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Role of Rainfall and Catchment Characteristics on Urban Stormwater Quality

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Contents

Abstract

Urbanisation significantly changes the characteristics of a catchment as natural areas are transformed to impervious surfaces such as roads, roofs and parking lots. The increased fraction of impervious surfaces leads to changes to the stormwater runoff characteristics, whilst a variety of 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 removed and transported by stormwater runoff and thereby contribute pollutant loads to receiving waters. In summary, urbanisation influences the stormwater characteristics of a catchment, including hydrology and water quality.

Due to the growing recognition that stormwater pollution is a significant environmental problem, the implementation of mitigation strategies to improve the quality of stormwater runoff is becoming increasingly common in urban areas. A scientifically robust stormwater quality treatment strategy is an essential requirement for effective urban stormwater management. The efficient design of treatment systems is closely dependent on the state of knowledge in relation to the primary factors influencing stormwater quality. In this regard, stormwater modelling outcomes provide designers with important guidance and datasets which significantly underpin the design of effective stormwater treatment systems. Therefore, the accuracy of modelling approaches and the reliability modelling outcomes are of particular concern.

This book discusses the inherent complexity and key characteristics in the areas of urban hydrology and stormwater quality, based on the influence exerted by a range of rainfall and catchment characteristics. A comprehensive field sampling and testing programme in relation to pollutant build-up, an urban catchment monitoring programme in relation to stormwater quality and the outcomes from advanced statistical analyses provided the platform for the knowledge creation.

Two case studies and two real-world applications are discussed to illustrate the translation of the knowledge created to practical use in relation to the role of rainfall and catchment characteristics on urban stormwater quality. An innovative rainfall classification based on stormwater quality was developed to support the effective and scientifically robust design of stormwater treatment systems. Underpinned by the rainfall classification methodology, a reliable approach for design rainfall selection is proposed in order to optimise stormwater treatment based on both, stormwater quality and quantity. This is a paradigm shift from the common approach where stormwater treatment systems are designed based solely on stormwater quantity data.

Additionally, how pollutant build-up and stormwater runoff quality vary with a range of catchment characteristics was also investigated. Based on the study outcomes, it can be concluded that the use of only a limited number of catchment parameters such as land use and impervious surface percentage, as it is the case in current modelling approaches, could result in appreciable error in water quality estimation. Influential factors which should be incorporated into modelling in relation to catchment characteristics, should also include urban form and impervious surface area distribution.

The knowledge created through the research investigations discussed in this monograph is expected to make a significant contribution to engineering practice such as hydrologic and stormwater quality modelling, stormwater treatment design and urban planning, as the study outcomes provide practical approaches and recommendations for urban stormwater quality enhancement. Furthermore, this monograph also demonstrates how fundamental knowledge of stormwater quality processes can be translated to provide guidance on engineering practice, the comprehensive application of multivariate data analyses techniques and a paradigm on integrative use of computer models and mathematical models to derive practical outcomes.

Chapter 1
Urbanisation and Stormwater Quality

Abstract Catchment urbanisation exerts significant impacts on water environments in the context of hydrology and water quality. The hydrologic changes due to urbanisation and the consequent increase in the impervious surface fraction include higher runoff volume and peak flow and reduced time to peak. The water quality changes are due to anthropogenic activities common to urban areas which generate a range of pollutants. These pollutants are transported to receiving waters during rainfall events, degrading the water environment. This Chapter provides a detailed discussion on common stormwater pollutants and their sources and highlights the fact that the involvement of these sources and resulting water quality is primarily influenced by catchment and rainfall characteristics. Catchment characteristics define the availability and mix of sources, whilst rainfall characteristics define the detachment and transport of pollutants.

Keywords Catchment urbanisation · Pollutant sources · Stormwater pollutants · Stormwater quality · Stormwater pollutant processes

1.1 Urbanisation

The movement of population to urban centres is a common phenomenon throughout the world. This can be attributed to a range of factors, such as better health care and educational facilities, greater employment opportunities and more advanced infrastructure and the relatively higher level of economic development compared to rural areas. Such relocation of population has led to ever-increasing urbanisation. According to the statistics released by the United Nations (2011), around 70 % of the population in Latin America, North America, the Caribbean, Oceania and Europe are living in cities. UN (2006) predicts that by 2030, almost two-thirds of the world's population will be living in urban areas.

Urbanisation exerts a range of critical influences on the living environment. These include the conversion of the natural environment to meet human settlement

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needs, increased vehicle use and the provision of transportation infrastructure to meet mobility needs and changes to people's lifestyle. The natural environment in the form of land cover and land use are changed due to the specific requirements of urban areas. The clearing of natural vegetation and the transformation of natural land cover into urban developments is the most common example. Additionally, the use of motor vehicles significantly increases since most of the urban population tends to live away from their workplaces and the commercial and entertainment areas. For example, according to traffic data in relation to Australia, the average annual traffic volume in the country grew by 3 % during the period of 2003–2008 (ABS 2008). This may have important implications in the context of the degradation of the natural environmental quality, such as air pollution due to vehicle emissions. Furthermore, due to the different characteristics of urban and rural areas, lifestyle also changes. Compared to a rural lifestyle, urban residents tend to consume more resources such as energy and water within the home, to meet landscape needs and for recreational activities. For example, watering of gardens, playing fields and parks are water uses typical to urban areas. In most urban areas of Australia, the biggest energy consumption is for street lighting. These factors have an important influence on the natural environment, such as the water environment.

1.2 Influence of Urbanisation on the Water Environment

Apart from the key influences noted in Sect. 1.1, urbanisation also exerts an important influence on urban water bodies, which are seen as important environmental, aesthetic and recreational resources. Urban hydrologic characteristics are altered by the transformation of land from natural to urban. On the other hand, a significant amount of pollutants are deposited on urban surfaces due to the occurrence of a number of anthropogenic activities common to urban areas such as vehicular traffic, industrial processes and construction and commercial activities, which are eventually transported by stormwater runoff to receiving water bodies. This undermines the quality of urban water bodies. In this context, the overall influence of urbanisation on the urban water environment can be categorised into hydrologic impacts and water quality impacts. A detailed discussion on these impacts is presented below.

1.2.1 Hydrologic Impacts

From a hydrologic perspective, there are two important physical changes to a catchment resulting from urbanisation. The first is the increased percentage of impervious surfaces such as roofs, roads, parking lots and sidewalks. Second is the conversion of the natural drainage system to an artificial conveyance system with the introduction of uniform slopes and pipe and channel systems with relatively reduced

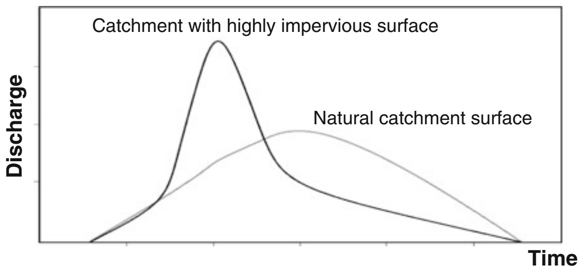

Fig. 1.1 Hydrologic impacts of urbanisation

roughness. These changes in combination lead to an increase in runoff volume and runoff peak and a decrease in the time to peak. Figure 1.1 illustrates the key hydrologic impacts of urbanisation.

1.2.1.1 Runoff Volume

A study undertaken by Barron et al. (2011) found that urbanisation and the consequent drainage system upgrades were responsible for a 30–100 % increase in the predicted runoff volume. Similarly, Chen et al. (2014) noted that because of rapid urbanisation, the mean annual runoff from middle and lower Yangzi River catchments in China increased by 16 and 15 %, respectively, over the period of 1955–2011. The above are some examples of the numerous research studies undertaken in the past on the impacts of urbanisation on stormwater runoff volume.

The increased fraction of impervious surfaces results in low interception of rainfall and reduced depression storage and infiltration losses, leading to the conversion of a high fraction of rainfall to surface runoff. For comparison, AR&R (1997) recommend that for Australian conditions, in the absence of actual data, the initial rainfall loss on a natural land surface should be assumed to be about 15–35 mm, while Boyd et al. (1993) found that common impervious surfaces result in an initial loss of around 5 mm.

The increase in runoff volume due to urbanisation can lead to the erosion of stream banks and bed and road embankments, leading to economic losses. Figure 1.2 provides an example of stream bank erosion resulting from increased runoff volume.

1.2.1.2 Runoff Peak

The urban area characteristics that cause an increase in the runoff volume are also responsible for an increase in the runoff peak. Uniform ground slopes, reduced roughness of surfaces and presence of an improved drainage system result in a relatively more rapid flow of stormwater runoff. This reduces the time of concentration, which refers to the time required for runoff to flow from the most remote part of the catchment to its outlet. This results in an increase in the runoff peak.

Fig. 1.2 Stream bank erosion due to the increased runoff volume

The increase in runoff peak is sensitive to the extent of urbanisation in the case of relatively small catchments (Du et al. 2012). This is due to the fact that in smaller catchments, the impervious area distribution is commonly more centralised, resulting in a shorter runoff travel distance, while the impervious areas in larger catchments tend to be more dispersed, leading to a relatively greater time of concentration.

The increase in peak runoff can enhance flood risk and consequent damage to property and land degradation. Essentially, the fraction of impervious surfaces compared to the total catchment area, spatial distribution of impervious surfaces, nature of the changes to the drainage channel network, catchment area extent and characteristics of the natural area exert influences on the magnitude of the increase in the runoff peak.

1.2.1.3 Time to Peak Flow

The time to peak flow decreases with urbanisation. Firstly, more streamlined drainage pathways introduced by urbanisation decrease the hydrograph duration. This phenomenon is essentially characterised by the “flashy” nature of an urban catchment in relation to stormwater runoff (Goonetilleke et al. 2014). This decrease can be quite significant in the case of some catchments, due to specific characteristics. For example, in a study undertaken in Taiwan by Huang et al. (2008) of a catchment undergoing continuous expansion of urbanisation, the time to peak flow had reduced from 9 to 6 h. The primary reason for the reduction in peak flow is the increase in impervious surfaces, which reduces infiltration losses and depression storage, and results in more uniform surface slopes. These phenomena are also closely linked to the increase in runoff peak flow and volume. Secondly, the spatial distribution of impervious surfaces contributes to the change in the time to peak flow. The runoff from a relatively centralised layout of impervious surfaces tends to have a faster response to rainfall than a decentralised layout of impervious surfaces, resulting in a relatively shorter time to peak flow. As the outcomes of research studies undertaken by Liu et al. (2012) and Alias (2012) have confirmed, the placement of stormwater drainage inlets also has a significant influence on the stormwater runoff travel time. The closer the impervious surfaces are to the catchment outlet, the quicker the runoff peak is reached.

1.2.2 Water Quality Impacts

Urbanisation not only impacts on the catchment hydrology, but also plays a significant role in influencing the stormwater quality. The changes in stormwater quality primarily include the deterioration of the physical, chemical and microbiological quality of water and consequently the degradation of the aquatic ecosystem of receiving water bodies. Anthropogenic activities common to urban areas are the primary factors responsible for urban stormwater pollution. The key anthropogenic activities that generate pollutants, which are eventually deposited on urban surfaces, include vehicular traffic, industrial processes, building construction and commercial activities, corrosion of surfaces, spills, waste disposal and sewer leakages.

Anthropogenic activities not only contribute to the generation of pollutants, but also influence their accumulation and transport characteristics. Commonly, in studies on stormwater quality, the fate of pollutants in the urban environment is lumped into two key processes, namely, pollutant build-up and wash-off. Build-up relates to pollutant generation and accumulation on urban surfaces, primarily influenced by the antecedent dry period and catchment characteristics in relation to traffic, land use and impervious surfaces. Wash-off refers to the mobilisation and transportation of pollutants by stormwater runoff. Although rainfall characteristics, including intensity and duration are considered as the key factors influencing pollutant wash-off, urban area surface characteristics such as slope and roughness also play an important role. A detailed discussion about pollutant build-up and wash-off, including the mathematical replication of these processes is provided in Chap. 2.

1.3 Pollutants and Pollutant Sources

1.3.1 Primary Stormwater Pollutants

The degree of deterioration of stormwater quality in urban areas is dependent on the pollutant species and load. Suspended solids are considered as the most critical stormwater pollutant, since most other pollutants can be absorbed to their surface. Along with suspended solids, other common stormwater pollutants include nutrients, organic carbon, toxicants and micropollutants. This work primarily focuses on suspended solids, nutrients and organic carbon. Toxicants and micropollutants are also briefly discussed due to the increasing research attention towards these pollutants and their impacts on the urban water environment.

1.3.1.1 Suspended Solids

On a volumetric basis, suspended solids are the largest non-point source pollutant in urban receiving waters (Munoz and Panero 2008) and commonly originate from road surfaces, rooftops and construction sites. Additionally, research has shown that the pervious areas within an urban catchment can also be a significant contributor. The influence of suspended solids on water quality can be categorised into physical and chemical impacts. The physical impacts include the reduction in water transparency and the consequent inhibition of photosynthesis. In addition, high loads of solids can also lead to the smothering of bottom dwelling fauna and flora and changes to the substrata.

Compared to the physical impacts of suspended solids on water quality, their chemical impact needs to be given more attention. The primary chemical impact of solids is the adsorption of other pollutants, and their transport into the receiving waters. Due to their key role in transporting other pollutants, suspended solids are considered as the most important pollutant species in the context of stormwater quality. Particle size exerts a significant influence on pollutant transport. The pollutant content adsorbed by small particles is relatively higher compared to larger particles. This is due to the fact that conditions favourable for pollutant adsorption to solids, such as specific surface area, organic carbon content, effective cation exchange capacity and clay forming mineral content, increase with the decrease in particle size. Generally, large particles are not easily suspended, whilst fine particles are easily suspended for relatively long periods of time and transported to receiving waters.

1.3.1.2 Nutrients

Nitrogen and phosphorus compounds are the most important nutrients and are relatively abundant in urban stormwater runoff. Excess nutrients in water bodies can lead to abundant plant growth, which in turn can decrease dissolved oxygen due to microbial degradation on death and decay of the plants. The decrease in dissolved oxygen can result in over production of anaerobic bacteria and the depletion of aquatic organisms, thereby degrading the ecological environment of water bodies. The phenomenon resulting from nutrient enrichment is referred to as eutrophication, which has become a serious environmental problem in urban areas. Therefore, nutrients are considered as important pollutants in stormwater runoff and have received significant research attention.

A variety of sources contribute nutrients to stormwater runoff. These primarily include plant debris, animal waste, lawn fertiliser and domestic and industrial wastewater. Stormwater runoff from residential land use generally has higher nutrient concentrations compared to other urban land uses due to the presence of greater vegetation-covered areas.

1.3.1.3 Organic Carbon

The most significant impact of organic matter is the decrease in dissolved oxygen in water bodies due to microbial oxidation. It can lead to undesirable odours, undermine the quality of drinking water and reduce the recreational value of waterways (Ellis 1989; Warren et al. 2003). Furthermore, organic carbon adsorbed to particulates increases their sorption capacity for combining with other pollutants, such as heavy metals. Organic carbon content commonly increases with the decrease in particle size and consequently leads to higher heavy metal loads being attached to the surfaces of smaller particles (Gunawardana et al. 2014). Even though this characteristic is considered as beneficial, organic matter is easily decomposed due to microbial action, thus returning the pollutants back to the water environment.

Street litter and plant debris are important contributors of organic carbon to urban receiving waters and the concentration and loads are influenced by catchment characteristics. Stormwater runoff from residential areas generally carries higher organic carbon loads, due to greater vegetation cover in the surrounding area. Also, organic carbon accumulates much faster on street surfaces than inorganic materials (Sartor and Boyd 1972). The possible reason is that in urban areas, leaves and litter are predominant over deposited sand and dust materials.

1.3.1.4 Toxicants

Toxicants in relation to urban stormwater quality primarily include heavy metals and petroleum hydrocarbons. These pollutants are mainly contributed by vehicular traffic activities. Vehicle emissions, tyre and brake wear, engine oil and lubricant leakages are the main sources of these toxicants. In this regard, heavy metals and petroleum hydrocarbons in stormwater runoff are of particular concern, due to their ubiquitous nature and potential toxicity. Therefore, in addition to understanding pollutant loads and concentrations in stormwater runoff, assessing the ecosystem and the human health risk posed by these pollutants is also important.

1.3.1.5 Micropollutants

Micropollutants are substances present in the water environment at extremely low concentrations, but are able to exert potentially chronic direct or indirect impacts on ecosystems and on human health. These pollutants, which include pharmaceuticals, pesticides, hormones, and other organic pollutants and their metabolites, are commonly referred to as pharmaceuticals and personal care products (PPCPs) and endocrine disrupting chemicals (EDCs). Micropollutants can originate from human usage and excretions and from fungicides and disinfectants used for industrial and domestic purposes. Currently, significant knowledge gaps exist in the understanding of micropollutants in stormwater runoff, since mainstream stormwater quality research studies are primarily focused on 'conventional' pollutants such as solids, nutrients, organic carbon, heavy metals and hydrocarbons.

1.3.2 Primary Pollutant Sources

Stormwater pollutants originate from sources that relate to anthropogenic activities common to urban areas. These sources primarily include vehicular traffic, industrial processes, vegetation inputs, construction and demolition activities, corrosion, spills and erosion. The existence of a wide range of pollutant sources results in the presence of a diversity of pollutant species and loads.

1.3.2.1 Vehicular Traffic

It is widely acknowledged that vehicular traffic is the most important stormwater pollutant source (Shorshani et al. 2014). Pollutants from vehicles are present in the form of solids, liquids and gases. These pollutants are mainly generated from vehicle exhaust emissions, wear of vehicle tyres and brake lining and the leakage of engine oil and lubricants. This results in a wide variety of pollutants built up on urban road surfaces, with traffic-related pollutant species being composed of organic and inorganic compounds. The pollutant loads on road surfaces are dependent on the traffic volume, degree of traffic congestion, road characteristics such as the location of traffic lights, road layout, pavement surface and driver habits. For example, parking lots tend to have relatively higher pollutant concentrations, even though the traffic density is relatively low (Mejia et al. 2013). This is attributed to the frequent stop-and-go activities in parking lots and the consequent deposition of pollutants such as tyre wear and engine oil leakages (see Fig. 1.3).

Fig. 1.3 Tyre wear and engine oil leakage on road surfaces

1.3.2.2 Industrial Processes

Modern industrial processes contribute many kinds of pollutants to urban areas. Pollutant species and their concentrations vary with the nature of the industry and management practices. Rainfall and runoff will erode materials from open stacks of raw products and finished products and together with emissions from industrial processes, process waste and frequent loading–unloading activities form the primary pollutant generation activities (see Fig. 1.4).

1.3.2.3 Vegetation Input

Plant debris are another pollutant source impacting on stormwater quality by introducing nutrients through leaves, pollen and bark (refer to Fig. 1.5). For example, a research study by Line et al. (2002) confirmed that the concentration of

Fig. 1.4 Solids accumulated the road surface near an industrial area

Fig. 1.5 Plant debris on road surface

Total Kjeldahl Nitrogen (TKN) increased during pollen deposition periods. However, there are some conflicting results in relation to the influence of vegetation input on stormwater quality. For example, Allison et al. (1998) found that the leaf litter was around two orders of magnitude smaller than the nutrient loads measured in stormwater runoff in Melbourne. These observations point to the significant role played by location-specific factors in dictating the characteristics of urban stormwater quality.

1.3.2.4 Construction and Demolition Activities

Construction and demolition activities are an important contributor to stormwater pollution in urban areas. Generally, the pollutants generated during construction are linked directly to the ongoing construction activity. The soil cover is removed during site preparation, with rainfall and the resulting runoff picking up solids from the loosened soil and then transporting these solids to the receiving water (see Fig. 1.6). Brick debris and cement particles are also notable pollutants during construction activities. The influence of construction and demolition activities on the urban environment stems from the fact that these activities can generate a large amount of solids and litter in a relatively short period of time. The major pollutant

Fig. 1.6 A construction site

contribution to stormwater quality from construction and demolition activities is the introduction of solids to stormwater runoff.

1.3.2.5 Corrosion

Metal surfaces, such as roofs and gutters in buildings in urban areas, are easily corroded by acid rain and aggressive gases (see Fig. 1.7). Rainfall washes off corroded materials and then transports these pollutants to receiving waters. The factors contributing to corrosion are the availability of corrodible materials, the

Fig. 1.7 Corroded roof surface

Fig. 1.8 Waste dumps which are not well managed

frequency of exposure to an aggressive environment, the drying-wetting frequency of the exposed surfaces and maintenance practices.

1.3.2.6 Spills

Spills can degrade stormwater quality physically, chemically and biologically. Vehicles, construction and demolition activities and industrial activities are the major sources of spills (see Fig. 1.8). The pollutant contribution from spills is difficult to quantify. Proper management and mitigation practices can mitigate spills from being a significant stormwater pollutant source.

1.3.2.7 Erosion

This primarily includes the erosion of stream banks and beds, various pervious surfaces and material stockpiles at construction, demolition, industrial, commercial and waste disposal sites. In relation to waterways in urban areas, erosion gradually increases due to changes in the hydrology as a result of urbanisation, as discussed in Sect. 1.2.1 (refer to Fig. 1.2). For example, Nelson and Booth (2002) undertaking a detailed study of a 144 km^2 urban catchment found that the annual sediment yield had increased by nearly 50 % due to urban development, with stream bank erosion accounting for around 20 %.

1.4 Summary

This chapter has reviewed the impacts of urbanisation on catchment hydrology and stormwater quality as well as the primary stormwater pollutants and their sources, in order to provide the platform and context for the subsequent discussion on the role of rainfall and catchment characteristics on stormwater quality, and the practical application of this knowledge for protecting the urban water environment. As highlighted above, anthropogenic activities due to urbanisation generate a range of pollutants in the urban environment, in the process of transforming the natural landscape to urban land use, thereby exerting a significant influence on stormwater quantity. The changes to water quality and quantity irrevocably alter the characteristics of receiving water bodies and pose a threat to human and ecosystem health.

Anthropogenic activities in an urban catchment introduce a wide range of pollutants to the urban environment. In terms of stormwater quality, these primarily consist of suspended solids, nutrients, organic carbon, toxicants and micropollutants. These pollutants are emitted by a diversity of sources, where road surfaces and, by implication, vehicular traffic, are seen as the most important source. Additionally, catchment characteristics and rainfall characteristics are two primary influential factors in relation to water quality, as these influence pollutant generation, accumulation and transportation.

The above discussions highlight the fact that urban stormwater transports a diversity of pollutant species generated from a range of sources. Accordingly, it further highlights the complexity inherent in effectively treating stormwater runoff, due to its highly variable characteristics and location-specific nature. Consequently, a stereotypical approach to mitigation can prove inadequate. Instead, an effective approach to stormwater mitigation and treatment design should specifically take into consideration catchment characteristics, rainfall characteristics and pollutant characteristics.

