TRANSLATION OF SMALL-PLOT SCALE POLLUTANT BUILD-UP AND WASH-OFF MEASUREMENTS TO URBAN CATCHMENT SCALE

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ABSTRACT

Accurate and reliable estimations are the most important factors for the development of efficient stormwater pollutant mitigation strategies. Modelling is the primary tool used for such estimations. The general architecture of typical modelling approaches is to replicate pollutant processes along with hydrologic processes on catchment surfaces. However, due to the lack of understanding of these pollutant processes and the underlying physical parameters, the estimations are subjected to gross errors. Furthermore, the essential requirement of model calibration leads to significant data and resource requirements. This underlines the necessity for simplified and robust stormwater pollutant estimation procedures.

The research described in this thesis primarily details the extensive knowledge developed on pollutant build-up and wash-off processes. Knowledge on both build-up and wash-off were generated by in-depth field investigations conducted on residential road and roof surfaces. Additionally, the research describes the use of a rainfall simulator as a tool in urban water quality research. The rainfall simulator was used to collect runoff samples from small-plot surfaces. The use of a rainfall simulator reduced the number of variables which are common to pollutant wash-off.

Pollutant build-up on road and roof surfaces was found to be rapid during the initial time period and the rate reduced when the antecedent dry days increase becoming asymptote to a constant value. However, build-up on roofs was gradual when compared to road surfaces where the build-up on the first two days was 66% of the total build-up. Though the variations were different, it was possible to develop a common replication equation in the form of a power function for build-up for the two surface types with *a* as a multiplication coefficient and *b* as a power coefficient. However, the values for the two build-up equation coefficients, *a*, and *b* were different in each case. It was understood that the power coefficient *b* varies only with the surface type. The multiplication coefficient varies with a range of parameters including land-use and traffic volume. Additionally, the build-up observed on road surfaces was highly dynamic. It was found that pollutant re-distribution occurs with finer particles being removed from the surface thus allowing coarser particles to build-

up. This process results in changes to the particle size composition of build-up. However, little evidence was noted of re-distribution of pollutants on roof surfaces. Furthermore, the particulate pollutants in both road and roof surfaces were high in adsorption capacity. More than 50% of the road and more than 60% of the roof surface particulates were finer than 100 μm which increases the capacity to adsorb other pollutants such as heavy metals and hydrocarbons. In addition, the samples contained a significant amount of DOC which would enhance the solubility of other pollutants.

The wash-off investigations on road and roof surfaces showed a high concentration of solid pollutants during the initial part of events. This confirmed the occurrence of the 'first flush' phenomenon. The observed wash-off patterns for road and roof surfaces were able to be mathematically replicated using an exponential equation. The exponential equation proposed is a modified version of an equation proposed in past research. The modification was primarily in terms of an additional parameter referred to as the 'capacity factor' (C_F). C_F defines the rainfall's ability to mobilise solid pollutants from a given surface. It was noted that C_F varies with rainfall intensity, particle size distribution and surface characteristics. Additional to the mathematical replication of wash-off, analysis further focused on understanding the physical processes governing wash-off. For this, both particle size distribution and physico-chemical parameters of wash-off pollutants were analysed. It was noted that there is little variation in the particle size distribution of particulates in wash-off with rainfall intensity and duration. This suggested that particle size is not an influential parameter in wash-off. It is hypothesised that the particulate density and adhesion to road surfaces are the primary criteria that govern wash-off. Additionally, significantly high pollutant contribution from roof surfaces was noted. This justifies the significance of roof surfaces as an urban pollutant source particularly in the case of first flush.

This dissertation further describes a procedure to translate the knowledge created on pollutant build-up and wash-off processes using small-plots to urban catchment scale. This leads to a simple and robust urban water quality estimation tool. Due to its basic architecture, the estimation tool is referred to as a 'translation procedure'. It is designed to operate without a calibration process which would require a large amount of data. This is done by using the pollutant nature of the catchment in terms of build-up and wash-off processes as the basis of measurements. Therefore, the translation procedure is an extension of the current estimation techniques which are typically complex and resource consuming. The use of a translation procedure is simple and based on the graphical estimation of parameters and tabular form of calculations. The translation procedure developed is particularly accurate in estimating water quality in the initial part of runoff events.

LIST OF PUBLICATIONS

Refereed Journal Papers

- **Egodawatta, P**., Thomas, E. and Goonetilleke, A. (2006). A mathematical interpretation of pollutant wash-off from urban road surfaces using simulated rainfall. Water Research, 41(13), 3025 - 3031.

Refereed International Conference Papers

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ABBREVIATIONS

AD	- Advection Dispersion
ARI	- Average Recurrence Interval
AS/NZS	- Australian and New Zealand Standards
Cd	- Cadmium
COD	- Chemical Oxygen Demand
Cr	- Chromium
Cu	- Copper
CV	- Coefficient of Variation
DHI	- Danish Hydraulic Institute
DOC	- Dissolved Organic Carbon
EC	- Electrical Conductivity
EMC	- Event Mean Concentration
GCCC	- Gold Coast City Council
GIS	- Geographical Information System
HEPA	- High Efficiency Particulate Air
IC	- Inorganic Carbon
IL	- Initial Loss
Ni	- Nickel
PAH	- Polycyclic Aromatic Hydrocarbon
Pb	- Lead
PC	- Principal Component
PCA	- Principal Component Analysis
Rf	- Reduction Factor
SD	- Standard Deviation
SWMM	- Stormwater Management Model
Tc	- Time of Concentration
TC	- Total Carbon
TDS	- Total Dissolved Solids
TN	- Total Nitrogen
TOC	- Total Organic Carbon
TP	- Total Phosphorous
TS	- Total Solids

TSS	- Total Suspended Solids
US EPA	- United States Environmental Protection Agency
USA	- United States of America
Zn	- Zinc

STATEMENT OF ORIGINAL AUTHORSHIP

The work contained in this thesis has not been previously submitted for a degree or diploma from any other higher education institution to the best of my knowledge and belief. The thesis contains no material previously published or written by another person except where due reference is made.

Prasanna Egodawatta

Date: / /

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DEDICATION

I wish to dedicate this thesis to my father, Ranjith Egodawatta, and mother, Chandra Walisinghe, for their unlimited support and love and to my two brothers, Chaminda and Kithsiri, and my sister Samanthi for their support and motivation.

Chapter 1 - Introduction

1.1 Background

Urbanisation leads to an increased percentage of impervious areas on catchment surfaces. Consequently, this leads to changes in the hydrologic and water quality characteristics of catchments. Many researchers have reported that increased flood frequencies and comparatively higher flood peaks are apparent in urban catchments when compared to rural catchments (ASCE, 1975; Riordan et al., 1978). Urban stormwater quality is also one of the key environmental concerns at the present time. Due to increased anthropogenic activities on urban lands, various pollutants accumulate on catchment surfaces. These pollutants are washed-off during storm events thereby contributing higher pollutant loads to receiving waters (Bannerman et al., 1993; Novotny et al., 1985; Sartor et al., 1974).

With the growing awareness of stormwater pollution, many regulatory authorities strive to implement stormwater management strategies to mitigate the adverse impacts. Numerous research studies and stormwater quality estimation procedures have been developed in order to support the decision making processes. Computer modelling is one such water quality prediction procedure that is widely used. There are a number of stormwater quality models available, but they are generally based on similar principles. They first estimate the runoff volume using given rainfall and geographical parameters. Then, the quality of the runoff is estimated using pollutant process equations. The pollutant process equations are either a simplified form of statistical relationships or replications of pollutant processes such as pollutant build-up and wash-off (Akan and Houghtalen, 2003; Zoppou, 2001).

Stormwater quality computer models which are generally based on a simplified form of pollutant export relationships using appropriate equations are termed 'lumped time base models'. These models estimate the long term pollutant export from catchments and are widely used for planning and decision making activities. The use of lumped time base models is limited due to two main issues. Firstly, the representation of catchment pollutant processes using a simplified pollutant export equation can be misleading. Pollutant processes on catchment surfaces have complex characteristics and are influenced by a range of factors such as land use, topography, rainfall and climatic characteristics. Secondly, these models need an extensive amount of data for calibration. The acquisition of such data can be difficult and expensive (Akan and Houghtalen, 2003; Rossman, 2004; XP-AQUALM-User-Manual).

Stormwater quality computer models which use separate mathematical replication equations for each pollutant process can be termed ‘continuous time base models’. The primary pollutant processes that are generally replicated in these models are pollutant build-up and wash-off. These models are capable of simulating water quality of each storm event in detail. They use replication equations for the two main pollutant processes: pollutant build-up and wash-off. However, due to limited knowledge of these pollutant processes, this type of water quality model can lead to gross errors (Akan and Houghtalen, 2003; Sartor et al., 1974).

1.2 Hypothesis

The knowledge on pollutant build-up and wash-off processes from small-plot urban impervious surfaces can be translated to an urban catchment scale to enable the estimation of stormwater quality.

1.3 Aims and Objectives

The primary objective of this research study was to develop a detailed knowledge on primary pollutant processes of pollutant build-up and wash-off in plot scale and translate this knowledge to catchment scale leading to a catchment scale water quality estimating tool.

The major aims of the study were to:

- Develop a detailed understanding of pollutant build-up and its relationship to antecedent dry days on common urban impervious surfaces such as road and roof surfaces using small plots.
- Develop a detailed understanding of pollutant wash-off with rainfall intensity and duration from road and roof surfaces using rainfall simulation on small-plot surfaces to eliminate the dependency on natural rainfall and its attendant difficulties.
- Develop an appropriate simplified approach to translate the knowledge on build-up and wash-off processes to an urban catchment scale in order to estimate catchment scale stormwater quality.

1.4 Justification for the Research

It is widely accepted that pollutants originating from urban surfaces dramatically alter receiving water quality. To mitigate the adverse impacts of stormwater pollution, it is essential to have appropriate management strategies and efficient treatment designs. However, the effectiveness of such mitigation measures strongly relies on the accuracy and reliability of stormwater quality estimations.

Modelling is the primary tool used for such estimations. The general architecture of typical modelling approaches is to replicate pollutant processes along with hydrologic processes on catchment surfaces. The common pollutant processes replicated in typical water quality models are pollutant build-up and wash-off. However, due to the lack of in-depth understanding of these pollutant processes and the underlying influential parameters, the estimations can be subjected to gross errors. Furthermore, the essential requirement of model calibration leads to significant data and resource requirements. Due to the dependency on naturally occurring rain events, generation of such data is difficult and time consuming. A further complexity is added due to the non-homogeneous nature of urban catchments.

The above discussion highlights the necessity for in-depth investigations into pollutant build-up and wash-off. However, in order to eliminate the physical constrains due to the heterogeneity of urban catchments and the dependency on naturally occurring rainfall events, special research methodologies were needed for the investigations. Selection of small-plot surfaces was the approach taken to eliminate the constraints arising from the heterogeneity of urban surfaces. It was hypothesised that the characteristics of influential variables are fairly uniform over a confined area of urban surface. Secondly, the use of artificially simulated rainfall was the best approach to eliminate the dependency on naturally occurring rainfall. This approach further provides better control over variables such as intensity and duration. However, once the in-depth knowledge on pollutant build-up and wash-off relating to small urban surface plots is created, this knowledge needs to be translated to catchment scale for practical applications. Hence the extension of the knowledge is on pollutant build-up and wash-off for the development of the translation procedure.

1.5 Description of the Research

Special research techniques were used to investigate pollutant build-up and wash-off on road and roof surfaces. The investigations into build-up and wash-off were undertaken on small-plot surfaces which were 3 m^2 in size. This eliminated the issues associated with non-homogeneous surface characteristics. The primary variability considered during pollutant build-up was the antecedent dry period. Variation of build-up due to other factors such as land-use was accounted for investigating multiple sites. A rainfall simulator was used for the wash-off investigations. This helped to overcome constraints associated with the dependency on natural rainfall events such as their unpredictable occurrence. The investigations were focused on understanding variability of wash-off due to variations of rainfall intensity and duration.

The primary data for the validation of the developed translation procedure was obtained from three urban catchments. All these catchments were residential in land-use but contained slightly different residential urban forms. The catchments had been monitored for quantitative and qualitative parameters of runoff. In order to maintain compatibility of measurements, the investigations into build-up and wash-off were conducted close to these three catchments. These investigations were conducted on three road sites and two roof surface types. Variation of build-up with antecedent dry days and variation of wash-off with rainfall intensity and duration were the primary focus of investigations.

Samples collected from build-up and wash-off investigations and from the three urban catchment outlets were tested for a range of physio-chemical parameters. However, the primary focus was to test parameters related to particulates such as total suspended solids, total dissolved solids and particle size distribution. This was due to the consideration of solids as the indicator pollutant for water quality.

A fundamental understanding of build-up and wash-off processes was created by the analysis of build-up and wash-off data from small-plot surfaces. The analysis primarily focused on developing mathematical replication equations and understanding the underlying physical processes. The mathematical replication equations for each process were simulated for selected storm events so that the water quality in the three catchments could be estimated. Based on the accuracy of estimation in comparison to measured water quality, a simplified modelling approach or translation procedure was developed for estimating catchment scale water quality using data obtained from small-plots.

1.6 Scope

This research focused on urban stormwater pollutant processes. The research developed a detailed understanding of pollutant build-up and wash-off processes and was confined to a specific investigation framework. The important issues in relation to this work are:

- The research was confined to the Gold Coast area. This limits the research outcomes in terms of regional and climatic parameters. However, the generic knowledge developed is applicable outside of the regional and climatic characteristics of the Gold Coast.
- The field investigations were conducted only for residential land-uses. This limits the wider applicability of some of the research outcomes where land-use is a

significantly influencing variable. However, once again, the generic knowledge developed is applicable for other land-uses.

- The research was only confined to two primary pollutant processes, namely pollutant build-up and wash-off. The transport of pollutants from catchment surfaces was considered to be only by advection, which can be replicated using typical runoff routing models.
- The investigation of pollutant processes was confined to road and roof surfaces. It was considered that these two surface types represent the dominant impervious fraction and are the most significant contributors to stormwater pollutant load.
- The seasonal variability of pollutant build-up was not considered during the investigations.
- Three road sites with variable urban-forms formed the study sites. The traffic volumes in these three sites are typical of residential urban roads. Variable traffic volumes were not considered for the study.

1.7 Outline of the Thesis

This thesis consists of nine chapters. Chapter 1 is the introduction to the thesis. Chapter 2 gives the outcomes of the state-of-the-art review of published research literature. It describes the background information relating to the research and identified knowledge gaps. Chapter 3 outlines details of the research tools used for the investigations. The study site selection is discussed in Chapter 4. Chapter 4 further describes the methodology adopted for small-plot pollutant process investigations and laboratory testing. The primary data analysis is discussed in Chapter 5 and Chapter 6. Chapter 5 focuses on the analysis of pollutant build-up on road and roof surfaces whilst Chapter 6 discusses the analysis of pollutant wash-off on road and roof surfaces. In these two chapters, the objective was to understand the physical processes governing pollutant build-up and wash-off, to develop mathematical replications of each process, and to understand the variability of physio-chemical parameters that influence the adsorption of other pollutants to particulate pollutants. Chapter 7 discusses the hydrologic modelling of study sites which was undertaken to obtain the essential hydrologic information for the development of the translation procedure. The translation procedure developed is discussed in Chapter 8. Chapter 9 provides the conclusions and recommendations for further research. Finally, references used throughout the thesis are listed. Appendices A to F contain information additional to the main text.

Chapter 2 – Urban Hydrology and Water Quality

2.1 Background

As the concept of sustainable development gains increase recognition around the world, understanding the adverse impacts of urbanisation on the water environment is highly important. Water is one of the essential resources for human existence. Urbanisation and consequent physical changes to catchment surfaces lead to the deterioration of water quality.

Urbanisation transforms rural lands into residential, commercial and industrial land-uses. The vegetated catchment surfaces are changed with the introduction of impervious surfaces such as roofs and road surfaces. Previously natural streams and waterways are lined and natural flow paths are changed due to the introduction of artificial drainage systems (Hollis, 1975; Kibler, 1982; Waananen, 1969; Waananen et al., 1961). Apart from the physical changes to the catchment surfaces, anthropogenic activities common to urban areas lead to the contribution of significant amounts of pollutants such as solids, heavy metals and hydrocarbons. The pollutants found in waterways are greater in load and diversity when compared to rural areas (ASCE, 1975; Bannerman et al., 1993; House et al., 1993).

Due to the severity of impacts of urbanisation on the water environment, regulatory authorities have sought to develop mitigation strategies. For mitigation actions to be efficient and productive, accurate estimation of impacts is critical. Estimations are primarily based on modelling approaches which replicate hydrologic and water quality processes (Akan and Houghtalen, 2003; Zoppou, 2001). However, lack of knowledge of primary processes and the necessity for a large array of data for model setup and calibration makes modelling inherently difficult.

This chapter focuses on identifying the primary processes and related influential parameters in urban hydrologic and water quality regimes. The chapter further discusses the estimation methods for quantitative and qualitative parameters of urban runoff. Additionally, the issues relating to qualitative modelling of runoff are discussed to explore possible knowledge gaps.

2.2 Hydrologic Impacts

The impacts of urbanisation on the hydrologic regime have received significant research interest. The impacts are apparent not only during storm events, but also in the long term. The long-term impacts are mainly changes in the natural water balance. Waananen (1969) noted that urbanisation causes increased long-term water volumes originating from catchments. The primary reason is the presence of a high fraction of impervious surfaces which reduces infiltration and increases the runoff volume. On the other hand, both Hollis (1975) and Waananen (1969) noted that urban creeks which were previously perennial can become ephemeral for significant periods of the year. As they suggested, lack of ground water recharge and consequent reduction of base flow are the primary reasons. This underlines the reasons for large floods and consequent droughts that urban catchments commonly undergo.

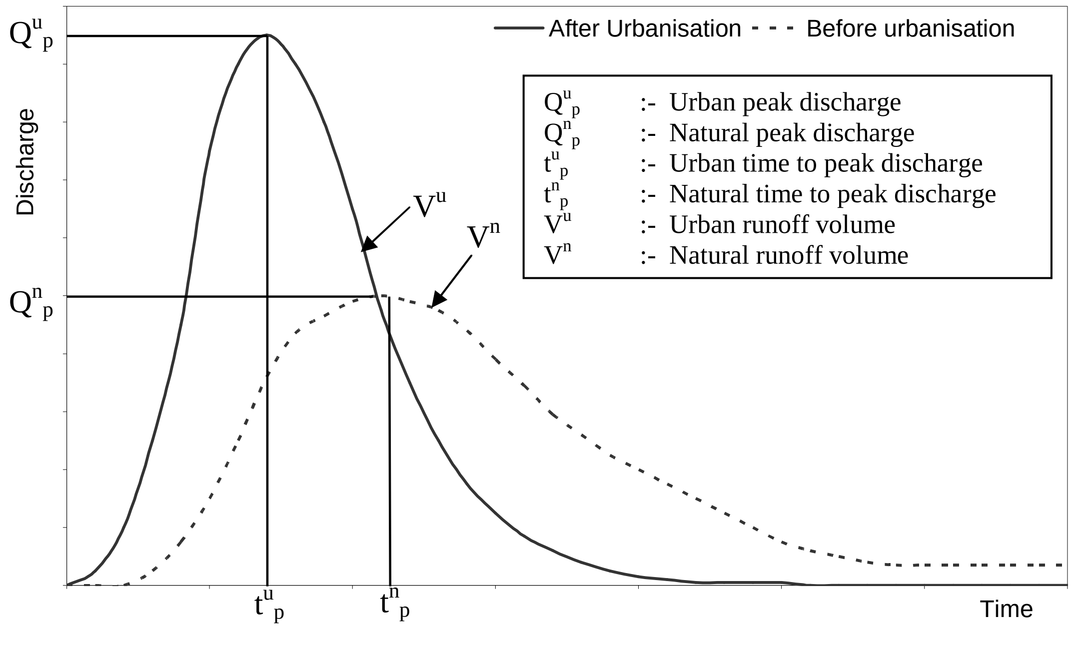


Figure 2.1 - Changes in runoff hydrograph after urbanisation (Adapted from Kibler 1982)

Event based impacts on the hydrologic regime due to urbanisation are the most serious. As noted by Rao and Delleur (1974) urbanisation causes significant increases in flood levels which can cause significant property damage. Though the increase of flood levels is commonly highlighted as a unique feature, it contributes to a range of changes to the hydrologic regime. As noted by Brater and Sangal (1969) and Kibler (1982), such changes in hydrologic regime can be better illustrated using a runoff hydrograph as shown in Figure 2.1.

As seen in Figure 2.1, the primary changes to the runoff hydrograph due to urbanisation include:

- Reduced time of concentration or catchment lag;
- Increased runoff peak flow;
- Increased runoff volume; and
- Reduced base flow.

Physical changes to catchment surfaces such as increased imperviousness cause such changes to the hydrograph. However, it is difficult to identify the exact cause of these changes to the runoff hydrograph. As explained by Hollis (1975), Kibler (1982) and Waananen (1969), the changes to the runoff hydrograph are caused by a combination of physical changes to catchment surfaces and the drainage network.

Reduced time of concentration is primarily due to improved hydraulic performance of catchments. The primary causes for improved hydraulic performances are introduction of impervious surfaces, uniform slopes and lined channels. The high fraction of impervious surfaces in urban catchments can decrease the surface roughness by a significant margin. This reduces the time of travel to the drainage inlets. The time of travel is further reduced due to regular slopes by limiting depression storages. The improved performance of the drainage network due to the introduction of pipes and lined channels conveys the runoff faster. This leads to the 'flashy' responses of urban catchments to rainfall events (Kibler, 1982; Mein et al., 1974; Seaburn, 1969). Such rapid concentration of runoff to the catchment outlet can further lead to an increase in peak flows, which is one of the most critical impacts of urbanisation (Rao and Delleur, 1974). Espey et al. (1969) reported a two to four times increment in peak discharge in the developed catchment that they studied compared to a similar undeveloped catchment. They further noted that the increase in peak flow is a simultaneous feature to the reduction in the time of concentration. They reported that the reduction in the time of concentration could be up to two-thirds, depending on the drainage channel improvements. Waananen (1969) also noted that the time of concentration may be reduced by as much as 70% in an urban catchment compared to its natural state.

Cech and Assaf (1976) observed that the highest peak runoffs occur in the most urbanised regions. They studied over 25 years of stream flow records in the coastal region of the Texas Gulf, USA. They observed that most urbanised and industrialised areas produce three to five times larger peak flows than the surrounding undeveloped areas. It was noted however, that these large differences could be attributed to smaller flood events. For large floods, the effects of urbanisation are partly overshadowed by the magnitude of the event. Hollis (1975) showed that the effect of urbanisation is greatest for small floods and as the size of the flood and its recurrence interval increases, the effect of urbanisation diminishes. This is due to two primary reasons:

1. Surface roughness significantly affects the stream flow regime for relatively smaller flow depths. Therefore, change in surface roughness in the catchment surface and drainage network is significant in altering flow conditions for relatively smaller storms rather than for larger storms (Boyd et al., 1987; Boyd et al., 1979).
2. For higher return period storms, rural catchments may become so saturated and its surfaces would behave similarly to impervious surfaces in an urban catchment. The magnitude of the higher return period storm events is capable of overshadowing the limited initial loss of stormwater and relatively small continuing losses due to saturated land surfaces. Furthermore, as most of the higher return period storms are preceded by small rainfall bursts there is more of a possibility of having saturated impervious-like catchment surfaces prior to the higher return period storms. In such situations, both initial losses and continuing losses become even less (Hollis, 1975).

It is difficult to draw a general estimate of the relative increase in flood peaks due to urbanisation as the ‘percentage impervious’ changes from catchment to catchment.

Furthermore, the simple measurement of 'percentage impervious' cannot show the full extent of the urbanisation impact. Additionally, differences in catchment sizes, topography, geology and improvements to the drainage network from catchment to catchment significantly alter the relative increment in peak flow (Hollis, 1975).

Urbanisation leads to an increase in runoff volume on an individual storm basis as well as annual water yield (ASCE, 1975; Seaburn, 1969; Waananen et al., 1961). A double mass curve analysis by Waananen et al. (1961) for Santa Clara Valley showed that outflow is only 76% of the inflow including sewer flows before development and it increased up to 126% with urban development. Seaburn (1969) has shown that the direct runoff from urban catchments can increase from 1.1 to 4.6 times greater than the corresponding runoff in the pre-urban period. Cech and Assaf (1976) noted the significant reduction of infiltration and depression storages as the main cause of the rise in runoff volume. They have argued that even 100% runoff is possible for some catchments under certain rainfall conditions. As an example, an urbanised catchment with saturated pervious surfaces by previous storms may produce 100% runoff.

Urbanisation leads to a reduction of base flow (Codner et al., 1988). The primary reason for this is the reduction of infiltration which in turn leads to a reduction of ground water recharge. Though artificial means of ground water recharge such as garden irrigation and leakages from water and sewer pipes are common in urban areas, research suggests that they are not particularly significant (ASCE, 1975; Kibler, 1982).

2.3 Water Quality Impacts

Urbanisation has a profound impact on the quality of stormwater runoff which consequently impacts on receiving water bodies. Rainfall and resulting surface runoff washes air and land surfaces which are a source of a range of materials of physical, chemical and biological origin. These materials are primarily generated due to anthropogenic activities common to urban areas. Consequent concentration of these materials in stormwater will dramatically impact on the receiving water ecosystem.

This leads to fundamental changes to the natural state of water bodies (House et al., 1993). The changes in hydrologic regime such as increased runoff velocities and volumes further compound the qualitative impacts due to enhanced erosion and dislodgement and entrainment of pollutants built-up on surfaces (Simpson and Stone, 1988).

Pollutants incorporated in stormwater have been recognised as a major contributor to the receiving water degradation. This is primarily due to the magnitude of the pollutant load carried and the wide diversity in pollutant types. Sonzogni et al. (1980) reported 10 to 100 times greater suspended solid and nutrient loads originating from urban areas compared to similar un-urbanised lands. Line et al. (2002) reported approximately ten times greater solids loads and more than two times increased nutrient loads from urbanised catchments compared to rural lands. Lind and Karro (1995) found that the heavy metal concentration in roadside top soil layer in Sweden is two to eight times greater when compared to rural lands. Apart from such high loads, the non-point source origin of stormwater pollutants makes the impact more critical as it is often difficult to implement appropriate control measures.

The difficulty of implementing control measures is further attributed to complexities inherent to pollutant processes. The complexities are primarily due to the involvement of many media, space and time scales in the pollutant generation and transport processes (Ahyerre et al., 1998). Anon (1981) noted that pollutant loads and concentrations show significant variation with the land-use. In a study involving 13 catchments in Victoria, Australia, the pollutant export from an industrial catchment was found to be approximately double compared to the residential catchments. Furthermore, the residential catchments showed further differences in pollutant export relative to their age of settlement. Goonetilleke et al. (2005) noted that variation of land-use is not the only factor that influences pollutant loads and types, but also the characteristics of pollutants. They noted that the degree of solubility and the fraction of pollutants associated with the finer particles vary with land-use characteristics. The authors further noted the inadequate understanding of the physical processes which govern stormwater pollution processes. This makes the development of appropriate mitigation strategies more difficult.

Therefore, in the context of mitigating the impacts of stormwater pollution, understanding the key elements and its primary characteristics is highly desirable (Bradford, 1977; Roesner, 1982). As reported in research literature, identification of the primary sources and understanding the processes that govern pollutant accumulation on these sources and mobilisation from them are most important steps (Bannerman et al., 1993; Sartor et al., 1974; Shaheen, 1975; Vaze and Chiew, 2002).

2.3.1 Pollutant Sources

Due to the impact of raindrops and turbulence created by runoff, pollutants are entrained in stormwater from various urban surfaces (Mackay, 1999). However, rain water can be polluted before it reaches the ground (Shiba et al., 2002; Vazquez et al., 2003). The source from which these pollutants originate is one of the most important factors that influence pollutant composition. The primary pollutant sources identified in the research literature are:

- Road surfaces;
- Roof surfaces; and
- Gardens and lawns.

(Bannerman et al., 1993)

Even though urban catchment surfaces have become the primary source of stormwater pollutants, these pollutants could be generated due to various anthropogenic activities which may take place in other areas. The most common anthropogenic activities that generate stormwater pollutants are:

- Traffic;
- Industrial processes;
- Construction and demolition activities; and
- Erosion and corrosion in the built environment.

Road surfaces are the most significant source of pollutants in urban stormwater (Bannerman et al., 1993; Sartor et al., 1974). The main reason for this is the direct and continuous anthropogenic activities such as vehicular traffic. The highest proportion of the materials present on road surfaces is traffic related. However, atmospheric depositions and eroded materials from adjacent land surfaces are significant for some land uses. The pollutants present on the road surfaces are mainly generated from:

- Vehicle exhaust emissions;
- Degradation of vehicle tyres and brake lining;
- Vehicle lubrication system losses;
- Degradation of road surfaces;
- Load losses from vehicles; and
- Atmospheric depositions and soil inputs.

