Water sensitive urban design guidelines. Melbourne, Mildura Rural City Council
Egodawatta P, Goonetilleke A (2006) Characteristics of pollutants build-up on residential road surfaces. The 7th international conference on hydroscience and engineering, Philadelphia, USA
Egodawatta P, Goonetilleke A, Ayoko GA, Thomas EC (2006) Understanding the interrelationships between stormwater quality and rainfall and runoff factors in residential catchments. In: 7th international conference on urban drainage modelling and the 4th international conference on water sensitive urban design, Melbourne, Australia

Hsieh CH, Davis AP (2005) Evaluation and optimization of bioretention media for treatment of urban stormwater runoff. J Environ Eng 131(11):1521–1531

Khalil WA, Goonetilleke A, Kokot S, Carroll S (2004) Use of chemometrics methods and multicriteria decision-making for site selection for sustainable on-site sewage effluent disposal. Anal Chim Acta 506(1):41–56

Kleinman PJA, Srinivasan MS, Dell CJ, Schmidt JP, Sharpley AN, Bryant RB (2006) Role of rainfall intensity and hydrology in nutrient transport via surface runoff. J Environ Qual 35:1248–1259

Kokot S, Grigg M, Panayioyou H, Phuong TD (1998) Data interpretation by some common chemometric methods. Electroanalysis 10:1081–1088

Liu A, Goonetilleke A, Egodawatta P (2012) Taxonomy for rainfall events based on pollutant wash-off potential in urban areas. Ecol Eng 47:110–114

Liu A, Egodawatta P, Guan YT, Goonetilleke A (2013a) Influence of rainfall and catchment characteristics on urban stormwater quality. Sci Total Environ 444:255–262

Liu A, Guan YT, Egodawatta P, Goonetilleke A (2013b) Selecting rainfall events for effective Water Sensitive Urban Design (WSUD) implementation. In: the 16th international conference on diffuse pollution and eutrophication, Beijing, China

Liu A, Egodawatta P, Goonetilleke A (2015) Role of rainfall and catchment characteristics on urban stormwater quality. Springer

Miguntanna N, Liu A, Egodawatta P, Goonetilleke A (2013) Characterising nutrients wash-off for effective urban stormwater treatment design. J Environ Manage 120:61–67

Vaze J, Chiew FHS (2002) Experimental study of pollutant accumulation on an urban road surface. Urban Water 4(4):379–389

Chapter 4
Assessing Constructed Wetland Treatment Performance

Abstract This chapter presents the assessment of the constructed wetland treatment performance. The assessment was done by partitioning the inflow runoff hydrograph into ten segments and then investigating the treatment performance of each runoff segment within a constructed wetland. Accordingly, the hydrologic and hydraulic factors generated by the conceptual model were also appropriately allocated to the ten segments. The analysis outcomes showed that large and small rainfall events are differently treated in a constructed wetland. The pollutant load reductions for the initial sector of runoff from large rainfall events were relatively low, due to the rapid mixing taking place within the system. This highlights the need to establish an inlet pond prior to the flow entering the constructed wetland, so that the inflow will initially stabilise. This is also supported by the fact that the initial sector of runoff generally carries higher pollutant loads.

Keywords Constructed wetlands · Inflow runoff hydrograph · Storm water quality · Treatment performance · Hydrologic and hydraulic factors

4.1 Background

A diverse range of processes are involved in storm water treatment in a constructed wetland including gravity settling of particulates, filtration, adsorption, vegetation uptake and biological decomposition. These processes are affected by a range of hydraulic factors such as hydraulic loading, retention time, depth of water, and quality and quantity characteristics of the inflows. The effective design of a constructed wetland closely relies on the in-depth understanding of the relationship between hydrologic and hydraulic factors and treatment performance.

Unlike a bioretention basin, which is commonly dry between storm events and its treatment efficiency primarily relies on the degree of dryness of the filter media (as discussed in Chap. 3), a constructed wetland is a water body which commonly pools to a certain depth all the time (refer to Sect. 1.2.6 in Chap. 1). When a rainfall event occurs, the inflow continuously enters the wetland system and mixes with the

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previously retained water (Mangangka et al. 2014). Mixing can occur during the whole period of the runoff event. This could result in differences in storm water treatment performance during the different sectors of a runoff event. This potential phenomena needs to be viewed in the context of the occurrence of first flush, which refers to a relatively higher pollutant load at the initial part of a runoff event and hence relatively more polluted storm water that will enter the system in the early sectors of the runoff hydrograph (Liu et al. 2010; Alias et al. 2014a, b). In this regard, first flush alone could lead to differences in treatment performance between early and later parts of the runoff hydrograph. In-depth understanding of these differences in treatment performance will contribute to the design of more efficient constructed wetland systems.

This chapter presents an assessment of a constructed wetland treatment performance with respect to a range of influential hydrologic and hydraulic factors. The assessment adopted an innovative approach, by partitioning the inflow runoff hydrograph and then investigating the treatment performance of each runoff segment within a constructed wetland. The hydrologic factors were obtained from a field monitoring program (see Sect. 2.22.2 in Chap. 2) while the relevant hydraulic factors in each segment of the hydrograph were generated by the conceptual model as discussed in Chap. 2. The new knowledge created will contribute to enhancing the design of constructed wetlands and thereby ensure more effective storm water treatment systems.

4.2 Selection of Hydrologic/Hydraulic Factors and Determination of Section Parameters

4.2.1 Selection of Hydrologic/Hydraulic Factors

Similar to the selection processes adopted for the bioretention basin, eleven rainfall events selected for the constructed wetland analysis were also less than one year ARI. Additionally, the eleven rainfall events accommodated the mid-range of the rainfall depth (3.0–44.6 mm) typical to the study area (Liu et al. 2012) and an appropriate number of storm water runoff samples were captured by the storm water monitoring stations installed at the inlet and outlet. The overall hydrologic and hydraulic characteristics of selected rainfall events are given in Table 4.1.

4.2.2 Determination of Section Parameters

In order to investigate the influence of hydraulic factors on wetland treatment as the rainfall event progresses, the inflow runoff hydrograph for each event was partitioned into 10 sectors, with each sector representing 10 % of the runoff volume.

Table 4.1 Selected rainfall events and hydrologic/hydraulic factors for constructed wetland analysis

Rainfall no.	Rainfall depth (mm)	Average retention time[a] (day)	Outflow peak[a] (L/s)	Average outflow discharge[a] (L/s)	Average depth of water[a] (m)
	RD	RT	OP	OQ	AD
W1	6.4	2.98	1.163	0.642	0.350
W2	18.4	2.56	2.319	1.197	0.465
W3	44.6	2.37	2.696	1.564	0.539
W4	6.8	3.97	1.071	0.302	0.250
W5	3.0	4.31	0.753	0.282	0.270
W6	25.8	2.48	2.477	1.255	0.452
W7	19.4	3.15	1.768	0.883	0.403
W8	4.8	4.24	0.969	0.398	0.283
W9	9.6	2.97	1.513	0.637	0.327
W10	20.2	1.92	2.536	1.358	0.497
W11	12.6	2.22	2.242	1.101	0.443

[a]generated from the wetland conceptual model

Based on this, pollutant load reduction was individually determined for every 10 % increment in runoff volume. The division of pollutant load reductions for the ten sectors of runoff volume was undertaken in the following steps and also illustrated in Fig. 4.1. Adopting a similar technique, the required hydraulic parameters were also generated by the use of the conceptual model so that the values corresponding to 10 % increment in runoff volume are available.

- Step I: The cumulative pollutant load (obtained from a number of monitored pollutant load data for inlet and outlet) versus cumulative inflow runoff volume was plotted as shown in Fig. 4.1.
- Step II: The cumulative pollutant load reduction for each sector of runoff volume was determined by the difference between cumulative pollutant loads at inlet and outlet for each 10 % sector in the plot.
- Step III: The pollutant load reduction for each 10 % sector was obtained by the difference between the cumulative pollutant load reductions of two consecutive 10 % sectors.