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Chapter 2
Stormwater Treatment Design

Abstract The implementation of scientifically robust stormwater management strategies needs to be underpinned by effective treatment systems. In this regard, stormwater quality models play a critical role for predicting pollutant loads and for determining important treatment system design parameters. A stormwater quality model is process driven, with the replication of pollutant build-up and wash-off processes being two key components. This chapter discusses the limitations in current modelling approaches and the need to have an in-depth understanding of pollutant processes and the role played by influential rainfall and catchment factors to enhance the accuracy and reliability of modelling results. Currently, only a limited number of parameters are incorporated in the model setup to represent the influence of catchment and rainfall characteristics on stormwater quality. This approach is inadequate as stormwater pollutant processes are complex and influenced by a range of factors. This highlights the importance of having an in-depth understanding of the role of rainfall and catchment characteristics on urban stormwater quality.

Keywords Hydrologic modelling · Stormwater quality · Stormwater pollutant processes · Stormwater treatment design · Stormwater quality modelling

2.1 Background

In an era where urban stormwater quality is recognised as a particular concern, the implementation of stormwater treatment strategies is common worldwide. As discussed in Chap. 1, stormwater quality is highly variable in the context of pollutant sources, species and loads, and is influenced by a range of factors such as rainfall characteristics and catchment characteristics. This underlines the complexity required for stormwater treatment approaches and treatment design. For treating stormwater quality, commonly adopted treatment approaches can be termed as a combination of structural and non-structural measures. Structural measures are treatment devices installed in or constructed at a site to mitigate changes to

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stormwater quantity and quality as a result of urbanisation. Non-structural approaches do not involve fixed permanent facilities, but entail changing behaviour in relation to pollutant generation and restricting pollutant entrainment to stormwater systems through regulations and/or economic instruments.

An overarching stormwater treatment strategy, which is a combination of structural and non-structural measures, is common in most parts of the world, though different terminology is used to describe these strategies. 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 widely used in China to refer to the strategy used for stormwater management. Best Management Practices (BMPs) is the term used in the United States. Sustainable Urban Drainage System (SUDs) and Stormwater Quality Improvement Devices (SQIDs) are also terms used in a number of other countries to define stormwater management strategies.

These stormwater treatment strategies subscribe to the common objective of mitigating the negative impacts of urbanisation on the water environment, by attempting to restore the pre-urbanised hydrologic and water quality characteristics. Typical structural stormwater treatment systems used are gross pollutant traps (GPTs), constructed wetlands, bioretention basins (rain gardens), sedimentation basins and vegetated swales (filter strips). Figure 2.1 shows examples of these typical structural stormwater treatment devices.

In terms of structural treatment systems, the ability to effectively treat stormwater is the most essential criterion for design. In stormwater treatment system design, answers to a number of key questions as listed below determine the overall functionality of the systems:

- What types of devices should be provided for a given catchment?
- Where should these be located?
- What sizes should these be and does it require a treatment train strategy (which is a combination of stormwater treatment devices in series with different treatment functions/objectives)?

Apart from these key questions to be answered at the design stage, a range of engineering design concepts are applied to determine the size and shape of the system, the characteristics of the structures to be used for conveyance and media to be used for treatment. In order to determine these important parameters and characteristics, hydrologic and water quality models are commonly used as an integral part of stormwater treatment design.

In this chapter, the discussion primarily focuses on stormwater modelling, which is an essential step in the treatment design. The discussion encompasses current modelling approaches and influential factors in relation to model reliability and accuracy. Additionally, this chapter also discusses how rainfall and catchment characteristics influence stormwater quality and the implications for enhancing the modelling approach adopted.

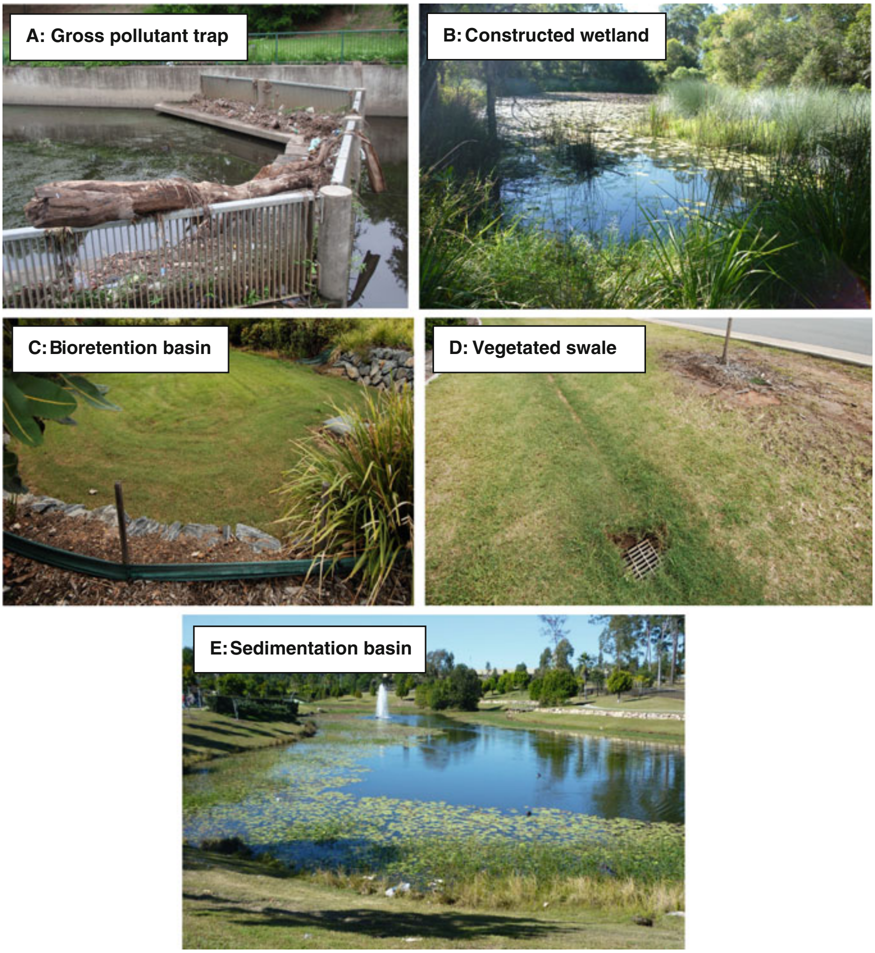

Fig. 2.1 Typical structural stormwater treatment systems **a** gross pollutant trap **b** constructed wetland **c** bioretention basin **d** vegetated swale **e** sedimentation basin

2.2 Use of Models in Stormwater Treatment Design

Modelling approaches used should be capable of estimating the quantity and quality of stormwater based on the catchment characteristics and rainfall characteristics for the range of pollutant species of interest. In this context, modelling outcomes provide designers with important guidance and datasets, significantly contributing to effective stormwater treatment design. Therefore, the accuracy and reliability of modelling approaches are of particular concern. Inadequacy of the modelling approach could lead to overestimation or underestimation of stormwater quantity and quality characteristics, resulting in ineffective treatment or high cost of construction and maintenance. For instance, in the case of the estimated stormwater runoff volume being too small, a large number of rainfall events will exceed the capacity of the treatment device and will achieve only limited treatment. Alternately, if the volume is overestimated, there will be increased cost as well as further treatment becoming negligible after a certain threshold.

2.3 Stormwater Models

Any model is an approximation of reality, and the reality is the urban stormwater system. A model is therefore only capable of replicating reality to the extent where scientific knowledge prevails. In model development, even the best available scientific knowledge has to be simplified to maintain practical viability. This means that a model can only replicate to a point. Therefore, significant efforts to explore cutting edge knowledge relevant to stormwater quantity and quality are critically needed to improve model replication accuracy and by implication, treatment design.

In the case of an urban stormwater model, the basic conceptualisation of transforming rainfall to runoff is termed as a hydrologic model, while estimation of pollutant loads transported by the runoff is termed as a water quality model. Generally, the hydrologic model and water quality model are simultaneously simulated to generate combined outcomes. The common approach used in most models, as illustrated in Fig. 2.2, is a simplification of the natural system as follows:

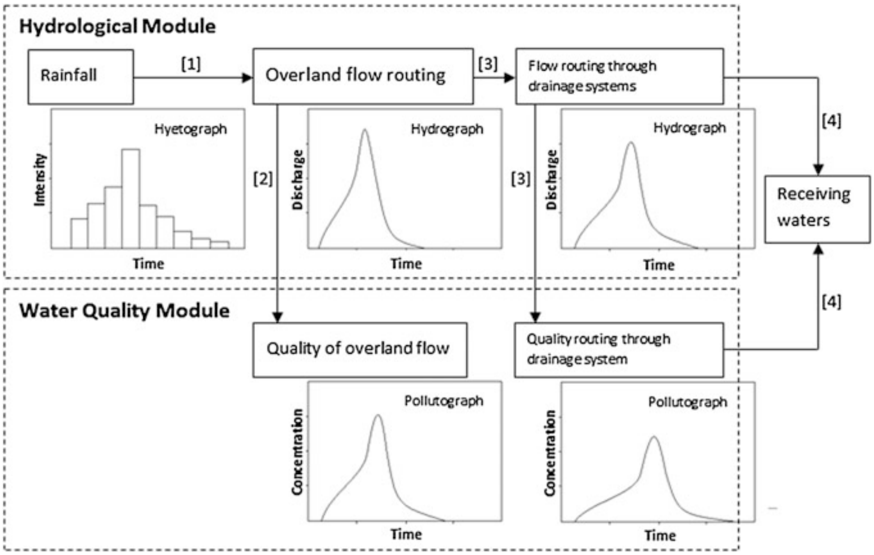

Fig. 2.2 Hydrologic and water quality models

- Rainfall is transformed to overland runoff based on catchment characteristics [1], where the surface runoff picks up pollutants on the catchment surfaces [2];
- Surface runoff, which incorporates pollutants, flows into the drainage system [3];
- The surface runoff with pollutants flows into the receiving waters via the drainage system [4].

2.3.1 Hydrologic Models

Hydrologic models commonly consist of two conceptual modules, namely, rainfall loss module and runoff routing module. The loss module is responsible for estimating the fraction of rainfall that is available to produce surface runoff, by eliminating losses such as infiltration and depression storage. A routing module transforms the effective rainfall (fraction of rainfall available to produce surface runoff) to a runoff hydrograph based on catchment characteristics. In this regard, rainfall is the input to the model and catchment characteristics play a critical part in influencing the loss module and routing module. The key influential catchment characteristics in relation to hydrologic modelling include:

(1) The topography of the catchment in terms of the direction and magnitude of the ground slope;
(2) The subsurface characteristics;
(3) The land use and land cover;
(4) The spatial distribution of urban areas (Mansell 2003).

The loss module replicates a typical hydrologic process in a catchment as illustrated in Fig. 2.3. A fraction of rainfall will contribute to runoff whilst the rest is lost due to evaporation or percolation into the ground. Different mathematical

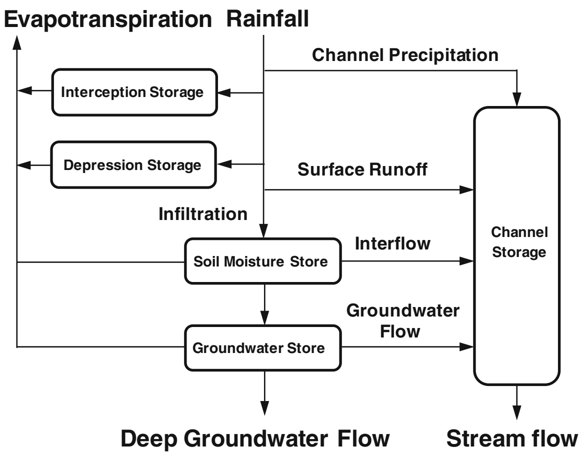

Fig. 2.3 Loss module in a hydrologic process

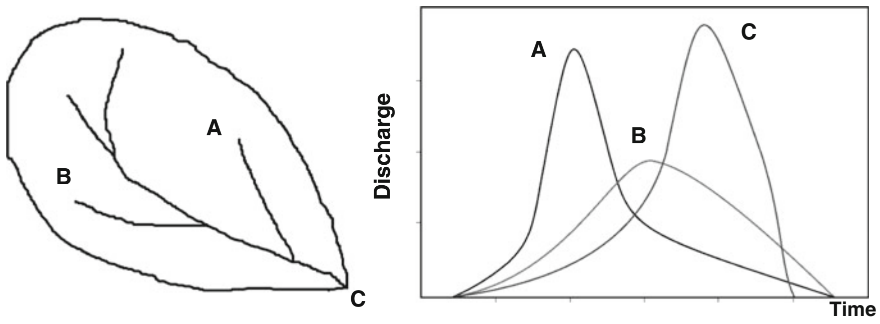

Fig. 2.4 Routing module in a hydrologic process

procedures are used to simulate the different components in the hydrologic process. As an example, Horton's infiltration equation is commonly used to estimate the precipitation-infiltration process, whilst Manning's equation is used to determine the characteristics of the free-surface flow driven by gravity.

A routing module is illustrated in Fig. 2.4. The stormwater runoff flows over the catchment surface and reaches the outlet, where the hydrograph forms. The hydrograph shape is strongly influenced by catchment characteristics. For example, a sharp rising limb with a high peak generally represents a catchment with a steep slope and large fraction of impervious surfaces, while a later peak in the hydrograph indicates that the impervious surfaces are located far from the catchment outlet.

2.3.2 Water Quality Models

Water quality models are used to estimate concentrations or loads of pollutants originating from a catchment. The data required for water quality modelling is mainly related to rainfall characteristics, catchment characteristics and pollutant build-up and wash-off. There are two fundamental approaches for undertaking water quality modelling, namely, the event-based approach and the long term continuous approach.

2.3.2.1 Event-Based Models

In the event-based approach, the processes that pollutants undergo can be divided into two types: pollutant build-up process and wash-off process. Pollutant build-up refers to pollutant accumulation on urban surfaces during dry weather while pollutant wash-off is the process that involves mobilising accumulated pollutants during stormwater runoff events (refer to Sect. 1.2.2). A range of empirical equations, as listed in Table 2.1, have been used to simulate these two processes in modelling approaches.

Table 2.1 Examples for empirical equations used in water quality models

Pollutant processes	Equations	Definitions	References
Build-up	• $y = a + \frac{b}{x}$ • $y = a + b\ln x$ • $y = ae^{-bx}$ • $y = \min(c, ax^{b})$	x-antecedent dry days; y-build-up load accumulated; a, b and c-coefficients	(Ball et al. 1998; Egodawatta 2007; MIKE URBAN 2008; O'Loughlin and Stack 2003)
Wash-off	• $W = W_0(1 - e^{-KIt})$ • $F_W = \frac{W}{W_0} = C_F(1 - e^{-KIt})$	W-weight of material mobilised after time t; W_0-initial weight of material on the surface; I-rainfall intensity; K-wash-off coefficient; F_W-fraction of wash-off; C_F-capacity factor	(Egodawatta et al. 2007; Sartor et al. 1974)

Models listed in Table 2.1 are primarily used to replicate suspended solids behaviour. Suspended solids are a major pollutant in their own right and commonly regarded as an indicator pollutant, due to the association of other pollutants with suspended solids. In this regard, other pollutant loads are generally estimated by assuming that the ratio of a particular pollutant to that of suspended solids is a constant for a given land use. Additionally, as shown in Table 2.1, pollutant build-up load is a function of antecedent dry days while pollutant wash-off is a function of rainfall intensity. In most event-based water quality models, antecedent dry days and rainfall intensity are the key parameters in the simulation of pollutant build-up and wash-off.

2.3.2.2 Long Term Continuous Models

Different from event-based models that focus on estimating pollutant loads and/or concentrations for a particular rainfall event or a series of rainfall events, long term continuous models focus on long-term pollutant load estimation, such as on a monthly or an annual basis. These types of models are generally used for urban planning and stormwater management decision-making.

In current engineering practice, the Model for Urban Stormwater Improvement Conceptualisation (MUSIC), which is a long term continuous model, is common. MUSIC is a stochastic stormwater quality model that assigns a particular water quality to events over a long term continuous period, such as 20 years, so that they fall into a pre-assigned probability distribution. Therefore, these models are generally termed as probabilistic models (McAuley and Knights 2009). Based on parameters related to land use or rainfall characteristics, long term continuous models are capable of estimating the annual pollutant export from a catchment. The same as for event-based models, different empirical equations are used by different models and have varying degrees of complexity.

2.4 Factors Affecting Model Accuracy

As a model replicates only a fraction of reality by utilising a simplifying form of scientific knowledge relating to the natural system, all modelling approaches are subject to uncertainty, due to a number of reasons. The presence of uncertainty in a modelling approach could lead to inaccurate outcomes if the uncertainty sources are not adequately understood. This highlights the importance of understanding uncertainty sources and underlying characteristics in stormwater quality modelling approaches. In this section, three important uncertainty sources, namely, model structure, input parameters and modelling approach, are discussed in detail.

2.4.1 *Model Structure*

Uncertainty resulting from the model structure is primarily related to the lack of knowledge on the influential factors in relation to stormwater quality, such as the influence exerted by rainfall and catchment characteristics in real-world systems. It depends on how accurately the models are developed to replicate the true system for a given situation. For example, current stormwater quality models estimate pollutant loads based only on land use and impervious surface fraction. However, the reality is that other than these two factors, a range of other catchment characteristics such as urban form, urban area locations and other site-specific characteristics, have a significant influence on water quality. Urban form commonly refers to the physical layout and design of the urban area (Breheny 1992). The definition of urban form is provided in Sect. 2.5.1. In other words, even though catchments may have the same land use type and impervious surface fraction, the stormwater quality generated from these catchments could still be different (Liu et al. 2012a). This could be attributed to the difference in the distribution of impervious surfaces and urban form. In this context, the model structure developed without considering other catchment characteristics could lead to inaccuracy in modelling outcomes and inaccurate stormwater treatment design.

2.4.2 *Input Parameters*

Inadequate input parameters, which primarily refer to the use of unrepresentative lumped parameters, are among the most important sources of model uncertainty. They affect model accuracy due to the lack of consideration of the variable nature of input parameters in a given situation. This is because lumped parameters generally are not able to accurately represent changes in stormwater quality throughout a rainfall event or within a particular land use, and this could lead to errors in modelling results. Taking land use as an example, most stormwater quality models commonly estimate pollutant loads for a particular land use by considering the land use as a lumped parameter without adequately representing their specific characteristics. However, the real-world situation is that there could be significant differences in different areas in terms of the influence exerted on pollutant processes, even though these areas have the same land use. For example, pollutants could accumulate at a higher rate in a residential catchment with high population density during the dry period (pollutant build-up) when compared to a residential catchment with low population density or different urban forms such as townhouse/detached housing development, although these catchments can be broadly categorised as residential development (Egodawatta and Goonetilleke 2006). Additionally, for some water quality parameters, variability in pollutant build-up within the same land use has been found to be even higher than the variability between different land uses (Liu et al. 2012b). This is attributed to the high degree of complexity of specific characteristics, such as traffic density, within the same land use rather than among different land uses. Consequently, assigning a single specific input parameter for a particular land use may not necessarily represent reality.

2.4.3 Modelling Approach Used

The use of an inappropriate modelling approach is a common source of model uncertainty. Even though the modelling approach itself cannot lead to uncertainty, it could undermine model accuracy if it is not adequate in the context of objectives and expectations. For instance, in the case of investigating relationships between rainfall characteristics and stormwater quality, using models based on stochastic concepts (such as the long term continuous model, MUSIC) could lead to errors. The stochastic modelling approach is to assign stormwater quality values to each rainfall event based on stochastic principles, where stochastic parameters are assigned to a rainfall event irrespective of the underlying characteristics. This approach does not necessarily consider the variable nature of stormwater quality with rainfall characteristics and thereby is not taken into consideration in the investigation into relationships between rainfall characteristics and stormwater quality. These facts highlight the influence of the selected modelling approach on model accuracy.

A further example is the application of solids as the indicator pollutant in conventional water quality models. Most of the event-based modelling approaches assume that other pollutants are attached to solids and transported along with these solids. However, an appreciable amount of pollutants are, in effect, not adsorbed to solids, but primarily present in dissolved form. Consequently, the approach of using solids as an indicator fails to accurately estimate these dissolved pollutants. For example, the research study undertaken by Miguntanna et al. (2013) found that nitrogen is primarily present in dissolved form whilst phosphorus is primarily present in particulate form. Consequently, the approach of using solids as an indicator is not appropriate in a situation where it is necessary to estimate dissolved pollutants such as nitrogen.

2.5 Understanding Influential Factors of Stormwater Quality-Improving the Modelling Approach

As the accuracy of stormwater models closely relies on how accurately the models replicate the natural systems, an in-depth understanding of the influence of external factors on stormwater quality can contribute to improving the modelling approach. Section 1.2.2 highlighted the primary influential factors in relation to stormwater quality as being catchment characteristics and rainfall characteristics. Catchment characteristics generally encompass a range of factors, such as land use and land cover, impervious surface area fraction, urban form and urban area location, whilst rainfall characteristics describe the variations in rainfall events primarily in relation to duration and intensity. In this section, a detailed discussion regarding these two factors with a focus on improving the modelling approach is provided.

2.5.1 Catchment Characteristics

Catchment characteristics generally play a significant role in pollutant build-up and hence, stormwater quality. Their role influences the pollutant species and loads generated, pollutant accumulation rate and the spatial and temporal distribution of the pollutants accumulated.

2.5.1.1 Land Use and Land Cover

Land use refers to the human modification of the natural environment for a specific purpose within the built environment. In terms of urban catchments, land use is typically categorised into residential, commercial and industrial. These different land use types are characterised by differences in various anthropogenic activities, such as traffic volume, vehicle types, vegetation cover and maintenance activities and population density. In addition to an individual land use, a mixed land use within a catchment contributes to the further complexity of factors which influences stormwater quality. Generally, a mixed urban catchment with range of land use types tends to produce high diversity of pollutant species (Lee et al. 2009). This could lead to a greater complexity in pollutant composition in stormwater runoff. This highlights the importance of linking urban planning with water quality improvement strategies.

Land cover refers to the physical material on the land surface such as grass, asphalt, concrete and roof surfaces. Land use and land cover have a significant influence on the urban environment. In terms of the water environment, different land use and land cover can produce different pollutant species and loads during dry periods (build-up) and hence play a key role in stormwater quality. Industrial land use tends to produce more solids, particularly fine particles, than other land uses

(Miguntanna et al. 2010). This can be attributed to the presence of specific industrial enterprises, traffic characteristics and loading and unloading activities. In the case of land cover (such as roof and road), solid loads from roofs have been noted to be significantly less compared to road surfaces, and to be of much finer in texture (Egodawatta et al. 2009). This is because, compared with roads, roofs are relatively difficult on which to hold pollutants due to the smooth surfaces and atmospheric deposition is the primary contributor to pollutants build-up on roofs.