(Bannerman et al., 1993; Shaheen, 1975)

Traffic volume and road surface conditions are the key parameters influencing traffic related pollutants on road surfaces which will vary from site to site (Novotny et al., 1985; Sartor et al., 1974). Sartor et al. (1974) carried out a comprehensive survey of a number of US cities for pollutant build-up on street surfaces. Their research showed that road surfaces are the most critical pollutant source in urban areas. The roads selected were subjected to moderately high traffic. According to their research, the amount and composition of road surface pollutants are influenced by a range of factors such as land-use, road surface conditions and antecedent dry days. The traffic volume was not considered as a separate variable and it was represented by land-use. The following is a summary of their findings:

1. Asphalt paved roads in fair to poor condition were found to have substantially higher amount of pollutants than good to fair roads and concrete paved roads;
2. The amount of pollutants present on the road surfaces is dependent on the time elapsed since the last clean either by street sweeping or by rain; and
3. The land-use of the adjacent areas has a significant influence on the pollutants present on the road surfaces.

Traffic volume is a critical factor that affects the amount of road surface pollutants. Shaheen (1975) attempted to quantify the amount of traffic related pollutants that accumulate on road surfaces. According to his estimations, 0.7 g/axle/km of pollutants is accumulated on road surfaces due to traffic. A high proportion of this amount is vehicle exhaust and tyre wear. However, the study failed to detect any discernable influence on pollutant accumulation on road surfaces due to factors such as vehicle speed, traffic mix or the composition of the road surface material.

The load and type of pollutants on road surfaces is influenced by a range of traffic related factors. Novotny et al. (1985) showed that the concentration of abrasion products such as tyre particles is significantly higher near traffic signal lights and other traffic bottlenecks such as bridges and bends. Furthermore, traffic volume, driver behaviour and road geometry influence the accumulation of pollution on road surfaces (Brinkmann, 1985).

Overall, the pollution concentration of roof surface runoff is not significant when compared to road surfaces (Bannerman et al., 1993; Van Metre and Mahler, 2003). However, in general, roof surfaces could represent the highest fraction of impervious surface, particularly in residential urban catchments. Therefore, for low traffic density catchments, roof surfaces may be a significant source of pollutants (Bannerman et al., 1993). At the same time, roof surfaces may be significant for certain pollutant types. As an example, the heavy metal contribution from roof surfaces may be significant compared to the other sources for a catchment having an appreciable percentage of metal roofs (Forster, 1996). Van Metre and Mahler (2003) showed that the amount of pollutants on roof tops is influenced by factors that are very site specific. They observed a higher amount of pollutants on roof tops near highways and industries than those further away.

Depending on the amount of runoff produced, gardens and lawn areas could be significant contributors to the stormwater pollutant load. For relatively large storms where gardens and lawn areas produce runoff, they contribute significantly to the suspended solids load. Furthermore, Bannerman et al. (1993) showed that there is a significant amount of nutrient loads originating from gardens and lawn areas. The study showed that 14% of particulate phosphorus in residential areas and 47% of particulate phosphorus in industrial areas originate from lawns.

2.3.2 Significance of Impervious Surfaces in Stormwater Pollution

A high proportion of pollutants introduced into urban runoff originates from catchment surfaces. Bed and bank erosion of the drainage network is relatively low since most urban channels are well protected. Catchment surfaces can be categorised into two groups: impervious and pervious. Road surfaces, roofs, parking lots and driveways are the most common impervious surfaces in urban catchments. Most of these impervious surfaces are directly connected to the drainage network. Gardens and lawn areas are the most common examples of pervious surfaces in urban catchments.

According to Novotny et al. (1985), impervious surfaces produce runoff for most of the rainfall events since the initial losses are comparatively low. Therefore, depending on the amount of pollutants accumulated during the dry period and the pollutant wash-off capacity of rainfall events, the pollutant load originating from impervious surfaces could be significantly high since runoff occurs more regularly. According to Sartor et al. (1974), there is a high possibility of accumulating a significant amount of pollutants within the first two days after a rain event. This means that impervious surfaces are important pollutant sources (Bannerman et al., 1993; Forster, 1996; Mackay, 1999; Sartor et al., 1974). Pervious surfaces on the other hand, produce runoff only for relatively larger rainfall events as infiltration and other initial losses are comparatively high. Australian Rainfall and Runoff (Pilgrim, 1998) states that the initial loss for Eastern Queensland is 15 to 35 mm. This indicates that at least 15 mm of rainfall is needed to produce runoff from pervious surfaces. Consequently, some amount of dissolved pollutants may infiltrate into the ground and a portion of particulate pollutants may get trapped within the pervious area due to relatively low runoff velocities. However, for relatively larger and longer duration storm events, pervious surfaces produce a significant amount of pollutant load, particularly suspended solids and nutrients, since they have an infinite pool of such pollutants (Mackay, 1999; Novotny et al., 1985).

It is important to evaluate the relative significance of urban surfaces as pollutant source areas. The significance varies with the land use, rainfall volume and other catchment and anthropogenic parameters. The water quality investigations by

Bannerman et al. (1993) describe the relative importance of source areas. The research was based on two typical urban sites: a residential site and an industrial site in Washington, USA. A small commercial centre was situated in the middle of the residential site. Runoff samples were collected from these two sites and analysed for three types of street surfaces, roof surfaces, lawn areas, driveways and parking lots. Table 2.1 shows the summary of the results obtained.

Table 2.1- Critical source area and contaminant-load percentages (Adapted from Bannerman et al 1993)

	Feeder Streets	Collector Streets	Arterial Street	Lawns	Drive Ways	Roofs	Parking Lots	Side Walks	Total Load
Residential Source Area									
Total Solids	**56**	**20**	_	7	12	_ _	_	5	5664kg
Suspended Solids	**62**	**18**	_	7	9	_ _	_	4	4182kg
Total Phosphorus	**39**	**19**	_	14	**20**	_ _	_	8	13109g
Dissolved Phosphorus	**31**	**15**	_	**22**	**23**	_ _	_	9	4717g
Dissolved Copper	**29**	**44**	_	3	16	2	_	6	125g
Total Recoverable Copper	**33**	**45**	_	3	13	1	_	5	288g
Total Recoverable Zinc	**42**	**38**	_	2	11	2	_	5	2061g
Fecal Coliform	**57**	**21**	_	5	12	_ _	_	5	
Commercial Source Area									
Total Solids	_	**22**	**35**	_	_	10	**31**	2	367kg
Suspended Solids	_	**27**	**41**	_	_	3	**27**	2	194kg
Total Phosphorus	_	**29**	**27**	_	_	11	**28**	5	597g
Dissolved Phosphorus	_	**30**	**20**	_	_	16	**27**	7	169g
Dissolved Copper	_	**19**	**31**	_	_	10	**39**	1	20.4g
Total Recoverable Copper	_	**22**	**38**	_	_	7	**32**	1	41.1g
Total Recoverable Zinc	_	11	**34**	_	_	**22**	**32**	1	503g
Fecal Coliform	_	**60**	**22**	_	_	3	10	5	
Industrial Source Area									
Total Solids	_	**17**	3	15	_	5	**60**	_	6707kg
Suspended Solids	_	**21**	4	16	_	4	**55**	_	4274kg
Total Phosphorus	_	17	2	**47**	_	5	**29**	_	10063g
Dissolved Phosphorus	_	**17**	1	**69**	_	2	11	_	3690g
Dissolved Copper	_	**14**	2	6	_	5	**73**	_	158g
Total Recoverable Copper	_	**19**	3	5	_	6	**67**	_	467g
Total Recoverable Zinc	_	7	2	1	_	**60**	**30**	_	7784g
Fecal Coliform	_	9	1	**70**	_	1	**19**	_	

_ indicates source area is not in the land use and _ _ indicates less than 1% of load

According to the research summarised in Table 2.1, street surfaces and parking lots are the most significant source areas for urban stormwater pollutants. They are the highest contributor for most of the pollutants irrespective of the land-use. Lawn areas are significant in terms of phosphorus load. Bannerman et al. (1993) further noted that the use of fertilisers may be the main reason for higher phosphorus load originating from the lawn areas. Roof surfaces, on the other hand, are not significant as a pollutant contributor except for metals such as Zinc. The use of metal roofing may be the main cause of high Zinc contribution from roofs at the industrial site.

2.3.3 Pollutant Build-up

Understanding the processes involved in pollutant accumulation is an important part of stormwater quality research. Pollutant accumulation is a complex process since many variables such as surface type, surface roughness, slope, antecedent dry days and land-use play an influential role. Numerous research studies have focused on understanding the variability of pollutant build-up and on developing suitable models. Such research has sought to understand issues such as:

- Factors that influence pollutant build-up;
- Composition of pollutants in the build-up; and
- Mathematical replication of pollutant build-up.

(Namdeo et al., 1999; Sartor and Boyd, 1972; Shaheen, 1975)

Many researchers have focused on studying pollutant build-up on road surfaces since roads are an important source area (Sartor et al., 1974; Shaheen, 1975). Theoretically, one can assume that the pollutant deposition on road surfaces is uniform, in relation to spatial uniformity of distribution of traffic and dry deposition. However, due to wind and traffic impacts, pollutants are constantly moved away from the turbulent areas and deposited in the kerb areas (Namdeo et al., 1999; Novotny et al., 1985). During this process, there are more possibilities of losing pollutants from the system by depositing them in pervious areas or being re-entrained into the atmosphere. Due to the continuous re-distribution process on road surfaces, a higher proportion of the total solids load is concentrated in the kerb and near kerb areas (Sartor et al., 1974). This type of pollutant re-distribution is common for roads where the traffic volume is significantly high.

The primary factors that affect pollutant re-distribution, and hence build-up, are wind and vehicle induced turbulence. According to Novotny et al. (1985), at least a 20 km/hr wind velocity is required for appreciable pollutant re-distribution. Furthermore, their research revealed that the mean particle size of the re-suspended particles is around 15 μm and only 22% of the particles are larger than 30 μm. However, the general particle size range of the road surface depositions discussed in other publications is well above the re-entrained particle size range. Sartor et al.

(1974) noted that only 5.9% of the near kerb depositions are less than 43 μm. Traffic and traffic-induced turbulence could be the most critical parameter that influences pollutant re-distribution. Studies by Sartor et al. (1974) and Ball et al. (1998) revealed that pollutant concentration in near kerb areas is significantly high compared to the centre of the road. As they have noted, the reason for this is the movement of pollutants to the less turbulent region due to vehicular induced wind turbulence. Furthermore, Vaze and Chiew (2002) noted that the pollutant build-up may vary along the longitudinal direction of the road depending on the slope and the presence of traffic signals and bottlenecks.

The composition and particle size distribution of accumulated pollutants on road surfaces are important parameters in water quality research. This is due to the variation of different particle size ranges in association with other pollutants, method of transport and the impact on the natural water environment. Sartor et al. (1974) found that most of the pollutants are adsorbed to particles less than 43 μm. They reported that 50% of the metals and one-third to one half of nutrients are absorbed to the finer fraction. The finer fraction (less than 43 μm) was only 5.9% of the total solids. Bradford (1977) also found that 60% of the heavy metals are associated with 6% of the finer fraction of solids. The concept of the coarser dominant particle weight and finer dominant pollutant adsorption was further supported by Shaheen (1975). He reported that the bulk of the accumulated particles are in the range of 500-2000 μm. Ball et al. (1998) noted the influence of regional and catchment management practices on pollutant build-up and its composition. They observed less pollutant load in typical suburban roads in Sydney, Australia when compared to North American roads. However, the particle size distribution of the accumulated pollutants that was observed was similar to that reported by Sartor et al. (1974).

Contradictory reporting is evident on build-up and its characteristics on road surfaces where the traffic volume is significantly less. Herngren et al. (2006a) found around 85% of the solids belong to finer particle size groups which was less than 75 μm in industrial and residential roads. The research was based on roads where the traffic volume is relatively low and the antecedent dry period was between one to seven days. However, similar to most other researchers, they observed higher pollution composition in the finer fraction of solids.

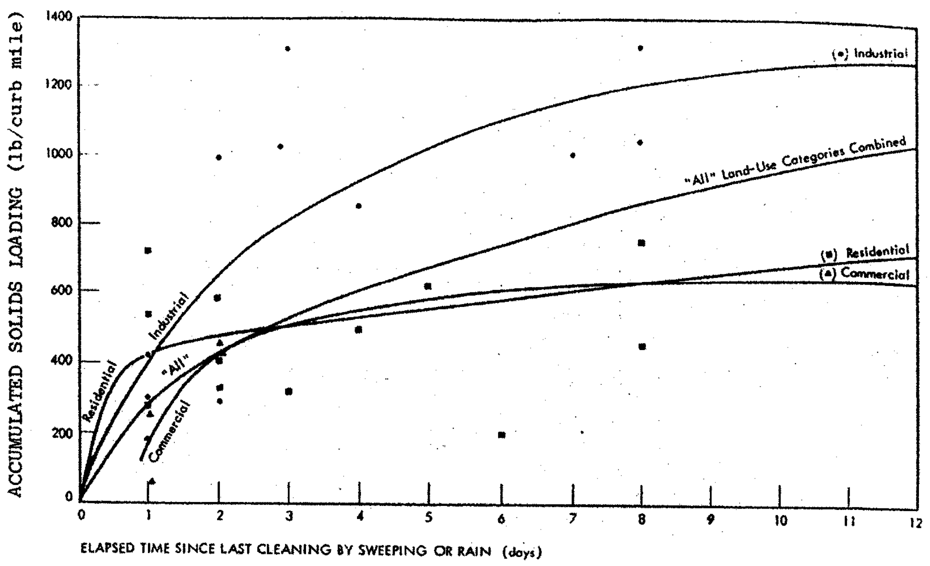


Figure 2.2 - Pollutant accumulation rate for different land uses (Adapted from Sartor et al., 1974)

Sartor et al. (1974) revealed that the pollutant accumulation on the road surfaces varies with the land-use of the surrounding area and is a function of antecedent dry days. They published pollutant accumulation curves for residential, industrial and commercial land-uses (see Figure 2.2). These pollutant accumulation curves are the basis for most urban stormwater quality models (Novotny et al., 1985). As Sartor et al. (1974) noted, the pollutant accumulation on road surfaces can be replicated mathematically using a decreasing rate increasing function. They developed an exponential function in the form of:

$$\frac{dP}{dt} = I - aP \quad \text{Equation 2.1}$$

Where,

P = Amount of pollutants in the kerb;

I = Sum of all inputs;

t = Time; and

a = Removal coefficient.

Ball et al. (1998) noted that build-up in the near kerb area can be replicated mathematically using a power equation. They tested a range of equations in different forms for build-up replication and recommended a power function as the most suitable. Their research was based on typical Australian suburban roads with relatively moderate traffic. As they recovered relatively less pollutants, the results obtained using the replication equation are significantly different from the equation proposed by Sartor et al. (1974). However, the phenomenon of decreasing rate increasing variation of build-up was confirmed. This suggested similar characteristics of build-up irrespective of land-use, traffic and other factors. However, due to greater variability of influential parameters such as land-use and traffic, the amount of build-up could be highly site specific.

2.3.4 Pollutant Wash-off

The pollutants accumulated on urban surfaces are subjected to wash-off during storm events. During the initial period of rainfall, the catchment surfaces get wet and most of the soluble pollutants begin to dissolve in a film of water. At the same time, some of the materials are loosened from the surface and suspended in the water film by the energy of the falling raindrops. As the water film builds up and begins to flow down slopes, it also develops an ability to hold pollutants in suspension due to the flow turbulence. The kinetic energy of the raindrops is comparatively higher than the flow energy for overland flow situations. However, when the flow is concentrated into channels and gutters and as the depth increases, the raindrop energy becomes less important (Mackay, 1999).

The amount of pollutants washed-off from impervious surfaces is primarily influenced by the amount available on the surface which in turn is related to the pollutant build-up process (Duncan, 1995). As discussed in Section 2.3.3, build-up is a dynamic process which primarily varies with the antecedent dry period. This indicates the influence of antecedent conditions on the amount of pollutant wash-off. However, as far as the wash-off process is concerned, the influence of the amount of build-up is limited. The other parameters, primarily rainfall and runoff parameters, are the most influential in the wash-off process (Novotny et al., 1985; Sartor et al., 1974).

Explanation for the processes governing pollutant wash-off varies in the research literature. However, all hypotheses centre around four influencing rainfall and runoff variables: rainfall intensity, rainfall volume, runoff rate and runoff volume (Mackay, 1999). These variables correlate with each other: therefore, it is difficult to discern the degree of influence exerted by them individually on wash-off. Chiew and McMahon (1999) investigated the relationship between pollutant wash-off and runoff volume in urban catchments in Australia. They showed that the event mean concentrations of suspended solids and total phosphorous can be better estimated using total runoff volume. This implies that the higher runoff volume carries a higher pollutant load. However, for an urban catchment with well protected pervious surfaces this may not be true since there should always be an upper limit of pollutant availability on the catchment surfaces. Chui (1997) showed that event mean concentration for total suspended solids (TSS) and chemical oxygen demand (COD) increases with the rainfall intensity rather than with rainfall volume. The rainfall intensity correlates with the rate of kinetic energy supplied by the raindrops. Therefore, the pollutant removal capacity of rainfall may increase with intensity.

Herngren et al. (2005a) showed that pollutant wash-off may be influenced by catchment surface properties such as texture depth. They used simulated rainfall over several road surface plots to investigate pollutant wash-off behaviour and found that relatively rough road surfaces are capable of holding a greater fraction of pollutants within the surface. Furthermore, they showed that pollutant wash-off is influenced by both rainfall intensity and runoff volume but they were not able to determine the relative importance of each parameter on pollutant wash-off.

The general understanding of pollutant wash-off implies that rain storms only remove a fraction of the pollutants from the catchment surface. The experimental study by Vaze and Chiew (2002) showed that after a significant rainfall event of 39.4 mm, only 35% of the total pollutants were washed-off. The following rainfall event of 4 mm reduced total pollutant load by 45%. Based on field measurements, Vaze and Chiew (2002) have proposed two possible pollutant wash-off concepts, as illustrated in Figure 2.3. These alternative processes are termed as ‘source limiting’ (Figure 2.3a) and transport limiting (Figure 2.3b). According to their research, pollutant wash-off from impervious surfaces that are subjected to more frequent rainfall events is more close to the source limiting process.

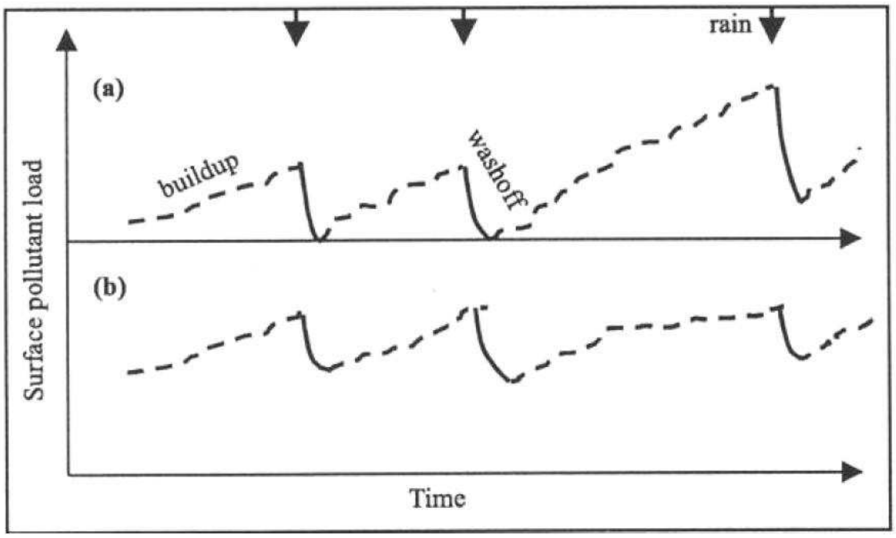


Figure 2.3 – Hydrologic representation of surface pollutant load over time (Adapted from Vaze and Chiew, 2002)

According to Sartor et al. (1974), the rate at which rainfall wash-off removes particulate pollutants from road surfaces depends on three primary factors: road surface characteristics, rainfall characteristics, and particle size. However, they have further suggested that the influence of rainfall intensity is comparatively higher for pollutant wash-off than for other parameters and the use of rainfall intensity alone in a pollutant wash-off equation produces acceptable outputs. The pollutant wash-off equation developed by Sartor et al. (1974) is in exponential form. Rosener (1982) suggested that the pollutant wash-off equation (Equation 2.2) developed by Sartor et al. (1974) could be used for all impervious surfaces. However, the equation was primarily developed based on research data from road surfaces.

$$W = W_o(1 - e^{-kIt}) \qquad \text{Equation 2.2}$$

Where,

W_o = Initial weight of the material of a given particle size;

t = Time of rainfall;

I = Rainfall intensity;

W = Weight of material of a given particle size removed after time t; and

k = Wash-off coefficient.

The wash-off coefficient '*k*' varied with the street surface characteristics but was found to be almost independent of particle size.

2.3.5 First Flush Phenomenon

As noted by numerous researchers, the 'first flush' is an important phenomenon which has strong links to pollutant wash-off and transport. The 'first flush' refers to the higher concentration of pollutants during the initial period of the storm events. It has been noted that the concentration peak precedes the runoff peak (Deletic, 1998; Duncan, 1995; Lee et al., 2002).

The first flush phenomenon is the primary justification for most stormwater treatment design. Most treatment facilities such as retention and detention basins have been designed so that they treat the initial runoff which in turn contains the highest concentration. The rest of the runoff is often bypassed without any treatment. However, the uncertainty of occurrence of 'first flush' and the presence of a high amount of dissolved pollutants which is difficult to treat using such facilities often leads to failure of treatment (Harrison and Wilson, 1985).

Although the occurrence of first flush has been commonly reported, the observations are not consistent. Hall and Ellis (1985) and Sonzogni et al. (1980) stated that the significance of the first flush is overemphasised and only 60% to 80% of the storms exhibit this phenomenon. Apart from the uncertainty of occurrence, Hoffman et al. (1984) noted that the timing of the peak concentration for different pollutants could vary. They noted that the peak of dissolved concentrations often occurs after the peak of particulate concentrations.

The occurrence and nature of first flush can be influenced by a range of factors. Harrison and Wilson (1985) noted that the occurrence of first flush is influenced by the temporal and aerial variation of rainfall events. It is often noted that the highest intensity rainfall bursts are in the initial period of rain events. This could cause higher pollutant wash-off during the initial part of the event which in turn magnifies the first flush. Furthermore, first flush can be magnified by the presence of a higher fraction of roof surfaces where most of the pollutant wash-off takes place during the initial period of runoff. Forster (1996) noted that roofs produce significant concentrations of pollutants during the initial period of runoff. Catchment characteristics also have a pronounced influence on the first flush. Lee and Bang (2000) and Lee et al. (2002) observed high strength first flush occurrence in smaller and highly impervious catchments compared to larger and less impervious catchments. However, Bertrand-Krajewski et al. (1998) noted that the influence of catchment size on first flush is minor.

2.4 Primary Stormwater Pollutants

As stormwater pollution leads to significant deterioration of the quality of receiving water bodies, identification of specific characteristics and types of urban pollutants is critically important. Unlike rural catchments, anthropogenic activities in urban catchments result in a diverse variety of pollutants. Industrial processes, vehicular traffic, construction and demolition activities and household chemical use are key anthropogenic activities in urban areas. The common pollutants present in urban catchments are:

- Litter;
- Nutrients;
- Heavy metals;
- Hydrocarbons;
- Organic carbon; and
- Suspended solids.

2.4.1 Litter

The primary categories of litter are packaging materials such as paper, glass, metals, plastics and grass and plant leaves. Litter is not a major concern in terms of water quality degradation. However, most urban catchments produce a significantly high volume and mass of litter. Litter contributes to drain blockage and gives an unsightly appearance to receiving waters. Therefore, the presence of litter in stormwater runoff is a considerable issue for urban drainage management (Armitage and Rooseboom, 1999; Marais et al., 2001). The research by Allison et al. (1998) in an inner suburban catchment in Melbourne, Australia, suggested that the nutrient contribution from litter is an order of magnitude smaller than the nutrients present in typical stormwater runoff. This implies that the significance of litter is comparatively low purely as a water pollution agent.

2.4.2 Nutrients

Nutrients are chemicals that are essentially required for plant growth. However, high contributions of nutrients from urban lands cause excessive growth of plants such as algae. The excessive growth of algae alters the visual appearance of water bodies. The visual impact may include colour, turbidity and floating matter. Consequently, death and decomposition of vegetation will alter water quality parameters such as dissolved oxygen demand (Brezonik and Stadelmann, 2002; O'Reagain et al., 2004).

Total nitrogen (TN) and total phosphorous (TP) are the most important nutrients that cause water quality degradation. Many researchers have shown that stormwater runoff is a significant source of nutrients (for example, Sonzogni et al. (1980). However, the primary source areas that they refer to are different. According to Bannerman et al. (1993) and Novotny et al. (1985), significant amounts of nutrients originate from gardens and lawns in residential catchments which could be the result of the use of fertiliser. Shaheen (1975) found that road surface runoff contains significant nitrogen and phosphorous compounds and that a significant fraction of these pollutants is due to vehicle exhausts. Forster (1996) showed that almost all the nitrogen compounds originating from roof surfaces are atmospheric depositions. Significant amounts of nutrients may originate from the degradation of leaf litter. However, Allison et al. (1998) showed that the nutrient contribution from leaf litter is two orders of magnitude less than the typical nutrient loads in urban stormwater.

2.4.3 Heavy Metals

Urban stormwater can contain significant amounts of heavy metals. The research by Lind and Karro (1995) showed that the top soil of urban roadside green areas contain two to eight times more heavy metals than top soil in rural areas. These roadside green areas are designed as stormwater infiltration areas in stormwater management practice. The common heavy metals found in stormwater runoff are Zinc (Zn), Lead (Pb), Copper (Cu), Cadmium (Cd), Nickel (Ni) and Chromium (Cr) (Lind and Karro, 1995; Sorme and Lagerkvist, 2002).

The main sources of heavy metals in the urban environment include household and commercial chemical use, traffic related pollutants, atmospheric depositions and building materials. Sorme and Lagerkvist (2002) observed that one of the main sources of Cu is tap water and roof runoff. Their research mainly focused on tracking heavy metal sources in the urban environment. Furthermore, they identified that one of the largest sources of Zn was galvanised building materials and car washing liquids. Sartor et al. (1974) and Zenders (2004) showed that road surfaces contain a significant amount of heavy metals. According to their research, vehicle exhausts, tyre and brake lining, and asphalt pavement contributions are the main sources of heavy metals in a road surface.

2.4.4 Hydrocarbons

Stormwater runoff is a major contributor of hydrocarbon load in an urban environment (Gray and Becker, 2002). Datry et al. (2003) showed that the bed sediment of stormwater detention basins contain significant amounts of hydrocarbons. They tested bed sediment of a stormwater detention basin in France which had operated for over thirty years. The results showed that 52.9 mg/kg of dry sediment were present including 15 types of hydrocarbons. According to their research, most of the hydrocarbons were attached to particulate matter and were rarely found in the dissolved phase.

Hydrocarbons can originate both from natural and anthropogenic sources. Natural sources such as degradation of organic matter and forest fires contribute a minor fraction of hydrocarbons to the urban environment. Anthropogenic activities are the major source of hydrocarbon load including Polycyclic Aromatic Hydrocarbons (PAHs). Van Metre et al. (2000) showed that the increasing trend of PAH in stormwater runoff is caused by combustion sources. They observed that PAH concentrations track closely with an increase in automobile use. However, Ngabe et al. (2000) commented that the chemical composition of PAHs found in stormwater runoff is more closely related to lubrication oil. Therefore, non-combusted oil losses could be a major source of hydrocarbons in road surface runoff.

2.4.5 Organic Carbon

Organic carbon is an oxygen demanding material which is commonly found in urban stormwater runoff. The major impact of organic carbon is the reduction of dissolved oxygen in water. Excessive loads of oxygen demanding materials can reduce the amount of dissolved oxygen in receiving water and hence cause significant damage to aquatic life (Warren et al., 2003).

Gromaire-Mertz et al. (1999) showed that the largest amount of organic carbons originates from road surfaces in urban environments. The variations of organic matter on urban surfaces were found to be dependent on a range of parameters such as antecedent time since the last street cleaning or rainfall event and land use characteristics. Sartor et al. (1974) showed that organic matter accumulates on road surfaces much faster than inorganic matter. Roger et al. (1998) showed that in road surface runoff the organic carbon concentration is significantly high in particles less than 50 μm.

2.4.6 Suspended Solids

In an urban environment, the pollutants available on paved surfaces such as roads, roofs, and gardens are mostly in particulate form. During rainfall events some of these pollutants dissolve in stormwater, but a significant amount is transported as particulate pollutants. These particulate pollutants are commonly referred to as suspended solids. It has been noted that particulate pollutants are kept in suspension by the raindrop induced turbulence in overland flow (Mackay, 1999).

The size range of the suspended solids varies from very fine solid particles to large particles depending on the turbulence created by the raindrops. Relatively larger and dense particles may settle and re-suspend during the flow and the possibility of settling in the receiving water bodies is high. The physical impact of these settable solids include smothering of bottom dwelling fauna and flora and changes to the substrate.

Finer particles remain in suspension for a longer period of time. This is due to the larger surface area compared to mass and the presence of electrostatic charges (Dong et al., 1983). Therefore, fine textured particles are most likely to reach receiving water bodies. Andral et al. (1999) noted that the higher fraction of finer particles which are less than 100 μm remains in suspension for a longer period of time whilst a higher fraction of coarser particles which are greater than 100 μm will settle rapidly. They further noted that treatment for the finer fraction will remove 90% of the solids which have a high potential to reach receiving waters.