Accordingly, the resulting water quality section variables for each rainfall event included ten load reduction values for each pollutant species and section hydraulic parameters consisting of outflow average discharge (OQ), average water depth in the wetland (AD), average retention time (RT) and outflow peak (OP). The reasons for selecting the four hydraulic factors can be found in Sect. 2.4.3 of Chap. 2. Same as for the bioretention basin analysis, pollutant types considered were total nitrogen (TN), nitrate (NO_3^-), nitrite (NO_2^-), ammonium (NH_4^+), total phosphorus (TP), phosphate (PO_4^{3-}) and total suspended solids (TSS). Based on this, a total of 70

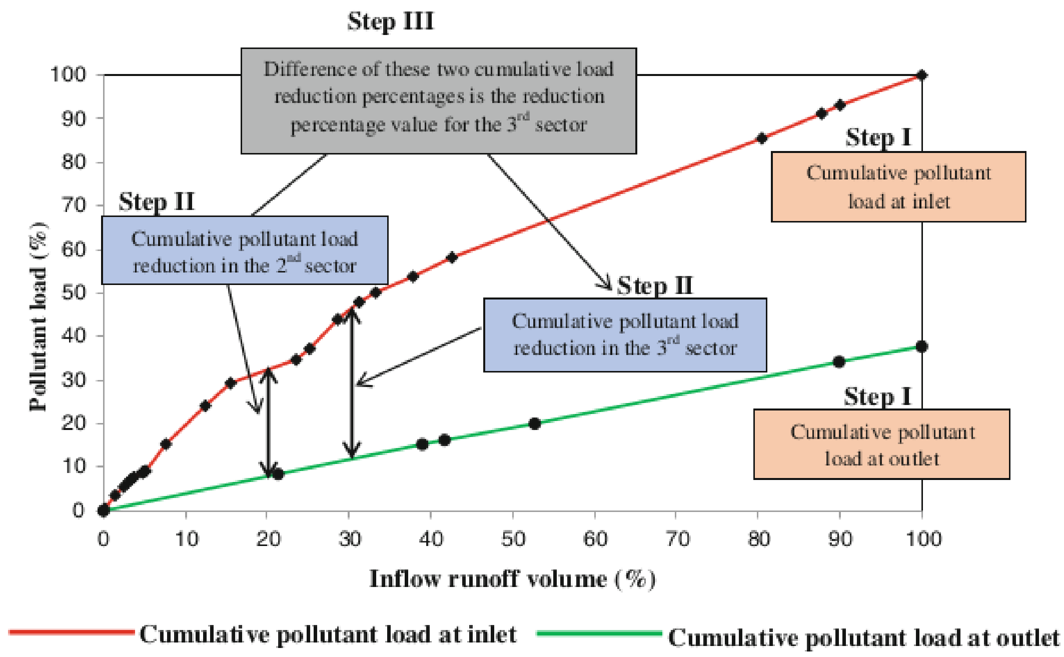

Fig. 4.1 Example of division of pollutant load reductions for the ten sectors of runoff volume. *Note* The cumulative pollutant load percentages at outlet were obtained by the total inflow pollutant loads dividing the outflow pollutant loads. Therefore, the cumulative pollutant load percentage at outlet does not reach 100 %

section pollutant load reduction values were generated for each rainfall event. The ten sectors of runoff volume for each event were represented as I, II, III, IV, V, VI, VII, VIII, IX and X.

4.3 Preliminary Investigation

The investigation was initially undertaken in order to have an overall understanding of the constructed wetland treatment performance. The PCA technique was used to undertake this analysis. A detailed explanation of PCA is presented in Appendix B. The data matrix used for PCA included 110 objects, which consisted of the 10 sectors for each rainfall event (10 sectors × 11 rainfall events), while variables were the seven pollutants (TN, NO_3^-, NO_2^-, NH_4^+, TP, PO_4^{3-} and TSS) and four hydraulic factors (RT, OP, AD and OQ). The resulting PCA biplot is shown in Fig. 4.2.

From Fig. 4.2, it is noted that all pollutant load removal vectors correlate with each other and are projected on the positive PC2. The four hydraulic factors are divided into two groups. OP, AD and OQ vectors are projected on the positive PC1 where most large rainfall events such as W3 and W10 are located (see Table 4.1). RT vector is projected in the negative PC1 direction, where most small rainfall

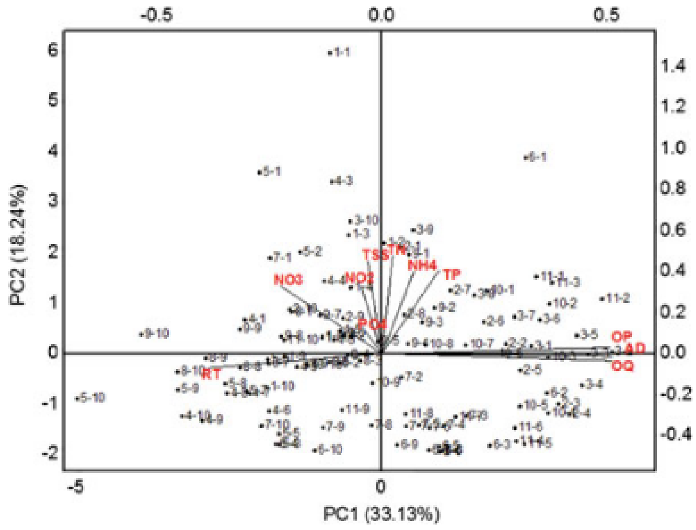

Fig. 4.2 PCA biplot for preliminary investigation of constructed wetland. The first digit is rainfall no. while the second digit represents the sector of runoff volume. For example, 5-6 represents the pollutant load reduction in the sixth 10 % sector of runoff volume in Rainfall No. 5; RT = retention time in each sector of runoff volume, OP = outflow peak in each sector of runoff volume, OQ = average outflow discharge in each sector of runoff volume and AD = average water depth in each sector of runoff volume

events such as W4 and W5 are located. This is due to the high runoff volumes generated during large rainfall events leading to elevated OP, OQ, and AD in wetland cells. However, this also results in the reduction in the RT as the storm water rapidly flows through the wetland system with a shorter retention time.

Since the pollutant species vectors are closely related to each other, the representative pollutants were selected for the following analysis. This was to avoid too many variables overshadowing the important relationships (Egodawatta et al. 2006). In this regard, TSS, TN and TP were selected for further analysis, since these three pollutants are the most common storm water pollutants in the urban environment (Goonetilleke et al. 2005).

4.4 Analysis of Different Rainfall Hydrograph Sectors

Factor analysis (FA) was initially performed for deriving a general understanding of the treatment performance of the constructed wetland from the beginning and towards the end of the runoff events. Factor analysis is a statistical method used to describe the variability among observed, correlated variables in terms of a potentially lower number of unobserved variables called factors. In factor analysis, the factors can be rotated to new axes that better separate the data. The number of factors is less than or equal to the number of original variables. Principal component extraction method with orthogonal VARIMAX rotation was adopted for the factor analysis. VARIMAX technique rotates the original factors such that the factors are

Table 4.2 Factor analysis

Sector of runoff volume	Factor 1	Factor 2
I	0.266	**−0.911**
II	0.314	**−0.927**
III	0.475	**−0.859**
IV	0.566	**−0.798**
V	0.678	**−0.708**
VI	**0.752**	−0.640
VII	**0.841**	−0.536
VIII	**0.900**	−0.434
IX	**0.932**	−0.345
X	**0.948**	−0.260

strongly correlated with a specific set of variables, while weakly correlated with the others (Abdi 2003). Detailed information in relation to factor analysis is provided in Appendix B. For this analysis, the variables included the load reduction values for the ten sectors of the inflow runoff hydrograph, while the objects were the three pollutant parameter values (TSS, TN and TP) for the eleven rainfall events. Accordingly, the data matrix was 33×10. After careful investigation of the rotated component matrix, two underlying factors were found sufficient. These factors were extracted based on the initial eigenvalue criteria ≥1. Table 4.2 shows the factor analysis results.

As shown in Table 4.2, the section parameters representing initial sectors of the inflow runoff hydrograph (I, II, III,IV and V) tend to correspond to Factor 2, while the later section parameters (VI, VII, VIII, IX and X) tend to relate to Factor 1. This implies that the treatment behaviour of the constructed wetland is different for the early and later sectors of the inflow runoff hydrograph. In other words, the treatment characteristics vary along with the runoff flow process. This highlights the need to understand the treatment characteristics of the constructed wetland based on different sectors of the inflow runoff hydrograph, rather than using lumped parameters.

4.5 Comparison of Treatment Characteristics for Different Sectors of the Inflow Runoff Hydrograph

The treatment characteristics of the constructed wetland during the runoff process are illustrated, using a boxplot as shown in Fig. 4.3. It is evident that although mean values of load reductions are not notably different among the ten sectors of the runoff hydrograph for the different pollutant species, the data ranges show differences in the early and later sectors. The first five sectors (the first 50 % of runoff volume) generally have relatively wider data ranges than the later sectors, particularly in the case of TSS and TN. However, the data ranges for TP load reduction are relatively similar throughout the whole runoff flow process.