2.5.1.2 Impervious Surface Fraction

Impervious surface fraction is considered as the one of the most important factors influencing stormwater quality. Compared with pervious surfaces, pollutants on impervious surfaces can be easily removed by stormwater runoff due to the low surface roughness and transported to receiving waters. This needs to be viewed in the context of how impervious area characteristics influence stormwater runoff characteristics. The impervious surface fraction primarily influences pollutant wash-off loads and runoff volume. However, past research studies have found that in modelling approaches, the impervious surface fraction itself is not adequate for accurately estimating stormwater quality. Other parameters, such as the impervious surface type (such as roof and road), are also important characteristics that should be taken into account in modelling. Even though pollutant build-up and wash-off from roof and road surfaces can be replicated using the equations provided in Table 2.1, the coefficients used for these two impervious surfaces are different. For example, as shown in Table 2.2, the wash-off capacity factor (C_F, the capacity of a specific rainfall intensity to mobilise pollutants available on impervious surfaces) for roofs is higher than for roads (Egodawatta 2007). This is attributed to the fact that pollutants on roofs are more easily washed off compared to roads, due to their relatively reduced roughness and steeper slope.

However, in catchments with relatively higher percentages of roof area, the transport of pollutants to the catchment outlet has been found to be slower, particularly when experiencing small rainfall events (Alias 2012). This is due to the fact that distance between the roof and the catchment outlet is commonly longer, compared to a road in an urban catchment. This further confirms the inadequacy of only taking into consideration the impervious surface fraction in water quality modelling.

Table 2.2 Wash-off capacity factors for roads and roofs (Egodawatta 2007)

Rainfall intensity (mm/h)	C_F values	
	Roads	Roofs
20–40	0.3–0.5	0.75–0.91
40–90	0.5	0.91
90–115	0.5–1	0.91–1.0

2.5.1.3 Urban Form

Urban form is an important factor in relation to the impact of urbanisation on the water environment. Urban form, which refers to the physical layout and design of the urban area, including population density, street layout, transportation network and urban design features, can affect water quantity and quality (Breheny 1992). For example, street layout can affect the distribution of drainage systems and the time and velocity of surface runoff while population density and the transportation network are responsible for pollutant generation. Researchers such as Goonetilleke et al. (2005) have found that high-density residential development would be the preferred option in terms of safeguarding water quality, since this type of urban form results in a relatively smaller footprint. Unfortunately, there has been only limited research undertaken to investigate the relationship between urban form and stormwater quality.

2.5.1.4 Urban Area Location

Urban area location is defined as the spatial distribution of urban areas in a catchment. It primarily relates to the distance of the various urban areas from the drainage system or catchment outlet. Changes in urban area location can modify the runoff process, such as the starting time of pervious surface runoff, flow velocity and pollutant load and thereby stormwater quality. When pervious surfaces are located away from the drainage system, the pervious surface runoff may not reach the drainage system, or it will be significantly delayed due to the relatively long travel distance. Also, the required rainfall amount needed to activate pervious surface runoff would have to increase, since a greater runoff loss would occur due to percolation into the ground. Figure 2.5 shows a conceptual illustration of the variations in the inception of runoff due to different pervious and impervious area configurations.

2.5.2 Rainfall Characteristics

Rainfall characteristics are the key influential factor in pollutant wash-off. It is well known that rainfall intensity has an important influence on pollutant wash-off due to the rainfall kinetic energy. The square of the rainfall intensity is used to assess the kinetic energy available in rainfall for the wash-off process (Brodie and Rosewell 2007). However, it is also noted that only a fraction of pollutants built up on the surface are washed off and this is dependent on rainfall intensity (Egodawatta et al. 2007). Vaze and Chiew (2002) proposed two possible alternative concepts of wash-off, namely source limiting (Fig. 2.6a) and transport limiting (Fig. 2.6b). The former represents the scenario where pollutants accumulate from zero and then revert back to the original state after a wash-off event. The latter represents the scenario where

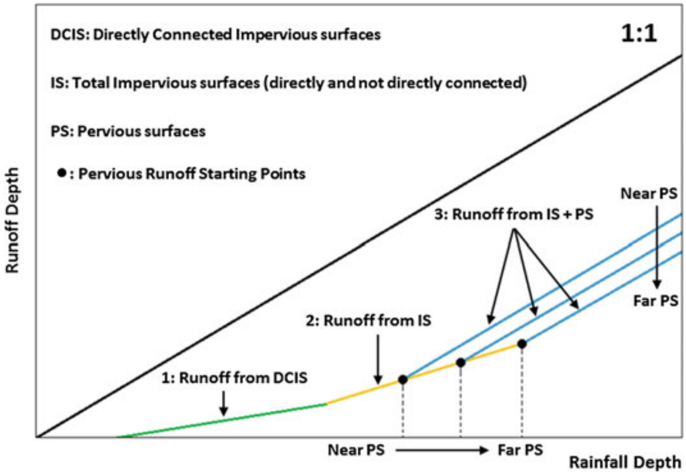

Fig. 2.5 Conceptual illustration of the variations due to different pervious and impervious area configurations (when pervious areas are located further away, runoff has to travel further to enter the drainage system and hence leads to greater continuing loss. This results in a reduced amount of runoff reaching the drainage system)

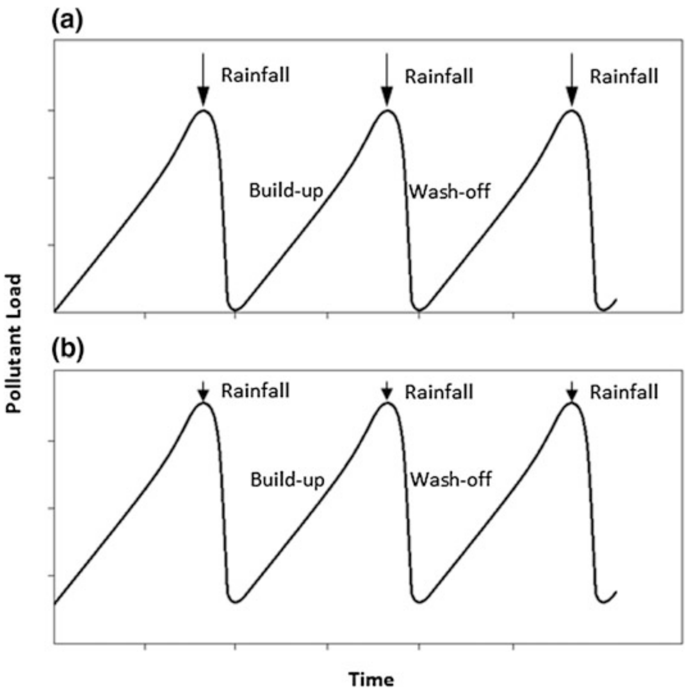

Fig. 2.6 Hypothetical representation of surface pollutant load over time **a** source limiting **b** transport limiting

only a fraction of the pollutants is removed by the wash-off process and the pollutant load is restored back over time to almost the same level as before the rainfall event. Both, the source limiting scenario and the transport limiting scenario may vary for different pollutant types.

In terms of the transport limiting scenario, a capacity factor (C_F, see Table 2.1) has been defined to assess the capacity of solids wash-off. The capacity factor varies between 0 and 1 depending on the rainfall intensity (Egodawatta 2007). When the rainfall intensity is less than 40 mm/h, the capacity factor (C_F) will increase linearly from 0 to 0.5, which is followed by a constant value of 0.5 for 40–90 mm/h intensity, and then varies from 0.5 to 1 as the intensity increases beyond 90 mm/h (see Fig. 2.7). This would imply that it is inaccurate for current models to consider water quality as a continuous function of rainfall intensity rather than a step-wise function, as illustrated in Fig. 2.7.

Although using lumped rainfall characteristics such as average rainfall intensity, it is possible to investigate stormwater quality characteristics, in reality, different sectors of the rainfall event (sectional effect) have different characteristics in the context of their influence on pollutant wash-off. Therefore, the different sectors of a runoff event could exert different influences on stormwater quality. This can be viewed in the context of the occurrence of the first flush phenomenon, which refers to the wash-off of a relatively higher pollutant load at the initial part of a runoff event. Accordingly, it can be concluded that the common approach of using lumped rainfall parameters could overshadow the critical relationships between pollutant wash-off and rainfall characteristics and will not provide an in-depth understanding of the pollutant wash-off process. For example, the occurrence of high intensity in the initial period of a rainfall event will generate a relatively higher magnitude first flush. This is despite the fact that the total rainfall amount could be the same

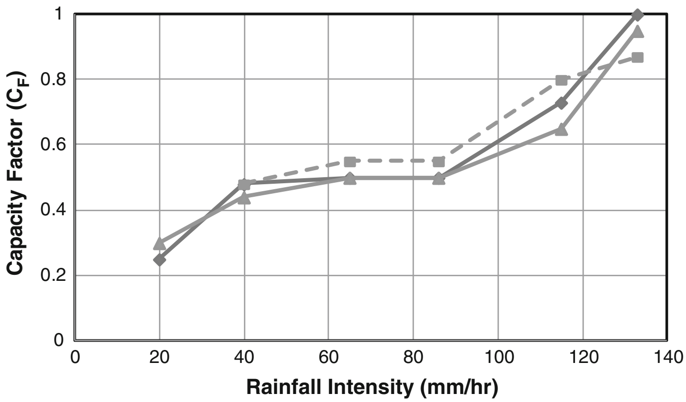

Fig. 2.7 Capacity of solid wash-off with rainfall intensity (Egodawatta 2007) (the three curves represent three residential road surfaces in Gold Coast, Queensland, Australia investigated by Egodawatta 2007)

(Alias et al. 2014a, b). This underlines the fact that the rainfall pattern also plays a critical role in the pollutant wash-off process. In this context, applying this knowledge to current modelling approaches is beneficial for enhancing the accuracy of the estimation of water quality, leading to more effective stormwater treatment design.

2.6 Summary

This chapter has focused on hydrologic and water quality modelling approaches for structural stormwater treatment design. As the primary tool for stormwater treatment design, water quality modelling outcomes require accuracy and reliability. These strongly depend on an in-depth understanding of pollutant processes and the role played by influential factors, including rainfall and catchment characteristics, in influencing the various pollutant processes.

Pollutant build-up and wash-off are the key pollutant processes in relation to stormwater quality. They represent pollutant generation, accumulation and transportation. Current water quality models are primarily developed based on these two processes. However, due to the fact that any model is capable of replicating reality only to an extent based on the prevailing scientific knowledge, the accuracy of modelling outcomes can be questionable. This relates to common issues, such as inadequate model structure, input parameters and modelling approach used.

In this context, significant efforts to explore cutting edge knowledge relevant to stormwater quantity and quality are critically required in order to improve model replication accuracy and thereby, treatment design. Furthermore, it is also essential to understand the influence of catchment characteristics and rainfall characteristics on stormwater quality. Other than conventional catchment characteristics such as land use and impervious surface fraction, other characteristics, including impervious area distribution, urban form and urban area location, are also recommended to be taken into consideration in the modelling approach, due to their role in influencing stormwater quality. Furthermore, it is noteworthy that taking lumped rainfall characteristics such as average rainfall intensity as the factor influencing water quality is not adequate, since other rainfall parameters such as rainfall pattern have been found to exert a significant influence on pollutant wash-off. The practical application of this knowledge can significantly improve model reliability and accuracy, leading to more effective stormwater treatment design.

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Chapter 3
Case Studies

Abstract The outcomes from two case studies which investigated the role of catchment and rainfall characteristics in influencing stormwater quality are presented in this Chapter. The case study which investigated the role of rainfall characteristics provides an innovative approach to classify natural rainfall events into three different types in the context of water quality. The proposed approach is in contrast to conventional approaches where rainfall events are classified solely based on quantity. The second case study confirmed the important role played by catchment characteristics such as urban form and impervious area layout in influencing pollutant wash-off. Therefore, the common practice of only considering land use and impervious area fraction to represent catchment characteristics can be questionable. Use of additional parameters in stormwater quality modeling enables more accurate accounting of the characteristics of urban catchments.

Keywords Rainfall classification · Stormwater pollutant processes · Stormwater quality · Urban form · Impervious surface layout

3.1 Background

As discussed in the previous chapters, rainfall characteristics and catchment characteristics are the key factors that influence stormwater quality. Current modelling practices are based on the extent to which relevant knowledge is available. For further enhancement of the accuracy and reliability of modelling approaches, it is crucial to create an in-depth understanding of the role of rainfall and catchment characteristics on stormwater quality.

The primary objective of this chapter is to present the new knowledge created through a research study that investigated the role of catchment and rainfall characteristics on stormwater quality, which is presented in the form of two case studies. The two case studies are based on the analysis of monitored rainfall-runoff and

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stormwater quality data from four urban residential catchments over a three-year period. Outcomes of these case studies are presented along with recommendations and guidance for practical application in urban stormwater quality modelling.

3.2 Study Approach

3.2.1 Study Sites

The four study catchments selected for the two case studies are located in the Gold Coast region, Queensland, Australia. The study catchments included one primary catchment, Highland Park. Three smaller subcatchments, Birdlife Park, Alextown and Gumbeel, are located within the primary catchment, as shown in Fig. 3.1. Highland Park is a mixed-land-use catchment with a significant fraction of residential development, while the three small catchments consist of residential land use, but have different urban forms, as described in Table 3.1. A small tributary of the Nerang River, Bunyip Brook, is the primary stormwater drainage. It starts from the westward hilly region and flows towards the Nerang River. The integrated pipe and channel network connecting various parts of the Highland Park catchment to the tributary facilitates stormwater drainage. The study catchments have the same geology based on the Neranleigh-Fernvale metasediments and similar predominant soil types, mainly, Kurosols. This ensured that, for this study, these factors would not differently influence the stormwater runoff quality characteristics.

3.2.2 Data Collection and Pollutant Parameter Selection

Automatic monitoring stations have been established at the outlet of each study catchment to record the water quantity data, including streamflow, and to collect stormwater samples for laboratory testing of pre-determined water quality parameters. These stations were equipped with: (1) depth gauges fixed to a V-notch weir to record the water depth at 15-min intervals and thereby determine the stream flow using calibrated rating curves; (2) water quality probes to automatically measure parameters including pH and turbidity; and (3) automatic water samplers for collecting runoff samples for laboratory testing for additional water quality parameters. The sample collection equipment had been set to trigger when the flow reaches a pre-determined depth. This depth was dependent on the downstream structure at the collection point. Hence, it varied from sampling station to sampling station. Samples were collected in 5-min intervals once the sampler was triggered. Each sampler had the capacity to collect 24 samples for a single event. The sampler was able to create a log of the sampling times. Figure 3.2 shows a monitoring station installed at a catchment outlet.

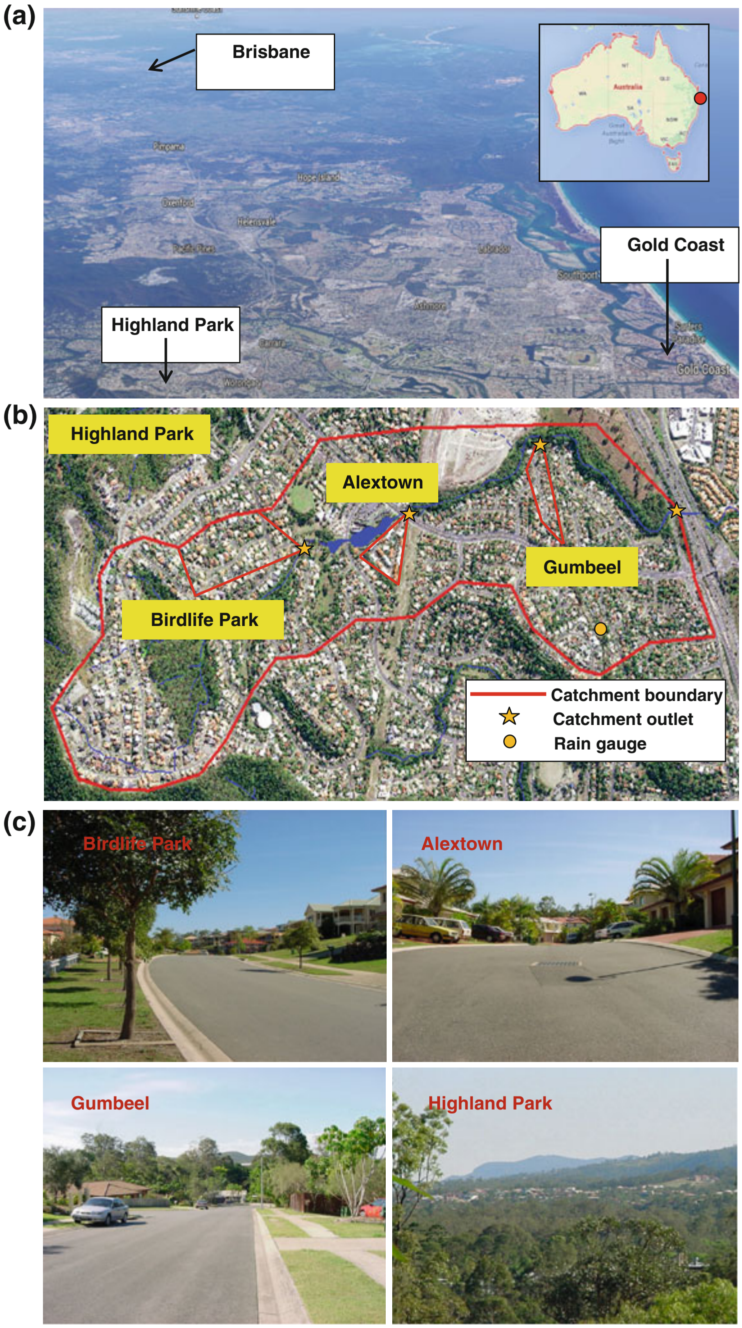


Fig. 3.1 Study catchments. **a** Study catchment location (from Google Maps). **b** The four study catchments (from Google Maps). **c** A detailed view of the four study catchments

Table 3.1 Study catchment characteristics

Catchment	Area (ha)	Impervious area fraction (%)	Land use	Urban form
Alextown	1.7	70	Residential	Townhouses; mild catchment slope; pervious area near to drainage systems
Gumbeel	1.2	70	Residential	Duplex housing developed around cul-de-sac; the access road is the drainage line; ridge area with houses and gardens below drainage line; pervious area far from drainage systems
Birdlife Park	7.5	45.8	Residential	Detached housing; through roads connected to busy arterial roads; large extent of road surfaces; steep catchment slope; pervious area near to drainage system
Highland Park	105.1	40	Mixed land use with a significant fraction of residential areas	Mixed urban form; located close to busy highway and roadways; steep catchment slope to the west and milder slope to the east

Due to the fact that solids, nutrients and organic matter are among the most important pollutants responsible for the degradation of urban receiving water quality, total suspended solids (TSS), total nitrogen (TN), total phosphorus (TP) and total organic carbon (TOC) were selected as pollutant parameters to be measured. The laboratory test methods adopted are summarised in Table 3.2. Event mean concentration (EMC, mg/L) values rather than the instantaneous concentrations were used in the analysis, due to two reasons:

(1) Instantaneous concentrations have a relatively high variation with time while the EMC represents the average pollutant concentration value for a rainfall event. Therefore, the EMC value can be considered as an event characterisation in terms of stormwater quality.
(2) EMC is the parameter adopted to estimate the pollutant loads and is typically used in the stormwater quality treatment design.

A total of 41 rainfall events over the period of 2002–2004 were selected for analysis after an assessment of the available data. Due to the fact that rainfall intensity smaller than 5 mm/h does not have a significant effect on pollutant wash-off, intensity larger than a threshold value of 5 mm/h was considered to define the start and end points of a selected rainfall event. Rainfall events below 5 mm/h are considered as ineffective in creating wash-off due to their low kinetic energy. The EMC data for 41 events were not consistently available for all four catchments. Equipment failure and variability of rainfall within the catchments were largely responsible for the non-availability of data across all four catchments for every

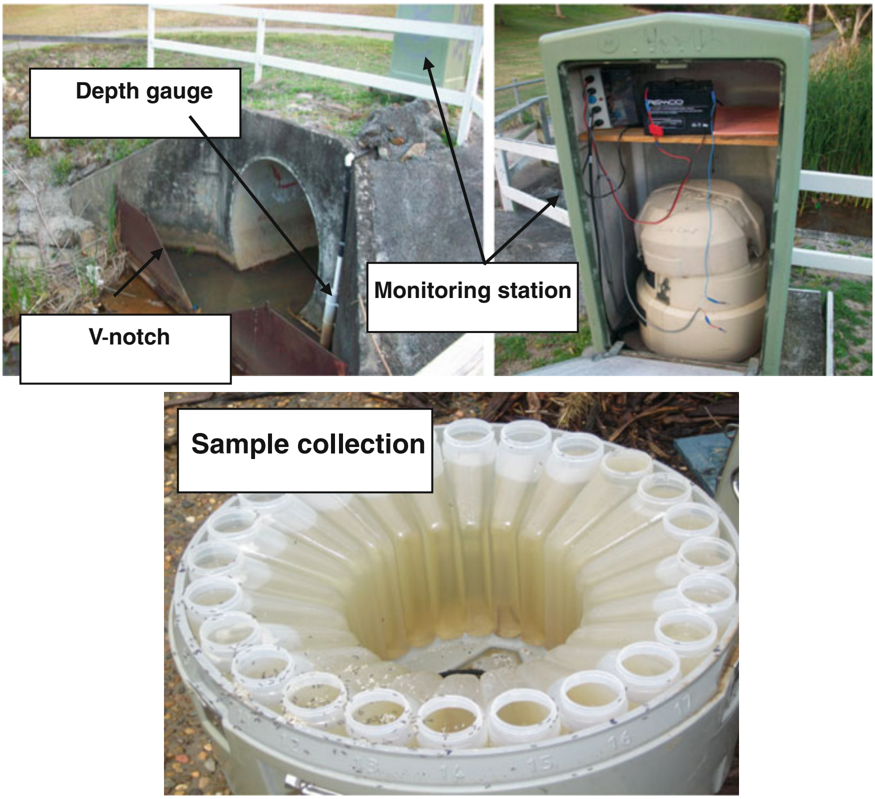


Fig. 3.2 Monitoring station

Table 3.2 Sample testing methods

Parameters		Test method (APHA 2005)	Apparatus	Comments
TSS		2540C		
TN	**NO_2^--N**	4500-NO2-B	Smartchem 140; Westco Block Digestor 40/20 (digestion for TP and TKN)	TN = NO_2^- + NO_3^- + TKN
	NO_3^--N	4500-NO3-E		
	TKN	4500-Norg-B		
TP		4500-P–B		
TOC		5310B	Shimadzu TOC-5000A Total Organic Carbon Analyser	

rainfall event considered. Accordingly, the number of applicable rainfall events for the individual catchments was: Highland Park (18), Alextown (21), Gumbeel (17) and Birdlife Park (17), which amounted to 73 datasets in total. Additionally, a further 153 rainfall events, which occurred during the same period as the

41 monitored events, were also included in the case study. These 153 events only had recorded rainfall characteristics. This data was used to validate the outcomes of the analysis undertaken using the selected 41 rainfall events.

3.3 Case Study I-Role of Rainfall Characteristics on Urban Stormwater Quality

This case study focuses on the role of rainfall characteristics on urban stormwater quality. As discussed in Sect. 2.3.2, the current engineering practice is to consider variations in stormwater quality as stochastic parameters without utilising the available knowledge base relating to the linkage between rainfall characteristics and stormwater quality. Such an approach has been a constraint to the effectiveness of stormwater treatment design. In this context, an in-depth understanding of the relationship between rainfall characteristics and stormwater quality can assist in improvements to the modelling approach adopted and thereby enhance the efficiency of stormwater quality treatment strategies.