Finer particle ranges are not only actively available in water bodies by being in suspension but they are also associated with a high fraction of other pollutants such as hydrocarbons and heavy metals. Herngren et al. (2005a) showed that heavy metal and hydrocarbon concentrations are strongly correlated with the total suspended solids load. Sartor et al. (1974) noted a significantly high percentage of nutrients and organic material in the finer fraction less than 43 μm which was only 5.9% of the total solids. Since the correlation of suspended solids to other pollutants is strong, the use of suspended solids as a surrogate to estimate other pollutants is a common practice. This is the primary reason for the common approach of selecting suspended solids as an indicator pollutant in stormwater quality research (Akan and Houghtalen, 2003). The capacity for adsorbing other molecules varies with the size, structure and physio-chemical properties such as electrical conductivity of the particles (Pechacek, 1994; Tai, 1991). As noted by Hamilton et al. (1984) and Warren et al. (2003), the other factors influencing pollutant adsorption are organic carbon concentration and pH.

2.5 Hydrologic and Water Quality Modelling Approaches

With growing awareness of both the hydrologic and water quality impact of urbanisation, hydrologic modelling and water quality modelling are increasingly used as estimation tools for understanding the quantity and quality impacts of stormwater runoff (Zoppou, 2001). Hydrologic models are generally used as a flood estimation tool for simulating individual storm events or a series of events which has occurred over a period of time. Unlike hydrologic models, water quality models have been developed to estimate the long-term pollutant impact on receiving waters. However, there are a number of models, such as SWMM which have been developed to estimate pollutant load from an individual storm event (Rossman, 2004). Both hydrologic and water quality models were first developed for natural or rural catchments. With the increasing demand for urban hydrologic and pollution models, both types of models have been modified to handle urban characteristics (Ahyerre et al., 1998; Zoppou, 2001). In this section, the technical capabilities of hydrologic and water quality models in an urban context are discussed.

2.5.1 Urban Hydrologic Models

Hydrologic models are usually a combination of mathematical procedures used to replicate hydrologic processes. This combination ultimately generates quantitative estimates of stream flow runoff. The main hydrologic processes in a catchment are illustrated in Figure 2.4.

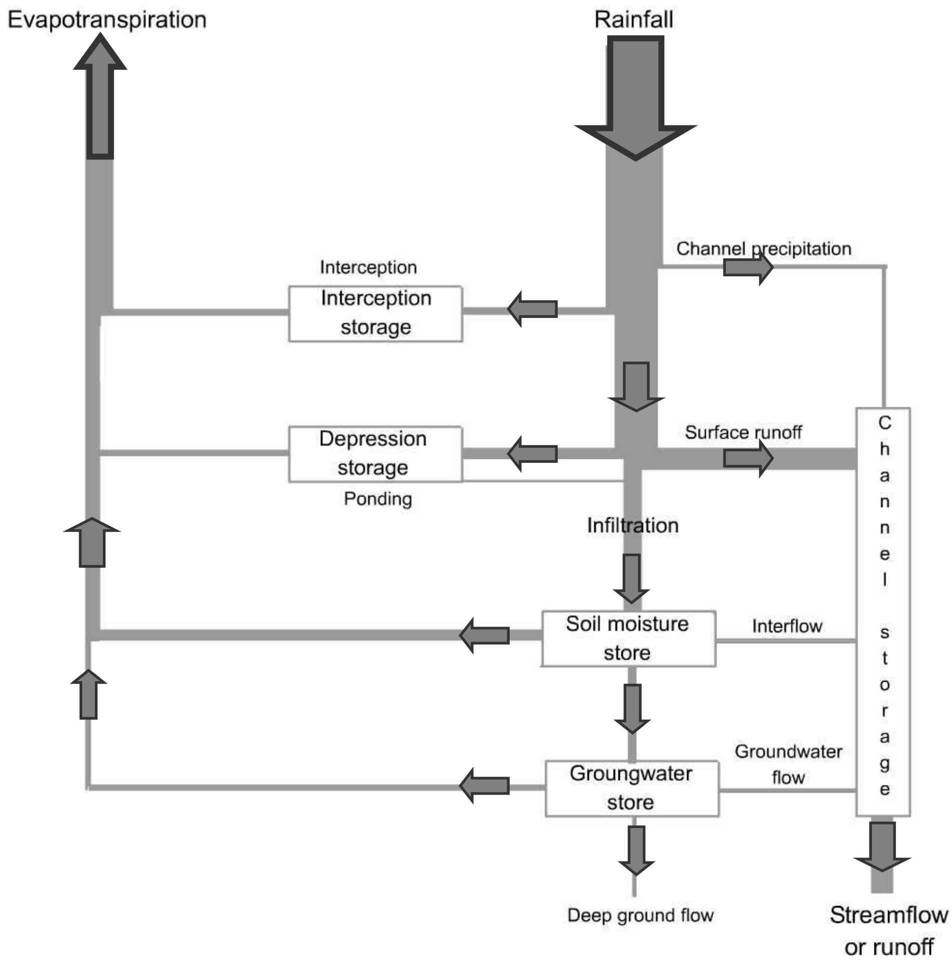


Figure 2.4– Hydrologic processes
(Adapted from O'Loughlin and Stack, 2004)

Different mathematical procedures have been developed to estimate each component of the hydrologic processes (Boyd et al., 2003; Laurenson and Mein, 1995; O'Loughlin and Stack, 2004). As an example, Horton's infiltration equation is a recognised estimation procedure for rainwater infiltration. However, most of the developed mathematical procedures focus on rural or natural catchments. There are significant quantitative differences in urban hydrologic processes when compared to rural hydrologic processes in relation to infiltration and depression storage (Laurenson, 1962; Waananen et al., 1961). Models that do not account for these differences may lead to erroneous estimations. In order to overcome these estimation errors, modifications have been included in rural hydrologic models so that they can replicate urbanisation effects. In most cases, urban catchment surfaces are considered as a combination of three different land cover types: impervious – directly connected, impervious – supplementary and pervious. Separate mathematical procedures have been developed to replicate rainfall and runoff processes in these three types of surfaces (Boyd et al., 2003; O'Loughlin and Stack, 2004).

With the advancement of research knowledge, accurate and complex mathematical procedures have been developed to replicate each rainfall and runoff process. Use of these procedures in a hydrologic model increases its complexity. Therefore, model users often simplify the aspects of urban hydrology to a manageable level of complexity. However, oversimplification of catchment behaviour may lead to errors. On the other hand, more complex models need more computational effort and data resources (Goonetilleke, 1998; Phillips and Yu, 2001; Zoppou, 2001). The simplicity or complexity of a model depends on the needs. However, a number of primary features have been recommended to be included in hydrologic models in order to improve their prediction power (Laurenson, 1964). These are:

- Temporal and spatial variation of rainfall excess;
- Distributed nature of the catchment; and
- Non-linearity of the catchment response.

Hydrologic models which use different mathematical procedures with different complexity are available. The types of models vary from simple models which are only capable of estimating peak discharge to complex models that can be used to estimate the runoff hydrograph. The decision on which model to use depends on the capabilities of the model and the complexity to which users are accustomed (O'Loughlin and Stack 2004).

2.5.2 Hydrologic Modelling Approaches

The rational formula is the simplest form of the hydrologic model (Rossmiller, 1980). It is a simple statistical relationship between measurable parameters such as rainfall intensity, peak discharge and catchment physical properties. The formula is only capable of estimating peak discharge. The primary advantage of using the rational formula is its simplicity. It requires comparatively less data and resources to perform calculations. Although the formula is widely used in the urban context, care has to be taken in selecting an appropriate runoff coefficient. Furthermore, due to the level of simplicity, the estimations could be far from reality. The fundamental assumptions used are:

- The design storm is uniformly distributed in time and space;
- The storm duration is equal to the time of concentration;
- Peak flow is a fraction of average rainfall rather than the rainfall excess;
- The return period of the peak flow is equal to the return period of storm; and
- Rainfall runoff response is linear.

(Dayaratne, 2000; Goonetilleke, 1998).

With the advent of computers it has become possible to create models that can handle complex rainfall temporal patterns as inputs and use complex mathematical replications as hydrologic processes. In this type of complex model, the mathematical procedures used for estimation can be separated into a loss model and a routing model.

The loss model represents the rainfall and runoff processes such as interception, depression storage, infiltration and evaporation. The loss model enables the estimation of the rainfall excess which is the portion of water available for runoff. The most common types of loss models are:

- Initial loss – continuing loss model;
- Initial loss – proportional loss model; and
- Infiltration models such as Horton's infiltration equation.

(Boyd et al., 2003; Laurenson and Mein, 1995; O'Loughlin and Stack, 2004)

For urban catchments, two different loss models are used for impervious and pervious surfaces. For impervious surfaces, only an initial loss is commonly subtracted from the rainfall in order to calculate rainfall excess. The general range of initial loss for impervious surfaces is 0 to 5 mm (Boyd et al., 2003; O'Loughlin and Stack, 2004). For the pervious area, the initial loss – continuing loss model is the most widely used and it is the recommended model for most parts of Australia (Pilgrim, 1998). The common procedure is to subtract complete losses from the rainfall prior to routing. However, there are some models which subtract depression storages first, then calculate the runoff using the routing model and subtract infiltration losses from the runoff. This latter approach is more realistic since infiltration may occur continuously during the runoff period (O'Loughlin and Stack, 2004).

The routing model transforms the rainfall excess into a runoff hydrograph using catchment properties. Routing models incorporate peak attenuation and travel time of runoff due to the storage action of the catchment and channels. Some of these routing models are theoretically based and others are conceptual models. The main types of routing models are:

- Unit hydrograph models;
- Kinematic wave routing models;
- Artificial storage routing models; and
- Time area routing models.

A Unit Hydrograph Models

The unit hydrograph is the catchment response for a unit of excess rainfall. Models developed based on unit hydrograph methods derive flood hydrographs from the given rainfall excess hyetograph. To keep computational effort to a minimum, the catchment parameters are limited to area, length and slope (Espey et al., 1969; Pilgrim et al., 1981; Sarma et al., 1973).

The basic theoretical contradiction of the unit hydrograph method is its linearity. In the unit hydrograph method, the rainfall excess and runoff are assumed to be linearly related (Kitheka et al., 1991). However, it is clearly understood that the rainfall-runoff relationship for any catchment is nonlinear (Aitken, 1975; Askew, 1970; Laurenson, 1962). Researchers have attempted to include modifications to the unit hydrograph method to adapt it to an urban context. In some cases, such as in the work of Espey et al. (1969), attempts have been made to modify the unit hydrograph for urban catchments. They have investigated runoff responses from various urban catchments in order to develop a general urban unit hydrograph. In other cases, the parameters of conceptual models based on the unit hydrograph have been modified in order to replicate urbanisation effects (Sarma et al., 1973). The latter method was relatively more successful than the former. However, the use of models based on the unit hydrograph is becoming less popular with the rise of non-linear, more theoretically-sound, physically-based models.

B Kinematic Wave Models

Mathematical models have been developed to simulate the overland flow of general irregular surfaces. These models have been used in hydrologic modelling of catchments. The capability of simulating accurate behaviour and routing of flow in irregular and complex catchment surfaces using these models is not well known. However, there are several approximate models commercially available. The use of a simplified form of kinematic wave equation is one of the most popular forms of mathematical models. These models are generally referred to as 'physically-based models' (Liu et al., 2004; Sugiyama et al., 1997).

Even though the kinematic wave models are a simplified form, they are relatively accurate for low flow depths and steep slopes. Although physically-based models provide similar reliability and accuracy as the storage routing models and time area routing models (to be discussed later), they need more computational effort. Therefore, the inclusion of the distributed nature of the catchment into the model by subdividing it into a number of subcatchments is complex. These are the main reasons for the relatively low use of kinematic wave models in Australia (Pilgrim et al., 1981; Zoppou, 2001).

C Storage Routing Models

Storage routing models are among the most popular in urban hydrologic modelling. The storage routing method is simple and requires less computational effort when compared to physically-based models. Storage routing models have been developed for rural catchments and most of them are capable of analysing partially urbanised catchments with necessary modifications to the model structure. The pioneering storage routing model was proposed by Laurenson (1964). In his model, the catchment was subdivided into sub-areas on the basis of lines of equal travel time or isochrones. Each sub-area was considered as a reservoir with non-linear outflow behaviour (Boyd et al., 1979; Boyd et al., 1996; Carroll, 2002; Laurenson, 1962, 1964; Mein et al., 1974).

The basis for most of the storage routing models is very similar to the Laurenson (1964) model. The main difference in each model is the method of interpreting physical derivations of sub-areas into a reservoir network and the parameters of the non-linear equation. RAFTS (Laurenson, 1964), RORB (Laurenson and Mein, 1995) and WBNM (Boyd et al., 2003) are the most common models developed based on the storage routing procedure.

D Time Area Routing Models

The time area diagram shows the variation of contributing area to the flow with time at the outlet for a constant rainfall event. The runoff hydrograph for a given catchment and given rainfall event can be calculated using a time area diagram as illustrated in Figure 2.5.

The time area diagram is drawn based on the calculations of the time of concentration for the various parts of the catchment. For urban catchments, the time of concentration is the sum of property drainage time, overland flow time and gutter flow time. Separate calculation procedures are available to calculate each flow time depending on the physical properties of each drainage item (O'Loughlin and Stack, 2004). The time area diagram could be of concave or convex shape depending on the shape of the catchment and other factors. However, most of the time area routing models consider time area diagram as linear. Models such as ILSAX and DRAINS are the most widely used hydrologic models in Australia that are based on time area routing (O'Loughlin and Stack, 2004). These two models have been specifically developed for urban catchments. The models also contain hydraulic procedures to calculate pipe and channel flow.

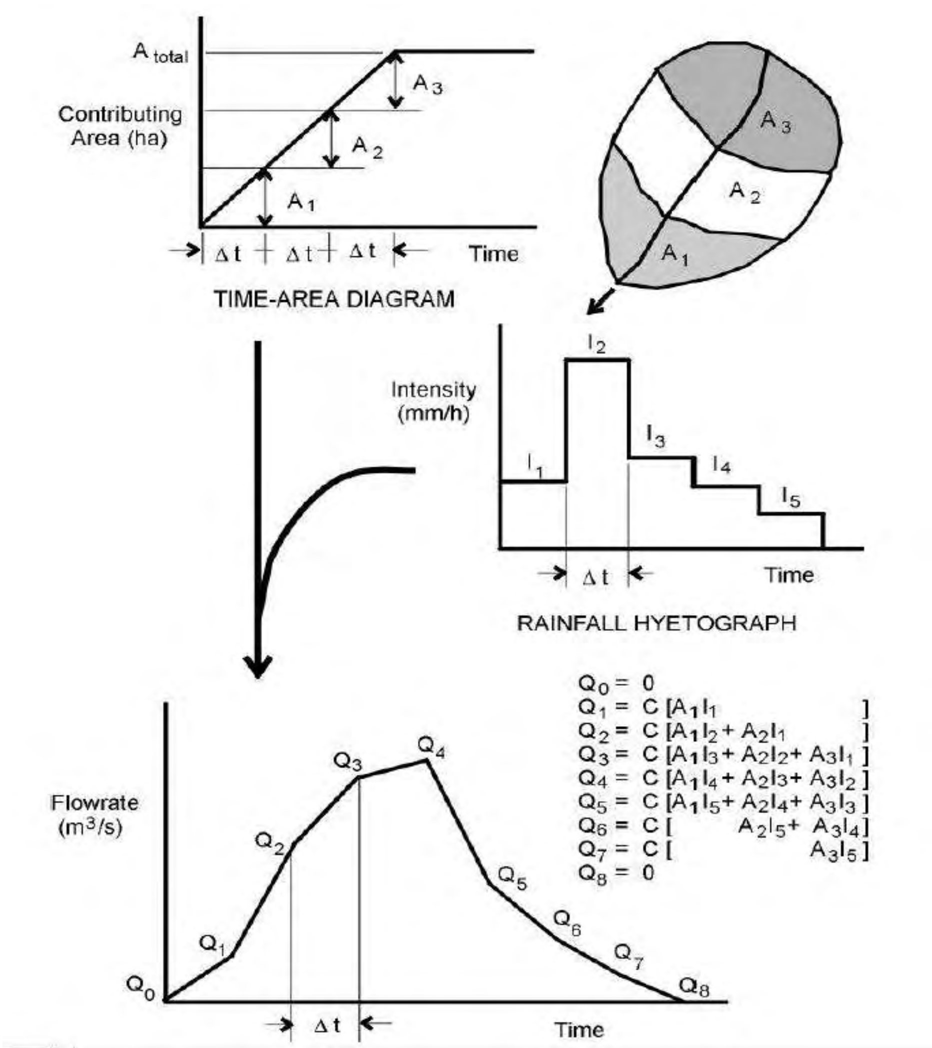


Figure 2.5 – Time area calculation
Adapted from O'Loughlin and Stack (2004)

2.5.3 Urban Water Quality Models

The techniques used for water quality simulation are very similar to hydrologic simulations (Zoppou, 2001). The primary inputs for water quality models are rainfall data, geographical data and pollutant load data. The water quality models provide estimations of pollutant concentrations or loads originating from a catchment. There are a number of modelling approaches adopted (Zoppou, 2001).

Stormwater quality modelling can be performed on a lumped time base or on a continuous time base (Akan and Houghtalen, 2003). Lumped time base modelling is relatively easier and produce estimates of pollutant load (in kilograms) generated from a catchment over a relatively long period of time (say a month or year). These types of models are based on general pollutant export equations for the entire catchment. Continuous time based models are relatively complex and produce estimates for pollutant concentration in relatively shorter time steps (a few minutes). (Akan and Houghtalen, 2003; Zoppou, 2001).

A Continuous Time Based Models

Continuous time based models are based on a combination of mathematical procedures which are used to replicate stormwater pollutant processes. The common pollutant processes that these models replicate are pollutant build-up and wash-off. In most cases, the replication equations are only for suspended solids. Suspended solids are considered as the indicator pollutant and other pollutant concentrations are estimated assuming a constant ratio to the suspended solids concentration (Akan and Houghtalen, 2003).

Different models use different forms of pollutant build-up equations. However, most of these models use build-up equation in the form of decreasing rate increasing function. The most common equations in this form are power function or exponential function. An exponential function in the form of Equation 2.2 is the most common form of replication equation for pollutant wash-off (Akan and Houghtalen, 2003; Ball et al., 1998; Novotny et al., 1985; Sartor et al., 1974; Tsihrintzis and Hamid, 1997; Zoppou, 2001).

The replication of pollutant processes alone is not adequate for water quality modelling. Estimations of hydrologic parameters such as runoff volume are essential to estimate pollutant concentration. Furthermore, the calculated pollutant concentration should be routed to the catchment outlet. This highlights the necessity of parallel simulation of a hydrologic model. A similar procedure to a hydrologic model is commonly used to route the pollutant concentrations. In this regard, the pollutant is assumed to be transported only via advection. Advection is the primary mode of particulate transport in fast flowing water (Akan and Houghtalen, 2003).

Model calibration, which is the refinement of adjustable model parameters in order to represent the actual performance of the catchment, is the most important process in stormwater quality modelling. Measured boundary data, such as pollutograph or instantaneous water quality data is used to calibrate the water quality model (Gaume et al., 1998). The calibration parameters are in two sets. Firstly, parameters related to the build-up equation need to be adjusted until close correlation is achieved between measured and predicted pollutant load. Secondly, the parameters relating to the wash-off equation need to be adjusted until close agreement with the measured and predicted pollutograph is achieved. Though these parameters represent unique characteristics, separate calibration of them is difficult. Therefore, simultaneous calibration of parameters is highly recommended (Mike-TRAP, Version 2004).

B Lumped Time Based Models

Continuous time based models provide detailed pollutant load and concentration estimations. This level of detailed estimations is not required for many engineering applications, particularly planning level studies (Akan and Houghtalen, 2003). Mean annual loading rates are often adequate for such applications. Lumped time based modelling is one such long-term pollutant load estimation procedure (Ahyerre et al., 1998; Charbeneau and Barrett, 1998; Phillips and Yu, 2001).

The fundamental concept in the lumped time based modelling is very straightforward. The model estimates the annual pollutant export from a particular catchment using catchment, land-use or rainfall parameters. There are different types of models that use different pollutant export equations of varying complexity (Letcher et al., 1999). For example, the equation developed by the US Environmental Protection Agency (EPA) to estimate annual pollutant loading is one of the widely used methods (Akan and Houghtalen, 2003). The equation is:

$$M_s = \alpha \, P \, f \, s \qquad \text{Equation 2.3}$$

Where,

M_s = Weight of pollutant generated per unit land per year;

α = Pollutant loading factor;

P = Annual precipitation;

f = Population density function; and

s = Street sweeping factor.

(Akan and Houghtalen, 2003)

The information on pollutant loading (the pollutant loading factor α) needs to be estimated depending on factors such as land-use, population density and traffic volume (Letcher et al., 1999).

Comprehensive modelling packages have been developed based on the lumped time based method, including estimation tools for quantitative and qualitative parameters and management tools. XP-AQUALM is one such model designed for long-term runoff and pollutant export estimations and costing and policy assessments (XP-AQUALM-User-Manual, 1996). The non-point source water quality analysis model of XP-AQUALM consists of a hydrologic model and non-point source pollutant export model. The hydrologic model is a continuous model, which calculates runoff on a daily basis. Water quality is estimated using pollutant export equations. These equations typically consist of a runoff parameter and calibration coefficients. Runoff parameters are pre-estimates using the hydrologic model whilst calibration parameters have to be obtained using the calibration procedure (XP-AQUALM-User-Manual, 1996). Measured event mean concentrations at catchment outlets are often used as data for calibration exercises (Chiew and McMahon, 1999; Phillips and Yu, 2001).

2.7 Conclusions

The following discussion summarises the important conclusions drawn from the review of research literature relating to the hydrologic and water quality regime. The conclusions are mainly focused on the current state of knowledge with respect to hydrologic and water quality impacts of urbanisation, key pollutant processes and current modelling approaches and related issues.

Changes to the hydrologic cycle and quantitative impacts of urbanisation are well documented in literature. Due to the presence of impervious surfaces and lined channels in urban catchments, both rainfall loss parameters and runoff parameters undergo changes. Consequently, this leads to an increase in peak discharge, runoff volume and reduction of base flow. Furthermore, urban catchments commonly exhibit a rapid response to rainfall events. There can be a diversity of hydrologic impacts of urbanisation due to climatic, land-use and topographic changes.

The focus on water quality impacts of urbanisation is of relatively recent origin. However, there is a significant amount of research that has been done in this field and fundamental knowledge on water quality is available. It is common knowledge that anthropogenic activities in urban catchment surfaces produce various pollutants. These pollutants are washed-off during storm events, creating significant impacts on receiving waters. In the context of stormwater quality, impervious surfaces are critically important due to two reasons. Firstly, most of the impervious surfaces such as roads hold significant amount of pollutants. Secondly, these surfaces are hydrologically active even for a small rainfall event.

Pollutant sources and pathways are clearly identified in stormwater quality research. Road surfaces have been recognised as the largest contributor to the pollutant load. However, the extent of contribution varies from place to place depending on the land use of the surrounding area, traffic volume and road surface conditions. On the other hand, other impervious and pervious surfaces are significantly dominant under certain conditions. The best examples for this are gardens and roof surfaces. Gardens are a significant source of suspended solids and nutrients for relatively large storm events. Metal roof surfaces can be a significant source of heavy metals.

Understanding key pollutant processes is critically important in urban water quality research. Significant research has been carried out on pollution build-up and wash-off from urban impervious surfaces. However, outcomes of most of this research are site specific. Due to the significant variation of pollutant processes with rainfall, topographic and land-use characteristics, it is difficult to explain pollutant processes in general terms. Furthermore, research in this respect exhibits significant data scatter. Therefore, the processes that have been developed for pollutant build-up and wash-off may not be directly applicable for all regions.

The primary water pollutants identified in literature include suspended solids, nutrients, hydrocarbons, heavy metals and organic carbon. Suspended solids are the most common pollutant in stormwater runoff. Most of the other pollutants are chemically adsorbed to these particulate pollutants. Hence, the chemical impacts of the suspended solids are of concern. Due to this characteristic, suspended solids are commonly considered as an indicator pollutant.

Numerous predictive models have been developed for quantity and quality estimation of stormwater runoff. The estimation of quantity characteristics of stormwater is a well developed field. There is a wide range of estimation tools available. Use of these tools for a specific problem depends on the nature of the problem and acceptance of the tool within the profession. The estimation tools for quality characteristics of stormwater have been developed recently. Due to the lack of understanding of underlying pollutant processes and variables, the use of water quality models can often lead to gross errors. An extensive amount of data is generally needed to calibrate water quality models. The production of such data is resource intensive and difficult. Furthermore, due to high costs and inherent difficulties involved in producing appropriate data, the accuracy of results from the use of water quality models can be questionable.

Chapter 3 - Study Tools

3.1 Background

Chapter 2 explained the necessity for an in-depth investigation into pollutant processes and the underlying parameters in stormwater quality research. Due to the complex nature of pollutant processes, significant array of data is required to understand them. As reported in research literature, the techniques used to generate such data are highly variable. For example, build-up sampling from urban surfaces has been conducted using vacuum systems. However, the specifications of the systems used in different research are varied. Vaze and Chiew (2002) used an industrial vacuuming system to collect street surface depositions. They noted that the higher power generated by the system increased the sampling efficiency which was termed as the ratio of collected pollutants to available pollutants. Deletic and Orr (2005) used a floor and carpet vacuuming system where actions of washing and vacuuming simultaneously apply. This was due to higher efficiency in retaining finer particles.

The techniques used to investigate pollutant wash-off show even greater variability. The variability is primarily in terms of concepts, scale and apparatus used. Sartor et al. (1974) and Herngren (2006a) used simulated rainfall for wash-off studies. However, the simulation techniques used and the small-plot area selected for simulation were significantly different. Vaze and Chiew (2002) used a completely different technique where they sampled pollutants from road surfaces before and after natural rain events. The investigation technique used by Roesner (1982) was further different, and involved the sampling of runoff at catchment outlets in order to understand the wash-off behaviour.

From the above discussion it is clear that a range of techniques is available to conduct investigations in water quality research. Each investigation technique has specific advantages and disadvantages. The best possible technique has often been selected by rating these advantages and disadvantages according to user preferences and to suit specific research requirements. Though the techniques are different, most of them have earned creditable recognition among the research community, given that their performances were verified under specific research conditions.

This chapter introduces the sampling apparatus and analytical tools used for this research. It was intended to use simple approaches for the investigations, so that these methods can be reproduced in future stages. The apparatus were selected to ensure the requirement of portability. The analytical tools were selected after close consideration of the requirements. The selected methods were simple and reliable for their designated use. The primary study apparatus and analytical tools used for the research included:

1) Vacuum collection system;
2) Rainfall simulator;
3) Model roof;
4) Statistical and chemometrics analytical tools; and
5) Hydrologic modelling software.

3.2 Vacuum Collection System

Sampling techniques used to collect pollutants from urban surfaces show significant variability. However, most of these techniques are in the following two categories:

1) Brushing / sweeping; and
2) Vacuuming.

These two methods have specific advantages and disadvantages. Researchers often used combinations of these methods in order to enhance the collection efficiency (Deletic and Orr, 2005; Robertson et al., 2003). Brushing or sweeping of road surfaces are generally efficient in collecting relatively larger particles. Robertson et al. (2003) noted that brushing and sweeping the road surface can result in biased outcomes for larger particles. They suggested that this method is more suitable when finer particles are not important. Bris et al. (1999) suggested that vacuuming is preferable in order to collect road surface pollutants due to the efficiency that can be achieved in collecting finer particles. They compared two vacuum collection systems and noted that a wet vacuum system was preferable over the conventional dry vacuum system. This is due to their high level of efficiency in the collection and retention of finer particles. The wet vacuum system used by Deletic and Orr (2005) was a modified form of a carpet cleaning system.

3.2.1 Selection of Vacuum System

It is commonly understood that more power is required to enhance the collection efficiency of particulate pollutants from road surfaces. Many researchers have used industrial vacuum systems which are relatively powerful (Shaheen, 1975; Vaze et al., 2000). However, Tai (1991) noted that the collection efficiency should not be the only criteria to be considered. The efficiency of the conventional domestic vacuum system he used was 96.4% and this was achieved purely due to the high level of efficiency in retaining finer particles. As he noted, higher retention efficiency can be achieved due to the fine and effective filtration system used in domestic vacuum systems. These findings highlight the necessity to use a vacuum system with a high powered and efficient filtration system for road surface pollutant sampling. However, it was difficult to find such a system in the open market. Therefore, additional steps were taken to include techniques that enhance the sample collection and retention efficiency.

It was decided to use a simple portable vacuum system for the research as a large number of sample collections had be carried out. The vacuum system selected was the Delonghi Aqualand model which consist of a highly compact 1500W motor and efficient filtration system. The same vacuum system had been used by Herngren (2005) for his research. In order to enhance the collection efficiency, an attachment consisting of a small vacuum foot with a brush was used. Use of the brush was primarily to enhance the collection efficiency by dislodging finer particles. As noted by Bris et al. (1999), the finer fraction is more strongly bound to the asphalt surface than the coarser particles. The use of a small foot in the vacuum system concentrates the air flow into a smaller area so that the power of the system is more effectively used to collect even the larger particles. Therefore, combined performance of the vacuum system with the brush and the smaller foot was in the range of industrial vacuum systems.