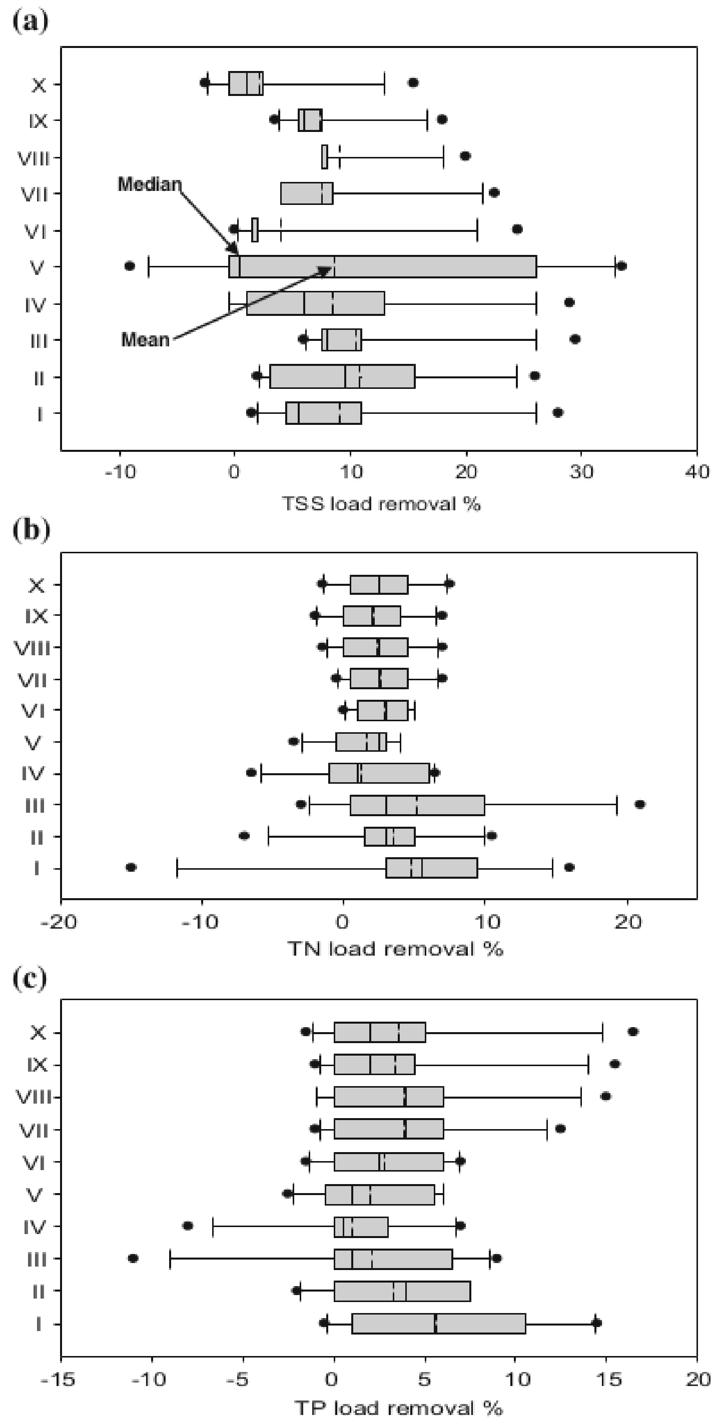

Fig. 4.3 Comparison of pollutant load reductions in different sectors of runoff hydrograph **a** TSS load removal **b** TN load removal **c** TP load removal

Since the data was collected from eleven events with different rainfall and hydraulic characteristics, these observations imply that the performance of the constructed wetland for TSS and TN removal are highly variable with hydrologic and hydraulic characteristics in the initial sectors of the runoff hydrograph. TP load reduction varies all the way through the runoff flow process. This means that the pollutant load reduction percentages (particularly for solids and nitrogen) for the initial flow could vary highly, based on the characteristics of each rainfall event such as ARI (rainfall frequency representing quantity) and antecedent dry days (representing pollutant load availability prior to rainfall). However, the corresponding percentages of the later flow would be relatively less variable although the characteristics of rainfall events producing runoff might be different. The relatively higher variability of TSS and TN load reductions in the initial sectors of the inflow runoff hydrograph is attributed to the mixing of incoming runoff with the stored water in the constructed wetland. Characteristics of the mixing that occur can be different for large and small events. For example, relatively larger rainfall events would lead to stronger disturbance when the runoff enters the wetland, while small runoff events would result in a relatively weaker mixing with the stored water.

In the case of TP, it could be attributed to the occurrence of both removal and release processes during the retention time. As noted by Lai and Lam (2009), phosphorus can be removed by adsorption while it can also re-enter the water column by desorption, depending on the physico-chemical properties of the soil and water in a constructed wetland. Therefore, TP load reductions could be variable within the runoff process.

Accordingly, it can be hypothesised that the hydraulic and hydrodynamic processes occurring in the wetland influence the treatment by the mixing of the water retained in the wetland with incoming storm water runoff. Additionally, the relatively higher variability of pollutant load reductions at the initial sectors of the runoff hydrograph (particularly for TSS and TN), caused by inflow mixing with the stored water, means that controlling and stabilising the inflow prior to it entering the constructed wetland would be a feasible approach to improve treatment performance. This is due to the fact that lower variability in inflow characteristics commonly leads to an improvement in storm water treatment.

4.6 Relationships Between Hydrologic/Hydraulic Factors and Treatment Performance

The treatment performance of the constructed wetland indicates different pollutant load reduction characteristics in different sectors of the inflow runoff hydrograph. In this context, it was important to further investigate how the treatment performance varies with hydrologic and hydraulic factors. This investigation was conducted using PROMETHEE and GAIA analysis due to its ability to identify relationships between criteria and actions (Liu et al. 2015). For details regarding the PROMETHEE method, refer to Sect. 3.2 in Chap. 3. The criteria used for this analysis were TSS, TN and TP load reduction values, and OP, OQ, AD and RT for

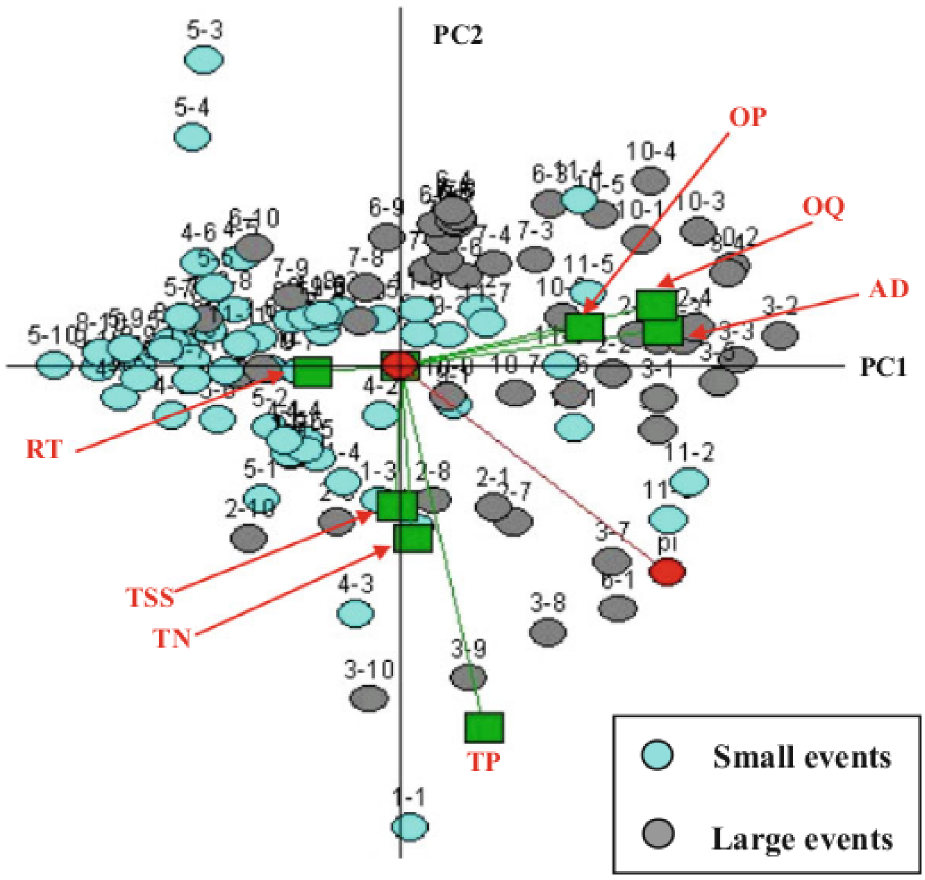

Fig. 4.4 GAIA biplots for constructed wetland analysis (Δ = 75.36 %)

each sector of the runoff hydrograph, while the actions were the ten sectors of the runoff hydrograph for the eleven rainfall events. Accordingly, a matrix (110 × 7) was submitted to PROMETHEE analysis to form the GAIA biplot for all rainfall events. The resulting GAIA biplot is given in Fig. 4.4.