3.3.1 Selection of Rainfall Characteristics

Selecting appropriate rainfall parameters is necessary for investigating the inherent relationship between rainfall characteristics and water quality. This is because too many correlating parameters can overshadow critical relationships between rainfall characteristics and water quality. For this purpose, a pre-analysis was undertaken to identify appropriate rainfall parameters for more detailed analysis. The rainfall parameters included in the pre-analysis were average rainfall intensity (AgI), initial 10-min average rainfall intensity (II10), maximum rainfall intensity (MaxI), rainfall duration (RD), rainfall depth (RDep) and antecedent dry days (ADD). The summation of the rainfall periods with significant precipitation was considered as the total rainfall duration. The average rainfall intensity was obtained by dividing the total rainfall depth by the rainfall duration. Maximum rainfall intensity and initial rainfall intensity (10-min average) were extracted directly from the rainfall records. Antecedent dry days were determined as the number of days between the individual rainfall events selected, based on the specified minimum intensity threshold criteria.

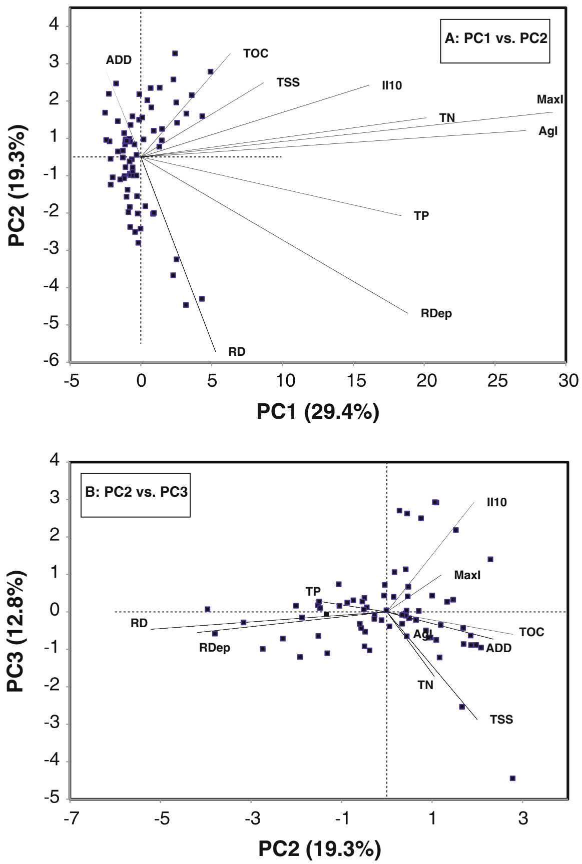
The reason for initially selecting these parameters is that they are common rainfall characteristics which can be used to represent event-to-event differences. The six rainfall parameters, along with pollutant EMC values (TN, TP, TSS and TOC) for the 41 monitored events, were investigated using both, Principal Component Analysis (PCA) and the correlation matrix approach to select appropriate rainfall parameters. A detailed discussion of the PCA technique is provided in Appendix A.

3.3.1.1 Principal Component Analysis (PCA)

PCA is performed on the transformed data by reducing a set of raw data to a number of principal components (PCs). There are as many PCs as the number of variables, but most of the variance is contained in the first few PCs. The number of significant PCs was selected using the Scree plot method (Adams 1995). PCA is a useful technique to analyse relationships between objects and variables. In this research study, the objects were the monitored rainfall events, while the variables were AgI, II10, RDep, RD, ADD, MaxI and EMC values of TSS, TN, TP and TOC. Accordingly, a data matrix (73 × 10, 18 events for Highland Park, 21 events for Alextow, 17 events for Gumbeel and 17 events for Birdlife Park) was submitted to PCA and the biplots derived are shown in Fig. 3.3. For this analysis, it was found that three PCs were the most appropriate.

Figure 3.3 consists of two biplots where Fig. 3.3a displays the PC1 vs. PC2 biplot and Fig. 3.3b shows the PC2 vs. PC3 biplot. As shown in Fig. 3.3a, b, the first three PCs contain 29.4, 19.3 and 12.8 % of the data variance adding to a total data

Fig. 3.3 PCA biplots for rainfall parameter selection



variance of around 61.5 %. This indicates that the inclusion of PC1, PC2 and PC3 axes in the analysis explains an appreciable part of the data variance.

In Fig. 3.3a, ADD is projected to the negative PC1 axis, whilst other rainfall variables and all pollutant EMCs are projected to the positive PC1 axis. Additionally, the three rainfall intensity values, MaxI, II10 and AgI, show strong correlation with each other and with pollutant EMCs. According to Fig. 3.3b, RD and RDep display a strong correlation as the angle between the vectors is very small. However, ADD is a relatively independent parameter in its definition.

3.3.1.2 Correlation Matrix Analysis

The six rainfall parameters along with pollutant EMC values (TN, TP, TSS and TOC) were also investigated using a correlation matrix based on the 41 monitored rainfall events as shown in Table 3.3, for rainfall parameter selection.

As shown in Table 3.3, three intensity parameters, AgI, II10 and MaxI, display strong correlations (0.737 for AgI-MaxI and 0.668 for II10-MaxI). RD and RDep also display a close correlation with a correlation coefficient of 0.735. RD, RDep and AgI are related to each other in their definition. However, ADD is an independent parameter as it has relatively lower correlation coefficients with the other rainfall parameters (−0.071 for ADD-RDep; −0.204 for ADD-RD; 0.055 for ADD-AgI; −0.061 for ADD-MaxI; 0.003 for ADD-II10).

Based on the outcomes of the PCA and the correlation matrix, the three rainfall intensity parameters (II10, MaxI and AgI) were found to closely correlate with each other while RD and RDep also show a close correlation. Furthermore, RD, RDep and AgI are essentially correlated with each other in their definition. However, ADD is relatively independent in its definition and has relatively lower correlation coefficients with the other rainfall parameters. Therefore, in order to avoid too many correlating variables, MaxI, II10 and RDep were removed from the analysis and AgI, RD and ADD were included in further analysis.

Table 3.3 Correlation matrix for rainfall parameter selection

	RDep	RD	AgI	ADD	II10	MaxI	TN	TP	TSS	TOC
RDep	1.000	0.735	0.398	−0.071	0.023	0.341	0.203	0.424	−0.008	−0.063
RD		1.000	−0.026	−0.204	−0.148	−0.005	−0.063	0.131	−0.106	−0.181
AgI			1.000	0.055	0.301	0.737	0.480	0.380	0.234	0.080
ADD				1.000	0.003	−0.061	−0.085	0.036	0.493	−0.085
II10					1.000	0.688	−0.140	0.136	0.330	−0.140
MaxI						1.000	0.090	−0.092	0.199	0.090
TN							1.000	0.207	0.313	0.146
TP								1.000	−0.016	0.074
TSS									1.000	0.173
TOC										1.000

RDep rainfall depth, *RD* rainfall duration, *AgI* average rainfall intensity, *ADD* antecedent dry days, *II10* initial rainfall intensity, *MaxI* maximum rainfall intensity, *TN* total nitrogen, *TP* total phosphorus, *TSS* total suspended solids and TOC total organic carbon

3.3.2 *Relationship Between Rainfall Characteristics and Stormwater Quality*

The 41 rainfall events and selected rainfall parameters were used to initially investigate relationships between rainfall characteristics and stormwater quality using PCA. Rainfall events were considered as objects whilst the average rainfall intensity (AgI), rainfall duration (RD), antecedent dry days (ADD) and the four pollutant EMCs (TSS, TN, TP and TOC) were considered as variables. Accordingly, a data matrix (73 × 7) was generated for PCA and the resulting biplots are shown in Fig. 3.4. Figure 3.4 consists of two biplots where Fig. 3.4a displays the PC1 vs. PC2 biplot and Fig. 3.4b shows the PC1 vs. PC3 biplot. The number of PCs needed for the analysis was determined based on the variance associated with each

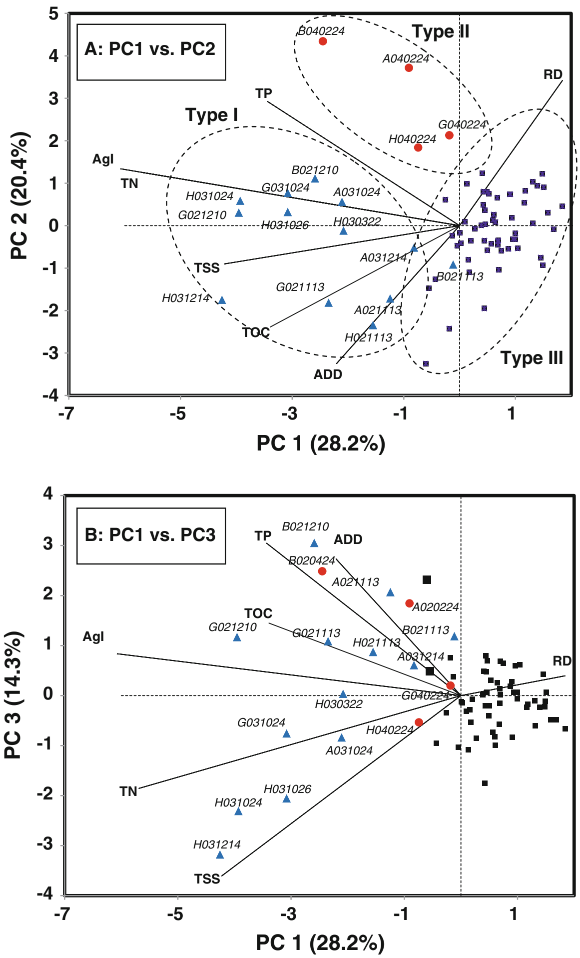


Fig. 3.4 PCA biplots for identifying relationship between rainfall characteristics and stormwater quality (The first letter in the label, A, G, B and H, corresponds to the rainfall events for Alextown, Gumbeel, Birdlife Park and Highland Park catchments, respectively. The six digits following the first letter are the rainfall event date. For example, B020224 represents the rainfall event which occurred on 24 February, 2002 at Birdlife Park catchment)

PC as indicated by a Scree plot (Adams 1995). The first three PCs contain 28.2, 20.4 and 14.3 % of data variance, with the total data variance explained by the PCs being 62.9 %. This implies that the inclusion of PC1, PC2 and PC3 axes in the analysis explains an appreciable data variance.

As shown in Fig. 3.4a, all rainfall events form three clusters in the PC1 vs. PC2 biplot and the clustering is based on rainfall characteristics rather than the four study catchments. The three clusters were named as Type I, Type II and Type III. A significant number of Type III (labelled as squares) rainfall events are positioned at the positive PC1 axis and clustered together while nearly all of the Type I (labelled as triangles) and all Type II (labelled as circles) rainfall events are on the negative PC1 axis and relatively scattered. This means that Type I and Type II events tend to generate high variation in water quality, while Type III produces relatively low variation.

Both, Fig. 3.4a, b show that the AgI and ADD vectors and pollutant EMC vectors point in the same direction. This result indicates that AgI and ADD are positively correlated with pollutant EMCs. Therefore, it can be concluded that high average rainfall intensity and long antecedent dry days can generate relatively high pollutant EMCs. In contrast, the RD vector pointing to the opposite implies that RD is negatively correlated with pollutant EMCs. This implies that longer rainfall duration could lead to the runoff dilution effect. Since most of the pollutants are commonly removed by runoff at the initial stage due to the occurrence of first flush (Alias et al. 2014), the pollutant concentrations in the later part of the runoff hydrograph in a longer-duration event could be relatively low.

Additionally, the AgI vector indicates a close correlation with all pollutant EMCs, while the ADD vector only indicates a close correlation with TOC. These observations confirm that AgI would play a more important role in influencing water quality rather than ADD. In other words, the ability to wash off built-up pollutants has a more significant influence on receiving water quality rather than the pollutant build-up characteristics. The phenomenon can be interpreted as follows.

(1) Pollutant build-up will reach equilibrium after a number of dry days (Egodawatta and Goonetilleke 2006). Accordingly, this will result in little difference in initial pollutant availability at the commencement of each rainfall event. In other words, pollutant build-up loads could be relatively similar before the occurrence of rainfall. In this case, stormwater quality is dictated by the ability of a rainfall event to remove pollutants;
(2) In the case of relatively low intensity rainfall events, due to low kinetic energy, only a fraction of built-up pollutants will be washed off. Therefore, stormwater quality is limited by the capacity of the rainfall for removing and transporting pollutants rather than the initially available load.

Table 3.4 gives the correlation matrix for the dataset used in the study. It can be seen that AgI shows positive correlations with all pollutants and the highest correlation values are with TN, TP and TSS EMCs, respectively (0.480 for TN-AgI, 0.380 for TP-AgI and 0.234 for TSS-AgI) whilst ADD shows the highest correlation with TOC EMC (0.197 for TOC-ADD). RD displays negative correlation

Table 3.4 Correlation matrix for rainfall classification

	RD	AgI	ADD	TN	TP	TSS	TOC
RD	1.000	−0.026	−0.204	−0.063	0.131	−0.106	−0.181
AgI		1.000	0.055	0.480	0.380	0.234	0.080
ADD			1.000	−0.085	−0.140	0.090	0.197
TN				1.000	0.207	0.313	0.146
TP					1.000	−0.016	0.074
TSS						1.000	0.173
TOC							1.000

values with most pollutants (−0.063 for TN-RD, −0.106 for TSS-RD and −0.181 for TOC-RD). This further confirms that AgI has a relatively close relationship with pollutant EMCs, followed by ADD, whilst RD has a negative influence on stormwater quality. In addition, TN, TSS and TOC EMCs display a negative relationship with RD whilst TP shows a positive relationship with RD. This implies that the wash-off process for TP is different compared to the other three pollutant species considered.

These analysis results show that rainfall events can be classified based on rainfall characteristics, so that they represent unique water quality characteristics (Type I, Type II and Type III). Additionally, due to the fact that these three clusters are not influenced by the study catchments which have a diversity of characteristics, it confirms that the classification is independent of catchment characteristics. In other words, the rainfall classification is valid, regardless of catchment characteristics.

3.3.3 Classification of Rainfall Events

The analysis in Sect. 3.3.2 classifies rainfall events into three types based on the resulting water quality. A further analysis was needed to be conducted to validate this classification. This was conducted by investigating the original dataset. Accordingly, all the rainfall events were plotted in an Intensity-Frequency-Duration (IFD) plot, which is a common approach used for investigating rainfall characteristics (Rahman et al. 2002; Westra and Sharma 2010). The standard IFD plot was developed based on the methodology provided in Australian Rainfall and Runoff (AR&R 1997). Figure 3.5 shows the IFD plot for the 41 monitored rainfall events as well as the extra 153 rainfall events. It is evident that nearly all of the rainfall events are located below the 1-year ARI curve. Currently, most typical stormwater treatment systems are designed for <1 year ARI rainfall events. This in turn indicates that these selected rainfall events provide a suitable dataset for stormwater quality analysis.

The 41 monitored rainfall events are also separated into three groups in the IFD plot, the same as the results obtained from the PCA. It can be noted from Fig. 3.5 that the extra 153 rainfall events are generally distributed within the envelope created by the monitored 41 events. This further validates the classification

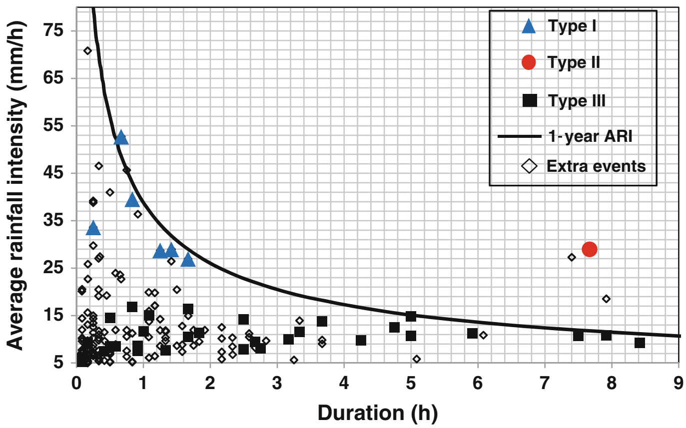


Fig. 3.5 IFD plot for the analysis of the monitored rainfall events

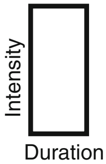
proposed initially using the 41 monitored rainfall events. The characteristics of the classified events, as demonstrated in Fig. 3.5, are as follows:

- Type I events (labelled as triangular) have higher average rainfall intensity (>20 mm/h), but shorter duration (<2 h);
- Type II event (labelled as circular) shows both, high average rainfall intensity (>20 mm/h) and duration (>2 h);
- About half of the Type III rainfall events (labelled as square) display relatively longer duration (>2 h), but lower average rainfall intensity (<20 mm/h).

Table 3.5 gives detailed characteristics of the three rainfall types including average rainfall intensity, rainfall duration and antecedent dry days for the 41 monitored rainfall events. As the PCA confirmed that the rainfall classification is independent of catchment characteristics, the dataset given in Table 3.5 is a combined dataset of the four catchments. According to Table 3.5, there is little difference in the antecedent dry days between the different rainfall types. These conclusions validate the classification of rainfall events into three types on the basis of average rainfall intensity and rainfall duration. For convenience of understanding, the three types can be illustrated with rectangular shapes, as shown in Table 3.5.

In terms of water quality, Table 3.6 shows the pollutant EMC values for the three rainfall types. Type I rainfall events display the highest mean EMC values with 6.85 mg/L, 225.03 mg/L and 14.63 mg/L for TN, TSS and TOC, respectively, whilst Type II shows the highest TP EMC value (3.29 mg/L). Additionally, Type I displays the highest standard deviations for TN, TSS and TOC, whilst Type II has the highest standard deviation for TP. Type III rainfall events do not have high mean values and standard deviations for any pollutants, and in fact have the lowest mean values and standard deviations for TN and TP. In terms of relative standard deviations, Type I indicates the highest values for TN, TP and TSS and the second highest value for TOC, compared to the other two types.

Table 3.5 Characteristics of the three rainfall types

Rainfall events			Average rainfall intensity (mm/h)	Rainfall duration (h)	Antecedent dry days (d)
Type I: High intensity (>20 mm/h)-short duration (<2 h)		021113[a]	26.9	1.6	16.2
		031024	28.9	1.4	4.3
		031214	28.7	1.2	8.0
		021210	39.5	0.8	5.1
		031026	33.6	0.2	2.5
		030322	52.7	0.6	4.1
Type II: High intensity (>20 mm/h)-long duration (>2 h)		040224	28.9	7.6	1.0
Type III: Low intensity (<20 mm/h)-long duration (>2 h)		Mean	9.9	2.4	3.3
		Range	5.3–16.8	0.08–8.4	0.1–26.5

[a]Rainfall event date (For example, 021113 represents the rainfall event which occurred on November 13th, 2002)

Table 3.6 Water quality characteristics of the three rainfall types

Rainfall types	Type I			Type II			Type III		
Parameter	Mean	SD	RSD %	Mean	SD	RSD %	Mean	SD	RSD %
TN (mg/L)	6.85	5.99	87.44	5.1	1.49	29.21	2.19	1.43	65.3
TP (mg/L)	1.16	1.25	107.76	3.29	3.06	93.01	0.55	0.44	80
TSS (mg/L)	225.03	260.89	115.94	83.5	57.33	68.66	92.49	84.21	91.05
TOC (mg/L)	14.63	5.75	39.3	8.816	2.15	24.39	11.36	5.13	45.16

SD standard deviation, *RSD* relative standard deviation

The difference in Type I and Type II, which represents events larger than a certain intensity threshold (such as 20 mm/h), shows that stormwater quality is a step-wise function with rainfall duration. In other words, when the average rainfall intensity is larger than a threshold (20 mm/h in this case study), short-duration events (such as Type I, < 2 h) will generate different stormwater quality from long-duration events (such as Type II, >2 h). Additionally, the difference in Type I and Type III indicates that the pollutant EMC values increase with the increase in rainfall intensity as Type I (high-intensity) events produced higher values than Type III (low-intensity). It is also evident that the influence of rainfall duration on stormwater quality in low-intensity events is minimal, since Type III events have a wide range of durations, but consistently produced lower pollutant EMC values (see Table 3.5 and Table 3.6).

Additionally, it is also evident from Table 3.5 that not all of the high-average-intensity events (Type I and Type II) have relatively long antecedent dry days.

Particularly in the case of two of them, (031026 and 040224), the antecedent dry days are shorter than for over half of the Type III events. However, these events still generated high pollutant EMC values compared to the Type III events. This further confirms the more important influence of rainfall intensity in relation to pollutants wash-off rather than the antecedent dry days.

3.3.4 Summary of Findings

The case study outcomes confirmed the important role of rainfall characteristics on urban stormwater quality. It provides a novel approach to logically classify natural rainfall events into three different types based on average rainfall intensity and duration in the context of water quality. The three types are, high average intensity-short duration (Type I), high average intensity-long duration (Type II) and low average intensity-long duration (Type III). This classification is different from the conventional approach, which is based on water quantity such as ARI. The innovative rainfall classification enables the selection of appropriate rainfall events for stormwater treatment design based on the required treatment outcomes, which may differ between systems, between catchments or the water quality objectives of the receiving water bodies. This approach can also contribute to enhancing water quality modelling and prediction in contrast to conventional approaches where stormwater quality is considered solely as a stochastic variable, irrespective of rainfall characteristics.

Furthermore, current modelling approaches do not consider rainfall duration as a step-wise function and thereby could lead to errors in stormwater quality modelling results. In this context, a modelling approach, which determines stormwater quality based on different rainfall duration thresholds, would be more appropriate instead of the common approach where stormwater quality is considered as a continuous function of rainfall characteristics.

3.4 Case Study II-Role of Catchment Characteristics on Urban Stormwater Quality

This case study focuses on the role of catchment characteristics on urban stormwater quality. Researchers such as Hatt et al. (2004) have pointed out that assigning a pollutant output to a particular land use provides little insight into the processes impacting on water quality. It is hypothesised that conventional catchment characteristics such as land use or impervious surface fraction alone may not adequately explain the complexity of the stormwater quality responses or site-to-site differences in stormwater quality. This highlights the need to include additional catchment characteristics to ensure the accuracy of stormwater quality estimation. Therefore, in the case study, additional catchment characteristics, such as urban form (physical layout and design of the urban areas) and urban area location (spatial distribution of different catchment areas), were considered for detailed analysis (for details on catchment characteristics refer to Fig. 3.1 and Table 3.1), in addition to the conventional catchment characteristics such as land use and impervious surface fraction.