A water filtration system along with a High Efficiency Particulate Air (HEPA) filtration system attached to the Delonghi vacuum system ensured minimal escape of finer particles through the exhaust. The filtration system for the vacuum is shown in Figure 3.1.

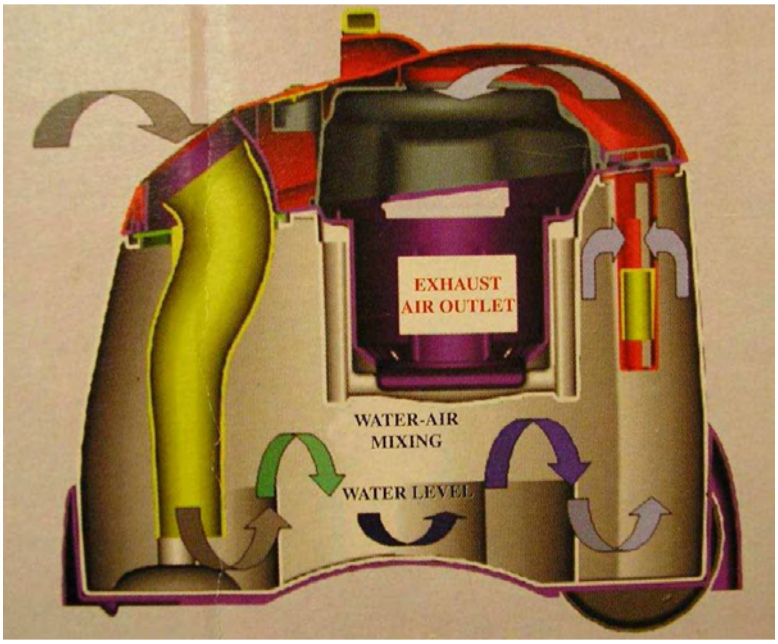
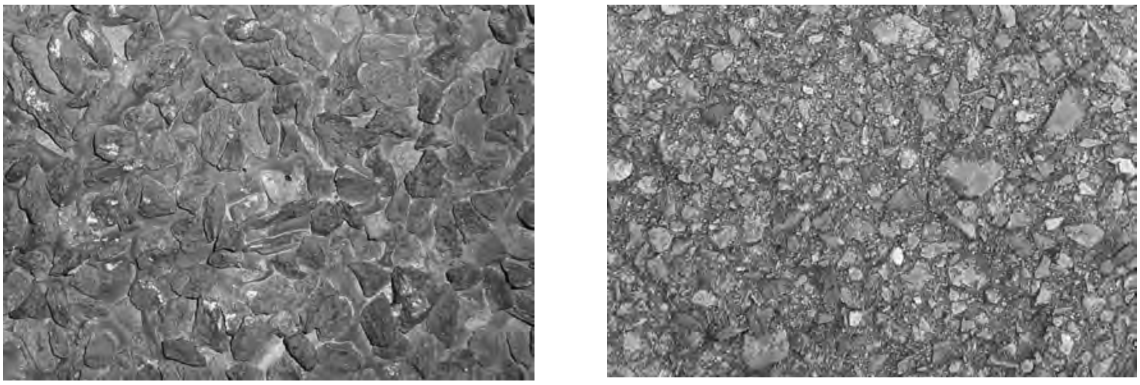


Figure 3.1 – Water filtration system in Delonghi Aqualand vacuum cleaner

The water filtration system consisted of a mechanism to direct the air intake through a column of water so that the particulate pollutants are retained in the water. The retention efficiency of the filtering system was found to be as high as 99.9% in the water column and the HEPA filter as noted in the manufacturer's specification. Since the collected particulate sample is retained in the water column, it is easy to extract samples from vacuum compartment and easy to prepare the vacuum system for the next sampling episode.

3.2.2 Sampling Efficiency

The sampling efficiency of the vacuum system was tested under laboratory conditions using a 400 x 400 mm sample road surface. The average texture depth of the sample surface was in the range of 800 to 900 μm. The condition was similar to the road surfaces encountered in the field sampling as described in Section 4.4.1. The pollutant sample used for the validation test was uniformly graded from 1 to 1018 μm. This was the particle size range expected during road surface pollutant sampling. Figure 3.2 shows the section of sample road surface and section of actual road surface that was used for the field sample collection. Photographs (a) and (b) in Figure 3.2 are in same scale.



(a) (b)

Figure 3.2 - a) Section of sample road surface and b) section of road surface at Gumbeel Court.

Particle size distribution of the pollutant sample was measured prior to spreading on the sample road surface. The sample surface was cleaned by repeated vacuuming and flushing with water and allowed to dry by applying a stream of air. A solids sample of 100 g mass and known particle size distribution was spread evenly on the surface using a straight edge and a fine brush. Care was taken to ensure that none of the solids spilled over the edge. After cleaning the water compartment, hoses and foot thoroughly, the vacuum system was filled with 3 L of deionised water. A blank sample was taken from the deionised water before pouring the water into the compartment. The solids sample spread on the sample surface was collected using the vacuum system. The procedure adopted was to vacuum the surface three times in perpendicular directions. After the collection, the vacuum cleaner compartment was emptied into a clean container and the compartment was washed thoroughly with deionised water. Also, all the hoses and the brush were washed four times using deionised water and poured into the container so that loss of particulate pollutants was minimal. The collected sample was oven dried and the recovered solids were weighed. The total weight recovered was 97 g. Additionally, a particle size distribution of the recovered solids was undertaken for comparison purposes. Figure 3.3 shows the comparison of particle size distribution of the original sample and recovered sample.

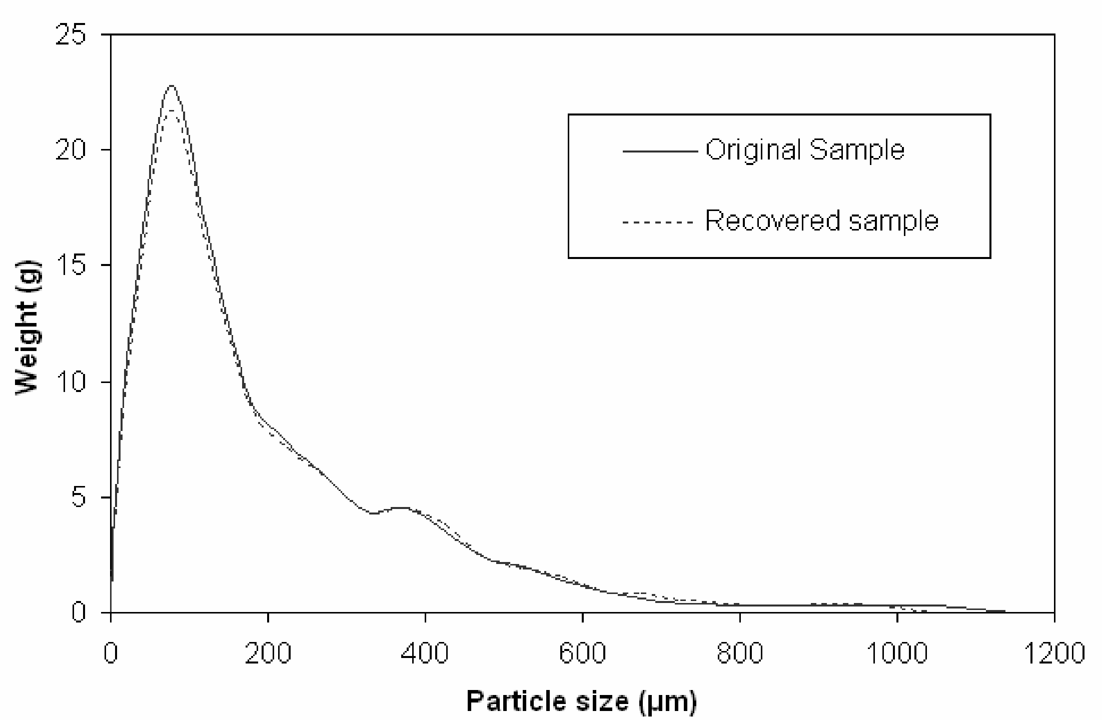


Figure 3.3 – Comparison of particle size ranges in the original sample and recovered sample

As evident in Figure 3.3, losses occur primarily in the 1 to 200 µm particle size ranges. The maximum percentage loss was for the 1 to 10 µm range, which was 8%. These losses are mainly attributed to systematic errors in sample filtration and entrapment of particles in the vacuum cleaner compartment and hoses. Furthermore, during the vacuuming process particles may be lost from the sample surface due to the action of the brush. The overall efficiency of the system was found to be 97%, which was considered adequate for the field investigations.

3.3 Rainfall Simulator

It is understood from the overview in Chapter 2 that pollutant wash-off is a complex process and varies with a range of rainfall, runoff, catchment and climatic parameters. Investigation of such complex processes by using naturally occurring rainfall events faces inherent difficulties. This is primarily due to the aerial and temporal variability of rainfall parameters such as rainfall intensity and kinetic energy. Furthermore, lack of control over the rainfall parameters and uncertainty of occurrence makes investigations difficult (Ahyerre et al., 1998; Herngren et al., 2005b). In such a context, the use of artificially generated rainfall events in urban water quality research is worthy of consideration. This eliminates a significant number of constraints that arise due to the random nature and variability of characteristics of naturally occurring rainfall events. Additionally, the use of rainfall simulation can produce a large amount of data in a short period of time (Herngren et al., 2005a; Herngren et al., 2005b).

A rainfall simulator has been designed and fabricated by the Queensland University of Technology water quality research group so that it can be used in urban stormwater quality research. Details on the design aspects of the rainfall simulator can be found in Herngren et al. (2005b) and Herngren (2005).

The rainfall simulator consisted of an A-frame structure with three Veejet 80100 nozzles equally spaced on a swinging nozzle boom (see Figure 3.4). The nozzle boom is connected to a small motor in order to swing in either direction. The speed of the swing and delay time is controlled using an electronic control box which in turn enables the simulator to be calibrated for different rainfall intensities. The water used for the simulations needs to be specially prepared according to regional rainwater quality and pumped to the simulator from an externally located tank. The water pressure at the nozzle boom can be adjusted by a valve so that the simulator creates the required drop size distribution.

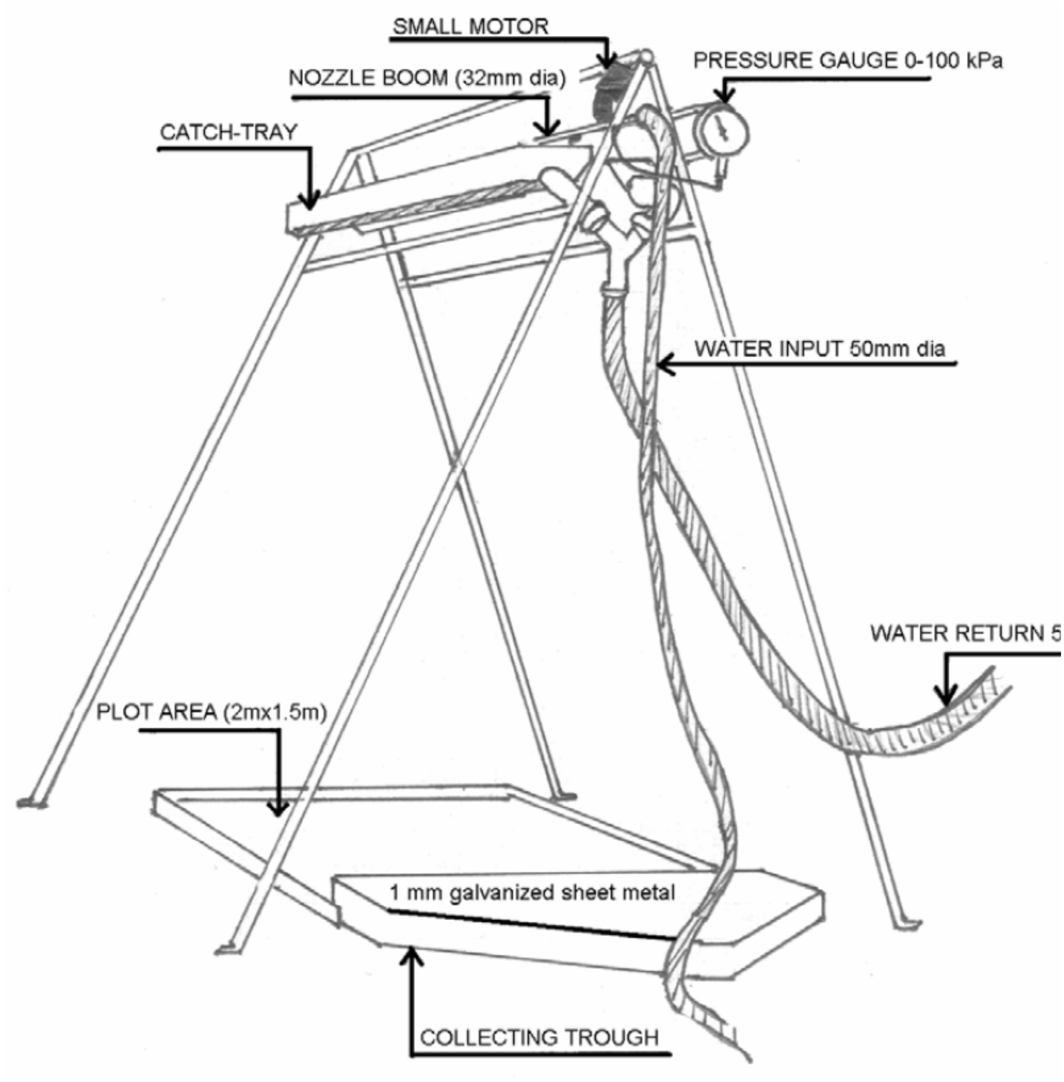


Figure 3.4 – Rainfall Simulator
(Adapted from Herngren, 2005)

3.3.2 Calibration of the Rainfall Simulator

The rainfall simulator had been designed using a combination of theoretical knowledge and field experience as reported in the research literature. As most of the researchers have noted, the primary objective of rainfall simulation is to replicate natural rainfall events as closely as possible (Assouline et al., 1997; Barnett and Dooley, 1972; Bubenzer et al 1985; Erpul et al., 1998; Grierson, 1977; Loch, 1982; Meyer and McCune, 1958). The performances of the simulator used and characteristics of the simulated rain need to be calibrated and verified prior to field investigations.

The rainfall simulator used for the field study had previously been calibrated for its intensities and verified for kinetic energy and drop size distribution in 2003 for the research published by Herngren (2005). The procedure he adopted was well documented (Herngren et al., 2005b). However, due to the need to introduce a new kinetic energy dissipater, the rainfall simulator had to be re-calibrated for this research study. The kinetic energy dissipater was necessary to reduce the original kinetic energy of the simulated rainfall to the required level to simulate rainfall intensities less than 40 mm/hr. The kinetic energy increases with rainfall intensity up to a threshold value and then remains constant (Rosewell, 1986). Additionally, re-calibration also helped to adjust the control box settings in order to allow for wear and tear of the mechanical components in the rainfall simulator.

3.3.3 Rainfall Intensity and Uniformity of Rainfall

Both rainfall intensity measurements and uniformity analysis of rainfall over the plot area were carried out by placing an array of containers under the simulator in a grid pattern and measuring the volume of water collected during a known simulated rain duration. A similar procedure had been used by Herngren (2005) and Loch (1982) to calibrate their rainfall simulators. In this instance fifteen containers were placed under the rainfall simulator in three rows (as shown in Figure 3.5) and exposed to 5 min of rainfall simulation. The amount of water collected was measured using a measuring cylinder and later converted to a depth of rain per unit time (mm/hr). The experiment was repeated for different settings of the control box. The control box consists of two control knobs: one to control the speed of oscillation and the other to control the delay time. The speed control was demarcated 1 to 5. The delay control was demarcated from A to M. The control box settings for the rainfall intensities used in this research are shown in Table 3.1. The complete intensity calibration can be found in Appendix A, Table A.1. The basis for the selected rainfall intensities is discussed in Section 4.4.1. It was found that the rainfall simulator was capable of simulating intensities ranging from 20 to 188 mm/hr.

Figure 3.5 - Intensity calibration and uniformity testing of rainfall simulator

Herngren (2005) observed that the simulated rainfall shows significant spatial variability over the plot surface. According to Herngren, spacing of the nozzles was selected so that the jet sprays overlap. In this way it was possible to minimise the longitudinal (in the direction of nozzle boom) variability of rainfall. However, Herngren observed higher longitudinal variability compared to cross sectional variability in the performance testing undertaken (see Figure 3.6).

Table 3.1 - Measured rainfall intensities for the different control box settings

Rainfall Intensity (mm/hr)	Speed Setting	Delay Setting
20	1	A
40	1	H
65	2	I
86	3	I
115	3	J
133	3	K

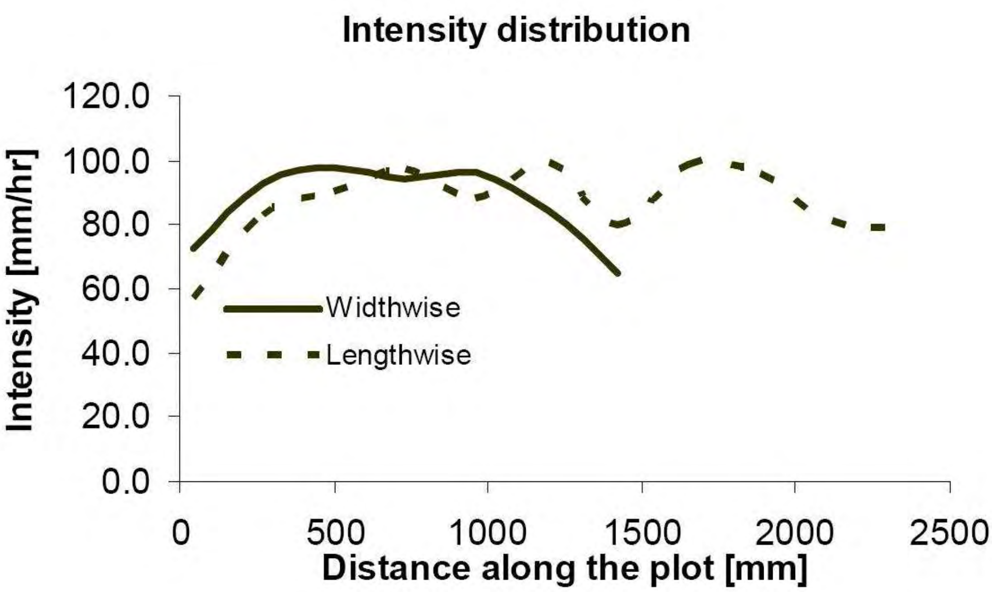


Figure 3.6 – Spatial variation of the rainfall intensity for control box setting 3–I (Adapted from Herngren, 2005)

It was not intended to investigate the characteristics of the spatial variability of simulated rainfall in this research. A realistic measure of the spatial variability; 'the uniformity coefficient' was calculated using the data collected during rainfall intensity calibration. The same coefficient was used by Christiansen (1942) and Herngren (2005) in order to describe the uniformity of the simulated rainfall. The formulation of the uniformity coefficient is as follows:

$$Cu = [1 - \frac{\sum X}{mxn}]x100 \qquad \text{Equation 3.1}$$

Where,

C_u = Coefficient of uniformity;

X = Deviation of individual observation from mean;

m = Mean value; and

n = Number of observations.

The uniformity coefficient is expressed as a percentage and higher percentages indicate little spatial variability. The average uniformity coefficient for the complete range of rainfall intensities tested for the current study was around 85%. This was in close agreement with the results obtained by Herngren (2005) where the uniformity coefficient was 80%. More details of the calculation of uniformity coefficient can be found in Appendix A, Table A.1.

3.3.4 Drop Size Distribution and Kinetic Energy of Rainfall

In simulating rainfall close to natural events, it is important to verify the kinetic energy and drop size distribution of the simulated rainfall. These two parameters, along with rainfall intensity, are the primary parameters essential for characterising rainfall events (Herngren et al., 2005b; Hudson, 1963; Loch, 1982). Considering an individual raindrop, the kinetic energy is greatly influenced by the size of the drop. This is due to the variation of both mass and terminal velocity associated with the drop. However, as far as a rain event is concerned, kinetic energy is influenced by rainfall intensity. Variation of kinetic energy can be simplified to a reducing rate of increasing variation from 0 to around 25 $J/m^2/mm$ for rainfall intensities of 0 to 40 mm/hr. Beyond that, the kinetic energy is fairly constant at around 25 $J/m^2/mm$ (Herngren et al., 2005b; Rosewell, 1986). The rainfall simulator was originally designed to simulate kinetic energy in this constant region where rainfall intensities are greater than 40 mm/hr. For this range, as recommended by Herngren et al. (2005b), the pressure at the nozzle boom should be adjusted to 41 kPa. During rainfall simulation, a change of rainfall intensity is achieved by varying the speed of the nozzle boom movement. Since there is no change to simulator hydraulics, there is expected to be the same kinetic energy for all the intensities. Therefore, the verification test was only to check the appropriateness of the pressure at the nozzle boom to simulate the required drop size and kinetic energy.

Two simple methods have been widely used for the direct measurement of raindrop size distribution. The first method is the use of stain marking media such as blotting paper. The second method is the use of pellet making media such as flour or cement. In both methods, the diameter of the stain mark or pellet has to be calibrated with the known diameter or weight of the water droplets (Assouline et al., 1997; Hudson, 1963). Due to easy preparation and measurement, the flour pellet method was chosen. The flour pellet method was developed by Hudson (1963). The procedure consists of using a thick, uncompacted layer of flour exposed to rain for a few seconds allowing a significant amount of raindrops to fall on the flour. Then the flour was oven dried and pellets were separated using a range of sieves. Hudson (1963) calibrated the procedure by establishing a relationship between raindrop and flour pellet diameters.

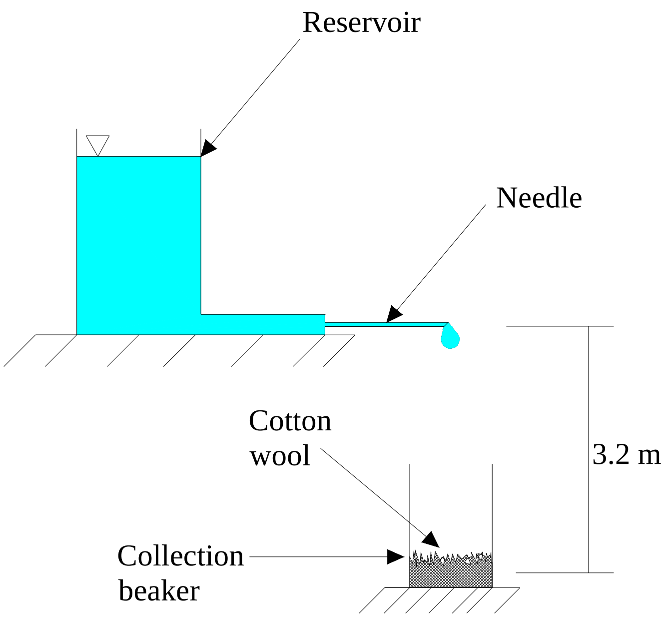


Figure 3.7 – Experimental setup for drop size test

The experimental procedure as developed by Hudson (1963) could be influenced by a range of factors. This includes the type of flour used and the degree of compaction of the flour. In order to eliminate the influence of these factors, a pilot experiment was conducted. The results from the pilot experiment were used to validate the relationship developed by Hudson (1963). The experimental setup is shown in Figure 3.7. The apparatus used for the experiment were a large reservoir of water, connection tube, ten medical needles of different diameters, a collection beaker and cotton wool. The connection tube was used to supply water from the reservoir to the needle. The reservoir connected to the needle was placed at a 3.2 m height in the laboratory so that water droplets emitting through the needles reach a velocity close to their terminal velocity during the fall.

Water was supplied to the needles at approximately constant pressure. Ten droplets were collected to a pre-weighed beaker in order to calculate the median weight of the water droplets. The beaker was lined with cotton wool to prevent splashing and evaporation. The mean diameter was then calculated using the standard density of water. Flour pellets were made simultaneously by replacing the beaker with a tray containing a thick layer of uncompacted flour. Ten distinct flour pellets were made and oven dried. Finally, the separated and cleaned flour pellets were weighed to determine the average weight. The experiment was repeated for each of the ten needle sizes and the data points were plotted on a graph, as shown in Figure 3.8. The flour pellets made during the experiment are shown in Figure 3.9. The pilot study was only able to verify the drop size range of the calibration curve developed by Hudson (1963). It was not possible to reproduce the smaller range of droplets using needles under laboratory conditions. However, the results obtained were in close agreement with the calibration curve. This suggested that the experimental procedure used was consistent with the Hudson (1963) procedure and the calibration curve Hudson developed could be used to determine rain drop sizes.

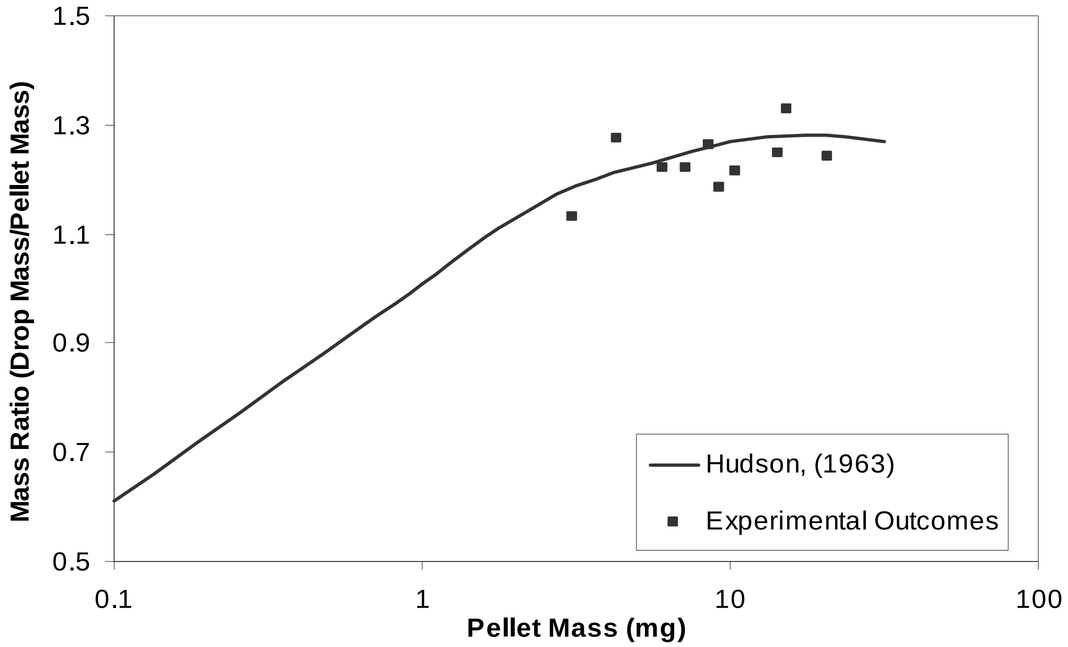


Figure 3.8 – Calibration curve for flour pellets

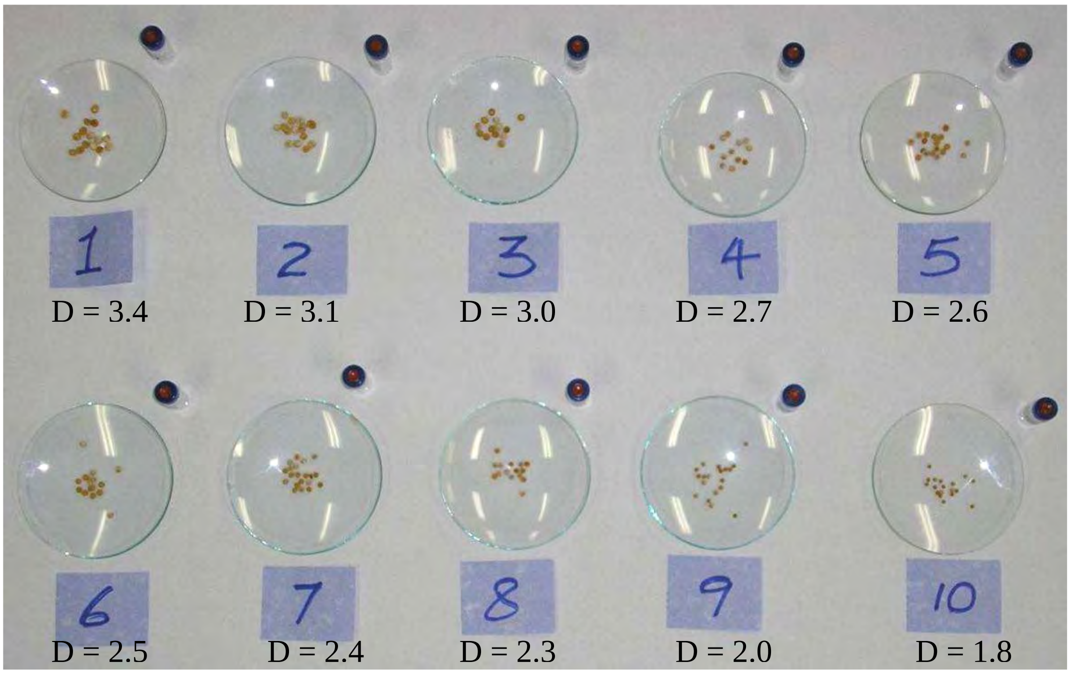


Figure 3.9 – Range of flour pellets developed during pilot experiment (Drop size diameter is indicated in mm)

The drop size distribution of the simulated rain was determined by exposing a tray (500 mm x 400 mm) of thick uncompacted flour into one swing of water spray from the simulator. The tray was then oven dried and the pellets were carefully separated from the flour. Later, the pellets were separated to seven size groups by passing them through a set of sieves. The size classes selected were:

1) > 4.75 mm
2) 4.75 – 3.35 mm
3) 3.35 – 2.36 mm
4) 2.36 – 1.68 mm
5) 1.68 – 1.18 mm
6) 1.18 – 0.85 mm
7) < 0.85 mm

Average weight of a pellet in each size class was calculated by dividing the weight of the pellets by the number of pellets available in one class. The average weight of a pellet was then converted to a drop size using the calibration curve developed by Hudson (1963). The median drop diameter was then calculated and was found to be

2.05 mm. The median drop size diameter for natural rainfall events is in the range of 2.0 to 2.5 mm (Hudson, 1963). The calculated median drop size was within the range of the natural drop diameter and therefore the drop size distribution of the simulated rainfall was considered to be satisfactory for the research study. A complete set of calculations of drop size distribution is shown in Appendix A, Table A.2.