In terms of Fig. 4.4, all the actions generally form two clusters primarily influenced by the rainfall depth. Most of the rainfall events clustering on the positive PC1 axis are relatively larger rainfall events, where their rainfall depths are larger than 15 mm, such as Event 3 and Event 10 (W3 and W10 in Table 4.1). Additionally, OP, OQ and AD vectors are also projected on the positive PC1 axis. However, most of the rainfall events positioning on the negative PC1 axis are relatively small events such as Event 4 and Event 5, and their rainfall depths are less than 15 mm (W4 and W5 in Table 4.1). Furthermore, these small rainfall events are closely related to RT. This means that larger rainfall events lead to higher outflow peak, outflow discharge and water depth in the wetland, thereby suggesting greater displacement of the water stored in the wetland and higher outflow velocities, while longer retention time tends to occur during small rainfall events.

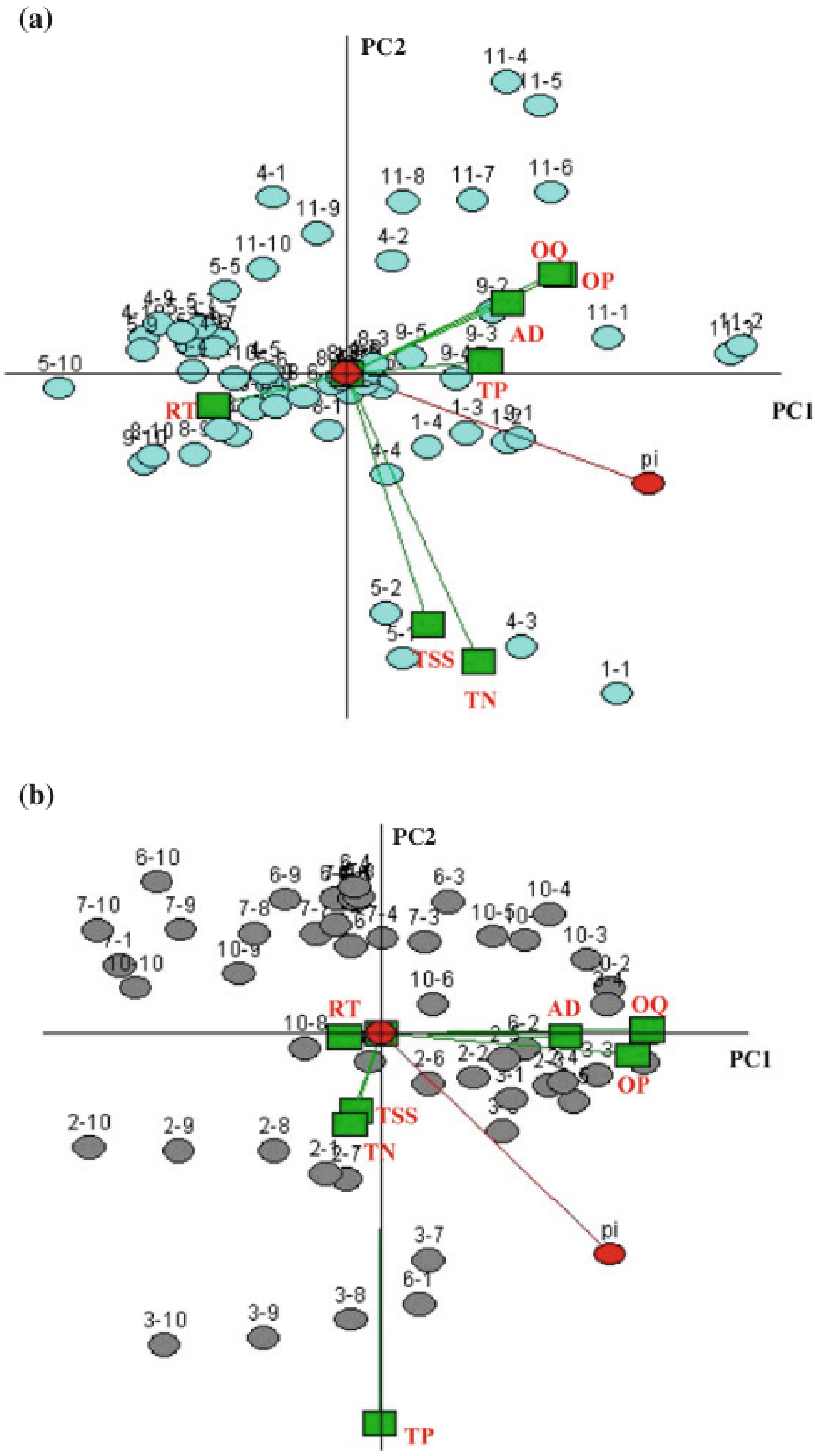

Fig. 4.5 GAIA biplots for small and large events analysis **a** GAIA biplot for small event data (Δ = 66.69 %) **b** GAIA biplot for large event data (Δ = 86.64 %)

As evident in Fig. 4.4, the actions scattered in the direction of TSS, TN and TP load reduction vectors primarily belong to the initial sectors of the runoff hydrographs for small rainfall events such as load reductions in the first 10 % of the runoff hydrograph in Event 1 (1-1) and load reductions in the third 10 % of the runoff hydrograph in Event 4 (4-3) and the end sectors of large rainfall events such as load reductions in the ninth and tenth 10 % of the runoff hydrograph in Event 3 (3-9 and 3-10). This is an indication of different treatment characteristics for large and small events, which require separate analysis to understand. For this purpose, two matrices for small (<15 mm, matrix 60 × 7) and large (>15 mm, matrix 50 × 7) rainfall events as identified above were created and the resulting GAIA biplots are given in Fig. 4.5a, b. According to Fig. 4.5a (small rainfall events), it is evident that actions located close to pollutant load reduction vectors are primarily the initial sectors of the runoff hydrograph (such as load reductions in the first and second 10 % of the runoff hydrograph in Event 5 (5-1 and 5-2). In terms of Fig. 4.5b (large rainfall events), actions located close to pollutant load reduction vectors are primarily the later sectors of the runoff hydrograph such as load reductions in the seventh, eighth, ninth and tenth 10 % of the runoff hydrograph in Event 2 (2-7, 2-8, 2-9 and 2-10).

These results can be also supported by the original data. Figure 4.6 shows the mean values of pollutant load reductions in each sector of the runoff hydrograph for small and large events. As evident in Fig. 4.6, in the initial sectors of the runoff hydrograph, small rainfall events generally have relatively higher pollutant load reductions compared to large rainfall events, while the opposite holds true for the later sectors of the runoff hydrograph.

These outcomes suggest that the treatment performance of a constructed wetland for small rainfall events and large rainfall events differs. In the case of small rainfall events, the relatively cleaner, treated storm water, which was already stored in wetland cells, flows out in the early stage of a runoff event. Later runoff from small rainfall events would mix with water already stored in the wetland, leading to the gradual increase in pollutant concentrations in the outflow. However, for large rainfall events, the trends in pollutant load reductions are generally lower at the beginning and gradually increase towards the end of a rainfall event. This is attributed to the rapid mixing of inflow runoff with the stored water in the wetland at the beginning, which typically carries high loads of pollutants termed as first flush (Li et al. 2007, 2010). However, with gradual decrease in velocity and the supply of particulate pollutants, treatment performance increases during the latter part of runoff events. This is attributed to the increased settling of particulate pollutants in the wetland cells. These analysis outcomes highlight the importance of ensuring that the inflow into a constructed wetland is not turbulent in order to achieve consistent treatment performance for both small and large rainfall events.