3.4.1 Preliminary Comparison of Stormwater Quality

A preliminary comparison of pollutant EMCs for the four study catchments was undertaken, as shown in Fig. 3.6. The data is the mean pollutant EMC values for each type rainfall event within each catchment. Significant differences in pollutant EMCs among the four catchments can be noted, even though Alextown, Birdlife Park and Gumbeel catchments have the same land use (residential), and Highland Park catchment includes a significant fraction of residential development (refer to Fig. 3.1 and Table 3.1). It is noteworthy that Gumbeel and Alextown have the same impervious area fraction (70 %). Gumbeel has the highest TOC EMC (19.1 mg/L)

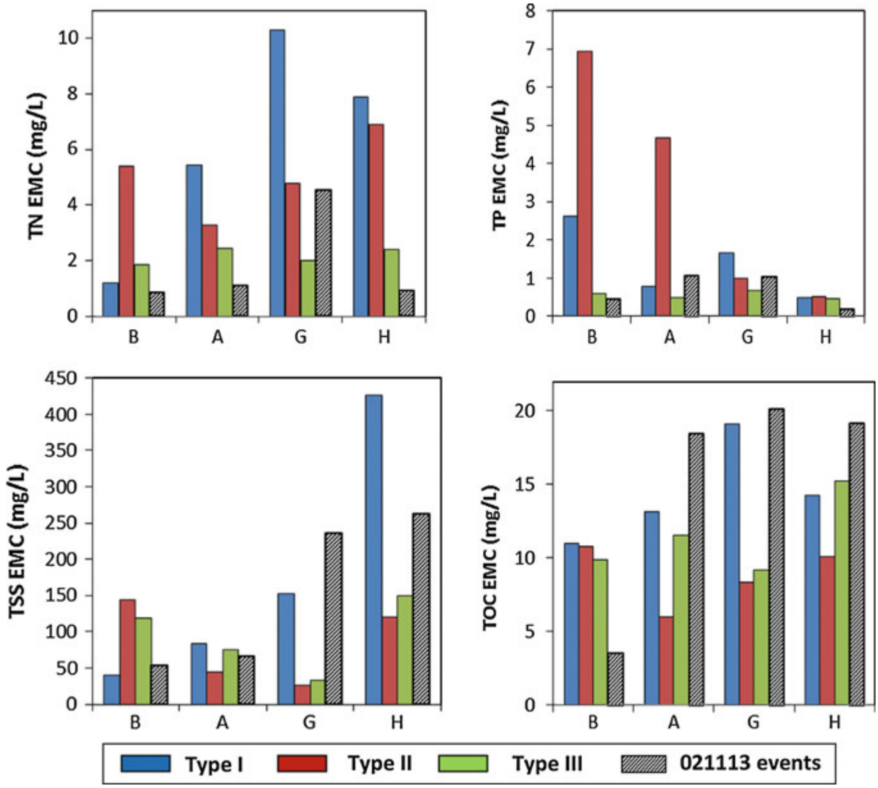


Fig. 3.6 Stormwater quality of the four catchments (*B* Birdlife Park, *A* Alextown, *G* Gumbeel, *H* Highland Park)

and TN EMC (10.3 mg/L) for Type I events while Alextown has much lower EMC values for the same type of rainfall events. Birdlife Park has the highest TP EMCs (6.9 mg/L) for Type II events while Highland Park has the highest TSS EMC (426.8 mg/L) for Type I events. This is despite the fact that Birdlife Park and Highland Park catchments have lower impervious area fractions (see Table 3.1).

Additionally, in order to highlight the difference in stormwater quality originating from the four catchments, the pollutant EMCs generated by the 021113 rainfall event (13 November, 2002), which were recorded for all the four catchments, were also compared. It was evident that there are still significant differences in pollutant EMCs although all catchments experienced the same event. These observations confirmed that the application of land use and impervious area fraction alone have limited ability to determine stormwater quality and additional catchment characteristics need to be taken into consideration. Furthermore, these outcomes also highlight the fact that stormwater quality can be greatly different within the same catchment, because of the influence of rainfall characteristics.

3.4.2 Relationship Between Catchment Characteristics and Stormwater Quality

In order to investigate the relationship between catchment characteristics and stormwater quality, analysis was undertaken on the basis of the impervious area fraction. According to Table 3.1, Alextown and Gumbeel have a relatively higher impervious surface fraction (70 %), while Birdlife Park and Highland Park are lower, with 45.8 and 40 %, respectively. Therefore, the dataset used in the analysis discussed in Sect. 3.3 was re-arranged into two groups on the basis of high (Alextown and Gumbeel) and low (Birdlife Park and Highland Park) impervious area fraction catchments. The rainfall characteristics were removed from this analysis, as the focus was on the influence of catchment characteristics on stormwater quality. The number of applicable rainfall events for the individual catchment was: Highland Park (18), Alextown (21), Gumbeel (17) and Birdlife Park (17), which amounted to 73 events in total.

The investigation was conducted using the multi-criteria decision making (MCDM) method, PROMETHEE (Preference Ranking Organisation Method for Enrichment Evaluation), due to its ability to identify relationships between criteria and actions. PROMETHEE is an unsupervised method for rank-ordering actions based on a number of criteria (Keller et al. 1991) while the GAIA (Graphical Analysis for Interactive Aid) biplot is the result of principal component analysis of the data matrix constructed from PROMETHEE results. A detailed discussion of the PROMETHEE and GAIA method is provided in Appendix A.

The criteria used for this case study were the four pollutant EMC values (TSS, TOC, TN and TP), while the actions were the rainfall events for high (Alextown and Gumbeel) and low (Birdlife Park and Highland Park) impervious area fraction catchments, individually. The two resulting GAIA biplots are given in Fig. 3.7.

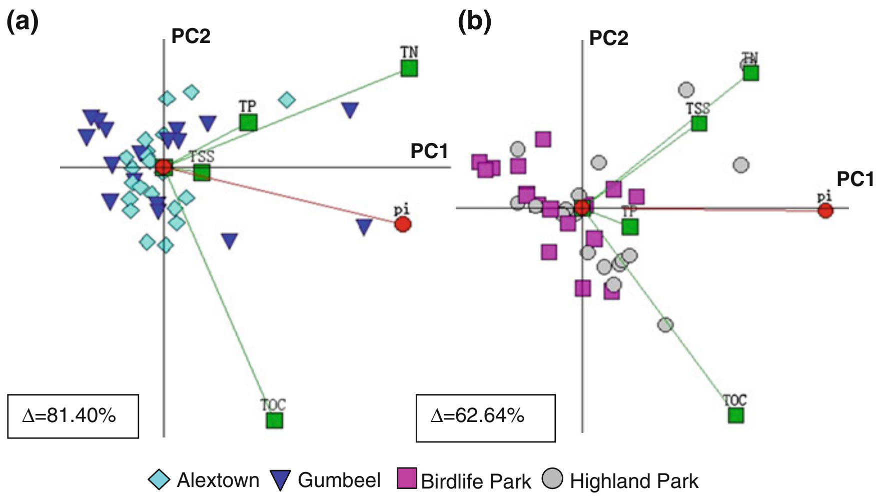


Fig. 3.7 GAIA biplots for the four catchments

3.4.2.1 High Impervious Surface Fraction

Figure 3.7a shows that the data distribution for Alextown and Gumbeel is different. This means that the stormwater quality characteristics of the two catchments are different, although the land use and the impervious area fraction are the same. Alextown data points are more clustered and spread along the PC2 axis. It is also evident that the PC2 axis separates the four pollutant species into two groups; TN and TP are positioned on the positive PC2 axis while TSS and TOC are projected on the negative PC2 axis. Additionally, Gumbeel events are relatively scattered and spread along the PC1 axis, where all pollutants have positive loadings. This indicates that the PC1 axis represents the pollutant EMC values while the PC2 axis represents the difference in pollutant species. This also means that in the case of Alextown (diamond labelled actions are scattered relatively along the PC2 axis), different pollutants would exhibit different wash-off processes. However, the wash-off processes in Gumbeel would be consistent regardless of the pollutant species. This phenomenon is attributed to the layout of the urban developments in the two catchments. Compared to Alextown, the impervious area in Gumbeel is spatially clustered as the access road is the major drainage path (see Table 3.1). This layout results in a shorter travel distance for runoff and hence faster transport of pollutants to the drainage system, resulting in a relatively consistent wash-off process due to the relatively shorter transport time. This would imply that compared to the impervious area fraction, the spatial distribution of impervious surfaces plays a more influential role in urban stormwater quality. Furthermore, Alextown is a townhouse development, which is maintained by a caretaker. However, in the case of Gumbeel, the residences have a varying degree of management and care. This could also be another reason for the relatively higher variation in pollutant EMC values in Gumbeel, in comparison to Alextown.

3.4.2.2 Low Impervious Surface Fraction

According to Fig. 3.7b, Birdlife Park and Highland Park also have different stormwater quality characteristics, even though Birdlife Park is a residential development whilst Highland Park also contains a significant fraction of residential area (see Fig. 3.1 and Table 3.1). Additionally, the impervious surface fractions of the catchments are quite similar (Birdlife Park is 45.8 % and Highland Park is 40 %). However, Highland Park events are more scattered in the GAIA plot than those of Birdlife Park. This implies that Highland Park tends to produce pollutant EMC values with higher variability. Furthermore, it is evident that rainfall events closely related to pollutant vectors are nearly all from Highland Park. This suggests that Highland Park would produce higher pollutant EMC values. These observations can be attributed to the greater complexity of the urban development at Highland Park, since it is a mixed-land-use urban catchment. As Lee et al. (2009) have noted, urban catchments with mixed land use present the worst-case scenario such as higher variability in terms of stormwater quality, since interspersed land uses lead to a complexity of drainage connections and more extended road systems to connect different land parcels.

3.4.3 Summary of Findings

The analysis outcomes illustrate the important role of other catchment characteristics such as urban form and impervious area layout in influencing pollutant wash-off, rather than solely land use and impervious area fraction. This means that only using a limited number of parameters, such as used in current modelling approaches, may not accurately represent the catchment characteristics. This could lead to errors in water quality estimation. Therefore, additional influential parameters in relation to catchment characteristics should be incorporated into modelling.

The research outcomes confirmed that conventional catchment characteristics alone, namely, land use and impervious fraction, are inadequate for providing a comprehensive understanding of stormwater quality characteristics. Therefore, modelling approaches based solely on these two parameters can lead to inaccurate predictions and thereby compromise the efficiency of stormwater quality treatment design. It was found that urban form also plays an important role in stormwater quality. This highlights the need to take urban form into account in stormwater quality modelling and prediction.

3.5 Conclusions

This chapter provides two case studies to illustrate the role of rainfall and catchment characteristics on urban stormwater quality. Based on the outcomes of an in-depth analysis of monitored rainfall-runoff and stormwater quality data, it was evident that urban stormwater quality is highly influenced by both, rainfall and catchment characteristics.

In terms of rainfall characteristics, natural rainfall events can be classified into three types according to average rainfall intensity and rainfall duration. The innovation in this classification is due to its implications for water quality modelling, which is different from the conventional quantity-based approach. This innovative approach can contribute to enhancing water quality modelling and prediction compared to conventional approaches, where stormwater quality is considered solely as a stochastic variable irrespective of rainfall characteristics, and will help to strengthen stormwater treatment design strategies. In terms of catchment characteristics, the research outcomes confirmed the inadequacy of solely using conventional catchment characteristics, such as land use and impervious surface fraction, to determine stormwater quality. It is recommended that additional characteristics, such as urban form and urban area location, should also be taken into consideration when estimating stormwater quality.

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Chapter 4
Practical Application of Study Outcomes for Stormwater Treatment Design

Abstract This chapter focuses on translating the new knowledge created in relation to the influence of catchment and rainfall characteristics on stormwater quality, into practical application. In the first practical application, an approach consisting of a three-component model for water quality modelling is discussed. Additionally, a technically robust approach for selecting appropriate rainfall events for treatment system design is presented. As the proposed approach takes into consideration stormwater quantity and quality, it provides guidance for rainfall event selection in relation to different treatment objectives, land area available and cost-effectiveness. Based on confirmation that there is high variability in pollutant build-up even within the same land use, the second practical application shows that considering land use as a lumped parameter could contribute to significant uncertainties in stormwater quality modelling outcomes. This underlines the importance of taking site specific characteristics into account when undertaking uncertainty analysis of stormwater quality models or in interpreting the modelling outcomes.

Keywords MIKE URBAN model · Stormwater pollutant processes · Stormwater quality · Stormwater treatment design · Water quality modelling

4.1 Background

Previous chapters have discussed the role of rainfall and catchment characteristics on urban stormwater quality. The discussions have been extended to introduce new concepts including the classification of rainfall events to reflect the difference in the stormwater quality they generate. In this context, it was confirmed that natural rainfall events can be classified into three types based on their influence on urban stormwater quality. It has also been pointed out that the conventional approach of using land use and impervious surface fraction alone is incapable of accurately estimating stormwater quality for a given catchment. Additional catchment

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characteristics representing site specific characteristics, including urban form and urban area location, should also be incorporated into the analysis.

This chapter focuses on the translation of the new knowledge into practical application for stormwater treatment design. In this regard, two key practical applications form the primary focus. The first is in relation to the selection of appropriate rainfall events for effective treatment design, while the second is in relation to the use of parameters in stormwater quality modelling to represent the variability in pollutant build-up. Rather than discussing these as facts, key concepts in the practical applications and their usability are demonstrated in the form of two pilot studies.

4.2 Practical Application I-Selecting Rainfall Events for Treatment Design

As discussed in Chap. 2, the conventional approach to stormwater treatment system design is to consider stormwater quality variations as stochastic, regardless of the nature of the rainfall event. Adopting such an approach can lead to inaccurate water quality predictions and ineffective treatment system design.

In this context, a holistic approach to select rainfall events for treatment design based on both, stormwater quantity and quality is needed in order to achieve an efficient design. Additionally, the proposed approach for selecting design events requires taking into account the important role played by rainfall characteristics on stormwater quality. Furthermore, selecting appropriate rainfall events should be done according to the real-world situation and treatment objectives, which can differ between catchments, targeted pollutants, land area available and budget.

Underpinned by the new knowledge presented in Chap. 3, the selection of appropriate rainfall events for treatment design is described, based on stormwater quality and quantity. The selection approach presented in this chapter is based on extensive hydrologic and stormwater quality modelling. Development of the selection approach is demonstrated by outlining the model development, model simulations and analysis of results. In this regard, modelling was undertaken for rainfall events recorded for a representative year and for catchments described in the case study area discussed in Chap. 3. Undertaking an extensive modelling exercise provided the basis for developing a statistical method for selecting rainfall events in the context of both, stormwater quantity and quality.

4.2.1 Modelling Approach

A series of models were used to develop the approach for rainfall event selection. The series of models consisted of three components to simulate catchment hydrology, pollutant build-up and pollutant wash-off. The decision to use a

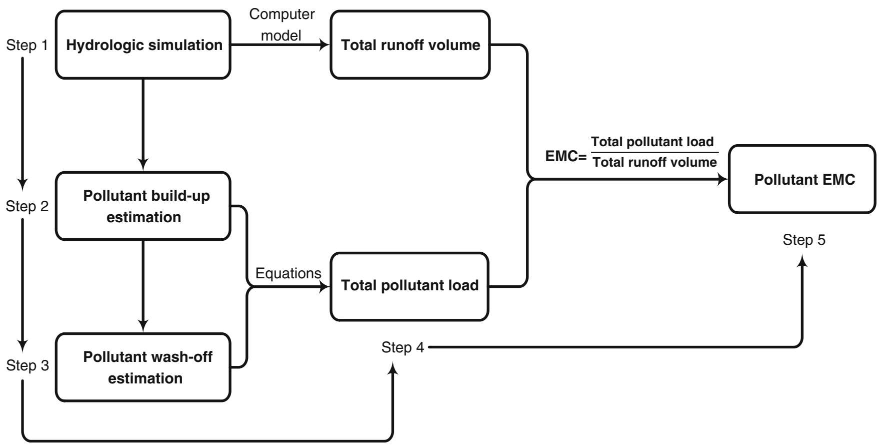

Fig. 4.1 The three-component modelling approach

three-component model rather than a commercially available model was due to the fact that current commercial water quality models are not sensitive to all the rainfall characteristics that were considered important, as discussed in Chap. 3. Consequently, this results in difficulties in investigating the relationship between a range of rainfall characteristics and stormwater quality with the use of currently available stormwater quality models. In this context, the combined application of numerous models focusing on different pollutant processes was the preferred option in order to ensure that the adopted models are sensitive to all of the investigated rainfall characteristics. The models used as well as the modelling steps are illustrated in Fig. 4.1.

The estimations of stormwater quality were undertaken for the four study catchments, Alextown, Gumbeel, Birdlife Park and Highland Park, which are the same as previously discussed in Chap. 3. The outcomes were used to validate the sensitivity of the three-component model in relation to the important rainfall parameters. This was to ensure that the three-component model could be applied for rainfall event selection. In the modelling process, the total solids (TS) were considered as the indicator pollutant representing stormwater quality. Even though TS does not actually represent all of the different types of stormwater pollutants as the dissolved pollutant fraction is not attached to solids (refer to Sect. 2.4.3), this analysis focused on particulate pollutants. This is because rainfall characteristics primarily influence pollutants transportation, and particulate pollutants wash-off is transport limiting. Secondly, stormwater quality treatment devices are commonly designed to remove particulate pollutants.

The three-component modelling approach was performed based on the following five steps:

Step 1 Hydrologic simulation: for simulating the runoff volume generated from the catchment area;
Step 2 TS build-up estimation: for estimating TS loads accumulated during the dry periods;
Step 3 TS wash-off estimation: for estimating the fraction of TS load transported by runoff;
Step 4 TS loads estimation: for estimating the TS loads transported by runoff;
Step 5 TS EMC calculation: for determining the TS EMC.

4.2.1.1 Hydrologic Simulation

MIKE URBAN, which is developed by the Danish Hydraulic Institute (DHI) (MIKE URBAN 2008), was selected to simulate runoff volume after a rigorous review of commonly-used models in Australia. A detailed description of the MIKE URBAN model is provided in Appendix B. The MIKE URBAN model was set up for the four catchments. Based on trial and error, the models were calibrated and validated for the four catchments. Detailed information on the model set up and the calibration and validation procedure adopted is also provided in Appendix B.

4.2.1.2 Build-up Estimation

The build-up equation (Eq. 4.1) developed by Egodawatta (2007) was used to estimate the pollutants accumulated during dry periods. The equation was developed based on the same catchments as the study sites in this research study. Additionally, the TS build-up was calculated based on antecedent dry days. This ensured the sensitivity of the models to antecedent dry days. The two sets of coefficients were applied based on low-population-density and high-population-density catchments.

$$y = \min\left(c, a\mathrm{D}^{b}\right) \tag{4.1}$$

where

a Build-up rate (g/m^2/d), 2.90 and 1.65 for high and low density catchments
b Time exponent, 0.16 for both high and low density catchments
c Maximum build-up load (g/m^2), 4.72 and 2.69 for high and low density catchments
D Antecedent dry days (d)
y build-up load (g/m^2)

Alextown and Gumbeel catchments are townhouse and duplex housing developments, respectively (see Fig. 3.1), and thereby considered as high-population-density catchments. Birdlife Park catchment is a detached housing development and considered as a low-population density catchment (see Fig. 3.1). Highland Park is a mixed-land-use catchment. Therefore, the Highland Park catchment was divided into a number of subcatchments based on high and low population densities. Then, the two sets of parameters (for high and low population density catchments, see parameter definitions in Eq. 4.1) were used for the different subcatchments and the total build-up load was the summation of the subcatchment build-up loads.

The antecedent dry days were used in Eq. 4.1 to calculate the build-up load per unit area. The total build-up load for each catchment was obtained by the build-up load per unit area multiplied by the total catchment area and impervious surface fractions. The outcomes were further used for estimating pollutant wash-off loads.

4.2.1.3 Wash-off Estimation

The wash-off equation (Eq. 4.2), developed by Egodawatta et al. (2007), was used to estimate TS wash-off. The equation for estimating pollutant wash-off was selected taking into consideration the sensitivity of the wash-off process to rainfall intensity. This wash-off equation is based on the principle that only a fraction of pollutants built up on the catchment surface will be washed off and the capacity for wash-off (capacity factor, C_F) is influenced by the rainfall intensity as illustrated in Table 4.1 (refer to Fig. 2.7).

$$\mathrm{Fw} = \frac{W}{W0} = C_F\left(1 - e^{-KIt}\right) \tag{4.2}$$

where

Fw Wash-off fraction
W Weight of the material washed off after time t
$W0$ Initial weight of the material on the catchment surface
C_F Capacity factor
I Rainfall intensity
K Wash-off coefficient

Table 4.1 Wash-off parameters (Egodawatta et al. 2007)

Parameters	Intensity range (mm/h)	Value
Capacity factor (C_F)	5–40	$(0.01 \times I) + 0.1$
	40–90	0.5
	>90	$(0.0098 \times I) - 0.38$
Wash-off coefficient (K)	All intensities	8×10^{-4}

I rainfall intensity

Based on the estimated TS build-up load on the catchment surfaces during the antecedent dry days and wash-off fraction for each rainfall event, the TS wash-off load for each rainfall event was obtained by multiplying the build-up load (Step 2, refer to Fig. 4.1) by the corresponding wash-off fraction (Step 3). TS EMC (mg/L) for each rainfall event was obtained by the TS wash-off loads (Step 4) divided by the total runoff volumes simulated by the MIKE URBAN model (Step 1). Detailed information on the calibration and validation of the water quality estimations is provided in Appendix B.

4.2.2 The Three-Component Model Validation

Validating the three-component model was undertaken by comparing the relationship between simulated TS EMC and rainfall characteristics with the relationship between monitored TS EMC (see Sect. 3.3) and rainfall characteristics. This was to assess the sensitivity of the three-component model to important rainfall characteristics. Principal Component Analysis (PCA) was selected as the analytical tool.

The 41 rainfall events used in Chap. 3 were simulated by the three-component model for each catchment. Consequently, the modelling results included 41 TS EMCs for each catchment. Additionally, average rainfall intensity (AgI), rainfall duration (RD), and antecedent dry days (ADD) were also available for the 41 rainfall events. These rainfall events were taken as objects in PCA whilst AgI, RD, ADD and TS EMC were considered as variables. Consequently, a matrix (164 × 4, 41 rainfall events for each catchment) was generated for PCA. As shown in Fig. 4.2, a total data variance of 67.5 % is explained by PC1 and PC2, and hence was considered to be adequately representative of the variance in the data.

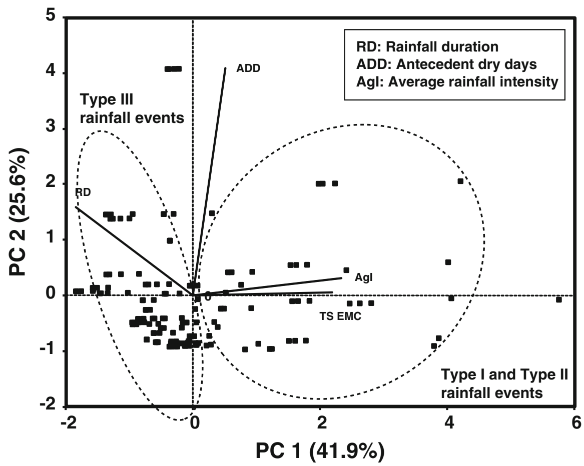

Fig. 4.2 Validating the three-component model

It is evident from Fig. 4.2 that all objects are clustered into two groups based on the PC1 axis. Most of the Type III rainfall events (low average intensity-long duration) are positioned on the negative PC1 axis and clustered together whilst Type I (high average intensity-short duration) and Type II (high average intensity-long duration) rainfall events are positioned on the positive side of the PC1 axis and are relatively scattered. Additionally, the average rainfall intensity (AgI) vector forms an acute angle with the TS EMC vector, followed by antecedent dry days (ADD) vector, whilst the rainfall duration (RD) vector is almost in the opposite direction to the TS EMC vector. Furthermore, both AgI and ADD as well as TS EMC vectors are projected on the positive PC1 axis whilst RD is projected on the negative PC1 axis.