The terminal velocity for each drop size class was estimated using the tables provided by Laws (1941). From the average drop size diameter and the corresponding terminal velocity, the kinetic energy was calculated. It was ensured that the raindrops produced by the rainfall simulator were reaching the terminal velocity. As described in Herngren et al. (2005b), the simulator height of 2.5 m is adequate to reach terminal velocity for any size of droplets with initial velocity provided by 41 kPa of internal pressure in a Veejet 80100 nozzle. The calculated kinetic energy was 21.3 J/m^2/mm and was close to the natural rainfall kinetic energy for South-East Queensland where the average as reported by Rosewell (1986), is around 25 J/m^2/mm. Further, Rosewell reported significant variability in rainfall kinetic energy around the average value.

As explained in Section 4.4.1, it was important to simulate 20 mm/hr rainfall intensity in order to encompass the rainfall intensity range in the study region. The typical rainfall kinetic energy for 20 mm/hr intensity is in the range of 16 to 18 J/m^2/mm (Rosewell, 1986). The simulator is only capable of simulating constant rainfall kinetic energy of 21.3 J/m^2/mm. Therefore, in order to simulate 20 mm/hr rainfall intensity, the kinetic energy needed to be reduced. However, physical changes to the simulator or changes to the hydraulic characteristics of the system were not options that were considered. This was due to the possibility of degrading fundamental simulator design concepts such as the longitudinal and cross sectional rainfall uniformity. Therefore, it was decided to use a system external to the original rainfall simulator setup in order to reduce the kinetic energy.

The best approach to reduce the kinetic energy was to reduce the average drop size of the simulated rain. This in turn would help to reduce the mass and terminal velocity of raindrops which would lead to kinetic energy reduction. The concept was to use a meshed frame placed just below the nozzles in order to break the large droplets. Two mesh materials, shade cloth and fly screen mesh, were tested for this purpose. The use of fly screen mesh showed satisfactory results as the calculated kinetic energy reduced to 16 $J/m^2/mm$. Reduction in kinetic energy was mainly due to a reduction in the drop sizes. The kinetic energy obtained was considered appropriate to simulate 20 mm/hr rainfall intensity. With the new setup, the rainfall simulator was re-calibrated for 20 mm/hr intensity. The re-calibration confirmed that the original control box setting for 20 mm/hr as stated in Table 3.1, was satisfactory. However, the presence of the kinetic energy dissipater reduced the uniformity coefficient to 78%. This was mainly due to the change of direction of the water droplets after coming into contact with the fly screen mesh. Nevertheless, the use of a fly screen mesh as an energy dissipater was considered appropriate for the simulation of 20 mm/hr rainfall intensity.

3.4 Model Roofs

For residential catchments with relatively less traffic-generated pollutants on roads, roof surfaces can be a significant contributor to urban stormwater pollution. This is primarily due to the presence of a high fraction of impervious surfaces. Though it is not conclusive, there is evidence to claim that the primary pollutant processes on roof surfaces are significantly different from the rood surfaces. As noted by Van Metre and Mahler (2003), build-up on roof surfaces primarily originates from atmospheric sources which are significantly site specific. Furthermore, the amount of pollutants and their characteristics were found to be significantly different from the road surface pollutants. Forster (1996) noted a comparatively high concentration of pollutants from roof surfaces during the initial period of runoff events. It was further suspected that the ‘flashy’ contribution from roof surfaces leads to a first flush. This suggested the possibility of differing wash-off characteristics in roof surfaces. These factors highlighted the necessity for separate investigations into pollutant build-up and wash-off on roof surfaces.

Due to the difficulty in coordinating and obtaining permission from residents and local authorities, residential roofs in the study catchment were not considered. Additionally, there were technical difficulties in using the rainfall simulator to investigate pollutant wash-off on actual roofs. It was decided to fabricate two model roof surfaces to support the research study.

3.4.1 Materials and Dimensions

The selection of roofing materials and dimensions of the model roofs were done so that they were representative for the study region and appropriate to be used under pre-established experimental methodology. As the test area for the rainfall simulator was 1.5 x 2.0 m, it was a requirement to design roofs to the same dimensions.

Two roofing material types, namely corrugated steel and concrete tiles are dominantly used within the study region as well as in South-East Queensland. The design guidelines for these roofing materials have been published by numerous manufacturers. The appropriate roofing angle is 15 to 30^0 (Bristile-Roofing, 2004; Stramit-Manual, 2005). Two model roofs were designed at an angle of 20^0. The roof surfaces were intended to be kept at a typical single storied roofing height. The primary reason for this was to limit the human influence and to reduce the influence of traffic-induced turbulence close to ground level. O'Hara et al. (2006) noted that a 2.5 m height is appropriate to minimise the influence of turbulence close to the ground in atmospheric deposition sampling. Consequently, the maximum height of the model roof surfaces was selected as 2.5 m.

3.4.2 Design and Performance Testing

A scissor lift arrangement was designed so that the roofs could be lifted to the 2.5m height and when needed, could be lowered to ground level for sample collection. In this way, the technical difficulties of rainfall simulations on roof surfaces were overcome.

The scissor arrangement used to mount the roof surfaces consisted of a base frame of 2.1 m x 1.5 m, double scissor arrangement and a top frame. A hydraulic jack powered by a 2.4 kW hydraulic pump was used to lift the arrangement. Figure 3.10 shows the scissor arrangement. The structural and mechanical design of the scissor lift was done with reference to 2615, AS/NZS (1995) for hydraulic trolley jacks and

2549, AS/NZS (1995) for cranes. The scissor arrangements were fabricated and assembled in the university workshop. They were tested for structural, mechanical and operational safety to satisfy university health and safety regulations. Tests were done according to testing procedures given in 2615 and 2549, AS/NZS (1995).

Figure 3.10 – Concrete tiled model roof mounted on scissor lifting arrangement

3.5 Statistical and Chemometrics Analytical Tools

Tools for analysis of the generated data were selected after careful consideration of data, capabilities of different analytical tools and the type of analysis to be performed. Extra effort was made to use the simplest analytical tool for each task. Therefore, simple univariate statistical methods were often selected. However, complex methods were used when they became more suitable for the analysis.

The purpose of using the analytical tools was primarily to understand the patterns of data variability. This was done using plotted graphs supported by simple univariate statistical measurements such as mean, standard deviation and coefficient of variation. However, the presence of pollutant processes which have high variability can limit the use of these simple methods. This problem was overcome by the use of multivariate analytical approaches. In this regard, analytical suitability of several multivariate approaches such as principal component analysis, cluster analysis and discriminate analysis was considered. Ultimately, principal component analysis (PCA) was selected due to its wide use in water quality research (Alberto et al., 2001; Bengraine and Marhaba, 2003; Petersen et al., 2001).

3.5.1 Mean, Standard Deviation and Coefficient of Variation

Three statistical measurements: mean, standard deviation (SD) and coefficient of variation (CV) are commonly used in order to describe the characteristics of a single variable date set. The mean is primarily the most representative single value that can be used to describe an entire data set. SD describes the spread or dispersion of data points with respect to the mean. A smaller SD represents a concentrated data set whereas a larger SD represents a spread data set (Hamburg, 1994).

SD is also useful in describing how far an individual data point departs from the mean of the data set. This is primarily done by calculating the 'standard score', by dividing the deviation of the individual data point from the mean by the SD. However, from an analytical point of view, a measure to describe dispersion of an entire data set from the mean is the most important. Such a measure is obtained by expressing standard deviation as a percentage of the mean, which is termed the coefficient of variation (CV). A data set with CV less than 10% is considered uniform (Hamburg, 1994).

3.5.2 Method of Least Square

Development of mathematical predictive equations for the observed variations of pollutant processes is one of the major components of this research. These mathematical equations needed to be the 'best fit' for the observed data. In this regard, it was important to establish criteria to define goodness of fit. Among many methods, the method of least squares was selected as the most appropriate. As noted by Hamburg (1994) this is the most commonly applied curve fitting technique. The method of least squares imposes the requirement that the sum of the squares of the deviations of observed values from the corresponding computed values must be the minimum. The method can be expressed in mathematical terms as:

$$\sum (O - P(x, y....))^2 \text{ is the minimum} \qquad \text{Equation 3.2}$$

Where,

O = Observed value;

P = Predicted value; and

$x, y\ldots$ = Coefficients influencing predicted value.

Minimisation of the square of deviations is typically done by adjusting coefficients on a systematic basis. Algorithms for such adjustment of coefficients are embedded into most analytical software. The algorithm used for this research was the 'Solver' in Microsoft XL. The final outcome of the method of least squares is an optimum set of coefficient values.

3.5.3 Principal Component Analysis

Principal Component Analysis, or PCA, is essentially a pattern recognition technique which can be used to understand the correlations among different variables and clusters among objects. It has been used extensively as an analytical tool in water quality research. For example, Bengraine and Marhaba (2003) used PCA to obtain the temporal and spatial variation in river water quality and Petersen et al. (2001) used it to understand the water quality processes in rivers. Regardless of the widespread use, as noted by Kokot et al. (1998), PCA is more an exploratory tool rather than one which can be used to obtain the final solution in pattern recognition.

The PCA technique is used to transform the original variables to a new orthogonal set of Principal Components (PCs) such that the first PC contains most of the data variance and the second PC contains the second largest variance and so on. The orthogonality of PCs enables user to interpret the data variance associated to each of PCs independently. Furthermore, though PCA produces the same amount of PCs as the original variables, the first few contain most of the variance. Therefore, the first few PCs are often selected for interpretation. This consequently reduces the number of variables without losing useful information in the original data set. The number of PCs to be used for interpretation is typically selected using the Scree plot method (Jackson, 1993). The Scree plot is the graphical variation of Eigen values extracted for each PC. Eigen value interprets the data variation associated with each PC (Adams, 1995). Detailed descriptions of PCA can be found elsewhere (Adams, 1995; Kokot et al., 1998).

To perform PCA, the data should be arranged in a matrix with selected variables arranged in columns and individual measurements or objects arranged in rows. Standard pre-treatment techniques are often used to eliminate the biased outcomes due to measurements being in different scales and units. Column standardisation is the most common pre-treatment method used (Kokot et al., 1991, 1992). This implies that each cell in a given column is divided by the standard deviation of that particular column. Hence, each variable is equally weighted with a standard deviation of one.

The application of PCA to a data matrix generates a loading for each variable and a score for each object on the principal components. Consequently, the data can be presented diagrammatically by plotting the loading of each variable in the form of a vector and the score of each object in the form of a data point. This type of plot is referred to as a ‘Biplot’. The angle between variable vectors is the indicator of degree of correlation. An acute angle between two variables indicates a strong correlation whereas an obtuse angle indicates a negative correlation. A right angle between variables indicates no correlation. Clustered data points in a biplot indicate objects with similar characteristics.

3.6 Hydrologic Modelling Software

Hydrologic modelling is often used as a support tool in water quality modelling. As noted by Zoppou (2001), hydrologic modelling tools supply the essential runoff information to the water quality modelling tools in order to calculate pollutant concentrations and hence facilitate estimating pollutant transport to catchment outlets. For example, water quality model XP-AQUALM operates with a hydrologic model based on daily water balance.

In this study, calculation of pollutant response at the catchment outlets was to be determined using a similar procedure to that used in water quality models. This gave rise to the need for an accurate and reliable hydrologic modelling tool. As noted by Zoppou (2001), the selected hydrologic model needs to be highly compatible with the procedure adopted to calculate pollutant mobilisation. Additionally, ASCE (1985) lists a range of criteria in order to select a suitable hydrologic model. Considering all these facts, the following selection criteria were used to choose the hydrologic model:

1) Formulation of the model – The model needed to be based on the time-area method which is a scientifically based hydrologic analytical procedure (O'Loughlin and Stack, 2004). This was to ensure the compatibility of the hydrologic model to pollutant mobilisation calculations.
2) Output – Due to the relatively faster hydrologic and water quality response from small urban catchments, the ability to simulate fine times steps (1 min) was important.
3) Data availability – The accuracy and reliability of a model is based on the correct interpretation of catchment parameters and inputs. This suggested that model setup and input parameters should be based on an appropriate set of data. Since different models have different data requirements, the selection of the model should be in accordance with the available data.
4) Processes – The simulation of hydrologic and hydraulic processes using scientifically valid procedures is important. The requirement for the time-area method in hydrologic modelling has already been noted above. Additionally, it was also a requirement to have a scientifically valid pipe flow routing procedure to calculate the flow through the urban drainage network.
5) Parameters – Models with different mathematical formulations operate with different sets of parameters for representing catchment and input conditions. For successful modelling, these parameters should be able to be derived from the already available measured data or by calibration processes.

6) User-friendliness – It was important to select a model that can be easily setup, calibrated and simulated.
7) Acceptance – It was important to select a model that is widely used and accepted among the research community.

A number of models which are extensively used in Australia were evaluated against the selection criteria. The models evaluated were:

- WBNM (Boyd et al., 2003);
- DRAINS (O'Loughlin and Stack, 2004); and
- Mike STORM (Mike STORM, 2004).

Table 3.2 shows the comparison of the models against each selection criteria.

Table 3.2 – Comparison of model characteristics against selection criteria

Criteria	WBNM	DRAINS	Mike STORM
Hydrologic representation	Storage routing method	Time area method	Three different methods including time area method
Simulation frequency	Fine time steps (1 min)	Fine time steps (1 min)	Fine time steps (1 min)
Data requirement	Can be obtained by simple procedures	Can be obtained by simple procedures	Can be obtained by simple procedures
Pipe and channel flow routing	Channels are considered as a function of catchment area. Channel lag factor is used	Manning's equation	Three different procedures including dynamic wave routing
Nature of parameters	Parameters should be obtained by calibration	Parameters should be obtained by experience	Parameters should be obtained by calibration
User-friendliness	Easy to setup and simulate	Easy to setup and simulate	Easy to setup and simulate
Acceptance	Accepted for both design and investigation	Mostly accepted for design purposes	Accepted for both design and investigation

In consideration of all the above factors, the Mike STORM model was the most suitable. Mike STORM can simulate a range of hydrologic procedures including the time-area method. The number of parameters required to setup and simulate Mike STORM is comparatively small and the parameters are easily obtainable from the measured data. Furthermore, the pipe flow routing procedure available in the model is appropriate for the purpose. The model is user-friendly and well recognised among the research community. In addition to all the primary features, Mike STORM consists of an advection – dispersion simulation procedure which can be directly used to calculate pollutant transport.

3.7 Conclusions

The primary research apparatus used during this research were:

1) Vacuum collection system;
2) Rainfall simulator; and
3) Model roof surfaces.

The vacuum collection system was designed to collect particulate matter from road surfaces. The system was pre-tested for collection and retention efficiency and was found to be satisfactory. The rainfall simulator was calibrated to simulate six different rainfall intensities. A kinetic energy breaker was included in the system so that smaller rainfall intensities could also be simulated. Performance of the rainfall simulator was evaluated in terms of drop size distribution and kinetic energy. It was found that the simulated rainfall is a close replication of natural rainfall. In order to eliminate the technical difficulties of collecting build-up and wash-off samples from roof surfaces, two sets of model roofs were developed. These model roofs consisted of scissor arrangements where the roof can be lifted to the conventional roofing height for pollutant build-up and lowered to the ground level for build-up and wash-off sampling.

The analytical tools were selected so that they were best suited for the purpose of the analysis to be undertaken. The tools were selected on a case by case basis and extra effort was made to select the simplest tool. PCA was selected to perform analysis when multiple variables are involved. After evaluation of a number of commonly used models, Mike STORM was selected according to pre-established selection criteria. This was to support the pollutant transport calculations.

Chapter 4 - Study Area and Sample Collection and Testing

4.1 Background

The field investigation methodology was designed to obtain the data specifically required to develop essential knowledge on stormwater pollutant processes. The investigations were in two phases. Catchment scale investigations were required to accomplish the data required for validation of the translation procedure. For this, three urban catchments where in-depth catchment monitoring programs have been in place were selected. The primary investigation was to obtain both quality and quantity data at the catchment outlets. The data collected by runoff sampling at catchment outlets were used to derive knowledge on the combined impact of heterogeneous urban surfaces and anthropogenic activities on catchment surfaces.

Small-plot scale investigations were required to develop a relevant knowledge base on pollutant build-up and wash-off processes for road and roof surfaces. Knowledge on these processes was needed as the basis for the development of the translation procedure. The investigations were planned to be conducted on selected sites. As noted by Herngren (2005) and Vaze and Chiew (2002), investigations on defined and limited surfaces enable researchers to obtain more specific and detailed knowledge.

4.2 Study Area

The study area was selected after careful consideration of water sampling and field data collection infrastructure in place. The Gold Coast is one of the few places in Australia where a comprehensive catchment monitoring program has been established. The Gold Coast is the Australia's sixth largest city. The city is located along the coastline, just north of the New South Wales and Queensland border. The city spans 1042 km^2 of land, featuring 70 km of coast line. The city's population is approximately 469,000 and is expected to reach 700,000 in 2021. The Gold Coast is one of the most famous tourist destinations in Australia with approximately 12% of the population being visitors. The beaches and waterways in particular are the most important tourist attractions (GCCC-Web, 2006).

The Gold Coast has a subtropical climate with moderate temperatures and summer dominant precipitation. The summer average temperature ranges from 19^0 to 29^0C and winter temperatures range from 16^0 to 21^0C. The city's stormwater drainage system features many natural and artificial waterways. These waterways include five major rivers and numerous creeks, many of which connect to artificial lakes and canals. The city's major drainage basins are shown in Figure 4.1. These waterways flow from the surrounding westward hilly area towards the Pacific Ocean coastline. Natural vegetation occupies a significant fraction of the regional land particularly west of the city. High density urban areas are located close to the coastline. Most of the residential settlements have been developed adjacent to the City's integrated waterways promoting luxurious waterside living. However, this extensive urban development alongside waterways influences key environmental values of the waterway ecology (GCCC-Web, 2006).

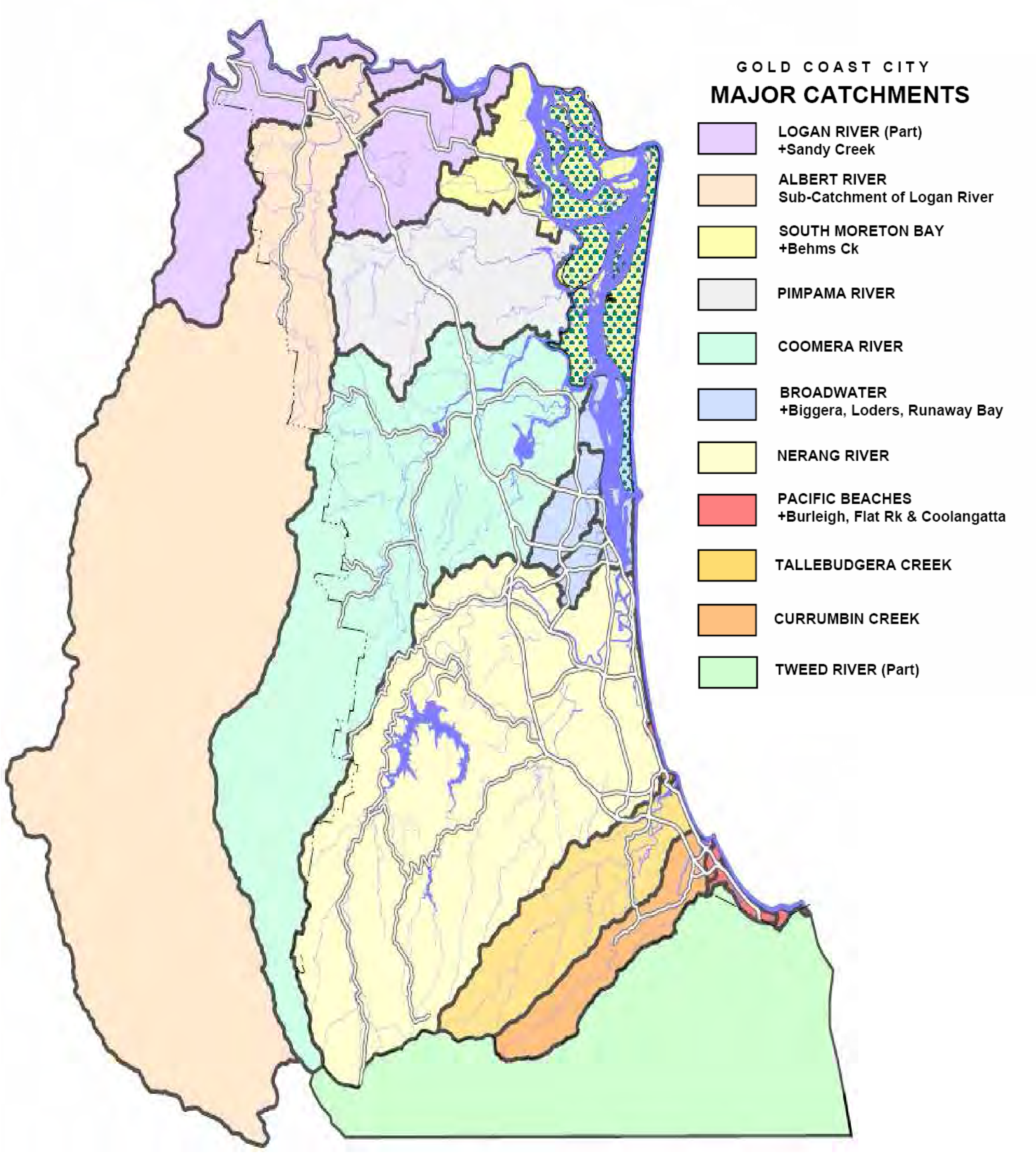


Figure 4.1 - Waterways of Gold Coast city

(Adapted from GCCC-Web, 2006)

4.3 Catchment Scale Investigation

Among the many catchments monitored by Gold Coast City Council (GCCC), three small catchments within the Highland Park residential area were selected for further investigations. This was primarily due to their residential land-use. Highland Park is within the boundary of the Nerang River catchment. A small tributary, Bunyip Brook is the study catchment's primary stormwater drainage. It starts from the westward hilly area and flows towards the Nerang River. The integrated pipe and channel network connecting various parts of the area to the tributary further facilitates the stormwater drainage. Highland Park is totally sewered and consists of several forms of urban residential developments. The three small catchments were selected to account for these residential forms (see Figure 4.2). The residential urban forms of these three catchments are:

1. Alextown, which is a tenement townhouse development of around 60 properties;
2. Gumbeel, which is a duplex housing development with around 20 dual occupancy residences; and
3. Birdlife Park, which is a high socio-economic area with single detached houses.

4.3.1 Catchment Characteristics

Most of the catchment details were provided by GCCC in the form of maps. These included:

- Contour map with 5 m height intervals;
- Land use maps;
- Detailed drainage network including creek, pipes, channels and locations of gully pits (manholes); and
- Aerial photographs.

The provided maps can be found in Appendix B, Figure B.1 to B.4.

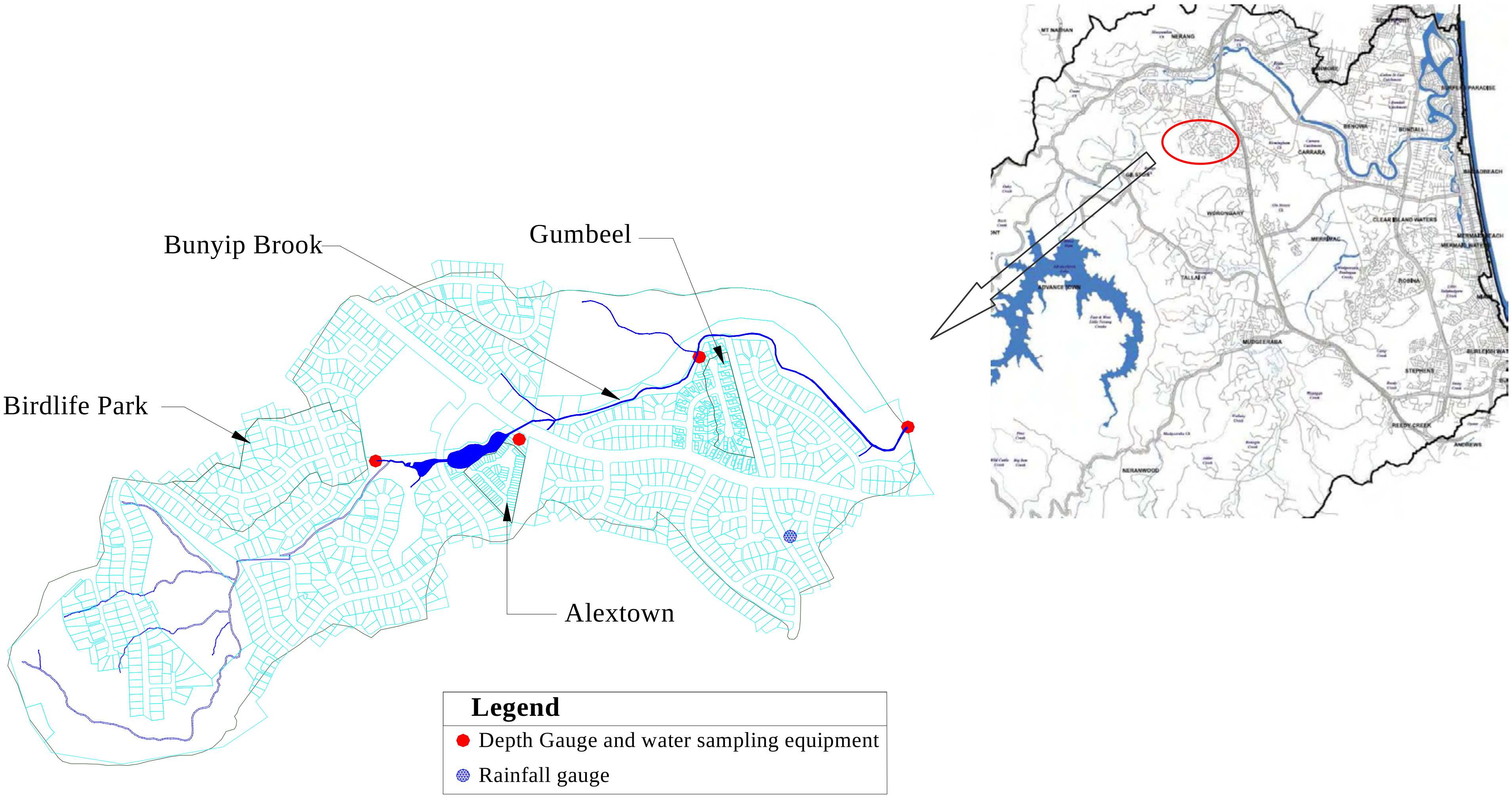


Figure 4.2 – Highland Park residential area, demarcation of three catchments and locations of the gauging instruments

These maps were used to obtain the primary parameters of the study areas. The parameters obtained included: catchment areas, impervious fractions for various surface cover types, locations and sizes of pipes and stormwater gullies and the catchment and drainage line slopes. The parameter values obtained for the catchment areas and impervious surface fractions are shown in Table 4.1. These parameters were used in various stages of the research and in particular in the catchment modelling.

Table 4.1– Characteristics of Alextown, Gumbeel and Birdlife Park catchments

Catchment	Area (ha)	Impervious Fraction (%)
Alextown	1.9	Road surfaces – 10.5 Roof surfaces – 38.1 Driveways – 8.6
Gumbeel	2.1	Road surfaces – 10.3 Roof surfaces – 19.2 Driveways – 11.2
Birdlife Park	8.6	Road surfaces - 12.4 Roof surfaces - 23.4 Driveways – 11.2

Simple techniques were used to obtain most of the catchment parameters. Information from contour maps and drainage network maps was used to demarcate catchment boundaries. Catchment area was measured based on these boundaries using functions in MapInfo GIS software (MapInfo, 2006). The impervious fraction of each subcatchment was determined from aerial photographs. By visual inspection of aerial photographs, it was possible to demarcate different surface covers such as roads, roofs and driveways. Such demarcations were done for the entire area of each catchment. These areas were measured separately as catchment area measurement. A similar technique was used by Charlesworth (2000) to identify the fraction imperviousness for water quality modelling. Boyd and Milevski (1996) suggested that the use of aerial photographs is one of the preferred methods to calculate fraction imperviousness. Figure 4.3 shows a sample demarcation carried out to obtain the impervious fraction for the Birdlife Park catchment.