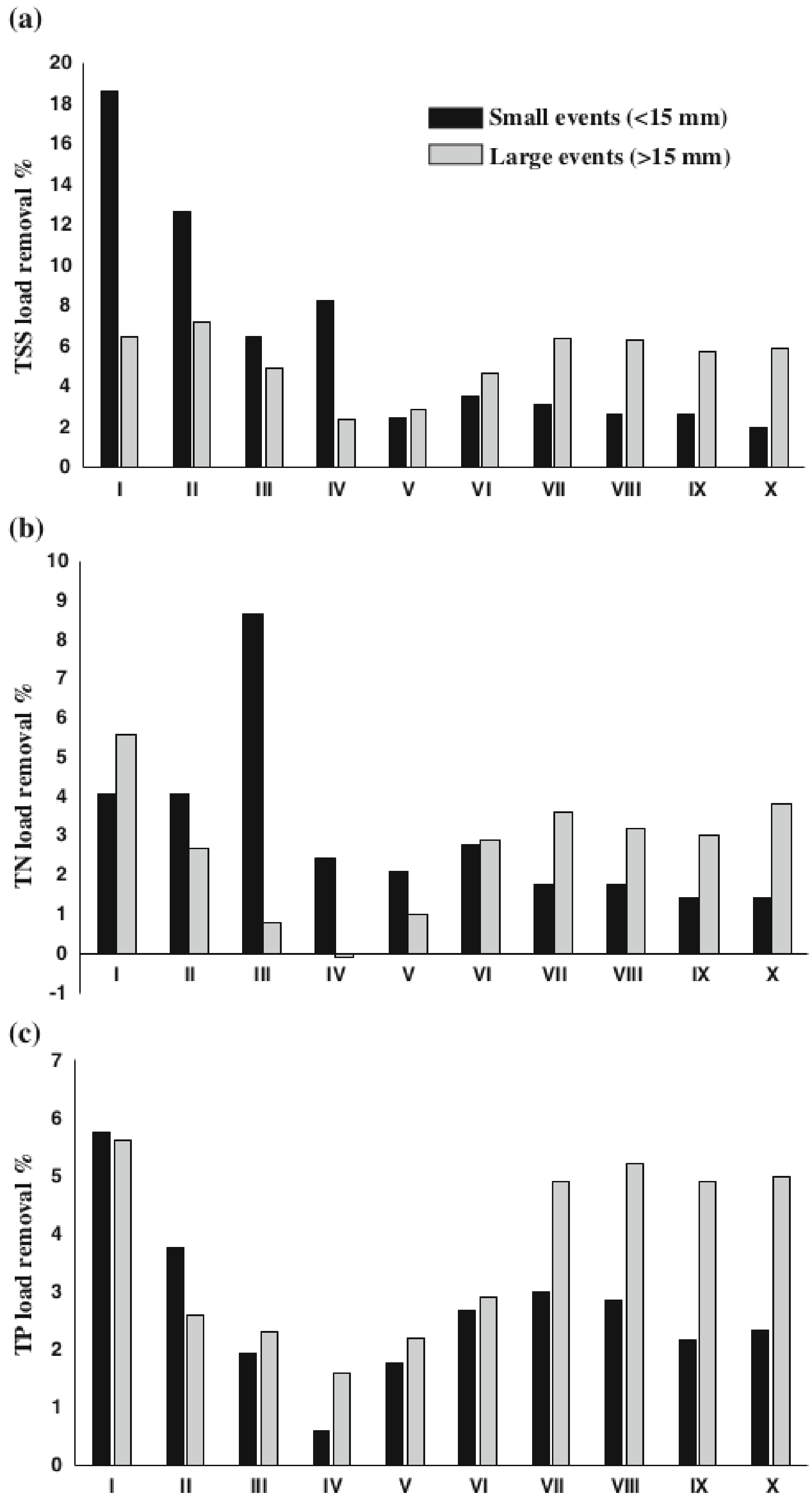

Fig. 4.6 Comparison of pollutant load reductions for small and large rainfall events **a** TSS **b** TN **c** TP

4.7 Conclusions

This chapter discussed the treatment performance of a constructed wetland and its relationship with hydrologic/hydraulic factors. It is noted that large and small rainfall events are differently treated in a constructed wetland. The pollutant load reductions for the initial sector of runoff from large rainfall events are relatively low, due to the rapid mixing. This means that it is critical to control the inflow to reduce turbulence before runoff enters a constructed wetland, particularly for the large events. Accordingly, it may be necessary to establish an inlet pond prior to the flow entering the constructed wetland so that the inflow will initially stabilise. This is further supported by the occurrence of the first flush phenomenon where the initial sector of runoff generally carries higher pollutant loads. Therefore, enhancing the treatment of the initial sector of runoff could significantly contribute to the improvement of the overall treatment efficiency of a wetland. Additionally, the provision of a bypass system is recommended to control the runoff to the constructed wetland. This will protect the constructed wetland from erosion damage resulting from high runoff rates.

References

Abdi H (2003) Factor rotations. SAGE, Thousand Oaks

Alias N, Liu A, Egodawatta P, Goonetilleke A (2014a) Sectional analysis of the pollutant wash-off process based on runoff hydrograph. J Environ Manage 134:63–69

Alias N, Liu A, Goonetilleke A, Egodawatta P (2014b) Time as the critical factor in the investigation of the relationship between pollutant wash-off and rainfall characteristics. Ecol Eng 64:301–305

Egodawatta P, Goonetilleke A, Ayoko GA, Thomas EC (2006) Understanding the interrelationships between stormwater quality and rainfall and runoff factors in residential catchments. In: 7th international conference on urban drainage modelling and the 4th international conference on water sensitive urban design, Melbourne, Australia

Goonetilleke A, Thomas E, Ginn S, Gilbert D (2005) Understanding the role of land use in urban stormwater quality management. J Environ Manage 74:31–42

Lai DYF, Lam KC (2009) Phosphorus sorption by sediments in a subtropical constructed wetland receiving stormwater runoff. Ecol Eng 35(5):735–743

Li LQ, Yin CQ, He QC, Kong LL (2007) First flush of storm runoff pollution from an urban catchment in China. J Environ Sci 19:295–299

Liu WC, Huang WZ, Yang AY (2010) Characterization of suspended solids and heavy metal distributions during first flush in highway runoff. J Environ Sci Eng 4(9):44–50

Liu A, Goonetilleke A, Egodawatta P (2012) Taxonomy for rainfall events based on pollutant wash-off potential in urban areas. Ecol Eng 47:110–114

Liu A, Egodawatta P, Goonetilleke A (2015) Role of rainfall and catchment characteristics on urban stormwater quality. Springer

Mangangka IR, Liu A, Egodawatta P, Goonetilleke A (2014) Sectional analysis of stormwater treatment performance of a constructed wetland. Ecol Eng 77:172–179

Chapter 5
Implications for Engineering Practice

Abstract This chapter provides a consolidated summary of outcomes from the research study undertaken on the influence of hydrologic and hydraulic factors on bioretention basin and constructed wetland treatment performance, using the two conceptual models developed. The knowledge created is expected to provide practical guidance and recommendations for storm water treatment designers and hydrologic/hydraulic model developers. This chapter also briefly discusses key areas where currently there are significant knowledge gaps and areas for further investigation. These include, investigating other typical storm water treatment systems and pollutant behaviour in addition to what has been investigated in the research study. Additionally, the use of laboratory scale models to investigate the relationship between hydraulic factors and water quality treatment is recommended in order to validate the outcomes obtained by using the conceptual models.

Keywords Bioretention basins · Constructed wetlands · Treatment performance · Hydrologic and hydraulic factors · Conceptual models · Storm water quality

5.1 Background

Urbanisation transforms natural land cover into impervious surfaces such as roads, roofs and parking lots. The high fraction of impervious surfaces leads to an increase in runoff volume and peak flows. Furthermore, anthropogenic activities common to urban areas generate a range of pollutants, such as nutrients, solids and organic matter. These pollutants accumulate on catchment surfaces and are washed off during storm events, leading to adverse ecological impacts on the receiving water environment. Consequently, urban storm water runoff is of significant environmental concern.

Due to an increasing understanding of the detrimental impacts of urban storm water pollution on aquatic ecosystems, the implementation of storm water treatment strategies is becoming common. In this context, constructed wetlands and bioretention basins are commonly used storm water treatment systems. These two types

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of systems are typically designed and installed based purely on stereotypical guidelines. This is due to reasons such as the lack of fundamental knowledge on performance characteristics of these systems and the variation in treatment performance due to hydrologic and hydraulic factors. This, in turn, has led to ineffective treatment performance resulting in resources wastage and increasing vulnerability of urban water environments.