It is noteworthy that the modelling outcomes show similar relationships between rainfall characteristics and stormwater quality as the data analysis in Chap. 3, where the data was obtained from the rainfall-runoff and water quality monitoring program (refer to Sect. 3.2). The TS EMC is strongly related to the average rainfall intensity, followed by antecedent dry days whilst rainfall duration is negatively correlated to TS EMC. The agreement in results between simulated data and monitoring data implies that the three-component model is sensitive to all important rainfall characteristics (average rainfall intensity, antecedent dry days and rainfall duration). Therefore, the three-component model with hydrologic, build-up and wash-off components has good ability to represent the relationship between rainfall characteristics and stormwater quality and hence can be used for rainfall event selection.

4.2.3 Selecting Rainfall Events in a Representative Year

For stormwater treatment design, it was important to select a representative year where the rainfall characteristics are typical for the study region, because the annual pollutant load is one of the most important parameters applied to determine pollutant export from a given catchment. By confirming the suitability of the three-component model, the same modelling approach was used to simulate long-term stormwater quality, in this case for a representative year.

Two key criteria were adopted in selecting the representative year. Firstly, the rainfall events occurring in the selected representative year were required to have moderate characteristics rather than extreme characteristics such as extremely high rainfall amounts or rainfall frequency. Secondly, it was essential that the representative year should include the three rainfall types as identified in Chap. 3, in the context of stormwater quality.

The annual rainfall depth and the number of rainfall events which occurred each year were extracted from the rainfall records for the study area for the period 1992–2010. Figure 4.3 shows the annual rainfall depth and the number of rainfall events over this period. It was found that the average annual rainfall depth in the period of 1992–2010 was 1352.7 mm for the investigated period, whilst the average number of rainfall events occurring in 1 year was 132. The characteristics of rainfall events in 2003 were the closest to both, the average annual rainfall depth and the

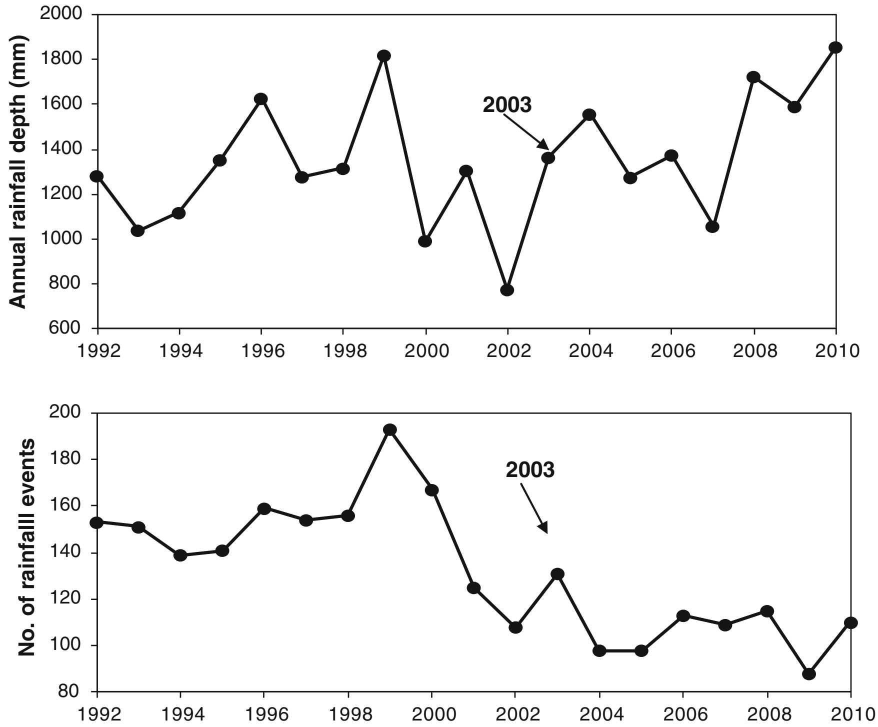

Fig. 4.3 Rainfall events over the period of 1992–2010

number of rainfall events; 1363.7 mm and 131 events, respectively. Therefore, the rainfall events in 2003 generally met the first selection criterion and were further analysed in order to ensure that the three rainfall types were present within the dataset.

Among the 131 rainfall events that occurred in 2003, there were 65 rainfall events where the rainfall intensity was less than 5 mm/h. This means that these rainfall events were unlikely to produce significant pollutant loads. As noted by Egodawatta (2007), low intensity rainfall is less effective in dislodging pollutants from urban surfaces due to reduced kinetic energy. Based on this hypothesis, the remaining 66 rainfall events were considered for further analysis. Accordingly, the rainfall characteristics including average rainfall intensity, rainfall duration and antecedent dry days were extracted for the selected 66 rainfall events.

The 66 rainfall events were plotted on Intensity-Frequency-Duration (IFD) curves as shown in Fig. 4.4. Fifteen events (shown as diamond shapes) have a relatively high average intensity (more than 20 mm/h), but short duration (less than 1.5 h), whilst 50 events (shown as circle shapes) have a lower average intensity (less than 20 mm/h) and most of them have relatively long duration. One event (shown as a square shape) has an average intensity of 27.3 mm/h and 7.4 h duration. It was found that the rainfall events in 2003 encompassed the three rainfall types, namely high average intensity-short duration (Type I), high average intensity-long

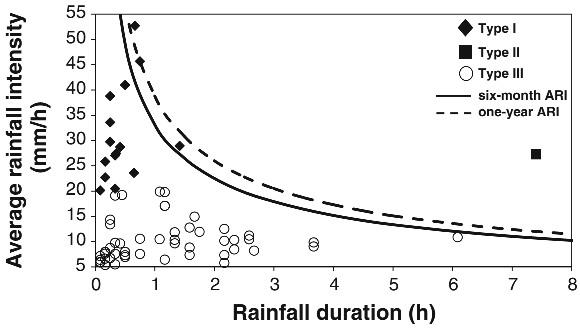

Fig. 4.4 IFD plot for rainfall events in 2003

duration (Type II) and low average intensity-long duration (Type III). Therefore, 2003 was considered appropriate for selection as the representative year for the envisaged investigations.

4.2.4 Analysis of Modelling Outcomes

The selected 66 rainfall events in 2003 were modelled using the validated three-component model to generate both, runoff volume and TS loads for the four study catchments. The cumulative simulated runoff volumes and TS loads for the different rainfall types were determined by the addition of all runoff volumes and loads derived for the four catchments within the same rainfall type. Figure 4.5 provides a comparison of the percentages of TS load and runoff volume generated by the Type I, Type II and Type III rainfall events for all four catchments, together with the number of rainfall events of each type.

As shown in Fig. 4.5, although the number of Type I rainfall events only accounts for 22.7 % of all rainfall events, they generated 58.0 % of the TS load. The total runoff volume from Type I events only accounts for 29.1 %. This means that compared to the other two types, Type I rainfall events (high average intensity-short

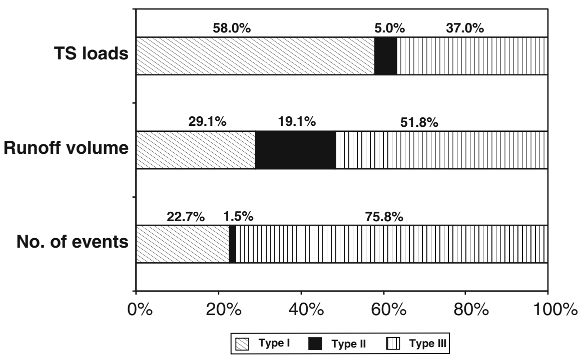

Fig. 4.5 Comparison of the three types of rainfall events

duration) are responsible for most of the pollutant export from a catchment. This is despite the fact that Type I events occur relatively less frequently. Type II events occur even more rarely and only produced 5 % of TS load, but generated 19.1 % of the runoff volume. Type III events occur more frequently, but do not generate high pollutant loads.

These observations imply that focusing on the Type I events, which are high average intensity-short duration rainfall events, can lead to greater efficiency in stormwater treatment system's performance due to their greater pollutant generation ability. This can be further supported by the relatively smaller total runoff volume generated by Type I events. This is due to the fact that a smaller runoff volume can be effectively captured by the treatment system, whilst a larger runoff volume may significantly bypass the treatment system without achieving the desired removal of pollutants.

An effective stormwater treatment design should take both, quality and quantity into consideration. Although Type I (high average intensity-short duration) rainfall events should be targeted by stormwater treatment design, not all of these rainfall events can be captured effectively by treatment systems due to the fact that a large runoff volume may flow through the treatment system at relatively high velocity, resulting in little residence time for adequate treatment. This implies that stormwater treatment should also be designed based on an appropriate runoff volume rather than based on the concept, "the bigger, the better", in the context of treatment efficiency and cost-effectiveness. In this context, other than rainfall types, a threshold in relation to runoff volume should be used in selecting rainfall events as well. This means that the rainfall events larger than the threshold are not considered in the treatment design due to their large runoff volume. The rainfall events less than the threshold will generate most of the total annual runoff volume and will also include a significant fraction of the exported pollutant load. This ensures that a significant fraction of the runoff volume and pollutant load can be effectively subjected to treatment.

As shown in Fig. 4.4, most of the rainfall events are less than 1-year ARI. This may also mean that an ARI less than 1-year could be appropriate in terms of stormwater quality treatment design. Consequently, 6-month ARI was also investigated in relation to the suitability of such rainfall events in stormwater treatment system design. Figure 4.6 compares the total runoff volume and TS loads for the rainfall events above 6-month ARI (four events, accounting for 6 %) and below 6-month ARI (62 events, accounting for 94 %) for the four catchments combined. It is evident that rainfall events below 6-month ARI generate 68.4 % of annual total runoff volume and include 68.6 % of the TS load exported.

These observations suggest that rainfall events less than 6-month ARI produce most of the runoff volume with most of the pollutant load. Furthermore, it further confirms that stormwater treatment design based on larger rainfall events may not provide a satisfactory cost-benefit outcome. The rainfall events less than 1-year ARI, such as 6-month ARI, could be targeted in stormwater treatment design. In this regard, treating frequent rainfall events should be the preferred option since their benefits include efficiency in treatment performance, cost-effectiveness and possible savings in land area needed.

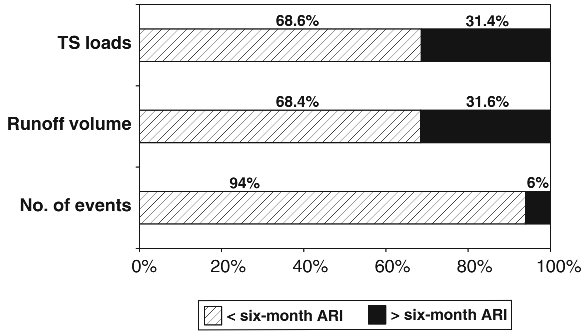

Fig. 4.6 Comparisons based on 6-month ARI

4.2.5 Summary of Findings

This section provides a robust approach to selecting rainfall events for treatment design using the three-component model, which consists of a hydrologic model and pollutant build-up and wash-off equations. This three-component model shows appropriate sensitivity to all important rainfall characteristics such as rainfall intensity, rainfall duration and antecedent dry days and hence is capable of undertaking robust simulations based on the relationship between rainfall characteristics and stormwater quality.

The analysis outcomes indicate that selecting smaller ARI events with high intensity-short duration as the threshold for the design of treatment systems is the feasible approach, since these events cumulatively produce a major fraction of the annual pollutant load compared to the other types of rainfall events, despite producing a relatively smaller runoff volume. This confirms that designs based on smaller and more frequent rainfall events rather than larger rainfall events would be appropriate. Such an approach takes both, stormwater quantity and quality into consideration and hence can be a guide for selecting appropriate rainfall events in the context of different treatment objectives, land area available and budget.

4.3 Practical Application II-Understanding Variability in Pollutants Build-up

Previous chapters have noted that the conventional approach to defining catchment characteristics using only land use does not help to accurately characterise stormwater quality. Accordingly, modelling approaches based solely on land use will diminish the accuracy of modelling outcomes and hence misguide treatment design.

As the primary catchment characteristic, land use is the key input parameter in current water quality models and is typically considered as a lumped parameter and pollutant build-up loads are assigned accordingly. However, there can be significant variability in build-up characteristics even within the same land use due to site-specific characteristics such as differences in traffic characteristics, road surface conditions and various anthropogenic activities. The possible spatial variation in build-up even within the same land use can exert changes in temporal variations in the pollutant wash-off load at the catchment outlet. Therefore, this practical application serves to illustrate how to quantify this variability and to identify which build-up parameter/s tend to be more highly variable within the same land use. This can assist in adequately interpreting the water quality modelling results relevant to modelling uncertainty and thereby contribute to effective stormwater treatment design.

4.3.1 Study Sites

The study sites were identified from three suburbs located at Gold Coast, southeast of the Queensland State capital, Brisbane, Australia (see Fig. 4.7). The study sites included three typical urban land uses, namely, residential, commercial and industrial. The land use characteristics are shown in Table 4.2. For each land use, four asphalt paved road surfaces were selected for pollutant build-up sampling.

4.3.2 Sampling and Parameters Investigated

Build-up samples were collected from 1.5 m × 2 m plots using a dry and wet vacuum system (see Fig. 4.8). The validity of the collection methodology has been confirmed in previous research studies (Herngren 2005). Before using the vacuum system, all component parts including the water compartment, hoses and vacuum foot were cleaned with deionised water. A measured amount of 3 L of deionised water was poured into the water compartment as the filtration medium. A deionised water sample was taken as a field blank. In dry sampling, the surface was vacuumed three times in perpendicular directions. Then deionised water was sprayed on the surface without creating any wash-off (see Fig. 4.8b). Wet sampling was undertaken to collect dislodged pollutants during the wetting process. The same vacuuming procedure as for the dry sample collection was used. As the last step, the sample was transferred into a polyethylene container along with the residue after washing all the vacuum system components including the water compartment, hoses and brush. Deionised water was used for washing.

Two build-up samples were collected from each road surface in order to represent two different antecedent dry days. Consequently, a total of 24 build-up samples were collected from 12 road surfaces representing three typical urban land uses, namely, residential, industrial and commercial. The average road surface

Fig. 4.7 Study sites, **a** study site location (from Google Map), **b** the three land uses

texture depths were measured using the Austroads Method No. AGPT-T250-08 (Austroads 2008) and were found to be, 0.815 mm for residential, 0.868 mm for commercial and 1.055 mm for the industrial land use.

The parameters investigated for each sample included D_{10}, D_{50} and D_{90} (mean diameter in 10, 50 and 90 % of total particle volume) representing particle size distribution (PSD) characteristics as well as total nitrogen (TN), total solids (TS), total phosphorus (TP) and total organic carbon (TOC) build-up loads. The testing methods adopted are given in Table 3.2.

Table 4.2 Study site characteristics

Land use	Road sites	Texture depth (mm)	Slope (°)	General site characteristics
Residential	R1	0.76	2.24	Detached houses with small gardens. The roads are used by residents for access and the surface is relatively flat
	R2	0.86	1.32	
	R3	0.84	2.87	
	R4	0.80	1.30	
Commercial	C1	0.90	Flat	A large number of shops, restaurants and hotels; the traffic volume is high; the road surface is relatively flat
	C2	0.62	Flat	
	C3	0.84	Flat	
	C4	1.11	Flat	
Industrial	I1	1.10	5.91	There are diverse industrial enterprises and the road surface is in a poor condition due to usage by heavy vehicles and has been subjected to oil spills
	I2	1.05	1.59	
	I3	0.93	0.72	
	I4	1.14	1.70	

4.3.3 Variability of Pollutant Build-up Parameters

The pollutant build-up parameters derived for the three different land uses are illustrated as boxplots in Fig. 4.9. It is evident that most of the pollutant build-up parameters display a significant range of data values rather than constant values even within the same land use. This underlines the high variability and the resulting uncertainty in stormwater quality modelling outcomes when land use alone is considered as a lumped parameter. Furthermore, Fig. 4.9 illustrates the degree of variability within the same land use and the difference among land use types and the pollutant species. Taking PSD as an example, the industrial land use shows the highest variability except for D_{50}. Residential or commercial land uses display the highest variability for TN, TOC and TP.

These observations are attributed to the highly variable nature of anthropogenic activities and natural processes, even within the same land use. Additionally, the higher variability of PSD in industrial land use implies that surface texture would also be an influential parameter since industrial areas had the highest road surface texture depth (see Table 4.2). Surface roughness can influence processes such as the re-distribution of fine particles. As such, site-specific characteristics such as road surface condition would also be a factor influencing pollutant build-up characteristics even within the same land use.

4.3.4 Correlation Between Land Use and Pollutants Build-up

It was noted in Sect. 4.3.3 that the variability of build-up parameters within the same land use is high. For assessment of underlying uncertainty in water quality

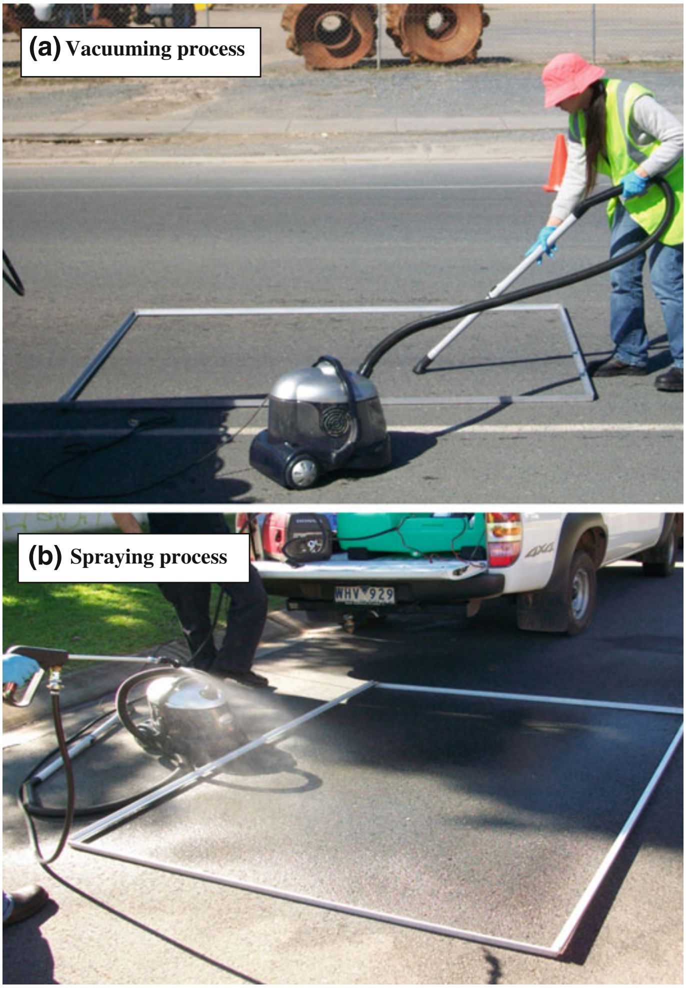

Fig. 4.8 Build-up sample collection

modelling, it is important to compare the degree of variability of build-up parameters within the same land use to the corresponding variability among different land use types. In this context, the multi-criteria decision making (MCDM) method, PROMETHEE, was selected to further investigate the correlation between land use and pollutant build-up. Detailed information on PROMETHEE method can be found in Appendix A. The criteria used for this analysis were TN, TP, TOC and TS loads (g/m^2), while the actions were the 24 build-up samples collected (12 roads with two different antecedent dry days). Accordingly, a matrix (24 × 4) was submitted to PROMETHEE analysis and the GAIA biplot as shown in Fig. 4.10.

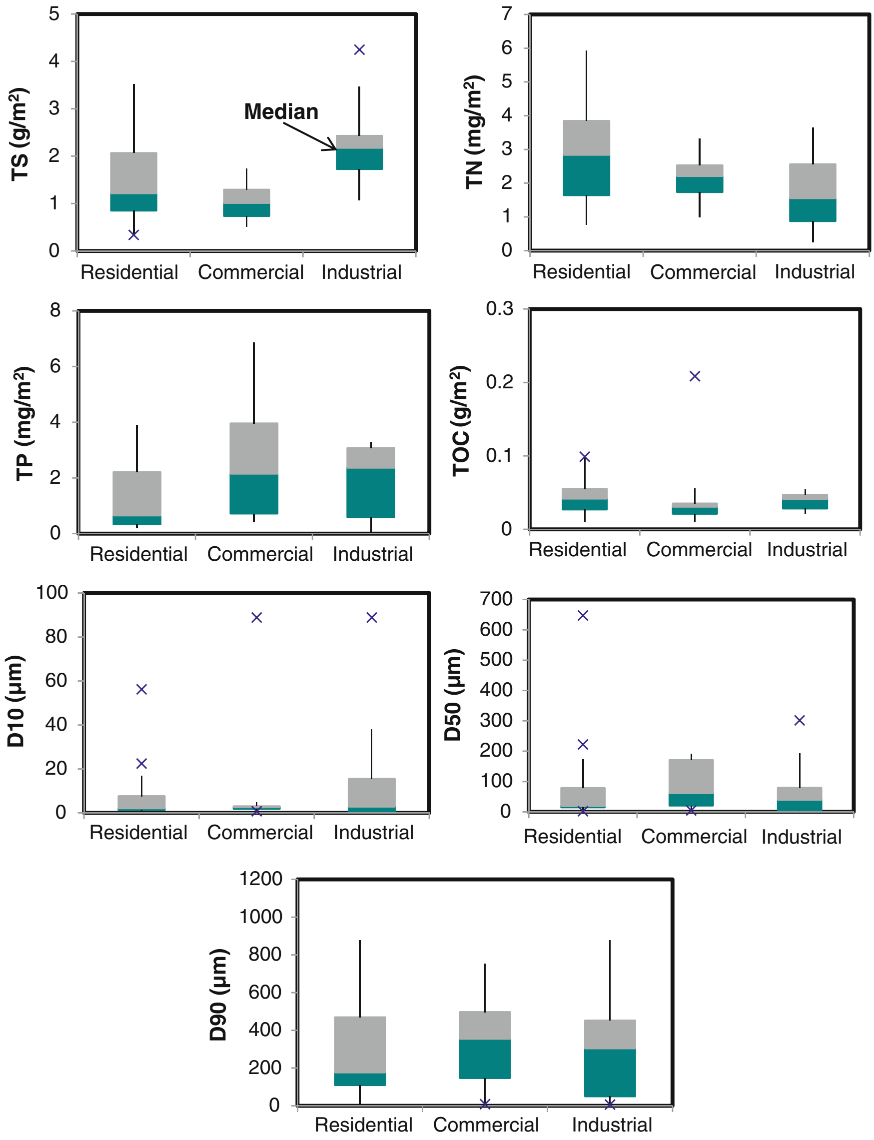

Fig. 4.9 Pollutants build-up for different land uses

According to Fig. 4.10, build-up samples are primarily clustered based on land use types along the PC2 axis. The significant scatter within the same land use is found primarily along the PC1 axis, which is the axis demonstrating the highest variability (Adams 1995). This further confirms that although pollutant build-up parameters are influenced by land use, they are highly variable even within the

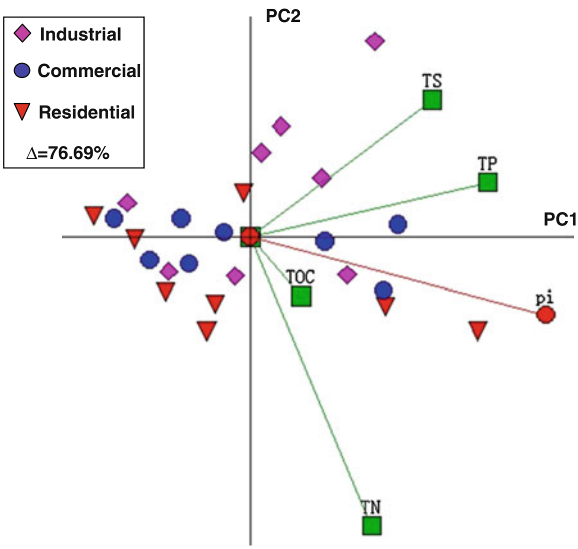

Fig. 4.10 GAIA biplot for pollutants build-up

same land use. This also highlights the fact that the variability related to land use is secondary to the variability within the same land.