Figure 4.3 – Calculation of Fraction Imperviousness

Most of the other catchment parameters, such as location and size of pipes and gullies, had been included in the maps in the form of data points. The information was directly extracted from the maps.

4.3.2 Catchment Monitoring

The three catchments, Alextown, Gumbeel and Birdlife Park, have been monitored since 2002 by the GCCC. This was done by establishing monitoring stations at catchment outlets which were equipped with:

1. Depth gauges which record water depth at 15 min intervals; and
2. Automatic water sample collection equipment.

The depth gauges were fixed just upstream of V-notch structures which had calibrated rating curves to convert the depth measurements to flow measurements. Figure 4.4 shows the V-notch structures and depth gauges at the three catchment outlets.

Figure 4.4 - Depth gauges and V-notches at the three catchment outlets

Figure 4.5 – Interior of automated monitoring stations

The sample collection equipments (see Figure 4.5) have been set to trigger when the flow depth reaches a pre-set depth. This depth varies from sampling station to sampling station depending on the downstream structure at the collection point. Once the sampler is triggered, samples are collected in 30 min intervals until the runoff depth is above the datum. Each sampler has the capacity to retain 24 samples. The sampler itself creates a log of the sampling time. More details on the protocol followed during sample transportation and storage can be found in Section 4.5.

4.4 Small-plot Scale Investigations

As stated in Section 2.3.2, a high fraction of stormwater pollutants originates from urban impervious surfaces. In particular, road surfaces are the most critical. House et al.(1993) and Novotny et al.(1985) noted that pollutant impacts associated with road surface runoff can be significantly higher than secondary treated domestic sewage effluent. As they further noted, the higher pollutant load from road surfaces often overshadows the contribution from other sources. However, in general roof surfaces can represent the highest impervious fraction particularly for residential catchments. Therefore, the pollutant contribution from roofs could also be significant (Bannerman et al., 1993). As such, investigations into small-plot pollutant processes were conducted on both road and roof surfaces.

4.4.1 Road Surface Investigation

A Study Sites

All the small-plot investigations on road surfaces were conducted within the Highland Park area. This was to obtain representative measurements for the study catchment. Most of the roads within the catchment are access roads which are primarily used by local traffic. The roads are in fair to good condition. Except for the most upstream portion of the catchment where construction activities are ongoing, most of the pervious areas are well turfed and maintained.

Highland Park is predominantly a residential area. However, there are differences in residential urban form in different parts. In order to encompass such variability, study sites were selected within each of the urban forms. However, due to restricted access into Alextown, the townhouse area, no sites were selected within this catchment. The access roads selected for the study were Lauder Court, Gumbeel Court and Piccadilly Place (see Figure 4.6).

The exact study locations on these three roads were selected after consideration of longitudinal slope and alignment, traffic conditions, traffic safety and space for investigations. A straight road section of about 50 m length with mild slope was selected for the investigations. Wide road sections were selected so that local traffic flow was not affected. Furthermore, it was decided to select sites with different traffic volumes. In this regard, the traffic volume was assumed to be proportional to the number of surrounding households.

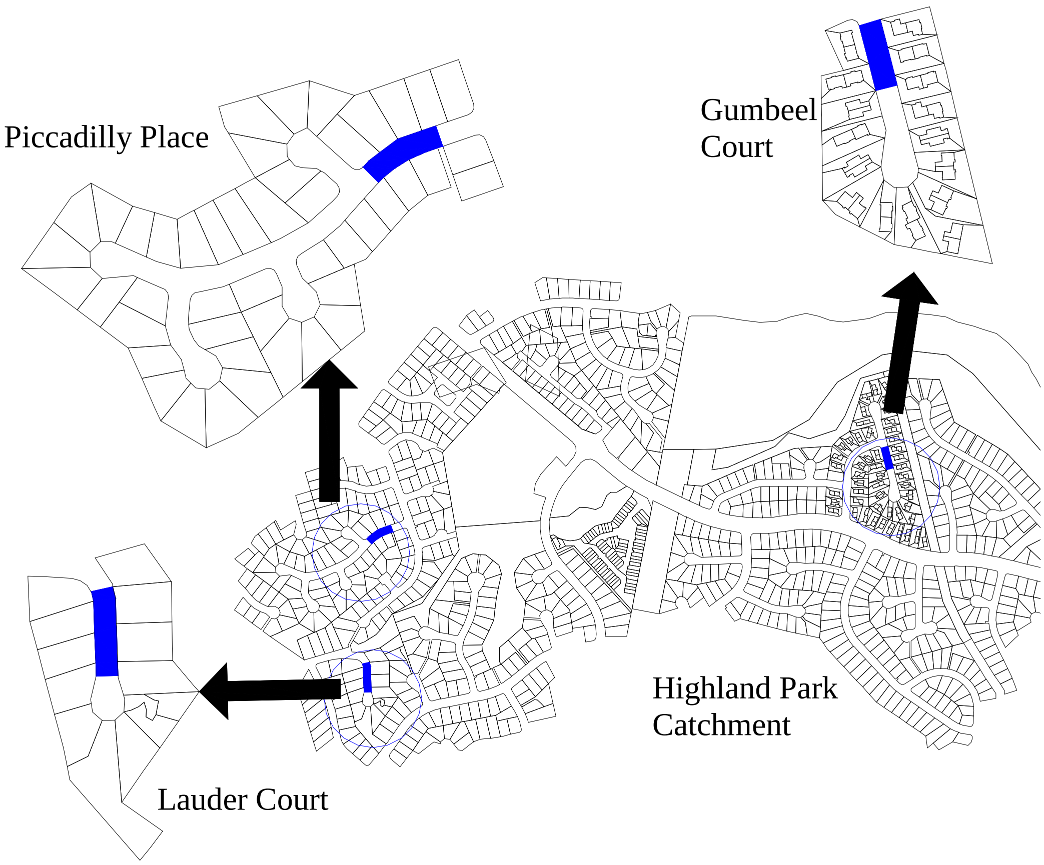


Figure 4.6 – Locations of the study sites within Highland Park catchment

Primary characteristics of the road surfaces were obtained prior to the investigations. These characteristics included surrounding urban form, number of surrounding households, longitudinal slope of the road and texture depth of the road surface. Table 4.2 shows the summary of these characteristics. The texture depth was measured using the sand patch test as explained in Test Method No E 965 (ASTM, 2006). The procedure was to spread a measured quantity of glass beads in a circular patch on the cleaned road surface and measure the final diameter. An empirical equation is available to relate the diameter of the patch to the texture depth of the surface. The texture depth is considered to be more descriptive in describing the road surface condition in relation to pollutant build-up and wash-off.

Table 4.2 – Characteristics of road sites

Site	Residential urban-form	Slope of the road (%)	Texture depth of the surface (mm)	Number of households
Lauder Court	Single detached housing area	10	0.66	12
Gumbeel Court	Duplex housing area	7.2	0.92	25
Piccadilly Place	Single detached housing	10.8	0.83	41

Investigations were conducted on one side of the road so that traffic was not disrupted. The small-plot surfaces for the investigations were selected in the middle of one traffic lane along the road. There was an implicit assumption that the pollutant distribution on the road surface was uniform. As noted by Sartor et al. (1974) road surface pollutants are concentrated in the near kerb area and concentration gradually reduces towards the centre line of the road. As they have hypothesised, this is caused by re-distribution of pollutants due to vehicle-induced wind turbulence. Therefore, selection of the middle strip of one traffic lane for investigation provided an average concentration of pollutants across the road section.

B Sampling Pollutant Build-up

As stated in Section 2.3.3, pollutant build-up is a dynamic process which varies with a range of parameters. These parameters include land-use, traffic volume, road surface characteristics and antecedent dry period. Since the study focused only on residential catchments, land-use variability was not considered. However, the three sites selected had slightly different residential urban form. Traffic volumes were relatively uniform for the catchment. However, a minor variation of traffic was incorporated by selecting sites with different numbers of surrounding households.

The road surface conditions for the selected road sites were typical to residential catchments. The only variability considered during the investigation was that due to antecedent dry days.

Three road surface plots of size 2.0 m length x 1.5 m width were selected at each road site for the investigations. These plots were clearly demarcated for later identification. Plots were initially cleaned by repeated vacuuming and pollutant build-up was allowed to occur for the required antecedent dry days. At the end of each antecedent dry period, pollutants were collected from the plot surfaces. The antecedent dry periods considered were 1, 2, 3, 7, 14 and 21 days. The vacuum system (discussed in Section 3.2) was used to collect the build-up samples.

Figure 4.7 - Dry sample collections from road surface plots

In order to maintain consistency of sample collection, the same procedure and equipment was consistently used. The components of the vacuum system were first cleaned and 3 L of deionised water was added to the compartment as the filtration agent. Vacuuming was done three times in perpendicular directions in order to ensure all the available pollutants were collected. The boundary of the plot was demarcated by placing a wooden frame (see Figure 4.7). At the end of the collection, the samples retained in the filtration compartment were transferred to polyethylene containers.

The vacuum compartment and all the hoses were thoroughly washed and the water was added to the container. Sample containers were pre-washed according to Standard Methods (APHA 1999). The protocol followed in the sample transport and storage is discussed in Section 4.5.

For uninterrupted investigation, a long dry period was needed. However, there were a few rain events which affected the continuation of the dry periods. After such interruptions, the plot surface was cleaned and sampling was undertaken after the requisite antecedent dry period.

C Sampling Pollutant Wash-off

Pollutant wash-off on a surface is a process which is influenced by a range of parameters. These parameters include rainfall intensity, duration and road surface condition. Since the variability of road surface condition is accounted for by selecting multiple sites, the primary variables considered during the investigations were rainfall intensity and duration. These were replicated using the rainfall simulator. Further details on the rainfall simulator are available in Section 3.3.

Wash-off investigations were conducted in the same sites where the build-up investigations were conducted. However, the other side of the road was used in order to reduce the influence of wash-off on build-up investigations. Altogether, seven plot surfaces were selected at each site using the same procedure as described for build-up sampling. This was to simulate six rainfall intensities and to collect a sample of the initially available pollutants. The space between plots was such that the simulation of rain in one plot would not influence the adjacent plots.

It has been noted that wash-off from road surfaces is influenced by the initially available pollutants on the surface (Duncan, 1995). Hence, it was decided to collect a representative build-up sample from each road site prior to wash-off investigations. It was assumed that the pollutant distribution is uniform throughout the road section.

Six rainfall intensities were selected so that they encompassed the common range of regional rainfall events. This range was determined by undertaking a statistical analysis of rainfall intensities over a five year period from 1999 to 2003. The rainfall data used for the analysis was obtained from the rain gauge established within the study catchment, as shown in Figure 4.2. Data obtained was compared with the data from adjacent rain gauges obtained from Department of Meteorology to verify the accuracy. For the analysis, the maximum 5 min rainfall intensity from every significant rain event was extracted. For the analysis, the maximum 5 min rainfall intensity from every significant rain event was extracted. The extracted intensities ranged from 5 mm/hr to 150 mm/hr. The analysis revealed that rainfall intensities were in the range of 15 to 140 mm/hr for more than 99% of the total number of events. However, the selected six intensities were in the range of 20 to 133 mm/hr. It was not possible to expand the selected intensity range further due to technical difficulties in simulating rainfall using the rainfall simulator. Nevertheless, it was noted that the selected intensity range represents more than 90% of the regional rainfall events. The rainfall durations were selected based on results published by Herngren (2005). He observed that there was no significant wash-off of pollutants beyond a threshold rainfall duration. The selected rainfall intensities and durations used are given in Table 4.3.

Table 4.3 – Rainfall intensities and durations simulated during the study

Rainfall Intensity (mm/hr)	Rainfall Duration (min)			
	Event 1	Event 2	Event 3	Event 4
20	10	20	30	40
40	10	15	25	35
65	10	15	20	30
86	10	15	20	25
115	5	10	15	20
133	5	10	15	20

A plastic frame with dimensions 1.5 m x 2.0 m was used to demarcate the plot area during wash-off investigations. This was to prevent water entering or leaving the demarcated plot so that the total runoff could be collected. A rubber flap was attached to the plastic frame and the inward side of the rubber flap was fixed to the road surface using waterproof tape. This further ensured watertightness around the plastic frame. One end of the plastic frame was kept open to fix the catch tray used for runoff collection. More details of the rainfall simulator can be found in Section 3.3. Figure 4.8 shows the arrangements for plot area demarcation and runoff collection. Figure 4.9 shows the rainfall simulator set up in the field.

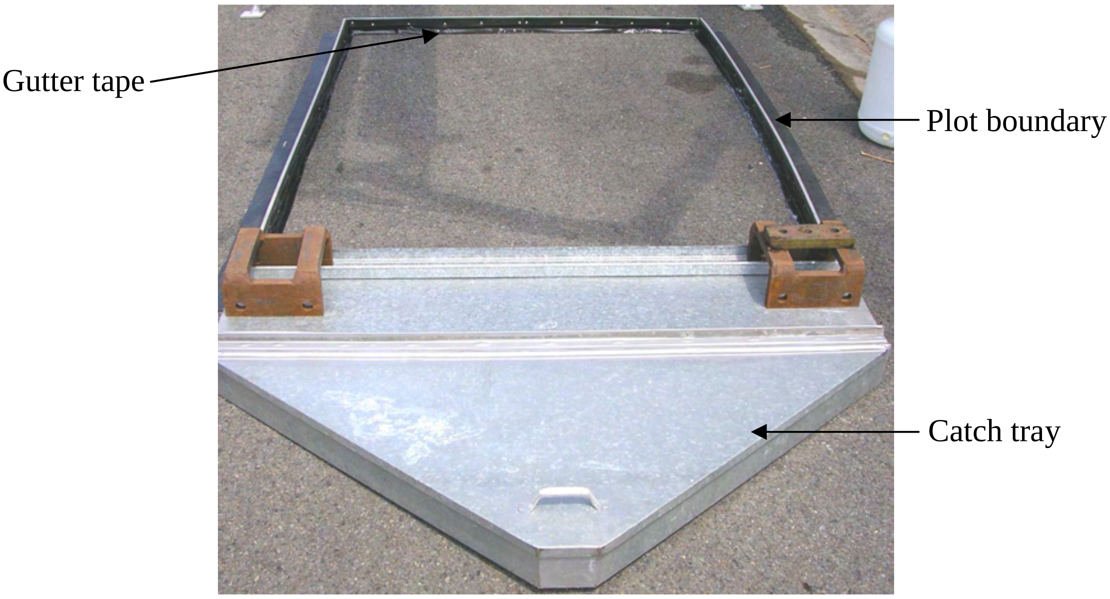


Figure 4.8 – Plot Surfaces Boundary and sealing method

Figure 4.9 – Rainfall simulator setup at Gumbeel Ct.

The runoff samples were collected into polyethylene containers using the vacuum system through a narrow opening in the catch tray. Figure 4.10 shows the collection of runoff into containers. The vacuum system was the same as discussed in Section 3.2. The collected samples were transported to laboratories, and preserved and stored under stipulated conditions. Further details on sample transport and storage are discussed in Section 4.5.

Figure 4.10 – Collection of runoff samples to polyethylene containers

The efficiency of the runoff collection system was primarily dependent on the quality of the sealing of the plot boundary and catch tray. The loss of runoff during collection into the polyethylene containers was minimal due to careful handling. The overall efficiency of the runoff collection was monitored by comparing the water volume used for simulation with the collected water volume. Table 4.4 gives the percentage recovery of runoff.

Table 4.4 – Percentage recovery of runoff volume comparison with simulated rain volume

Simulated rain Intensity (mm/hr)	Percentage recovery of runoff (%)		
	Gumbeel Ct.	Lauder Ct.	Piccadilly Pl.
20	78.2	-	90.2
40	84.1	72.7	85.5
65	59.6	72.1	72.1
86	50.3	64.3	55.1
115	49.6	76.0	69.8
133	81.2	81.4	89.1
Total	62.3	70.4	73.5

As seen in Table 4.4, the runoff volume can be appreciably less compared to the simulated rain volume. This could be due to factors such as initial and continuing losses on road surfaces. During simulations, it took one to three min for runoff to reach the catch tray, indicating almost complete loss of rainfall during this period. This is considering the fact that the length of the plot was 2.0 m. A similar range of rainfall losses was observed by Boyd et al. (2003). They noted that typical rainfall loss for road surfaces was in the range of 2 to 5 mm. This is equivalent to a 1.5 to 4.5 min delay of runoff for a 65 mm/hr rainfall simulation. Additionally, possible water leakages through the plastic plot boundary could have led to comparison errors. Furthermore, the recovery water volume percentage for 86 mm/hr is significantly lower compared to other intensities. Since this is common to all three sites, error in simulating rainfall intensities would be the primary reason. However, these errors were kept to a minimum by careful plot surface sealing, control box settings and constant monitoring of simulator intensities. Therefore, it was hypothesised that the volume reduction was primarily due to losses.

4.4.2 Roof Surface Investigation

A Study Site

The roof surface investigations were conducted using the model roof surface described in Section 3.4. As the model roofs were operated with mechanical lifting arrangements it was decided to install them in a lock-up space for safety reasons. There was no suitable place available with lock-up facilities in the Highland Park catchment. Therefore, it was decided to relocate the roof surface investigation to a location outside of the original study catchment.

The study site was selected after careful investigation of security, accessibility and surrounding land use of a number of GCCC-owned properties. Table 4.5 shows the characteristics of the sites and their suitability for the envisaged investigation.

Considering the above criteria, the Southport Depot was selected as the study site. This was primarily due to the availability of lock-up space and the presence of commercial and residential land use in close vicinity. Additionally, a significant number of other roads including the Smith Motorway are within 1 km distance. However, the site was an unpaved storage facility where there is occasional entry of vehicles. The dust created by such vehicle movement could influence the outcome of the investigation.

Table 4.5 – Characteristics of the possible site for roof surface investigation

Site	Characteristics
Carrara Depot	No lock-up space available. Limited public access granted on request. Unused grass-land around the premises. Residential area is around 2km away from the premises.
Southport Depot	Lock-up space available. Limited public access granted on request. Space available is adequate to place the model roofs. Surrounding land use is commercial and residential.
Bundall Pumping Station	No lock-up space available. Limited public access granted on request. Space is not adequate to place the model roofs. Residential area is around 2km away from the premises.

B Sampling Pollutant Build-up

Due to the lack of detailed research, there is limited knowledge on pollutant build-up on roof surfaces. However, the general influential factors such as land-use, roofing material and antecedent dry days could be the most significant on pollutant build-up. Due to the fact that the model roofs were kept in one location, the issue of land use would not arise. The model roofs were made from two common roofing materials and hence it was possible to investigate the factor of material. Therefore, as in the study on road surface build-up, the primary variable investigated was antecedent dry days.

During the investigation, samples were collected from roof surfaces for different antecedent dry periods. The same antecedent dry periods as for road surfaces were used. At the end of each antecedent dry period, samples were collected by washing the roof surface four times with 7 L of deionised water. A soft brush was used for brushing the surface. A common roof gutter was placed to collect the sample and to direct it to a polyethylene container kept underneath the gutter opening. The gutter was thoroughly washed before and after each sample collection. The model roofs were lifted to the typical roofing height after each sample collection and prepared for the next antecedent dry period. The collected samples were transported to laboratories and stored under prescribed conditions. The protocol followed during transportation and storage is discussed in Section 4.5.

C Sampling for Pollutant Wash-off

Similar to wash-off investigations for road surfaces, wash-off on roof surfaces was also conducted using the rainfall simulator. Therefore, the primary variables considered were rainfall intensity and duration. However, unlike road surface wash-off investigations, different rainfall intensities were simulated on different days due to the fact that only one model roof was available for each roofing material. In order to ensure that an appreciable amount of pollutants was build-up on the roofs, the interval between simulations was set at seven days. In order to obtain the exact amount of pollutants available on the model roofs, initially available pollutant samples were collected from half of each roof surface prior to each rainfall simulation.

Only four rainfall intensities, 20, 40, 86 and 115 mm/hr, were simulated on roof surfaces. The 65 mm/hr intensity was not simulated due to similar wash-off behaviour observed for 40 and 86 mm/hr intensities. The 133 mm/hr intensity was not simulated due to the rapid wash-off observed. Frequent sampling was not technically feasible for intensities greater than 115 mm/hr. The durations for these intensities were selected on site. Frequent samples were collected during the initial period of each event and simulations were conducted until relatively clean runoff resulted from the roofs. During simulations, the rainfall simulator was placed exactly above the lowered model roof (see Figure 4.11). The simulator was raised to maintain 2.5 m average height from roof to nozzle boom. A common roof gutter was placed to collect roof surface runoff and to direct it to the polyethylene containers. Samples were transported to laboratories and stored under prescribed conditions.

Figure 4.11 – Rainfall simulation on roof surfaces

4.5 Treatment and Transport of Samples

Two types of treatment procedures were used to handle and transport samples that were collected in the field. Samples collected during pollution build-up studies and from catchment outlets were transported to the laboratory immediately after collection. The average time taken to reach the laboratory from collection was around one hour. The samples were tested for pH and EC immediately after they reached the laboratory. A portion of each sample was preserved for further testing by refrigerating under 4^0C as specified in Australia / New Zealand Standards for Water Quality Sampling (AS/NZS, 1998). Deionised water blanks and field water blanks were included during each sample collection in order to maintain standard quality control procedure as specified in AS/NZS (1998). Wash-off samples took a longer time to collect in the field and the average volume of each individual sample was around 15 L. The samples were transported and a portion preserved similar to the build-up samples after recording pH and EC.

4.6 Laboratory Testing

It is commonly understood that a significant fraction of pollutants are associated with particulates in stormwater runoff (Pechacek, 1994; Sartor et al., 1974). This is the primary reason for using suspended solids as the indicator pollutant in stormwater quality modelling. A common approach used in modelling is to estimate suspended solids using rainfall and runoff parameters and predict other pollutants by proportioning (Akan and Houghtalen, 2003). Therefore, in-depth knowledge of suspended solid characteristics in stormwater runoff is critical.

Laboratory testing was primarily focussed on solids in both build-up and wash-off samples. Therefore, priority was given to test total suspended solids (TSS), total dissolved solids (TDS) and particle size distribution. Additionally, the physio-chemical parameters that influence the adsorption of other pollutants to particulate pollutants were also tested. As discussed in Section 2.4.6, the primary physio-chemical parameters that influence the adsorption of other pollutants to solids are pH, EC, total organic carbon (TOC) and dissolved organic carbon (DOC) (Hamilton et al., 1984; Pechacek, 1994; Tai, 1991; Warren et al., 2003). Therefore, laboratory tests were conducted to obtain these parameters. Since direct testing for TOC and DOC is difficult, total carbon (TC) and inorganic carbon (IC) for original sample and filtrate were tested. The complete set of parameters tested during the laboratory analysis was:

1) Particle size distribution;
2) TSS;
3) TDS;
4) pH and EC; and
5) TC and IC for original sample and filtrate.

4.6.1 Particle Size Distribution

Different techniques have been used to investigate the particle size distribution of suspended solids. Among many methods, wet or dry sieving is the most widely used. For example, Vaze and Chiew (2002) used 13 sieves, ranging from 38 to 2800 μm, to categorise samples into size classes. However, due to the greater number of samples to be tested, a faster, accurate and a less labour intensive method was needed. Therefore, a Malvern Mastersizer S instrument was used in this research.

The Malvern Mastersizer S uses a laser diffraction technique to analyse the particle size distribution. The laser beam creates a scatter pattern from a flow of particles. It then uses a Reverse Fourier lens to determine the size of particles from the scatter pattern. The specific lens used in this research was a Reverse Fourier lens of 300 mm diameter. As specified, it is capable of analysing particles in the range of 0.05-900 µm. The accuracy of the process is specified as ±2% of the volume median diameter in this size range (Malvern-Instrument-Ltd, 1997).

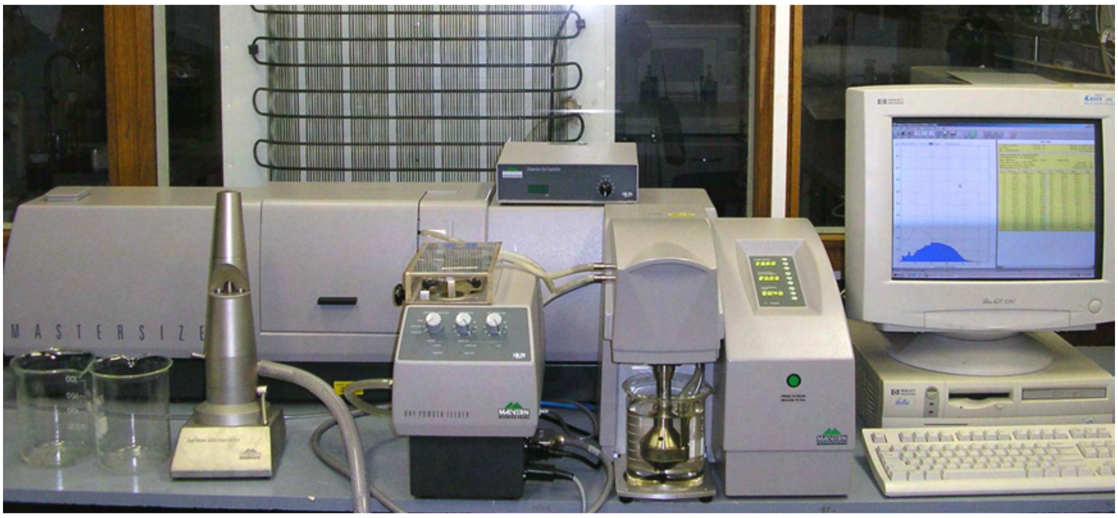


Figure 4.12 - Malvern Mastersizer model S

The Malvern Mastersizer S consists of a sample dispersion unit connected by two flow cells to the optical unit (see Figure 4.12). The results obtained from the optical unit were converted to percentage particle size distribution using specialised software supplied by the manufacturer. Two important issues to note in the interpretation of results from the Malvern Mastesizer are:

1. The particle size distribution is volume based; and
2. The particle size is determined by analysing volume initially and equating this volume to an equivalent sphere.

(Malvern-Instrument-Ltd, 1997)

4.6.2 Other Physio-chemical Parameters

The test methods specified in Standard Methods for Water and Wastewater (APHA, 1999) were used for the laboratory analysis. The analytical procedure followed for each test parameter is as follows:

A Total Suspended Solids and Total Dissolved Solids

TSS concentration was analysed by measuring the dry weight of solids retained on a glass fibre filter paper (1 μm pore size). For the filtration, a known volume of sample was used. The sample volume was chosen so that the increase in dry weight of filter paper is significant. The sample volumes used were 200 mL for build-up samples and 500 mL for wash-off samples. The filter papers used were pre-washed and oven dried before use. TDS was analysed by measuring the dry weight of solids dissolved in a known volume of water. In this regard, 20 mL of filtrated sample was used. The Petri dishes used for the analysis were pre-washed and oven dried before use. The oven temperature used was 103^0C to 105^0C. The test methods used were 2540C and 2540D (APHA 1999).

B pH and EC

pH and EC were measured immediately after the samples reached the laboratory. A combined pH /EC meter was used for the measurements and the instrument was pre-calibrated using standard solutions. The test methods used were 4500H and 2520B (APHA 1999).

C Organic Carbon

Organic carbon was measured using a Shimadzu TOC-5000A Total Organic Carbon Analyser. The instrument is capable of measuring inorganic carbon and total carbon separately. The original sample and filtrate was analysed separately to obtain the dissolved component of organic carbon.

4.7 Conclusions

Two different approaches were adopted to collect the necessary data for the research. Catchment scale investigations were undertaken to obtain the necessary data for validation of the translation procedure. For this, water samples collected from three catchment outlets were tested for a range of water quality parameters. Small-plot scale investigations were undertaken to obtain primary knowledge on pollutant build-up and wash-off processes for road and roof surfaces.

The primary variable considered for pollutant build-up was the antecedent dry period. Build-up samples were collected from road and roof surfaces belonging to a range of antecedent dry periods. The primary variables considered for wash-off investigations were rainfall intensity and duration. Wash-off samples were collected by simulating a range of rainfall intensities for different durations on both road and roof surfaces.

Samples collected were tested based on prescribed laboratory test procedures. The primary parameters tested were TSS, TDS, particle size distribution, pH, EC, TC and IC.

Chapter 5 - Analysis of Pollutant Build-up

5.1 Background

Among the knowledge requirements for the development of the translation procedure is detailed understanding of pollutant build-up processes. The field investigations, as discussed in Section 4.3, generated the primary data on build-up. The main focus of this chapter is to discuss the analysis of the data to derive relevant knowledge on build-up processes and for better understanding of the underlying physical processes of build-up.

Fundamental knowledge on the build-up process which was essential for the translation procedure was developed by the analysis of solid pollutant loads. In this regard, the processes were defined in the form of mathematical replication equations. However, it was necessary to understand the underlying physical processes of build-up.