This book identifies the key hydrologic and hydraulic factors that influence the performance of constructed wetlands and bioretention basins. The knowledge gained primarily explains the behaviour of bioretention basins and constructed wetlands in terms of hydraulic characteristics during rainfall events. The relationships derived, incorporating this knowledge with the treatment performance, enable the understanding of the characteristics of treatment processes within these systems during runoff events. The study outcomes provide practical guidance and recommendations for effective storm water treatment design.

5.2 Application to Engineering Practice

5.2.1 Bioretention Basins

Bioretention basins remove pollutants primarily by filtration. According to research outcomes, an antecedent dry period is the factor which mostly influences their treatment performance, compared to other hydrologic and hydraulic factors. This is because a long antecedent dry period will result in relatively low moisture content in the filter media, which can enhance the runoff retention capacity and consequently, improve treatment performance. The mean EMC reduction percentages of TSS, TN and TP for rainfall events occurring after a relatively longer dry period (>6 days) are 38.65, −43.01 and 26.23 % individually, while the corresponding values are 23.26, −25.49 and −31.15 % for rainfall events after a relatively shorter dry period (<6 days). These outcomes generally demonstrate higher EMC reduction percentages for longer dry days than the corresponding values for rainfall events after a relatively shorter dry period except for TN EMC reduction percentages. This confirms the important role played by the antecedent dry period. In this context, selecting appropriate vegetation, particularly vegetation with a high evapotranspiration capacity, would be the preferred option for enhancing the treatment efficiency of a bioretention basin.

Other than the differences in treatment performance for long and short dry periods, treatment performance in relation to nitrogen species particularly shows significant sensitivity towards antecedent dry days. A longer dry period and the resulting higher volume retention capacity increases NO_2^- and NH_4^+ removal, but decreases NO_3^- removal. This is attributed to the fact that a longer antecedent dry period allows NH_4^+ and NO_2^- oxidation, thus reducing their concentrations, and increasing NO_3^- concentration. This outcome implies that nitrification occurs in the bioretention basin during the dry period.

The research results also show negative values for pollutant reduction percentages, particularly nitrogen and phosphorus, as discussed above. This suggests the occurrence of nutrient leaching within a bioretention basin. Nutrient leaching can be attributed to the flushing of runoff retained in the filter media from the preceding rainfall events, which could have contained elevated concentrations. Furthermore, nutrients present in the bioretention filter media itself could also contribute to pollutant leaching. This means that the increase in pollutant retention in the filter media in the long term can potentially cause pollutant export. This highlights the importance of regular maintenance, particularly timely replacement of filter media in order to reduce nutrient accumulation. Additionally, it is also important to select appropriate filter media to enhance nutrient sorption.

5.2.2 *Constructed Wetlands*

As a water body, constructed wetlands regularly receive inflows, which mix with the water originally retained. This could result in differences in treatment performance at different time periods (sectors) of a runoff event. In this context, the treatment performance of constructed wetlands was investigated by partitioning the inflow runoff hydrograph and then analysing the treatment performance of each segment.

The research outcomes show that the treatment behaviour of the constructed wetland is different for the early and later sectors of the inflow runoff hydrograph, which implies that the treatment characteristics vary along with the runoff flow process. Additionally, this variability is strongly related to pollutant species and rainfall characteristics. In terms of rainfall characteristics, the pollutant load reductions for the initial sector of the runoff hydrograph from larger rainfall events (rainfall depth >15 mm) are relatively low due to the rapid mixing, while small rainfall events (rainfall depth <15 mm) generally result in relatively higher pollutant load reductions for the initial runoff volume.

In terms of removal of different pollutant species in constructed wetlands, TSS and TN removal is highly variable, with hydrologic and hydraulic characteristics in the initial sectors of the runoff hydrograph. TP load reduction is relatively unchanged through the runoff flow process. The relatively higher variability of TSS and TN load reductions in the initial sectors of the inflow runoff hydrograph is attributed to the mixing of incoming runoff with the stored water in the constructed wetland. Commonly, the relatively larger rainfall events would lead to stronger disturbance when the runoff enters the wetland, while small runoff events would result in a relatively weaker mixing with the stored water. In the case of TP, it could be attributed to the occurrence of both removal and release processes during the retention time. While phosphorus can be removed by adsorption, it can also re-enter the water column by desorption depending on the physico-chemical properties of soil and water in a constructed wetland.

In summary, due to the relatively high variability in pollutant removal in the initial sector of the runoff volume, it is important to establish an inlet pond prior to the flow entering the constructed wetland, so that the inflow will initially stabilise. This is further supported by the occurrence of the first flush phenomenon, where the initial sector of runoff generally carries higher pollutant loads. Therefore, enhancing the treatment of the initial sector of runoff could significantly contribute to the improvement in the overall treatment efficiency of a wetland. Additionally, the provision of a bypass system is recommended to control the runoff to the constructed wetland. This will protect the system from erosion damage resulting from high runoff rates.

5.3 Knowledge Gaps for Future Research

This monograph presents the outcomes of a research study undertaken and the knowledge created relating to the treatment performance of two typical storm water treatment systems, namely, bioretention basins and constructed wetlands. By using conceptual models, it was found that a range of hydrologic and hydraulic factors play a critical role in influencing their pollutant removal efficiencies. However, as urban storm water runoff quality is complex in terms of various pollutant sources, species and concentrations, a diversity of treatment systems is commonly required rather than a sole dependency on bioretention basins and constructed wetlands. Additionally, although conceptual models can generate hydrologic/hydraulic factors, models are typically approximations of reality and hence only capable of replicating reality to the extent where scientific knowledge prevails. These facts highlight the need to extend the current knowledge in a number of areas, as discussed below.

5.3.1 Investigation of the Removal of Other Common Storm Water Pollutants

The degree of deterioration of storm water quality in urban areas is dependent on the pollutant species and load. Other than suspended solids and nutrients, urban storm water commonly includes a wide range of pollutants, such as heavy metals, hydrocarbons and micropollutants. As these pollutants can be toxic, their effective removal from storm water runoff is important. Due to the different characteristics of these pollutants, their removal mechanisms could be different within a treatment system. Consequently, these pollutants could be influenced differently by hydrologic/hydraulic factors. For example, heavy metals are found to exist in storm water runoff by adsorption with solids (Gunawardana et al. 2014). Therefore, their removal is more dependent on the adsorption mechanisms. This would involve the investigation on the influence of hydrologic/hydraulic factors on adsorption/desorption capacity of media used in treatment systems. Additionally, hydrocarbon removal primarily relies on biodegradation (Haritash and Kaushik 2009). Therefore, the understanding of the relationship between hydrologic/hydraulic factors and biodegradation within the treatment systems is also required. In this context, relating different removal mechanisms (such as adsorption and biodegradation) to hydrologic/hydraulic factors needs to be focused on, in future research. This will help in more specific treatment design, which targets particular pollutant types.

5.3.2 Investigating Other Typical Storm Water Treatment Systems

There are a range of storm water treatment systems in urban areas, as discussed in Chap. 1. These treatment systems differ in terms of their design, pollutant removal mechanisms and ability. In this context, the influence of hydrologic and hydraulic factors on their treatment performance might differ among these treatment systems. For example, a grass swale is commonly located along roads as a primary treatment process. The runoff velocity over the swale could play an important role in treatment performance. A high rainfall intensity resulting in high runoff velocity could reduce the pollutant removal efficiency since the retention time is reduced. In the case of a sedimentation basin, stabilising the inflow and not disturbing the water already retained is important since the system removes pollutants by sedimentation. This means that hydraulic factors such as inflow stability would exert an essential influence on treatment performance of a sedimentation basin. These facts underline the need to analyse relationships between other typical storm water treatment systems and hydrologic/hydraulic factors.

5.3.3 Laboratory Scale Models to Investigate Relationship Between Hydraulic Factors and Water Quality Treatment Performance

The research study was undertaken to investigate the performance of storm water treatment systems using a model based on fundamental theory, conceptual approaches and multivariate analysis. The conceptual models developed included a range of mathematical equations and are an approximation of reality. In this regard, it is recommended that detailed investigations should be undertaken using laboratory scale models to further investigate the relationships between hydraulic factors and water quality treatment processes in order to validate the outcomes obtained from this research study. This will provide data from both mathematical models and laboratory scale models and hence further confirm the conclusions derived, regarding the influence of hydraulic factors on the performance of storm water treatment systems.