Additionally, most of the industrial land use data is scattered in the positive PC2 quadrants, where the TS build-up vectors are also projected whilst TN, TP and TOC vectors are more related to residential and commercial land use data points. These observations mean that industrial land use displays a higher variability in solids build-up whilst residential and commercial land use displays relatively higher variability in nutrients and organic carbon build-up. This confirms that pollutant build-up parameters varies with both, land use type and pollutant species. These outcomes highlight the importance of taking into account the land use type and targeted pollutant species when interpreting modelling results or undertaking uncertainty analysis in relation to stormwater quality models.

4.3.5 Comparing Variability in Pollutant Build-up

A comprehensive analysis of the variability of build-up parameters was considered to be able to further assist in comparing their degree of variability within the same land use. For this purpose, the coefficient of variation (CV) was calculated for each build-up parameter in order to convert their variability to comparable values since these build-up parameters (TN, TP, TSS and TOC loads and D_{10}, D_{50} and D_{90}) do not have a similar value magnitude.

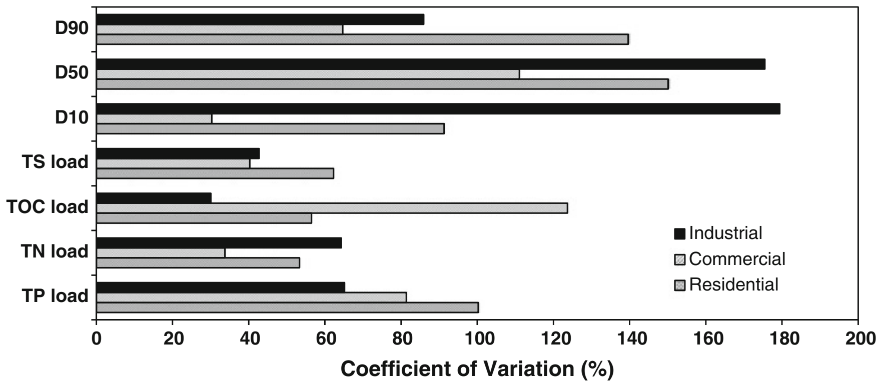

Fig. 4.11 Variability of build-up parameters

Figure 4.11 provides the comparison of the CV values derived for the different land uses and within the same land use. It can be noted that all build-up parameters show relatively high CV values (larger than 25 %) irrespective of land use. This further confirms the high variability of pollutant build-up even within the same land use. As pointed out by Hamburg (1994), a dataset with CV greater than 10 % is considered as having a high variability. Additionally, the parameters (D_{10}, D_{50} and D_{90}) representing particle size distribution tend to be highly variable for all land uses compared to the other parameters. The high variability in particle size distribution illustrates the dissimilarities associated with the small and large particle size fractions even within the same land use. This can lead to differences in stormwater quality in relation to other pollutants adsorbed to different particle sizes.

4.3.6 Summary of Findings

This section investigated the variability of pollutant build-up with land use and within the same land use. It was found that there is significant variability when considering land use as a lumped parameter. For some parameters, such as particle size distribution, variability in pollutant build-up within the same land use was even higher than the variability between different land uses. Therefore, the approach of considering land use as a lumped parameter would contribute to significant uncertainty in stormwater quality modelling results. Furthermore, it is evident that the influence exerted by land use on the build-up characteristics of solids, nutrients and organic carbon is different. These outcomes point to the importance of taking into consideration the site-specific characteristics within a land use and the targeted pollutant species when interpreting stormwater quality modelling outcomes for treatment design.

4.4 Conclusions

This chapter showcases two practical applications of the research study outcomes for stormwater treatment design. The technically robust approach to selecting appropriate rainfall events using the three-component model takes into consideration the influence of rainfall characteristics on stormwater quality, considering both, quantity and quality, and hence can provide a guide to rainfall event selection in relation to different treatment objectives, land area available and cost-effectiveness.

Additionally, it was confirmed that there is high variability in pollutant build-up even within the same land use. Therefore, using land use as a lumped parameter could contribute to significant uncertainties in stormwater quality modelling. It was also found that the variability in pollutant build-up can also be significant depending on the pollutant type. This underlines the importance of taking into account specific land use characteristics and the targeted pollutant species when undertaking uncertainty analysis of stormwater quality models or interpreting the modelling outcomes.

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Chapter 5
Implications for Engineering Practice and Identification of New Areas for Knowledge Creation

Abstract This chapter provides a consolidated summary of the research study outcomes on the role of catchment and rainfall characteristics on stormwater quality. The knowledge created is expected to provide practical guidance and recommendations for stormwater treatment designers, urban planners and hydrologic and stormwater quality model developers. This chapter also discusses briefly key areas where currently there are significant knowledge gaps. These areas include, stormwater reuse, micropollutants in stormwater and the operation and maintenance of stormwater treatment systems.

Keywords Catchment characteristics · Rainfall characteristics · Stormwater pollutants · Stormwater reuse · Stormwater treatment systems

5.1 Implications for Engineering Practice

Urbanisation and the resulting population expansion in urban areas have had significant impacts on the water environment, in the context of both, quantity and quality. Due to enhanced attention on environmental protection, mitigation strategies to improve the quality of urban stormwater runoff are becoming increasingly common in urban areas. In this context, the implementation of effective stormwater quality treatment mitigation strategies is important for urban stormwater management. This is closely dependent on the state of knowledge in relation to the primary factors influencing the quality of urban stormwater. Based on the outcomes of an in-depth research study and underpinned by comprehensive catchment monitoring and statistical data analysis, this research monograph discusses the complexity, analysis and key features inherent in urban hydrology and stormwater quality based on two important influential factors, namely, catchment and rainfall characteristics. Key findings of the research study provide guidance for the development of practical solutions for effective stormwater treatment design and for strengthening the protection of the urban water environment.

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This monograph further provides guidance on engineering practice, including stormwater treatment design and modelling approach development. The implications of the outcomes of the study for engineering practice are discussed. These provide practical guidance and recommendations for stormwater treatment designers, urban planners and hydrologic and stormwater quality model developers.

5.1.1 Implications of the Research Study Outcomes in Relation to Rainfall Characteristics

An innovative approach is provided to logically classify a seemingly chaotic mix of natural rainfall events into three different types, based on the quality and the pollutant load transported by stormwater runoff. The three rainfall types are High average intensity-short duration (Type I); High average intensity-long duration (Type II); and Low average intensity-long duration (Type III). The stormwater runoff resulting from high-average-intensity rainfall events (Type I and Type II) is more polluted, but highly variable whilst it is less polluted and relatively consistent for low-average-intensity rainfall events (Type III). Therefore, in the case of low-average-intensity rainfall events (Type III), it would be much easier to predict the treatment performance due to the low variation in stormwater quality. However, it is important to take into consideration a relatively wider stormwater quality range for high-average-intensity rainfall events (Type I and Type II) in estimating the treatment performance. This innovative classification extends the knowledge base, considering the fact that in the conventional approach to modelling, stormwater quality is considered solely as a stochastic variable, irrespective of the characteristics of the rainfall event. Furthermore, this classification will assist in selecting the appropriate rainfall events for water quality treatment design based on the required treatment outcomes, which may differ between systems, between catchments or the water quality objectives of the receiving water bodies.

The extension of knowledge discussed in this manuscript also demonstrates that the average rainfall intensity exerts a more important influence on stormwater quality than the antecedent dry days. This means that the rainfall characteristics, in other words the ability to wash off built-up pollutants, would have a more significant influence on receiving water quality than pollutant accumulation characteristics during dry periods, which relates to the pollutants available for wash-off. This highlights the importance of taking rainfall characteristics into account when predicting stormwater quality at the treatment design stage.

The new knowledge presented in this manuscript also confirmed that stormwater quality shows a step-wise relationship with rainfall duration based on rainfall intensity. In other words, when the average rainfall intensity is higher than a specific threshold value (20 mm/h in this case study), short-duration events (such as Type I, <2 h) will generate different stormwater quality compared to long-duration events (such as Type II, >2 h). The short-duration events (such as less than 2 h in the study) display the highest mean EMC values with 6.85, 225.03 and 14.63 mg/L for TN, TSS and TOC, respectively, whilst the long-duration events (larger than 2 h in the study) show the highest TP EMC value (3.29 mg/L). Additionally, the short-duration events display the highest standard deviations for TN, TSS and TOC, whilst the long-duration events have the highest standard deviation for TP. Additionally, the influence of rainfall duration on stormwater quality in low-intensity events is minimal, since Type III events have a wide range of durations, but consistently produce lower pollutant EMC values. These study outcomes have confirmed that the stormwater quality predictions obtained by current models can be misleading, since they typically assume a continuous variation of water quality with rainfall intensity and duration. Therefore, for enhancing model accuracy, determining stormwater quality based on different rainfall intensity and duration thresholds would be more appropriate than the current approach.

Underpinned by the new knowledge created in relation to rainfall characteristics, a robust approach to selecting rainfall events for treatment design is provided using a three-component model. Such an approach takes stormwater quantity and quality into consideration and hence can be a guide for selecting appropriate rainfall events in the context of different treatment objectives, land area available and budget. According to the study outcomes, although the number of Type I rainfall only accounts for 22.7 % of all rainfall events, these were found to generate 58.0 % of the TS load. The total runoff volume from Type I events only accounts for 29.1 %. Therefore, focusing on Type I events, which are high average intensity-short duration rainfall events, can lead to greater efficiency in stormwater treatment system's performance due to their greater pollutant generation ability. This can be further supported by the relatively smaller total runoff volume generated by Type I events. This is due to the fact that a smaller runoff volume can be effectively captured by the treatment system, whilst a larger runoff volume may significantly bypass the treatment system without achieving the desired removal of pollutants. Research outcomes also show that events smaller than 6-month ARI generate 68.4 % of the annual total runoff volume and include 68.6 % of the TS load exported. These findings imply that selecting smaller ARI events with high intensity-short duration as the threshold for the design of treatment systems is the feasible approach, since these events cumulatively produce a major fraction of the annual pollutant load compared to the other types of rainfall events, despite producing a relatively smaller runoff volume.

5.1.2 Implications of the Research Study Outcomes in Relation to Catchment Characteristics

Other than conventional catchment characteristics, such as land use and impervious surface fraction, urban form and impervious area layout also play an important role in influencing stormwater quality. For example, the urban form with a townhouse development could generate a relatively lower variation in pollutant EMC values in stormwater runoff than a conventional duplex housing development. This is due to the varying degree of maintenance, management and care exercised in the two different residential urban forms. Furthermore, the outcomes show that a catchment with mixed-land-use development presents the worst-case scenario, such as higher variability in terms of stormwater quality, in comparison to a relatively consistent land use. This is due to the fact that interspersed land uses lead to a complexity of drainage connections and the need for more extended road systems to connect different land parcels, and hence higher variability in stormwater quality. The extensive new knowledge presented in this work also shows that a clustered impervious surface distribution results in a shorter travel distance for runoff and hence faster transport of pollutants to the drainage system. This results in a relatively consistent wash-off process due to the shorter travel time, in comparison to a scattered distribution. This would imply that other than the impervious area fraction, the spatial distribution of the impervious areas also plays an influential role in urban stormwater quality.

The investigations in relation to different land uses indicated significant variability in pollutant build-up even within the same land use. Industrial land use displays a higher variability in solids build-up whilst residential and commercial land use displays relatively higher variability in nutrients and organic carbon build-up. This confirms the variability of pollutant build-up parameters with both land use type and pollutant species. These outcomes highlight the importance of taking into account the land use type and targeted pollutant species when interpreting modelling results or undertaking uncertainty analysis in relation to the outcomes derived from stormwater quality models.

For some parameters such as particle size distribution (average CV values of three land uses for D_{10}, D_{50} and D_{90} were 100.3, 145.6 and 96.7 %, respectively), variability in pollutant build-up within the same land use was even higher than the variability between different land uses. The high variability in particle size distribution illustrates the dissimilarities associated with the behaviour of small and large particle size fractions, even within the same land use. This can lead to differences in stormwater quality in relation to other pollutants which are adsorbed to particulates. This also means that the conventional water quality modelling approach of using land use as a lumped parameter could contribute to significant uncertainty in stormwater quality modelling results. Therefore, when interpreting the outcomes from modelling studies, assessing the possible uncertainty associated with these results is recommended.

This knowledge in relation to catchment characteristics implies that the use of only a limited number of parameters, which is the common practice in current modelling approaches could result in error in water quality estimation. Influential factors in relation to catchment characteristics, such as urban form and impervious surface area distribution, should be incorporated into modelling. For example, when dividing the catchment into a number of subcatchments for water quality modelling, it is recommended to take into consideration both, land use and urban form. This would ensure that the input parameters assigned to a specific subcatchment could be based on land use and urban form and thereby enhance the accuracy of modelling outcomes.

5.2 Areas for Further Knowledge Creation

This manuscript primarily focuses on knowledge creation in relation to two key influential factors in the context of urban stormwater quality, namely, rainfall characteristics and catchment characteristics, in order to provide guidance and recommendations to enhance the accuracy of stormwater treatment design. However, as urbanisation is an ongoing process, the water environment is under ever-increasing threat. Efficiently managing stormwater entails a number of challenges, and requires further knowledge creation to guide the development of enlightened stormwater management strategies.

5.2.1 Managing Stormwater as a Resource

As urbanisation is ongoing, the water demand for satisfying ever-increasing human needs is going to continue to escalate. In this context, finding alternate water resources is of high importance, particularly in water-deficient regions. Reuse of stormwater is an option that is becoming increasingly popular throughout the world, as the non-potable demand can be supplemented with reduced treatment and conveyance costs. However, due to its polluted nature and the complexity inherent in relation to quality characteristics, comprehensive utilisation of stormwater is limited. In order to ensure widespread usage, extensive knowledge on stormwater pollutant sources and pollutant species is required. This knowledge will strengthen stormwater reuse by providing greater guidance on the implementation of effective stormwater treatment and management strategies and more effective implementation of the concept of 'use of water fit-for-purpose', which in effect means that the quality of water is just adequate for the purpose for which it is being used.

5.2.2 Micropollutants in Stormwater Runoff

As discussed in Sect. 1.3.1, micropollutants in stormwater runoff are receiving increasing attention. Even though micropollutants are present in the water environment at extremely low concentrations (ng–µg/L), they can exert potentially chronic direct or indirect impacts on ecosystems and/or even on human health. These micropollutants in terms of both, species and content can differ significantly between regions, depending on social and economic factors. For example, in a region that has a relatively high ageing population, the stormwater could have a relatively higher content of micropollutants linked to pharmaceuticals that are related to diseases associated with ageing. Unfortunately, there are only limited research studies focusing on micropollutants in stormwater runoff and it is an area that requires further research effort.

5.2.3 Operation and Maintenance of Stormwater Treatment Systems

Scientifically robust operational and maintenance practices greatly contribute to guaranteeing the efficiency of treatment strategies. There are three critical stages in stormwater treatment systems: functional installation, establishment period and ongoing operational and maintenance activities (Thomson and Leinster 2007). Each of them is significantly responsible for the performance of a treatment system. This highlights the importance of effective operation and maintenance of a stormwater treatment system. For example, filter media is the key factor for the effectiveness of bioretention systems. However, it is very easy for the filter material to be unduly compacted and to be subject to clogging even in the first year after the system starts operating (Melbourne Water 2010). This can result in the failure of filter media in capturing pollutants when the stormwater passes through the system. Therefore, regular clean-up of the filter media is necessary to ensure its effectiveness. In terms of constructed wetlands and ponds, algal blooms are the main risk since they can reduce the dissolved oxygen levels within the water body and hence affect the ecosystem of the treatment system (Melbourne Water 2010). In this context, strategies to minimise the depletion of dissolved oxygen should be in place.

However, advanced knowledge on effective operation and maintenance of stormwater treatment systems is lacking in areas such as maintenance provision, asset life, replacement time and life cycle costs. Bridging these knowledge gaps will enhance the reuse of stormwater by gaining the confidence of stakeholders and encouraging investments by regulatory authorities. The current lack of knowledge means that stakeholders can be averse to the perceived risk of using what they may consider to be untested technologies and compounded by the lack of in-depth scientific understanding. Similarly, authorities can be reluctant to invest in the relevant technologies for the same reasons.

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Appendix A
Specialised Techniques Adopted for Data Analysis, Principal Component Analysis (PCA) and PROMETHEE and GAIA

Principal Component Analysis (PCA)

Principal Component Analysis (PCA) is a common, informative data display method, and is employed as a convenient technique for initial exploratory purposes for pattern recognition (Kokot et al. 1998). PCA is performed on the transformed data by reducing a set of raw data to a number of principal components (PCs). PC1 describes the largest data variance and PC2 describes the next largest data variance and so on. The number of PCs is less than or equal to the number of original variables (Adams, 1995). However, most of the variance is encompassed in the first few PCs. A total of over 60 % data variance explained by the first few PCs is generally considered adequate to analyse the dataset. The number of significant PCs may be selected with the use of the Scree plot method (Adams 1995). A Scree plot shows the variation of the eigenvalues in descending order with corresponding PCs. According to the point where the graph makes a significant change in direction, the number of principal components that should be taken into consideration is decided (see Fig. A.1).

In PCA, each object is identified by a score, and each variable by a loading value or weighting. The data displays may be obtained by plotting:

(i) PC_i vs PC_j scores (score plot, i, j = PC number);
(ii) loadings for a given PC (loading plot);
(iii) scores and loading vectors on the one plot (biplot).

The 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 on the relationship 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 90º is considered as uncorrelated parameters and 180º as inversely correlated. Objects with similar characteristics form clusters and are strongly correlated to the variables when their vectors point in the same direction as the variables.

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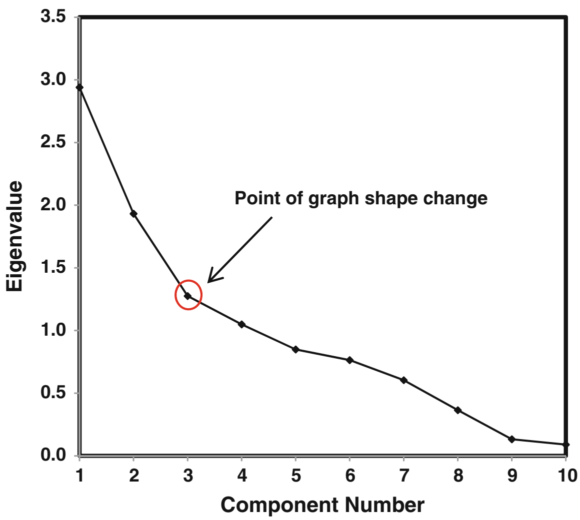


Fig. A.1 A typical Scree plot

PROMETHEE and GAIA

PROMETHEE (Preference Ranking Organisation Method for Enrichment Evaluation) is an unsupervised method for rank-ordering objects in order to facilitate decision-making when dealing with multivariate problems. The main objective of this method is to help decision-makers to resolve complex decision issues in a systematic, consistent and productive way. PROMETHEE has the ability to provide a ranking even for a few objects while GAIA (Graphical Analysis for Interactive Aid) is a principal component analysis biplot that provides a visual complement to the PROMETHEE ranking.

In PROMETHEE, the ranking order for objects is developed according to the net outranking flow, the φ values, for a number of available objects on the basis of a range of variables. To calculate the φ values, each variable must be modelled by the following three conditions:

(i) Supplying a preference function and thresholds to indicate how objects are to be compared;
(ii) Indicating how the objects are to be ordered: top-down (maximised) or bottom-up (minimised);
(iii) Supplying a weighting to reflect the importance of one variable over another (default value = 1).

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). In addition to the overlay of scores and loading vectors, the GAIA biplot also displays a vector, Pi (π), which is computed to indicate roughly the direction of the most preferred object(s). The preference decision is convincing if the length of the Pi (π) vector is relatively long and vice versa. The following steps show how to calculate the φ values between two objects 'a' and 'b' (Keller et al. 1991):

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

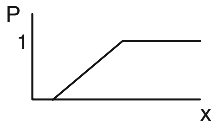
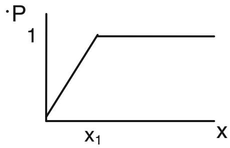
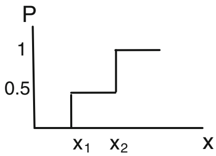
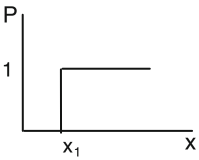
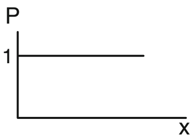
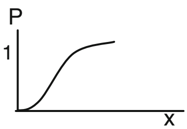
$$d_j = y_j(a) - y_j(b)$$

where y_j (a) and y_j (b) are the data points of objects 'a' and 'b' for criteria y_j.