5.2 Data and Pre-processing

The data obtained from the laboratory testing was subjected to extensive pre-processing prior to analysis. The pre-processing methodologies adopted were different for different test parameters. A complete set of the data used for pre-processing is shown in Appendix C, Tables C.1 and C.2.

A TSS and TDS

The laboratory test results for TSS and TDS parameters were in the form of concentrations (mg/L). Since build-up is typically expressed in terms of solid loads, it was necessary to convert concentration data into loads. For this, each data point was multiplied by the corresponding sample volume. The addition of loads obtained for TSS and TDS resulted in the total solids (TS) load for each sample. For standardisation, the TS loads were divided by the surface area where the samples were collected. The final outcome was in the form of (g/m^2).

B Particle Size Distribution

The laboratory results for particle size distribution were in the form of volumetric percentages. Since TS is given as a load, the particle size distribution also needed to be expressed in load percentages. This was done assuming that there is no variation in average particle density among different particle size classes. This assumption was made despite the understanding that particles originating from different sources can have different densities. For example, wear-off from tyres could be much lighter in density compared to wear-off from road surfaces. However, the assumption is still valid if particle size distribution of each density class is the same.

B pH and EC

pH and EC were analysed immediately after samples reached the laboratory. However, prior to measurements, the sample volume was brought up to 7 L which was the approximate volume for build-up samples. In this way, the measurements were standardised and therefore, the outcomes could be comparable with samples obtained from different sites. It was understood that the pH and EC measurements would be influenced by the initial pH and EC readings of the deionised water used in the vacuum system for sample collection. However, it was noted that the variation of pH and EC in the deionised water was low. The pH ranged from 6.7 to 7.0 for deionised water used in various stages of build-up sample collection and the variation of EC was 2 to 10 μS. Therefore, the laboratory test results obtained were directly used in the data analysis without further pre-processing.

C TC, TOC and DOC

As discussed in Section 4.6, the parameters obtained during laboratory testing were total carbon (TC) and inorganic carbon (IC) for the original sample and for the filtrate. From these parameters, values for total organic carbon (TOC) and dissolved organic carbon (DOC) were calculated. TOC was defined as the difference between TC and IC results for the original sample. DOC was considered to be the difference between the TC and IC results for the filtrate.

5.3 Build-up on Road Surfaces

The pollutant build-up on road surfaces within the study area was investigated based on three road surfaces. The road sites were Gumbeel Court, Lauder Court and Piccadilly Place. Details of these road sites are provided in Section 4.3.1. Six to eight build-up samples were collected from each site representing different antecedent dry days. The antecedent dry days considered were 1, 2, 3, 7, 14, and 21. The primary parameters used during build-up data analysis were TS, particle size distribution, pH, EC, TC, TOC and DOC.

5.3.1 Variability of Build-up

As discussed in Section 2.3.3, pollutant build-up on impervious surfaces is commonly understood as a decreasing rate increasing function with antecedent dry days. Although this behaviour is commonly accepted, many researchers have noted that the build-up rates and loads are site specific (Deletic and Orr, 2005; Herngren et al., 2006; Vaze and Chiew, 2002). The site specific nature is primarily attributed to the variability of the influential parameters such as climatic conditions, land-use, traffic volume and road surface conditions. However, the variability noted during this investigation was limited. This could be due to the investigation of only residential land-use. Nevertheless, the pollutant build-up did show appreciable variation, as shown in Figure 5.1.

As illustrated in Figure 5.1, pollutant build-up during the initial one to two days is high compared to longer dry periods. The average two day build-up is around 2.3 g/m^2/day or about 66% of the total average build-up for 21 days. After the initial two days, the rate of accumulation is significantly reduced. As the rate reduces, it could be assumed that the build-up asymptotes to a constant value when the dry days increase. As explained by Ball et al. (1998), there could be a state of dynamic equilibrium of build-up which occurs once the build-up reached its maximum level. In this dynamic equilibrium state, the accumulation of solids and removal due to wind and vehicular-induced turbulence balance. Therefore, the pattern of build-up observed can be considered as being in agreement with that hypothesised by other researchers (Ball et al., 1998; Sartor et al., 1974).

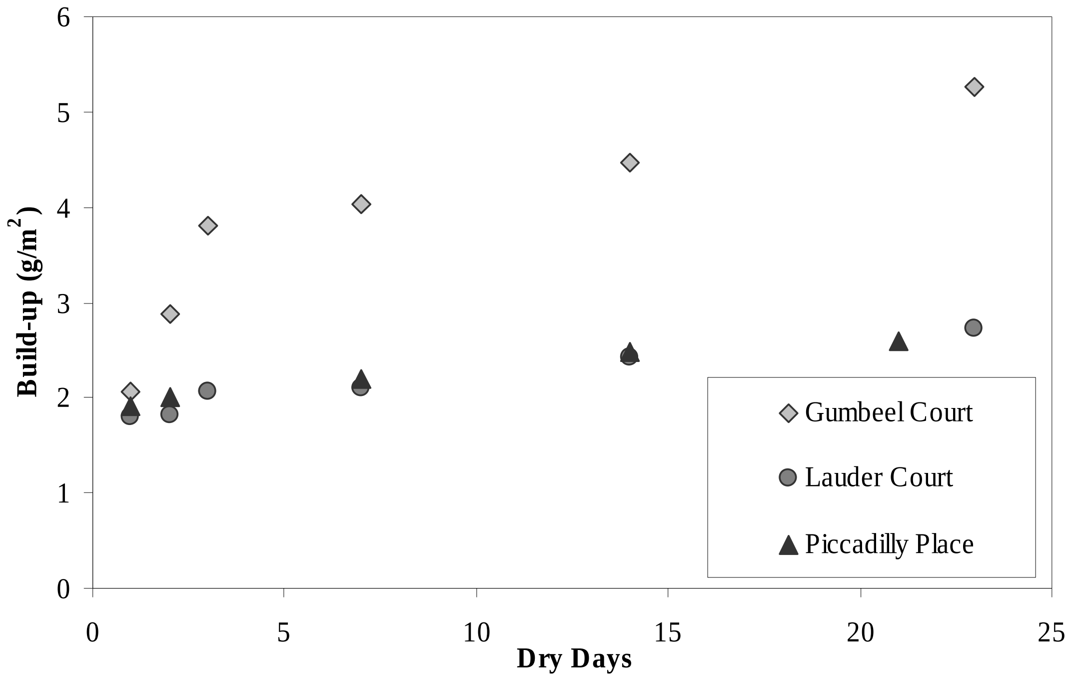


Figure 5.1 – Pollutant build-up on road surfaces

Although the observed pattern of build-up is in agreement with current knowledge, the amount of solids collected from road surfaces and the rate of build-up are significantly different. Sartor et al. (1974) observed around 113 g/m of solids in residential roadside kerbs, whereas Ball et al. (1998) observed only around 4 to 15 g/m. As noted by Ball et al. (1998) the variation of pollutant load when compared with results obtained by Sartor et al. (1974) was mainly due to differences in traffic volumes, land-uses and regional characteristics. However, both research studies were not completely comparable with research as the samples were collected from the middle of one traffic. Vaze and Chiew (2002) noted that the build-up load is highly variable depending on the site and was in the range of 8 to 40 g/m^2 for road surfaces that they investigated in Melbourne, Australia. The road sites were located close to the Melbourne CBD. Deletic and Orr (2005) observed 5 to 25 g/m^2 solids in the middle strip of residential roads in Aberdeen, Scotland. As seen in Figure 5.1, the maximum pollutant load collected from the three study sites varied from 3 to 6 g/m^2. This was significantly less compared to numerous other studies. This could be mainly due to the general variability associated with build-up arising from factors such as regional, climatic, land-use, traffic and road surface conditions. However, the build-up loads and rates observed in this research are representative for low traffic road surfaces in typical Australian residential land-uses. This can be further confirmed by the results reported by Herngren et al. (2006), where similar pollutant loads on road surfaces were observed for sites in the Gold Coast region. They noted 0.8 to 5.3 g/m^2 pollutants on low traffic roads in urban residential land-uses. However, the loads that they observed belonged to different antecedent dry days and were not in equilibrium conditions.

As evident in Figure 5.1, the build-up varies between the three study sites. The build-up in the Gumbeel Court site is significantly higher than in the other two sites. The maximum build-up load observed in Gumbeel Court site was 5.3 g/m^2, whereas for the other two sites it was around 2.7 g/m^2. It can be surmised that the variability of build-up load and rate is due to variation in urban-form, traffic volume and road surface conditions (see Table 4.2). However, the variation of traffic volume among the three sites is not significant. As discussed in Section 4.4.1, the variability of traffic volume is expressed in terms of surrounding households. The influence of traffic would not be significant since the highest number of households belongs to Piccadilly Place site where the build-up is comparatively less. Among urban-form and road surface conditions, urban-form would be the most influential on pollutant build-up. This is due to the high degree of indirect correlation of urban-form and consequent variation in population density with the degree of anthropogenic activities on catchment surfaces.

For the study area, the urban-form primarily describes the population density. Therefore, the influential variable for the pollutant build-up could be attributed to population density. There are two primary population density categories within the study area. Population density equivalent to townhouse areas such as those in the Gumbeel and Alextown catchments can be termed high population density areas. Therefore, the build-up in high population density areas can be considered as represented by the build-up variation observed in Gumbeel Court site. Low population density is equivalent to single detached housing areas such as Birdlife Park catchment. Build-up in such urban-form can be considered as represented by the build-up variations observed in Lauder Court and Piccadilly Place sites.

5.3.2 Mathematical Replication of Build-up

In the context of stormwater quality modelling, accurate replication of build-up is important. For this research, it is particularly essential, since mathematical replication was to be used in the proposed translation procedure. As two different build-up variations were noted for two population density areas, two different replications were needed.

As noted in Section 5.3.1, in a generic sense the build-up observed in this research study is closely comparable to the commonly accepted form. Therefore, it can be considered that a common replication equation with two different sets of parameters can be developed for the two build-up variations. In the research literature, a number of different replication formats have been proposed. It is hypothesised that these differences could be the result of inconsistency in research techniques and data interpretations. For example, Sartor et al. (1974) proposed an exponential form of a build-up equation which provided a reasonable level of accuracy to be used in stormwater quality models. Modified forms of this exponential equation are used widely in various stormwater quality models including SWMM (Huber and Dickinson, 1988). Ball et al. (1998) noted build-up is better replicated by a power function or a reciprocal function.

In order to identify the most suitable form for replicating pollutant build-up, four equations were investigated in-depth. These were:

1) Reciprocal format - $y = a + \frac{b}{x}$;
2) Logarithmic format - $y = a + b\ln(x)$;
3) Exponential format - $y = ae^{-bx}$; and
4) Power format - $y = ax^b$.

The equations were tested by developing best fit curves for each equation based on their ability to replicate the observed pollutant build-up. Since two build-up variations were noted, it was necessary to standardise these observations prior to testing. Standardising was done by dividing each data point by the maximum possible build-up for that site. In this regard, maximum build-up for Lauder Court and Piccadilly Place sites was considered to be the average of maximum build-up. It was assumed that the build-up for all three sites has reached equilibrium level at the end of each investigation period. The standardised parameter was termed the 'Fraction Build-up'. Figure 5.2 shows the performances of selected equation formats.

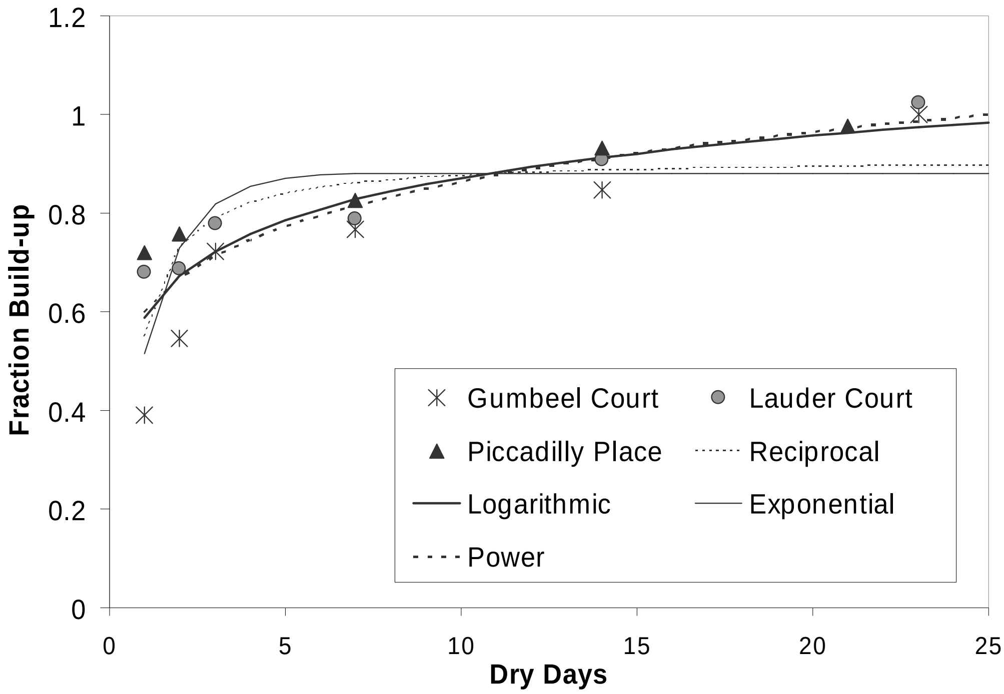


Figure 5.2 – Comparison of different form of equations with solid build-up on roads

As evident in Figure 5.2, predictions by both logarithmic and power equations are visually similar to the observed build-up variation. However, the power equation was preferred ahead of the logarithmic equation to replicate build-up. This was mainly due to the recommendation in a previous independent study by Ball et al. (1998). Hence, the form of the build-up replication equation for road surfaces was taken as:

$$B = aD^b \quad \text{Equation 5.1}$$

Where,

B = Build-up load on road surface (g/m^2);

D = Antecedent dry days; and

a and *b*= Build-up coefficients.

Appropriate values for the build-up coefficients, *a* and *b*, needed to be estimated before the use of the equation. For this research study, *a* and *b* were estimated based on the observed results from the three study areas. Therefore, the parameters would be most appropriate for the conditions in the study areas. Two sets of parameters were developed to account for the variability observed for the two population density areas.

According to the behaviour of the power equation, it was noted that a constant value for the power coefficient, *b*, would be appropriate. However, there is a possibility of variation of *b* with the surface type. Therefore, the constant value developed is valid only for similar road surfaces. More details of the surface characteristics can be found in Table 4.2. The multiplication coefficient, *a*, denotes the pollutant build-up rate on the road surface. The coefficient *a* is the primary parameter that accounts for the variability of population density areas. Therefore, two values were obtained for *a* to represent high and low population density. Although only population density was considered in this research, *a* could be influenced by other factors such as land-use, traffic volume and regional variables.

The two sets of build-up coefficients were developed using the method of least squares. This method adjusts the parameters such that the cumulative square of error associated with the prediction of each observed data point is minimal. More details on the method of least squares can be found in Section 3.5.2. The analysis was done for low and high population density areas separately. Table 5.1 shows the values obtained for *a* and *b*, and Figure 5.3 shows the predictive accuracy of the equation with the given parameters. Table 5.1 further shows the statistical significance of prediction in terms of Mean and CV. It is evident that the accuracy of prediction for low population density areas is quite good compared to high population density area.

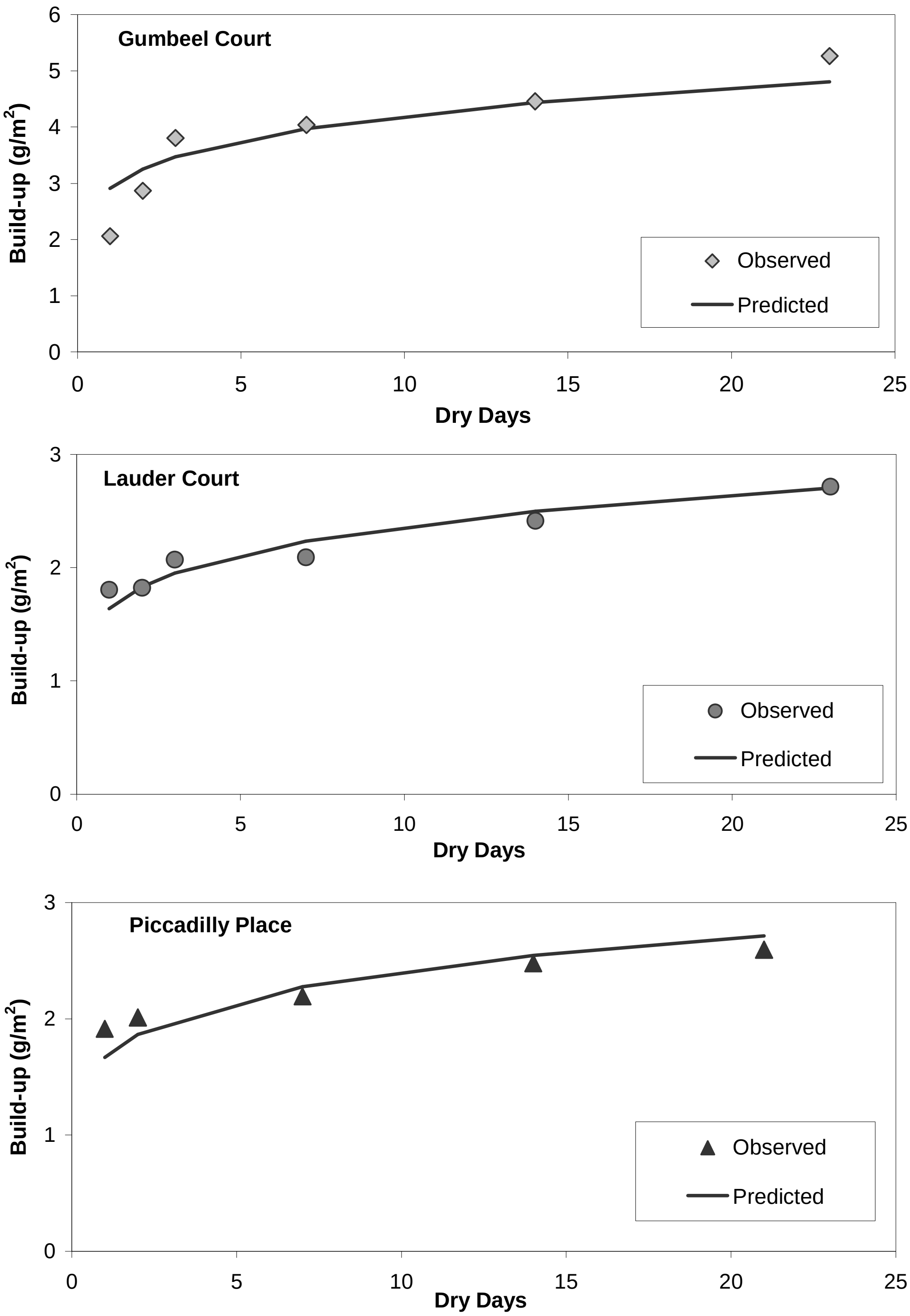


Figure 5.3 – Predictive ability of build-up equation for road surfaces

Table 5.1 – Build-up coefficients for road surfaces

Road Site	Characteristics	*a*	*b*	Mean	CV
Gumbeel Court	Townhouse region with high population density	2.90	0.16	1.05	19%
Lauder Court	Single detached housing regions with low population density	1.65	0.16	0.98	7%
Piccadilly Place		1.65	0.16		

5.3.3 Hypothetical Build-up Process

As explained in Section 4.4.1, the sampling plots were cleaned and pollutants allowed to build-up for a specified antecedent dry period. This would mean that the developed build-up equation relates to the build-up process starting from near zero initial pollutants. However, it is not reasonable to assume that build-up starts from near zero under typical conditions in the field. Based on the observations from wash-off investigations (Chapter 6), an appreciable amount of pollutants remain on an impervious surface even after a heavy storm event.

The possibility of an appreciable amount of pollutants being initially available on the road surfaces would mean that Equation 5.1 estimates only the lower limit of build-up. With the inclusion of initially available pollutants, the total pollutants present on surfaces would always be higher than the estimated amount given by Equation 5.1. Many researchers have noted that the simple addition of pre-existing pollutants after the last storm would not be appropriate to estimate the total build-up (Novotny et al., 1985; Sartor et al., 1974). Such an approach contradicts the already accepted physical process of pollutant build-up which was considered to asymptote to a constant value. An addition would unrealistically increase the estimated pollutant build-up.

The presence of pre-existing pollutants on the road surface would influence the initial part of the build-up processes, but it should still asymptote to the same constant value (Alley and Smith, 1981). However, since the time taken to reach the constant build-up is not known, it is reasonable to assume that the build-up process commences from a pre-existing amount and will vary parallel to the curve that would develop if there was no pre-existing pollutant amount. Based on these assumptions, a hypothetical build-up curve can be developed, as illustrated in Figure 5.4.

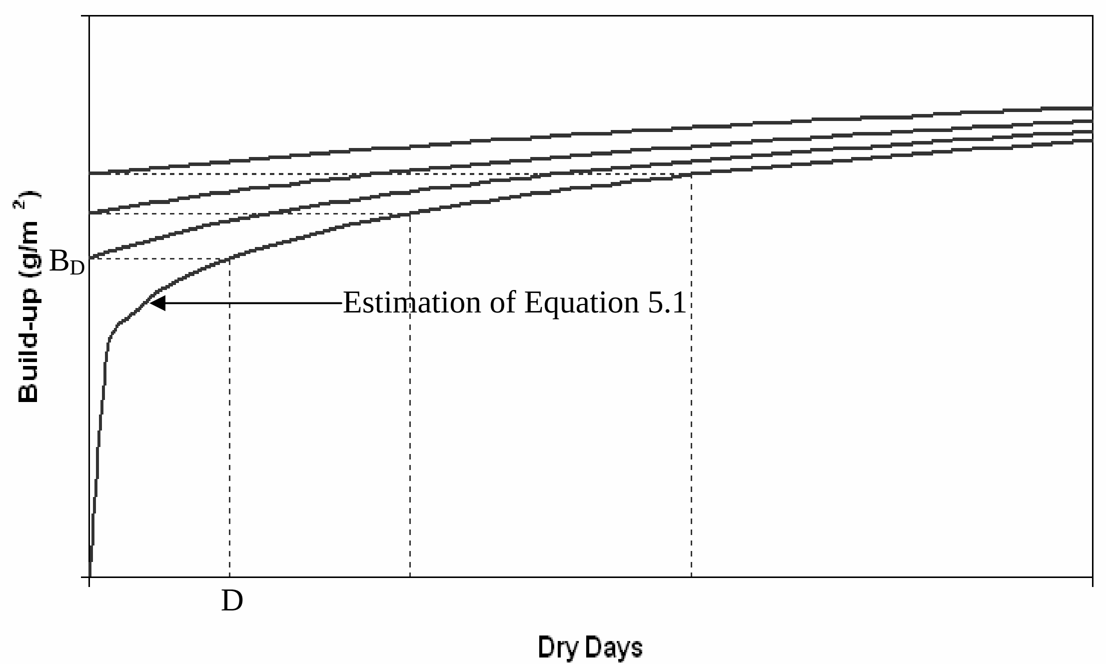


Figure 5.4 – Build-up hypothesis

As shown in Figure 5.4, the build-up equation developed in Section 5.3.2 represents the lower limit of the build-up process. Depending on the amount of pre-existing pollutants available, the build-up curve moves upwards. The amount of pre-existing pollutants should be estimated by the analysis of previous build-up and wash-off. More details relating to the wash-off process are discussed in Chapter 6. As evident in Figure 5.4, the influence of pre-existing pollutants at the initial period of build-up is high. Although as the number of antecedent dry days increase, the difference between curves reduces. Therefore, it can be assumed that Equation 5.1 alone is sufficiently accurate when the number of antecedent dry days is high.

5.3.4 Verification of Build-up Equation

Due to the compounding differences in land-use, traffic and regional conditions, the build-up load on Gold Coast residential roads may not be comparable with results from previous publications. This made it difficult to find an adequate amount of data from previous publications to test the validity of the build-up replication equation. Therefore, the data collected during the initial pollutant availability tests for pollutant wash-off was one set of data that was used for validation. For this data, the number for antecedent dry days was obtained by analysing the rainfall records from a Hinkler rain gauge which was less than 2 km distance to all the road sites. Other than this data set, the data published by Herngren et al. (2006) was partly comparable with this research. Their research was done in the same region and used exactly the same methods for sample collection and testing. However, the samples that they collected were from road surfaces where the surrounding land-uses included residential, industrial and commercial uses.

For the comparison of observed data, predictions were made with the corresponding antecedent dry days. However, it was borne in mind that the estimations resulting from Equation 5.1 were only for the lower limit of build-up. The observed pollutant loads and the predicted pollutant loads are shown in Table 5.2. The predicted pollutant load is given as a range, since two set of parameters were available.

Table 5.2– Comparison of observed and predicted build-up pollutants

Description	Site	Antecedent dry days	Observed pollutants (g/m^2)	Predicted pollutants (g/m^2)
Data from initial pollutant availability tests	Gumbeel	77	10.89	7.03
	Lauder	27	3.11	2.67
	Piccadilly	36	3.54	2.71
Data from Herngren et al. (2006)	Residential	2	0.82	1.87 – 2.93
	Industrial	7	2.29	2.23 – 3.96
	Commercial	1	5.29	1.72 – 2.48

As shown in Table 5.2, the amount of pollutants collected during investigation of the initially available pollutants was predicted by the build-up equation. However, it can be clearly seen that the observed pollutant loads were under predicted. This could be partly due to the presence of pre-existing pollutants. Therefore, Equation 5.1 typically provides an underestimation. Furthermore, the equation was developed using field data of up to 21 antecedent dry days. However, the three samples collected during the initial pollutant availability test were well outside the investigated range. The uncertainty of predictions always increases when an equation is used for extrapolation.

As seen in Table 5.2, the data from Herngren et al. (2006) shows significant variation with the predicted build-up ranges. Only the observed build-up for the industrial site falls within the predicted range whilst the build-up in the residential site is below the predicted range and in the commercial site it is above the predicted range. The commercial site was a parking lot which may retain more pollutants due to high anthropogenic activities and flatness of the surface. Furthermore, pollutant re-distribution would also be limited due to the reduced speed of vehicles. This suggested that the predictions made using Equation 5.1 are not suitable to estimate the pollutant build-up at commercial sites. Both the residential site and industrial sites were road surfaces which had similar characteristics to the road surfaces investigated in this research. In fact, the residential site was particularly similar to the Lauder Court site. Therefore, the differences between observed and estimated values could be due to errors in the estimation equation. This further highlighted the uncertainty associated with build-up predictions. However, it is important to bear in mind that it is pollutant wash-off that is significant rather than pollutant build-up, even though the former is influenced by the latter.

5.3.5 Particle Size Distribution

Detailed knowledge on the solids composition of pollutants and its variation with a range of influential parameters is essential for better understanding of the underlying physical processes of pollutant build-up. For this research study where the solids were considered the primary pollutant, the composition of build-up was investigated in terms of particle size distribution. It was well understood that the particle size distribution can vary with a range of land-use, regional and road surface parameters (Sartor et al., 1974; Shaheen, 1975).

The outcomes of particle size distribution measurements were in spectrum format which can be categorised into any size class according to user preference. More details on particle size distribution measurements can be found in Section 4.6.1. For ease of understanding, size spectrums were categorised into six size classes for the primary analysis. Table 5.3 shows the average volumetric particle size percentages for six size categories.

Table 5.3 – Average percentage particle size distribution

Size Class (μm)	Solids (Volumetric Percentage)		
	Gumbeel Court	Lauder Court	Piccadilly Place
<10	3.9	3.3	5.8
10-50	17.8	18.7	23.8
50-100	20.6	25.4	27.7
100-200	22.6	25.7	21.3
200-400	20.5	17.4	13.9
>400	14.5	9.5	7.4

As shown in Table 5.3, the particle size distribution for the three road sites is similar. This could be primarily attributed to similar traffic volumes in the three sites. However, the solids composition noted is different to the results reported in other research studies. On average, for all three sites around 50% and 70% of the solids are less than 100 μm and 200 μm size respectively. In contrast, Sartor et al.(1974) noted that only around 43% of the particles were smaller than the 246 μm size for the samples they collected from roadside kerbs. Furthermore, they found that only 5.9% of particles were smaller than 43 μm. Ball et al. (1998) noted a 10 to 30% particle fraction less than 200 μm on suburban road surfaces in Sydney. Deletic and Orr (2005) noted 50% of the road surface solids were less than 238 μm. They collected samples from the middle strip of a residential road in Scotland. Therefore, in comparison to previous research findings, the particulate pollutants observed in this research are significantly finer. This could be primarily attributed to the residential nature of the land-use, low traffic volumes on roads and catchment management practices.

Apart from the comparison with previous research, detailed analysis of the variation of particle size distribution with the increase of antecedent dry days was necessary to understand the primary physical processes of build-up. The outcomes of this analysis are shown in Figure 5.5.