References

Gunawardana C, Egodawatta P, Goonetilleke A (2014) Role of particle size and composition in metal adsorption by solids deposited on urban road surfaces. Environ Pollut 184:44–53

Haritash AK, Kaushik CP (2009) Biodegradation aspects of Polycyclic Aromatic Hydrocarbons (PAHs): a review. J Hazard Mater 169:1–15

Appendix A
Generating Wetland Volume Versus Depth Correlation Model

CurveExpert software Version 1.40 was used to derive the regression formulae for each wetland component. Volume versus depth relationship for all wetland components were developed using the Morgan-Mercer-Flodin (MMF) regression model. The model is widely known as a non-linear growth model. This model was selected primarily due to its best-fit. The MMF regression model is expressed by the following equation:

$$y = \frac{ab + cx^d}{b + x^d}$$

where:
y—Water depth (m)
x—Water volume (m^3)
a, b and c—Model coefficients.

The MMF regression models for all wetland components provided satisfactory accuracy with high coefficients of determination (R^2) and low standard error (S). The curves developed are shown in Fig. A.1, while the model coefficients, R^2 and S values, are presented in Table A.1.

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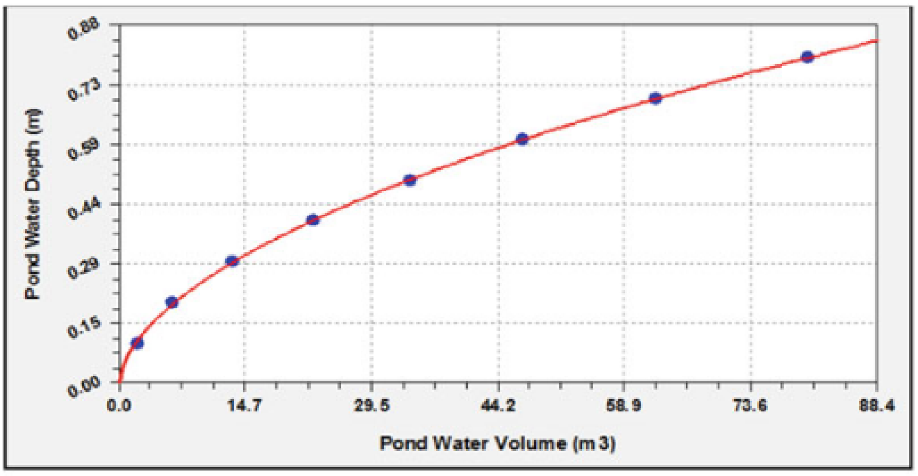
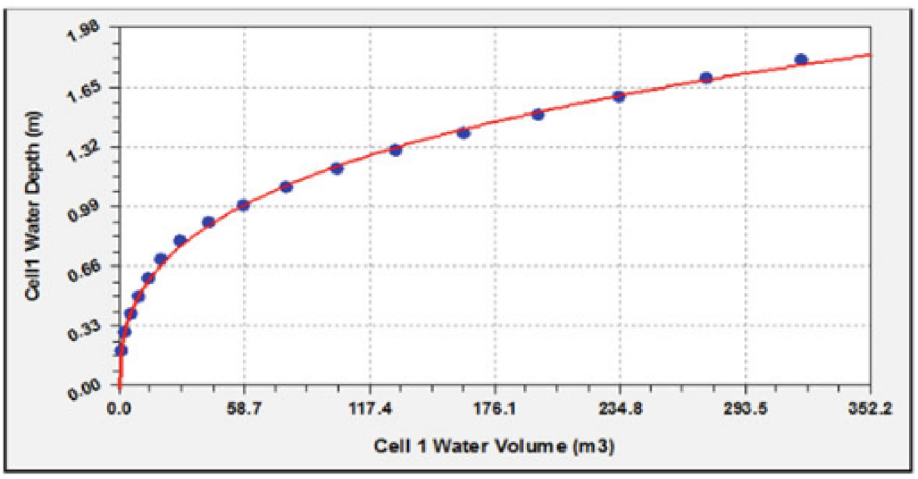
(a)



(b)



(c)

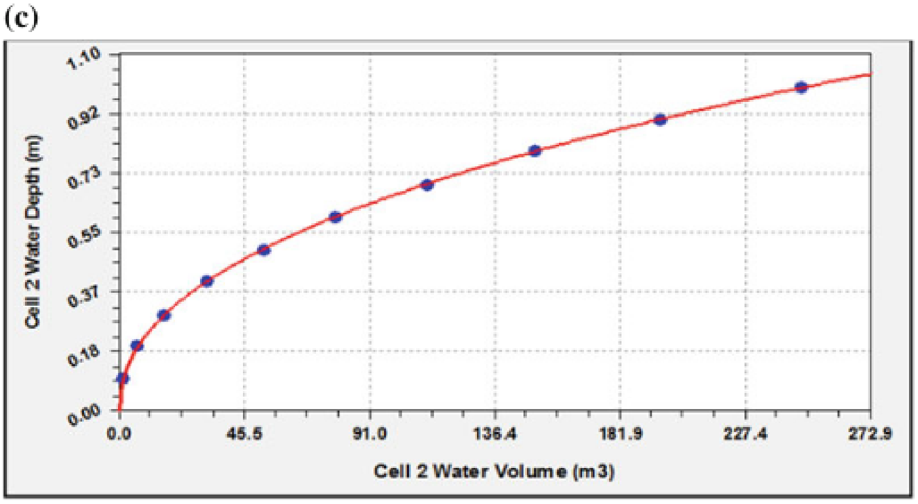


Fig. A.1 Volume versus depth curves for **a** Pond, **b** Cell 1, and **c** Cell 2

Table A.1 Model coefficient, R^2 and S values for the predicted model

Wetland component	Model coefficient	Coefficient of determination (R^2)	Standard error (S)
Pond	$a = -8.55055 \times 10^{-4}$ $b = 222.310$ $c = 15.7368$ $d = 0.565020$	0.999901	0.00345
Cell 1	$a = -1.59261 \times 10^{-2}$ $b = 38.8680$ $c = 8.91392$ $d = 0.394738$	0.999146	0.01801
Cell 2	$a = 3.35185 \times 10^{-3}$ $b = 386.642$ $c = 32.2859$ $d = 0.454851$	0.999945	0.00294

Appendix B
Data Analysis Techniques

PROMETHEE and GAIA

PROMETHEE (Preference Ranking Organisation METHod for Enrichment Evaluations) aided by the GAIA (Graphical Analysis for Interactive Aid) method is widely used in various environmental research studies to evaluate different alternatives against a set of criteria (for example Liu et al. 2013; Mangangka et al. 2015). PROMETHEE is a non-parametric method used to rank the actions on the basis of a set of pre-determined criteria while GAIA is a principal component analysis biplot that provides visual complement to the PROMETHEE ranking.

In PROMETHEE, the ranking order for actions is developed according to the net outranking flow, the φ values, for a number of available actions on the basis of a range of criteria. To calculate the φ values, each criterion must be provided with three conditions: a preference function, a preference order (maximise/minimise) and a weighting. In the GAIA biplot, an acute angle between two vectors indicates positive correlation and the smaller the acute angle, the stronger the correlation. On the other hand, an obtuse angle suggests that the vectors are inversely correlated, while a right angle indicates that they are not correlated (Espinasse et al. 1997). The following steps show how to calculate the φ values between two actions 'a' and 'b' (Keller et al. 1991):

- **Step 1**: Creation of a difference matrix (d_j) between 'a' and 'b' from the raw data matrix:

$$d_j = y_j(a) - y_j(b)$$

  where y_j (a) and y_j (b) are the data points of actions 'a' and 'b' for criteria y_j.
- **Step 2**: Definition of the preference for 'a' over 'b':
  A preference function P (a, b) is used to define the preference for 'a' over 'b' for each criterion. The following preference functions (Table B.1) are available for the user to select, depending on the criterion:

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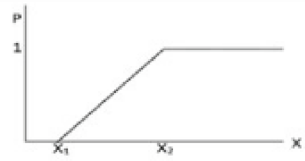
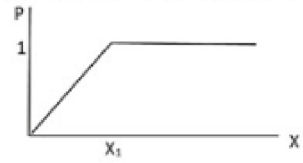
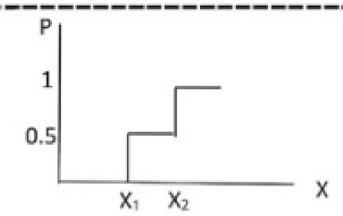
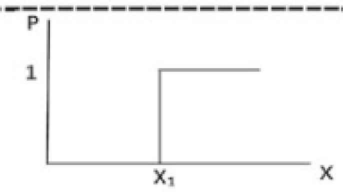
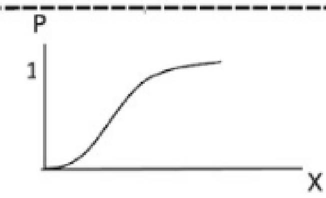
Table B.1 Preference functions