Step II: **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 variable. The following preference functions (Table A.1) are available for the user to select, depending on the characteristics of the variable:

Table A.1 Preference functions

Preference function	[a]Shape of the graph	Mathematical expression
Linear		$y(x)\begin{cases} 0 & x<x_1 \\ mx+c & x_1<x<x_2 \\ 1 & x>x_2 \end{cases}$
V-shape		$y(x)\begin{cases} mx & x<x_1 \\ 1 & x>x_1 \end{cases}$
Level		$y(x)\begin{cases} 0 & x<x_1 \\ 0.5 & x_1\leq x<x_2 \\ 1 & x\geq x_2 \end{cases}$
U-shape		$y(x)\begin{cases} 0 & x<x_1 \\ 1 & x\geq x_1 \end{cases}$
Usual		$y(x)\begin{cases} 0 & x<0 \\ 1 & x\geq 0 \end{cases}$
Gaussian		$y(x)=\frac{e^x}{1+e^x}$

[a]Labels used in the preference graph: *P* preference, *X* difference, x_1 indifference threshold, x_2 preference threshold

Step III: **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 variable needs to be emphasised in the selection of objects.

Step IV: **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 object ‘a’ is preferred over other objects, while negative outranking flow shows how much other objects are preferred relative to ‘a’.

Step V: **Production of partial ranking** (Table A.2)

Step VI: **Production of complete ranking**:

Complete ranking is produced based on the net outranking flow, φ (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 (Scenario 3 in Step V). However, the compromise may also reduce the reliability of the outcome. In addition, the φ values can be used to understand how far two objects are discriminated in PROMETHEE ranking. In the case where the difference between the φ values of two objects is over 10 % of the whole range, which is the difference between the maximum and the minimum values in the data matrix for that particular variable, they may be considered well discriminated (Ni et al. 2009). This is because an error over 10 % in the measurement is generally not acceptable.

Table A.2 Partial ranking rules

Scenario	Conditions	Results
Scenario 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’
Scenario 2	If $\varphi^{+}(a) = \varphi^{+}(b)$ and $\varphi^{-}(a) = \varphi^{-}(b)$	‘a’ and ‘b’ are equally preferred
Scenario 3	In all other cases	‘a’ and ‘b’ are not comparable

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Appendix B
Hydrologic and Water Quality Modelling

Hydrologic Modelling

Hydrologic Model Software Selection

The selection of software was based on several criteria including: (1) the ability to accurately simulate the hydrologic processes in the study catchments; (2) convenience in importing data from external sources for model setup. For example, in the research study, the drainage network data for the study catchments were obtained in Mapinfo file format, while rainfall records were obtained as an Excel file, which required the selected model to have the capability for importing different types of data files; (3) the ability to accurately simulate hydrologic processes based on individual rainfall events, since the investigation of the relationship between rainfall characteristics and urban stormwater quality was based on individual rainfall events rather than long term continuous rainfall.

According to these criteria, a range of models widely used were evaluated. Table B.1 shows the comparison of three different commercial models. MIKE URBAN is capable of accurately simulating hydrologic processes and requires event-based rainfall data. In terms of data import, MIKE URBAN displays strong capability for importing different types of data such as Mapinfo, Excel and Geographical Information System (GIS) databases since the software is a GIS-based hydrologic and hydraulic model. This translates to ease of model setup in MIKE URBAN compared with the other two models. Therefore, based on a comprehensive consideration on these criteria, MIKE URBAN was selected for the research study.

MIKE URBAN is developed by the Danish Hydraulic Institute (DHI). It combines a GIS-based data management package, a complete stormwater and wastewater modelling package and a complete water distribution network modelling package. MIKE URBAN is based on a GeoDatabase, which is a storage for GIS data and may also be operated directly using standard GIS applications.

MIKE URBAN needs three categories of input data for hydrologic and hydraulic simulations, namely, drainage system network and catchment and boundary data. Drainage system network inputs primarily consist of nodes and links. Node information is spatial location, dimensions and elevations of nodal structures such

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Table B.1 Comparison of three different commercial models

Criteria	MIKE URBAN	MUSIC	XP-SWMM
Accuracy	√	√	√
Event-based rainfall input	√	×	√
Capability for importing data	√	×	×

√Good performance × Poor performance

as manholes, basins and outlets. These node structures are connected by links, including pipes and channels. The main link inputs are type of link, their hydraulic properties such as roughness, and information on upstream and downstream nodes. Catchment inputs primarily include catchment area and the node to which the catchment drains. The catchment should drain to a pre-defined node from nodal inputs. There are three types of boundary inputs in MIKE URBAN, namely, catchment loads and meteorological boundary conditions, network loads and external water levels. In this research study, the first two boundary inputs were applied. Catchment loads and meteorological boundary inputs are the rainfall data in the form of rainfall intensity time series, while network load boundary inputs are the results of hydrologic simulation and are used in hydraulic simulation. Figure B.1 illustrates the hydrologic and hydraulic simulation sequence in MIKE URBAN.

Hydrologic Model Setup

In order to simulate the runoff hydrographs, the MIKE URBAN model was set up accordingly for the four catchments. Detailed maps of the drainage network, including sizes of gully pits and pipe diameters were supplied by the Gold Coast City Council (GCCC).

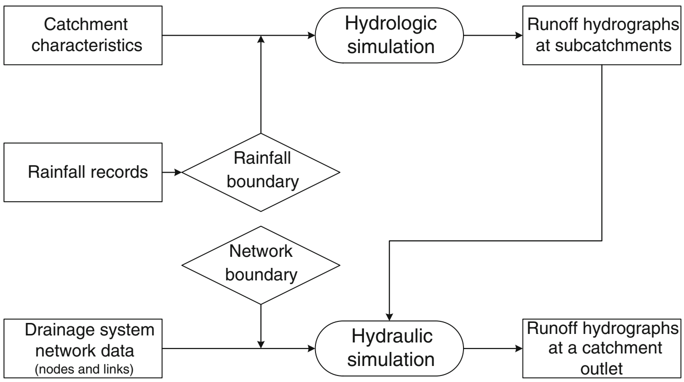


Fig. B.1 Hydrologic and hydraulic simulation sequence in MIKE URBAN

Alextown Catchment Model

Alextown is a townhouse development with an area of 1.7 ha. The percentage of impervious surfaces is 70 % (see Sect. 3.2.1). The catchment consists of an efficient drainage system with rectangular gully pits with steel mesh lids placed in the middle of the road to collect road runoff. For modelling, the catchment was divided into 28 subcatchments, so that its distributed nature can be adequately represented. The Alextown catchment model consisted of 28 nodes, one outlet and 28 pipes.

Other than the input data obtained directly from GCCC datasets, a number of assumptions were adopted during model setup. Firstly, a constant value was used for impervious surface percentage based on the assumption that impervious surfaces are distributed equally over the catchment surfaces. Secondly, MIKE URBAN considers the gully pits as cylindrical and a diameter is assigned as the primary dimensional parameter. However, all the catchment gully pits were of rectangular shape. An equivalent diameter, which was considered as the diagonal length of the rectangular manhole, was adopted for catchment modelling. According to the MIKE URBAN manual, the assignment of gully pits of different shapes does not introduce error to the modelling outcomes.

Gumbeel Catchment Model

Gumbeel is a duplex housing development and its area is 1.2 ha. The percentage of impervious surfaces is 70 % (see Sect. 3.2.1). The catchment is located along a ridge. Therefore, the runoff is primarily contributed by roads, which means that the percentage of connected impervious surfaces is relatively low. The drainage system in Gumbeel catchment is relatively simple and short, compared with the other study catchments. The catchment was divided into two subcatchments. The Gumbeel model consisted of three nodes, one outlet and three pipes.

Birdlife Park Catchment Model

Birdlife Park catchment is a detached housing development with an area of 7.5 ha. The percentage of impervious surfaces is 45.8 % (see Sect. 3.2.1). The catchment is located in a valley with a relatively greater slope than other study catchments. The runoff is collected by side manholes. Furthermore, the runoff contributed from pervious surfaces is also combined with the road runoff as most of the pervious surfaces are located in the front of houses and are relatively extended. Birdlife Park was divided into 77 subcatchments in the model, which consisted of 78 nodes, one outlet and 79 pipes.

Highland Park Catchment Model

Highland Park is a mixed-land-use catchment with an area of 105.1 ha. The catchment land use includes residential, commercial and forestry. The percentage of impervious surfaces is 40 % (see Sect. 3.2.1). The main drainage line is a small tributary, the Bunyip Brook. The integrated pipe and channel network connecting various parts of the catchment area to the tributary further facilitates stormwater drainage. Highland Park catchment was divided into 625 subcatchments. The Highland Park model consisted of 633 nodes, one outlet, 39 channels and 596 pipes. In the case of the drainage channels, the cross-sections were obtained from a Digital Elevation Model (DEM) supplied by GCCC.

Hydrologic Model Calibration and Validation

Calibration Parameters

A time-area method was used for the hydrologic simulation. The time-area method needs three parameters and time-area curves for calibration in MIKE URBAN. The three parameters are:

- Time of concentration
- Reduction factor
- Initial loss

Reduction factor and initial loss parameters influence the runoff volume whilst time of concentration and time-area curves influence the hydrograph shape. An initial value was decided for each calibration parameter. These parameters were then adjusted by “trial and error” until an acceptable agreement was obtained between simulated and observed results.

Calibration and Validation Performance Evaluation

Data for model calibrations were selected by a careful inspection of the available rainfall and runoff event data. Runoff discharge measured at the catchment outlets was applied to assess the goodness-of-fit between observed and simulated values. Two statistical parameters were used to describe the quality of the simulation results, namely, the root mean square error (RMSE) and the coefficient of determination (CD). The equations used are given below:

$$\mathrm{RMSE} = \sum_{i=1}^{n} \left[\frac{(S_i - O_i)^2}{n} \right]^{1/2} \tag{B.1}$$

$$\mathrm{CD} = \sum_{i=1}^{n} \left(O_t - \overline{O} \right)^2 \Bigg/ \sum_{i=1}^{n} \left(S_t - \overline{O} \right)^2 \tag{B.2}$$

where

S *Simulated results*
O *Observed results*
$\bar{O}$ *The average value of the observed results*
n *The total number of observations*

The RMSE value indicates the extent to which the simulations are overestimating or underestimating observed values. The smaller the RMSE value, the closer the simulation results to the observed data. The CD value describes the ratio of the scatter of the simulated values to that of the observed values. A CD value being close to 1 means that the observed and simulated results match closely.

Calibration and Validation Results

The RMSE and CD values for all discharge calibrations and validations are given in Table B.2. Figure B.2 shows the comparison between simulated and observed peak discharge values for the calibration and validation study, whilst Fig. B.3 shows the comparison between simulated runoff volumes and observed runoff volumes from the calibration and validation study.

As shown in Table B.2, the RMSE values range from 0.003 to 0.228 for all of the four catchments. These relatively small RMSE values indicate that the simulated results are close to the observed results. In addition, most of the CD values are close to 1. This further confirms that the calibration and validation results are reasonable. According to Figs. B.2 and B.3, it can be seen that both, peak discharge and total runoff volume show good agreement between observed and simulated results. It can be concluded that the runoff volumes were simulated appropriately by the calibrated models and that the runoff volumes from the calibrated models can in turn be used for the estimation of pollutant EMC values.

Water Quality Modelling

The water quality model consisted of build-up and wash-off estimation, which were undertaken using the two equations developed by Egodawatta (2007) and Egodawatta et al. (2007). These equations were developed based on the same catchments as the study sites in this research study.

Table B.2 RMSE and CD values for calibrations and validations

Catchment	Task	Rainfall event	RMSE	CD
Gumbeel	Calibration	2002-04-28	0.003	0.64
		2001-12-29	0.007	0.63
	Validation	2002-05-03	0.003	0.49
Alextown	Calibration	2003-12-06	0.003	0.74
		2003-11-24	0.006	0.66
		2002-04-12	0.010	0.48
		2002-10-27	0.006	0.69
	Validation	2002-11-13	0.010	0.82
		2002-08-21	0.005	0.72
		2002-08-25	0.002	0.83
		2002-11-15	0.007	0.82
Birdlife Park	Calibration	2002-02-01	0.009	0.64
		2002-10-27	0.013	0.78
		2002-06-02	0.011	0.65
	Validation	2001-12-31	0.006	0.54
		2002-02-02	0.006	0.87
Highland Park	Calibration	2002-04-12	0.079	0.83
		2002-08-21	0.122	0.81
		2002-04-28	0.102	0.76
		2002-05-03	0.137	0.67
	Validation	2002-06-04	0.057	0.77
		2002-09-20	0.127	0.53
		2001-03-21	0.228	0.61
		2002-11-15	0.219	0.63

TS EMC Estimation Steps

In order to estimate TS EMC, the TS wash-off load was estimated initially. TS wash-off load from the catchment surface was obtained by multiplying the TS build-up load (Eq. 4.1) by the wash-off fraction (Eq. 4.2) for the rainfall event. For different rainfall intensities, the capacity factor C_F for the wash-off fraction is different and can be calculated by the equations given in Table 4.2. In order to obtain the wash-off fraction for each rainfall event, the following steps were undertaken.

(I) Rainfall intensity threshold
Low intensity is not capable of producing a significant wash-off fraction. This meant the adoption of a threshold value for rainfall intensity. Intensities lower than the threshold value were not considered for the wash-off fraction calculations. The threshold rainfall intensity adopted was 5 mm/h.

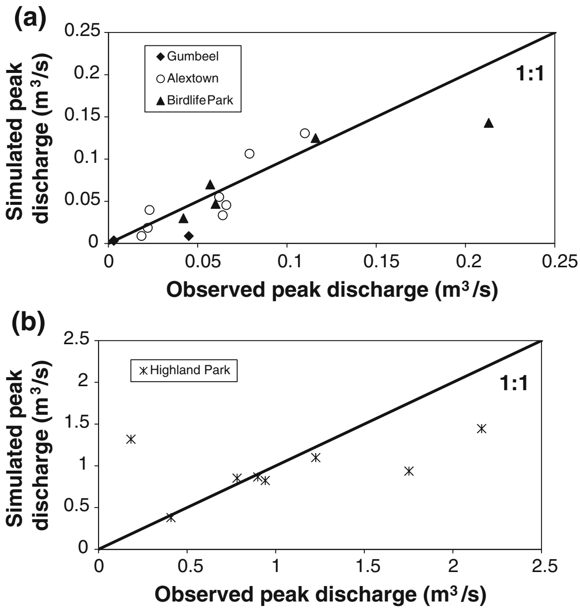


Fig. B.2 The comparison of observed and simulated peak discharges

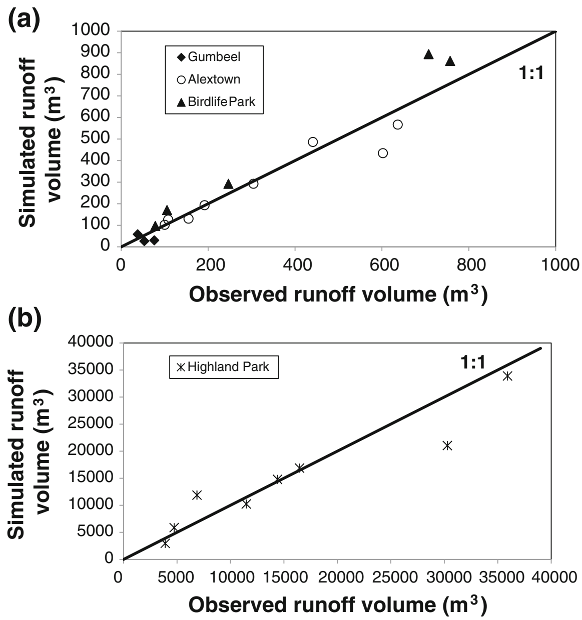


Fig. B.3 The comparison of observed and simulated total runoff volumes

(II) Wash-off fraction calculation
The wash-off fraction calculation commenced from the first 5 min time step where the rainfall intensity was larger than 5 mm/h. The wash-off fraction for the first time step was estimated using Eq. 4.2 and data given in Table 4.2. Then, for the second time step, the wash-off fraction was determined starting from the value previously obtained from the first time step. This procedure continued until the last time step of the rainfall event. Consequently, the cumulative wash-off fraction for the rainfall event was obtained.

(III) The estimation of TS wash-off loads
Based on the estimated TS build-up load on the catchment surfaces during the antecedent dry days and wash-off fraction for each rainfall event, the TS wash-off load for each rainfall event was obtained by multiplying the build-up load by the corresponding wash-off fraction.

(IV) The estimation of TS EMC
TS EMC (mg/L) for each rainfall event was obtained by the TS wash-off loads divided by the total runoff volumes simulated by the MIKE URBAN computer model. The estimated TS EMC values for the 41 rainfall events used in Sect. 3.2 are shown in Table B.3.

Calibration and Validation Results

Figure B.4 shows the comparison of estimated and measured TS EMC for the four catchments. It can be noted that Alextown and Gumbeel displays a relatively good agreement between estimated and measured EMC values, whilst for Birdlife Park and Highland Park, the EMC values are underestimated.

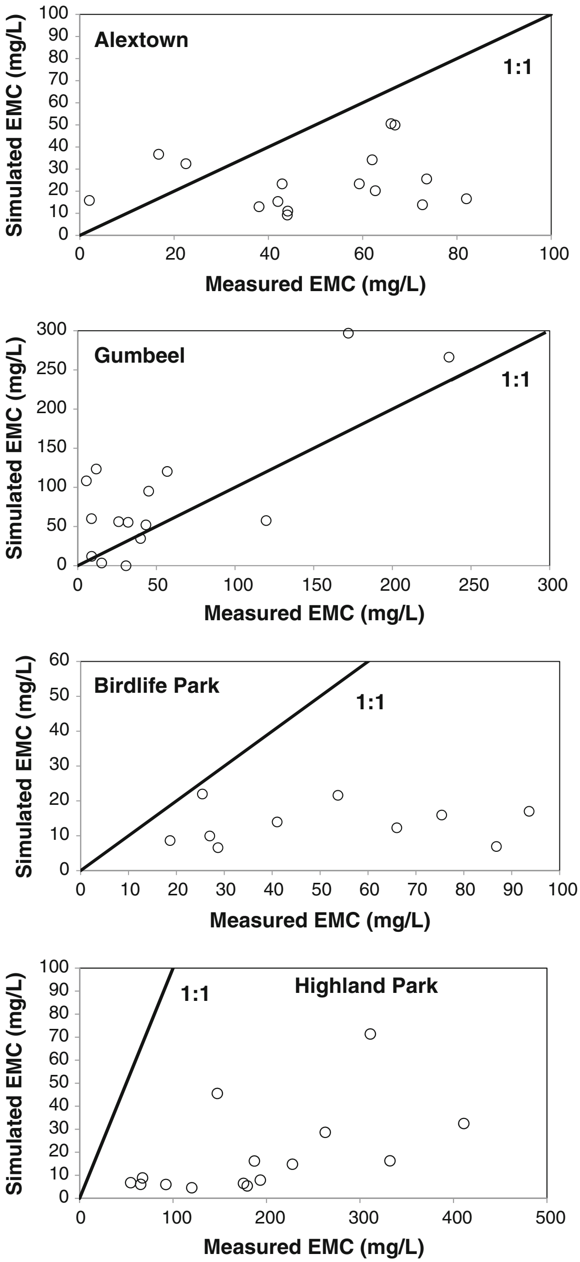
Additionally, it can be observed that the under estimation of TS EMC by the model for Highland Park catchment is relatively more significant than for Birdlife Park. This can be attributed to the following reasons.

1. Only the impervious surfaces were considered in both the runoff volume simulation and pollutant wash-off loads estimation. However, in the real catchments, both impervious and pervious surfaces may contribute to the pollutant load. Alextown and Gumbeel have the highest percentage of impervious surfaces (70 %) among the four catchments, followed by Birdlife Park at 45.8 % and Highland Park catchment at 40 %. Therefore, the pollutant EMC estimations performed relatively better for Alextown and Gumbeel due to the high percentage of impervious area, but poorly for Birdlife Park and Highland Park catchments.
2. Sampling of storm events for subsequent laboratory analysis for determining pollutant concentrations was done by pumping from a constant height above the drainage channel bed, irrespective of the flow depth. This could lead to the collection of non-representative samples with high TS loads.

Table B.3 Estimated TS EMC values for the four catchments

Rainfall events	TS EMC (mg/L)			
	Alextown	Gumbeel	Birdlife Park	Highland Park
2002-11-15	32.46	108.39	13.98	13.15
2003-12-03	22.49	38.07	9.34	5.15
2003-06-26	12.36	32.46	4.99	3.31
2003-12-06	14.49	23.34	5.77	2.27
2003-11-24	12.70	42.54	5.25	6.34
2002-04-28	28.98	95.19	12.31	11.75
2003-12-14	50.57	293.70	21.86	31.87
2004-01-14	16.59	55.48	7.18	6.09
2004-02-24	9.24	56.26	4.05	4.60
2003-02-01	15.35	23.09	6.05	3.50
2003-02-02	15.83	39.17	6.46	5.43
2003-02-03	13.00	90.95	5.58	5.70
2003-02-25	4.01	3.52	1.18	0.52
2003-02-26	3.89	3.55	1.27	0.49
2003-03-01	36.30	10.41	5.11	2.33
2003-03-07	36.99	52.43	14.65	7.92
2003-03-12	34.23	65.34	14.20	8.88
2003-03-13	15.53	52.16	6.60	6.08
2003-03-22	65.45	388.91	28.17	45.57
2003-04-27	20.23	55.06	8.64	6.51
2003-05-14	13.88	51.45	6.03	5.41
2003-10-24	52.40	296.92	22.63	32.52
2003-10-19	27.56	135.82	11.74	16.22
2003-10-26	75.12	354.63	29.09	71.40
2003-12-15	52.58	114.40	21.52	16.30
2002-04-29	41.70	123.51	15.97	17.13
2002-05-01	3.91	3.49	1.29	0.40
2002-05-03	29.25	60.12	12.37	5.50
2002-05-05	15.52	12.01	5.72	1.96
2002-06-02	24.96	57.67	10.52	7.35
2002-06-04	18.23	34.77	6.94	6.31
2002-06-16	71.56	233.78	29.75	35.87
2002-08-21	11.01	30.04	4.71	3.51
2002-08-25	23.35	52.15	9.72	6.81
2002-08-27	32.26	36.38	9.23	7.91
2002-09-21	40.60	120.38	17.03	14.82
2002-10-27	25.56	46.58	10.80	6.03
2002-11-13	49.95	266.33	21.62	28.68
2002-12-09	23.33	98.59	9.96	11.56
2002-12-10	51.22	280.35	21.99	32.98
2002-12-26	36.73	35.39	14.01	5.55

Fig. B.4 The comparison of estimated and measured TS EMC for the four catchments



3. EMC samples were prepared from the runoff samples typically collected 5 min apart. Due to the relatively smaller size of the catchments and the resulting “flashy” nature of stormwater runoff, water quality can vary significantly during this time interval. This can lead to non-representative EMC results.

4. The computer model and build-up and wash-off equations used for estimating TS EMC are based on a number of assumptions and conceptual descriptions of pollutant processes. This may introduce errors to the estimation of results.

Although the estimations of TS EMC were not satisfactory for all of the four catchments, these results were accepted, since the primary function of the study was to validate the three-component catchment models (hydrologic, build-up and wash-off) in terms of their sensitivity to the important rainfall parameters, rather than the prediction of TS EMC. Accordingly, the estimated TS EMC values for the four catchments were further analysed for the sensitivity of the three-component catchment model to important rainfall characteristics.

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