Preference function	Shape of the graph	Mathematical expression
Linear		$y_{(x)} = \left\{\begin{array}{cc} 0 & x < x_1 \\ mx + c & x_1 < x < x_2 \\ 1 & x > x_2 \end{array}\right\}$
V-shape		$y_{(x)} = \left\{\begin{array}{cc} mx & x < x_1 \\ 1 & x > x_1 \end{array}\right\}$
Level		$y_{(x)} = \left\{\begin{array}{cc} 0 & x < x_1 \\ 0.5 & x_1 \leq x < x_2 \\ 1 & x \geq x_2 \end{array}\right\}$
U-shape		$y_{(x)} = \left\{\begin{array}{c} 0\ x < x_1 \\ 1\ x \geq x_1 \end{array}\right\}$
Usual		$y_{(x)} = \left\{\begin{array}{c} 0\ x < 0 \\ 1\ x \geq 0 \end{array}\right\}$
Gaussian		$y_{(x)} = \dfrac{e^x}{1 + e^x}$

[a]Legends used in the preference graph: P (preference); X (difference); x_1 (indifference threshold); x_2 (preference threshold)

- **Step 3**: Calculation of global preference index, π:

$$\pi(a, b) = \sum_{j=1}^{k} W_j \times P_j(a, b)$$

where W_j is the weight, which is set to 1 by default. However, it can be changed subjectively in case one criterion needs to be emphasised in the selection of actions.

- **Step 4**: Calculation of outranking flows:

$$\text{Positive outranking flow } \varphi^+(a) = \frac{1}{(n-1)} \sum_{x \in A} \pi(a, x)$$

$$\text{Negative outranking flow } \varphi^-(a) = \frac{1}{(n-1)} \sum_{x \in A} \pi(x, a)$$

Positive outranking flow corresponds to how much action 'a' is preferred over other actions, while negative outranking flow shows how much other actions are preferred relative to 'a'.

- **Step 5**: Production of partial ranking (Table B.2)
- **Step 6**: Production of complete ranking:
Complete ranking is produced based on the net outranking flow, $\varphi(a)$, calculated from the following equation:

$$\varphi(a) = \varphi^+(a) - \varphi^-(a)$$

Complete ranking eliminates the constraint in comparing 'a' and 'b', even if they are directly not comparable (Case 3 in Step 5). However, the compromise may also reduce the reliability of the outcome. In addition, the φ values can be used to understand how far two actions are discriminated in PROMETHEE ranking. In the case where the difference between the φ values of two actions is over 10 % of the whole range, which is the difference between the maximum and the

Table B.2 Partial ranking rules

Case	Conditions	Results
Case 1	If $\varphi^+(a) > \varphi^+(b)$ and $\varphi^-(a) < \varphi^-(b)$ or $\varphi^+(a) > \varphi^+(b)$ and $\varphi^-(a) = \varphi^-(b)$ or $\varphi^+(a) = \varphi^+(b)$ and $\varphi^-(a) < \varphi^-(b)$	'a' is preferred over 'b'
Case 2	If $\varphi^+(a) = \varphi^+(b)$ and $\varphi^-(a) = \varphi^-(b)$	'a' and 'b' are equally preferred
Case 3	In all other cases	'a' and 'b' are not comparable

minimum values in the data matrix for that particular criterion, they may be considered well-discriminated (Ni et al. 2009). This is because an error over 10 % in the measurement is generally not acceptable.

Pearson Correlation

The Pearson correlation is a parametric measure and produces a sample correlation coefficient, which measures the strength and direction of linear relationships between pairs of continuous variables. The sample correlation coefficient between two variables 'x' and 'y' is denoted by 'r' and can be calculated using the following equation:

$$r = \frac{cov(x, y)}{\sqrt{var(x)} \cdot \sqrt{var(y)}}$$

where:
r—correlation coefficient
cov(x, y)—sample covariance of x and y
var(x)—sample variance of x
var(y)—sample variance of y.

Correlation can take on any value in the range [−1, 1]. The negative or positive of the correlation coefficient indicates the direction of the relationship, while the magnitude of the correlation (how close it is to −1 or +1), indicates the strength of the relationship.

- −1: perfectly negative linear relationship
- 0: no relationship
- 1: perfectly positive linear relationship

The strength can be assessed as follows (Cohen 1988):

- $0.1<|r|<0.3$: weak correlation
- $0.3<|r|<0.5$: moderate correlation
- $0.5<|r|$: strong correlation

Principal Component Analysis (PCA)

Principal Component Analysis (PCA) is performed on transformed data by reducing a set of raw data to a number of principal components (PCs). PC1 describes the largest data variance and PC2 the next largest data variance and so on. There are as many PCs as the number of variables, but most of the variance is accounted for in the first few PCs (Adams 1995). Each object is identified by a score, and each variable by a loading value or weighting. The data displayed may be obtained by plotting (i) PCi versus PCj scores (scores plot, i, j = PC number), (ii) loadings for a given PC (loadings plot) and (iii) scores and loading vectors on the one plot (biplot). The various display plots indicate relationships between objects, the significance of variables on each PC, and correlations between objects and variables. This analytical method can provide useful guidance regarding the relationships between objects and variables in a data matrix.

In the PCA biplot, the variables are considered as correlated when the angles between the vectors are small. An obtuse angle indicates a weak correlation. An angle of 90° is considered as uncorrelated parameters and 180° as inversely correlated. Objects with similar characteristics make clusters and are strongly correlated to the variables when their vectors point in the same direction as the variables.

Factor Analysis

Factor analysis is a statistical method used to describe the variability among observed, correlated variables in terms of a potentially lower number of unobserved variables called factors. In factor analysis, the factors can be rotated to new axes that better separate the data. The number of factors is less than or equal to the number of original variables. The total number of factors was ten in the case of the research study, since there are ten 10 % sectors of runoff volume for each rainfall event. However, most of the variance is in the first few factors. The number of significant factors may be selected by referring to the variation of the eigenvalues in descending order with corresponding factors (Kim and Mueller 1978). In the research study, the number of factors was selected based on the initial eigenvalue criteria ≥1 (namely the first two factors, Factor 1 and Factor 2) since it corresponds to 96.594 % of the total variance being explained, which includes almost all of the information in the original dataset (see Table B.3). Therefore, only Factor 1 and Factor 2 were selected in the study as shown in Table 4.2 of Chap. 4.

Table B.3 Eigenvalues for factor analysis in the research study

Factor	Eigenvalue	Cumulative percentage of the total variance explained %
Factor 1	**8.598**	**85.98**
Factor 2	**1.061**	**96.594**
Factor 3	0.253	99.124
Factor 4	0.065	99.776
Factor 5	0.013	99.902
Factor 6	0.007	99.97
Factor 7	0.002	99.992
Factor 8	0	99.996
Factor 9	0	99.999
Factor 10	0	100

References

Cohen J (1988) Statistical power analysis for the behavioral sciences 2nd edn. Lawrence Erlbaum Associates, Hillsdale, NJ

Espinasse B, Picolet G, Chouraqui E (1997) Negotiation support systems: a multi-criteria and multi-agent approach. Eur J Oper Res 103:389–409

Keller HR, Massart DL, Brans JP (1991) Multicriteria decision making: a case study. Chemometr Intell Lab Syst 11:175–189

Kim JO, Mueller CW (1978) Factor analysis: statistical methods and practical issues. SAGE Publications Inc., Newbury Park, California, USA

Liu A, Egodawatta P, Guan YT, Goonetilleke A (2013) Influence of rainfall and catchment characteristics on urban stormwater quality. Sci Total Environ 444:255–262

Mangangka IR, Liu A, Egodawatta P, Goonetilleke A (2015) Sectional analysis of stormwater treatment performance of a constructed wetland. Ecol Eng 77:172–179

Ni Y, Lai Y, Brandes S, Kokot S (2009) Multi-wavelength HPLC fingerprints from complex substances: an exploratory chemometrics study of the Cassia seed example. Anal Chim Acta 647:149–158

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