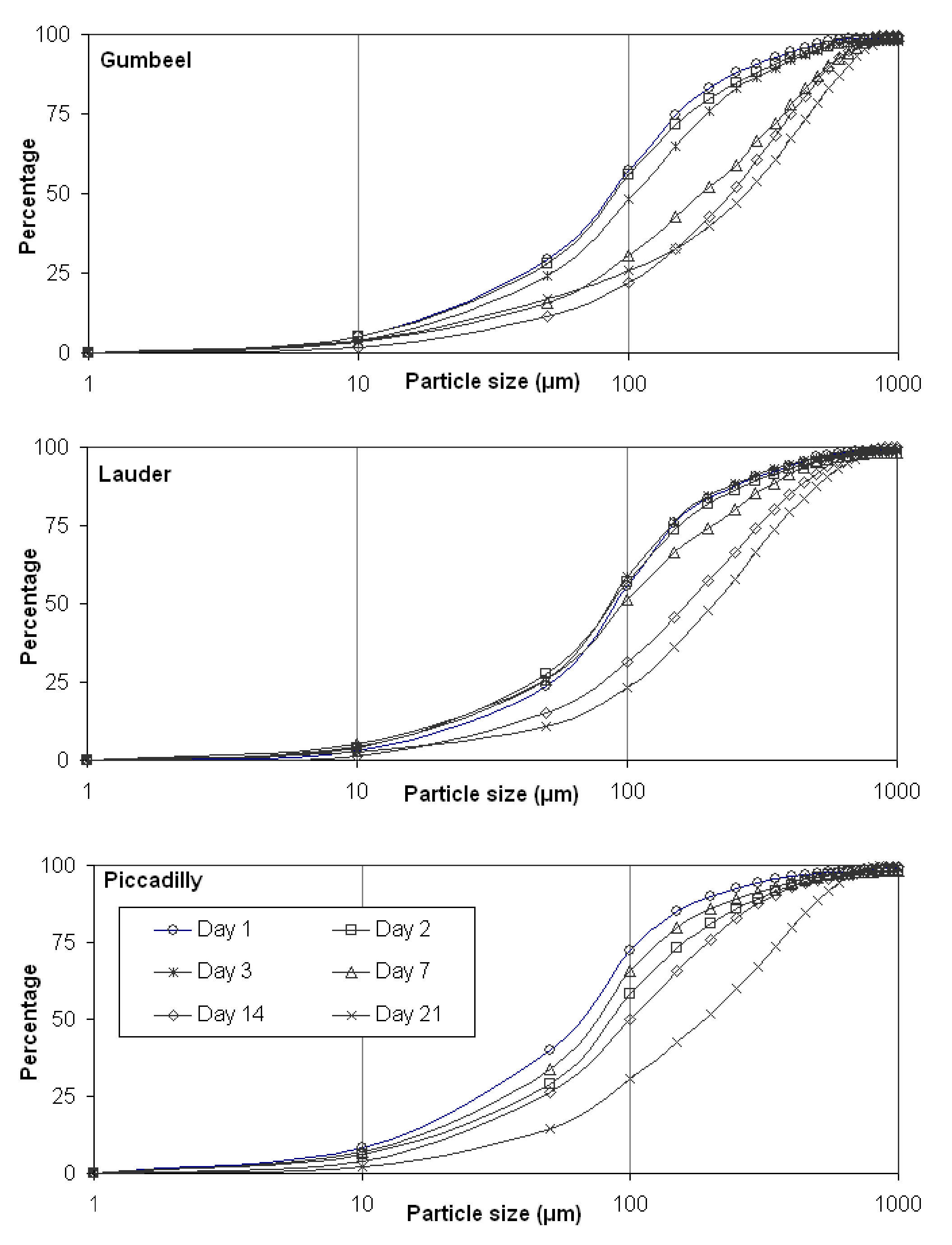


Figure 5.5 - Variation of particle size distribution with antecedent dry days for road surfaces build-up

Figure 5.5 shows a significant variation of solids composition with antecedent dry days. For all three sites, the semi-logarithmic curve for particle size distribution moves from left to right with the increase in antecedent dry days. This suggested that the fraction of coarser particles increases with the increase in the dry period. As noted by Roesner (1982), the particle size distribution of solids depositions can be assumed to be uniform for any given dry day. Therefore, it is hypothesised that it would be the re-distributing factors that change the particle size distribution during build-up by constantly removing finer particles from the surface. As noted by Namdeo et al. (1999) and Novotny et al. (1985), pollutant re-distribution occurs depending on the wind and traffic-induced turbulence by re-suspending finer particles. As they noted, there is a high possibility of these particles to be re-deposited in nearby pervious areas.

As noted in Section 5.3.2, it could be hypothesised that the pollutant loads asymptote to a constant value with the increase in dry days. However, the variation of particle size distribution illustrates the dynamic nature of build-up suggesting the ability to accumulate newer particles after the removal of older particles so that there is little variation in pollutant loads as the antecedent dry days increase. This would mean that the build-up on road surfaces continues as a dynamic process for a long duration even though the changes to the pollutant load are limited.

5.3.6 Analysis of Physio-chemical Parameters

Since this research focused on suspended solids, the range of chemical impacts exerted on receiving water due to stormwater pollution is not discussed in detail. However, as noted in previous research studies, the impacts of chemical pollutants such as hydrocarbons, heavy metals and nutrients are the most significant (House et al., 1993). Although the chemical pollutants were not specifically investigated, it was well understood that most of them are associated with particulate pollutants (Herngren et al., 2006; Sartor et al., 1974; Shaheen, 1975). Therefore, understanding the links between suspended solids and other chemical pollutants would improve the applicability of the research outcomes.

The amount of other pollutants adsorbed to solids varies with a range of parameters including factors influencing the availability of chemical pollutants and factors influencing the adsorption of these pollutants. Understanding the factors influencing the availability of chemical pollutants on a catchment surface is well beyond the objectives of this research study. However, understanding the factors influencing the adsorption of pollutants is important in order to link the outcomes derived from this research study to the existing knowledge on the estimations of other water quality pollutants. The fineness of the solids is one of the important properties in relation to the adsorption of other pollutants. This is discussed in detail in Section 5.2.4. The other parameters which influence adsorption include pH, EC, TC, TOC and DOC (Hamilton et al., 1984; Pechacek, 1994; Tai, 1991; Warren et al., 2003). Due to the availability of multiple variables, principal component analysis (PCA) was used for data analysis. A description of PCA can be found in Section 3.5.3.

The variables used in the analysis were pH, EC, TC, TOC, DOC and TS divided into six particle size ranges: <10, 10-50, 50-100, 100-200, 200-400, >400 μm. The number of samples used for the analysis was 24. A low number of samples used for the analysis would reduce the confidence in PCA outcomes. However, the number of samples used was adequate for the development of general understanding. For better interpretations of PCA outcomes, the original data obtained from laboratory tests was pre-processed. In this regard, TC, TOC and DOC concentrations were converted to loads, and solid loads in each size class were converted into fractions. This was to eliminate the influence of different build-up loads from the three different road sites. Before the analysis, the data in the matrix was subjected to column standardisation which is one of the standard pre-processing procedures used in multivariate analysis. The data matrix used for the analysis is given in Appendix C, Table C.3.

Figure 5.6 shows the PCA biplot which resulted from the analysis.

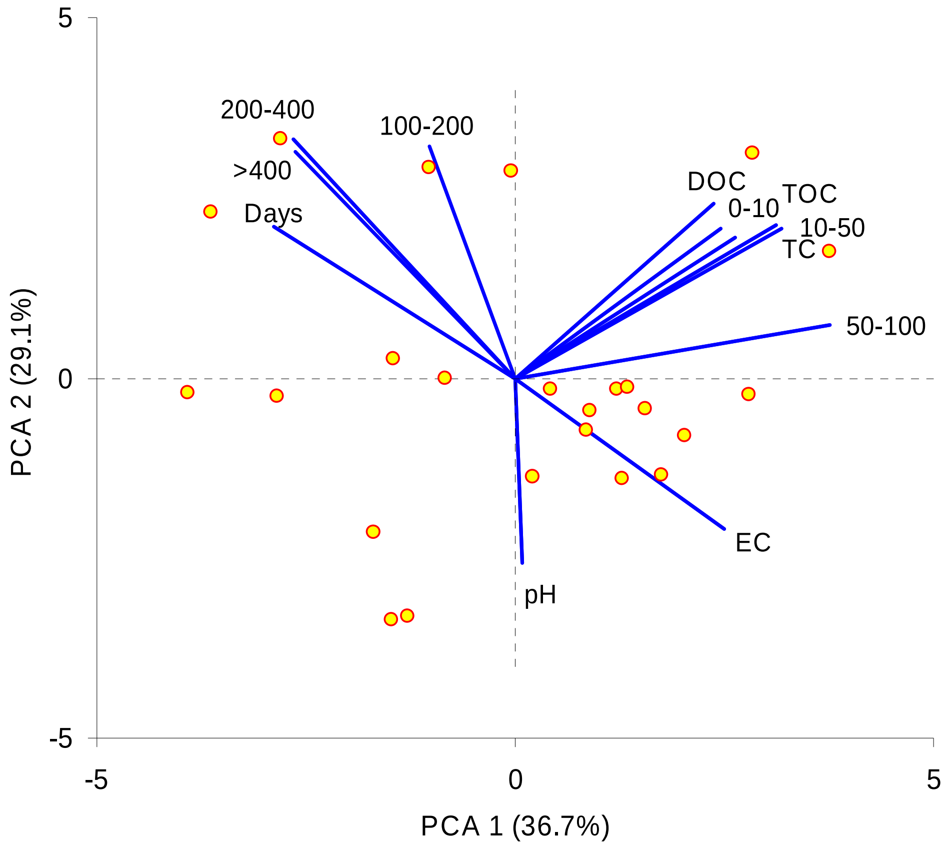


Figure 5.6 – Physio chemical parameters and antecedent dry days for road surfaces: Biplot of data against the first two principal components

The following primary observations can be derived from Figure 5.6:

1) Particle size classes 100-200, 200-400 and >400 μm correlate strongly with each other and also with antecedent dry days.
2) Particle size classes 0-10, 10-50 and 50-100 μm correlate strongly with each other. These size ranges show poor correlation to particle sizes greater than 100 μm and to antecedent dry days.
3) TC, TOC and DOC show high correlations to particle size classes 0-10, 10-50, 50-100 μm.

The strong correlation between particle size classes greater than 100 μm confirms the increase in coarse particles when the antecedent dry days increase. Additionally, the lack of correlation for the size ranges less than 100 μm suggests relatively unchanged solid loads for this size range. These conclusions mean that changes to the solid composition during the build-up process make the average particle size coarser. This observation further strengthens the description of the physical processes governing build-up as discussed previously. In Section 5.3.4, the dynamic nature of build-up was discussed in detail. The outcomes from this analysis confirmed that the threshold value of particle size that change the re-distribution characteristics is 100 μm. Size classes below this threshold size range would be subject to a high degree of re-distribution.

The correlation of chemical parameters with size classes less than 100 μm points to their high pollutant nature. A threshold value of 100 μm means that, on average, 50% of the solids have the capacity to adsorb other pollutants. It can be noted in Table 5.3 that, on average, 50% of the solids are less than the 100 μm size range. In contrast, Sartor et al. (1974) noted that the major fraction of the pollutants is associated with only 5.9% of particles which were less than 43 μm. The difference could be attributed to land-use and traffic volume as well as the method of investigation. The strong correlation of the size ranges less than 100 μm to TOC and DOC suggested most of these particles are organic. From the data matrix used for the PCA analysis, it was noted that more than 95% of the carbon compounds are organic and more than 80% of the organic carbon is in soluble form. Higher organic carbon content in build-up pollutants were also noted by Roger et al.(1998).

The presence of a high fraction of fine solids (less than 100 μm) suggests a high adsorption capacity in the build-up solids. Since the load of these particle size ranges is subjected to little variability when the antecedent dry days increase, this capacity remains fairly unchanged. The possibility of having high DOC was also noted in the build-up samples. This would lead to enhanced solubility of other pollutants such as hydrocarbons and heavy metals in stormwater. The solubility could be further enhanced due to low pH of build-up solids (Hamilton et al., 1984; Pechacek, 1994; Tai, 1991; Warren et al., 2003).

5.4 Build-up on Roof Surfaces

Two model roof surfaces, one with corrugated steel and another with concrete tiles, were used to collect build-up samples. Further details on the model roof surfaces can be found in Section 3.4. The methodology adopted for sample collection can be found in Section 4.4.2. Samples collected belonged to 1, 2, 3, 7, 14 and 21 antecedent dry day periods. The primary parameters obtained from the sample testing were TS, particle size distribution, pH, EC, TC, TOC and DOC.

5.4.1 Mathematical Replication of Build-up

Research studies relating to pollutant build-up on roof surface are extremely limited. Consequently, the physical processes relating to pollutant build-up on roof surfaces are not widely understood. In past studies, the primary understanding on roof surface build-up was gained by investigating roof surface runoff. For example, Van Metre and Mahler (2003) noted that pollutant concentrations originating from roof surfaces could vary from around 60 to 500 mg/L depending on the surrounding land-use, roof setup, and antecedent dry period. Bannerman et al. (1993) also noted the significant solids concentration that could originate from roof surfaces.

Similar to the data analysis undertaken for road surface build-up, the pollutant loads collected during field investigations were plotted to understand the variability of build-up with antecedent days. Figure 5.7 shows the results derived.

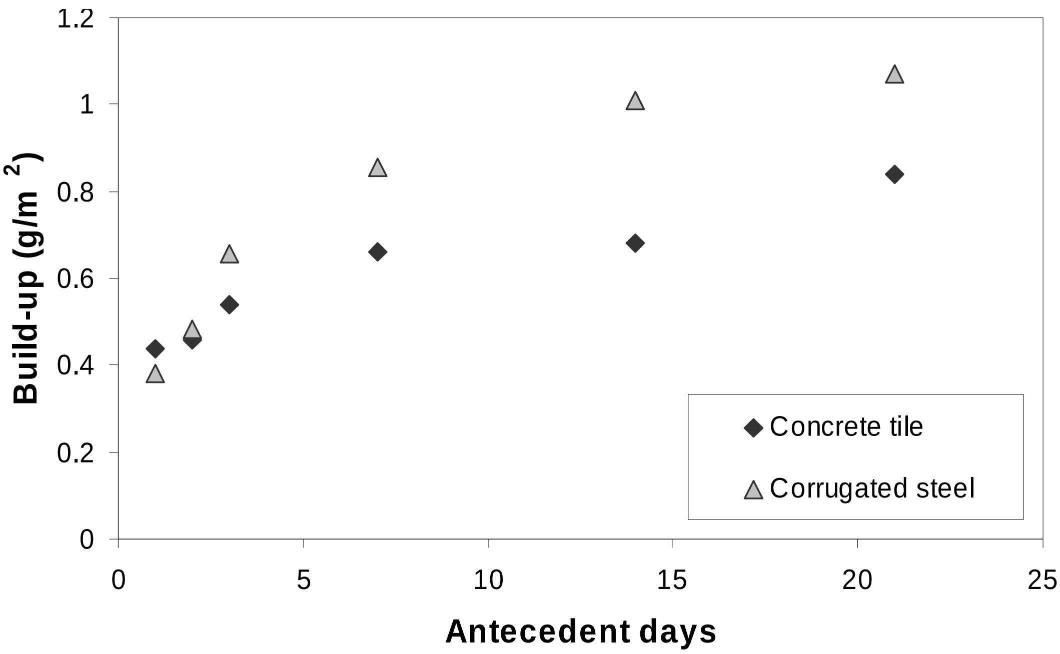


Figure 5.7 – Pollutant build-up on roof surfaces

As illustrated in Figure 5.7, the pollutant build-up on roof surfaces is gradual compared to road surface build-up. However, the variation is similar, having a decreasing rate increasing function. The rate of build-up is high for up to around 7 days, and beyond that, the rate of build-up significantly reduces. First day build-up for both roofing materials was in the range of 0.4 g/m^2, but as the number of days increased, the build-up on corrugated steel exceeded the build-up on concrete tile roofs. However, the deviation between the build-up on the two materials is not significant. The deviation of the 21 day build-up for the two materials was only 0.2 g/m^2, with around 1 and 0.8 g/m^2 build-up on corrugated steel and concrete tile roofs respectively. Therefore, it can be considered that the build-up is common for both roofing materials. The build-up loads obtained from the research study partially agreed with the outcomes of the study by Van Metre and Mahler (2003). They found that the build-up on roof surfaces varies in the range of 0.16 to 1.2 g/m^2 depending on the magnitude of the antecedent dry period. Their investigation was based on 4 m high roof surfaces close to an expressway.

To improve the validity of the proposed translation procedure, the development of a replication equation for roof surface build-up was important. It was decided to develop the replication equation for build-up in the form of a power function similar to Equation 5.1. It was previously discussed that the power function is the most appropriate to replicate build-up. However, the parameters for the power function needed to be specifically derived to suit the build-up on roof surfaces.

Due to significant similarities in build-up, a common parameter set was developed. The analytical methodology used for the development of coefficients was similar to the analytical methodology adopted for the road surface build-up data. The least squares method was adopted and the most suitable values for *a* and *b* were obtained such that the square of deviation between predicted and observed data points was minimal. More details on the method of least squares can be found in Section 3.5.2. The coefficient values obtained were 0.43 and 0.266 for *a* and *b* respectively. Figure 5.8 shows the predictive performances of the developed equation irrespective of the type of roof.

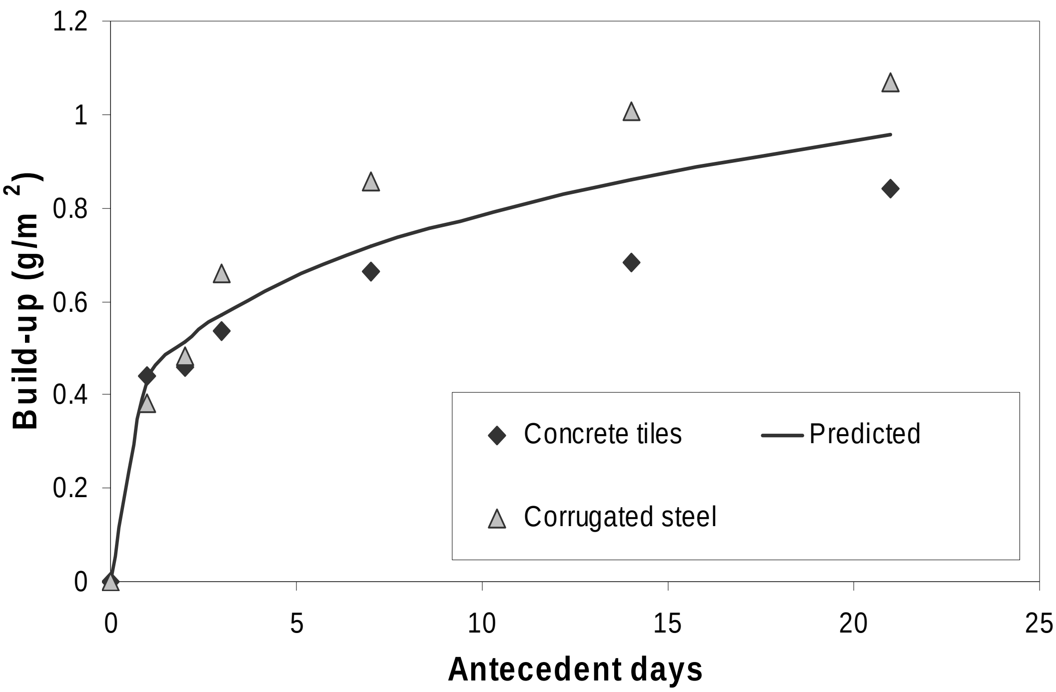


Figure 5.8 – Performances of the replication equations for Build-up on roof surfaces

The build-up replication equation developed for roof surfaces can be used for predictions. There was no requirement to incorporate a pre-existing pollutant load from the last storm event. This was due to the high fraction of wash-off from roof surfaces. Therefore, it can be considered that Equation 5.1 with relevant parameters would replicate the build-up process with sufficient accuracy.

Similar to the procedure adopted for the road surfaces, the validity of the build-up replication equation formulated was tested using the data obtained during the initial pollutant availability sampling. It was noted that the 7 day average build-up observed was 2.5 and 3.9 g/m^2 for concrete tile and corrugated steel surfaces respectively (see Table 6.2). The sampling was done three times and the amounts collected show significant variability. However, the prediction result using Equation 5.1 was 7.1 g/m^2 of pollutants, which is a significant overestimation. This illustrates the high degree of uncertainty associated with roof surface build-up predictions. The uncertainty would be primarily due to climatic factors such as wind.

5.4.2 Particle Size Distribution

Similar to the particle size distribution analysis for road surfaces, the particle size distributions for roof surfaces were analysed primarily by categorising into six size classes. Table 5.4 shows the volumetric percentages for the six classes.

Table 5.4 – Average percentage particle size distribution – for roof surfaces

Size Class (μm)	Solids (Volumetric Percentage)	
	Corrugated steel roof	Concrete tile roof
<10	3.34	3.27
10-50	29.72	22.59
50-100	24.79	24.23
100-200	16.16	19.50
200-400	14.23	16.71
>400	10.10	12.97

As shown in Table 5.4, only fractional differences were noted in particle size distributions between corrugated steel and concrete tile roof surfaces. For both roof surfaces, a higher fraction of the solids was particles less than 100 μm. Particularly for the corrugated steel roof, around 60% of the solids were less than 100 μm. This is comparatively higher than the finer fraction on road surfaces, which was 50%. This could be attributed to the fineness of atmospheric depositions. Furthermore, due to the reduced texture depth and greater slope of roof surfaces, larger particles may not remain on roof surfaces. Similar to analysis for road surface build-up, particle size distributions for roof surface build-up samples were analysed in order to understand the governing processes. Figure 5.9 gives the particle size distributions of build-up samples for the two roofing materials.

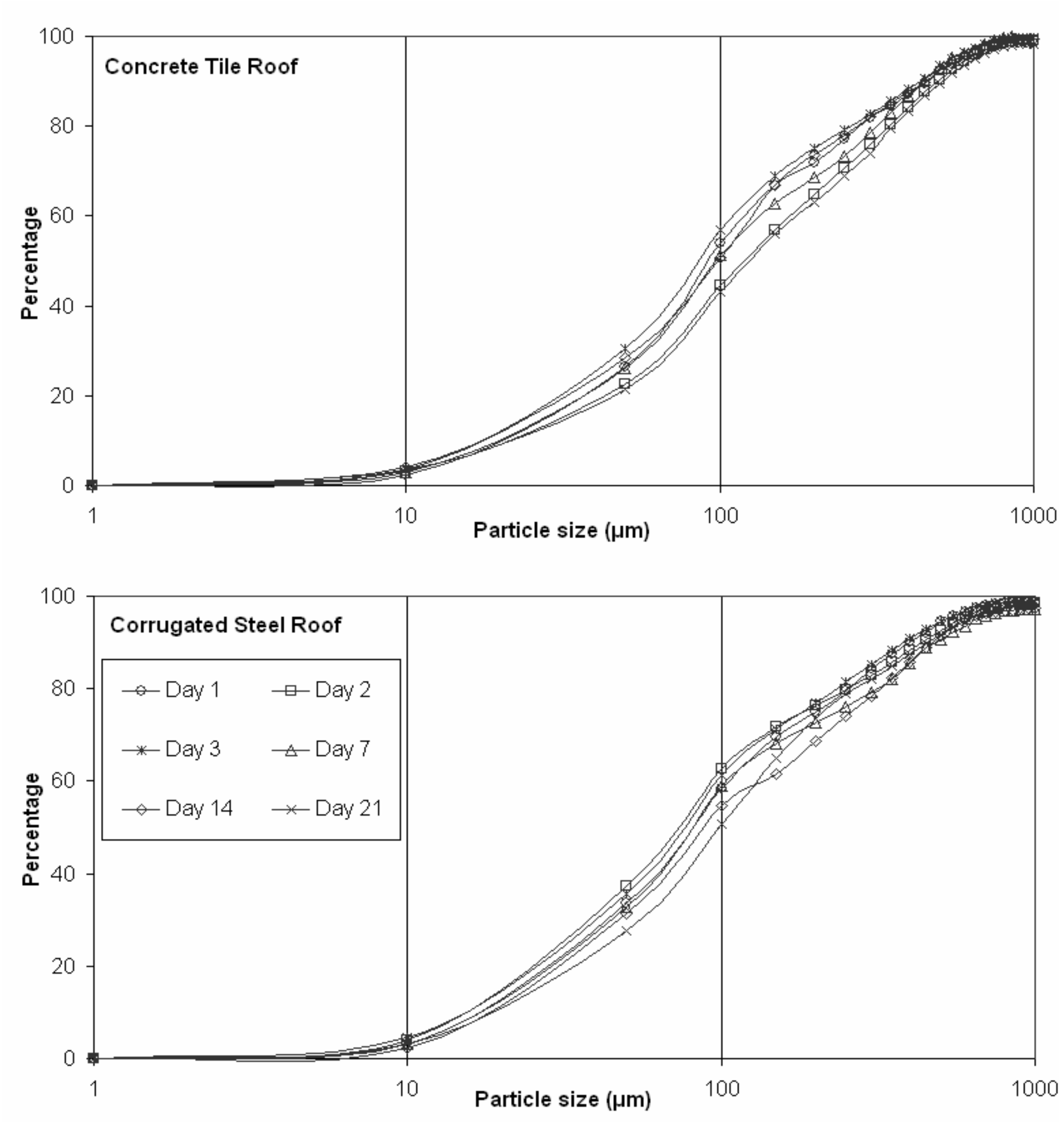


Figure 5.9 - Variation of particle size distribution with antecedent dry days for roof surfaces build-up

As evident in Figure 5.9, it is difficult to identify clear differences in particle size distribution with antecedent dry days for the two roofing materials. The changes in particle size distribution were only marginal for different antecedent dry periods and the differences do not show any clear pattern. This would suggest that only limited re-distribution occurs on roof surfaces and that initially deposited materials remain on the surfaces for a relatively longer period of time when compared to road surfaces. This could be attributed to the reduced influence of vehicular-induced wind turbulence. As noted in Section 2.3.3, the re-distribution of pollutants on road surfaces is primarily caused by the turbulence created by vehicle movements.

5.4.3 Analysis of Physio-chemical Parameters

A principal component analysis of physio-chemical parameters for roof surface build-up samples was undertaken as shown in Figure 5.10. The primary parameters analysed were pH, EC, TC, TOC, DOC and TS categorised into six particle size categories. The particle size categories used were <10, 10 to 50, 50 to 100, 100 to 200, 200 to 400 and >400 μm. The number of samples used for the analysis was 12. The data matrix used for the analysis is shown in Appendix C, Table C.4. The same pre-processing techniques were used as described in Section 5.3.6 to refine the data matrix.

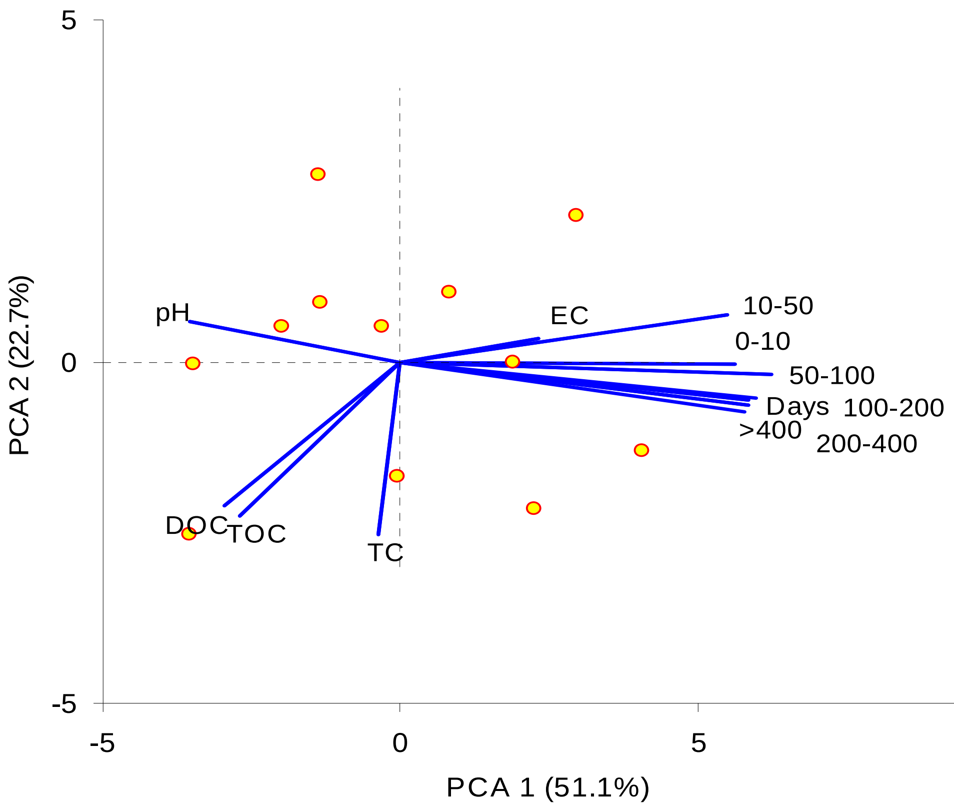


Figure 5.10 - Physio chemical parameters and antecedent dry days for roof surfaces: Biplot of data against the first two principal components

The following conclusions can be derived from the resulting biplot:

1) All particle classes strongly correlate with each other and with the antecedent dry days;
2) EC strongly correlates with all particle size groups whereas pH shows strong negative correlation with all the particle size classes; and
3) TC shows no correlation with the particle size groups whereas TOC and DOC show partial negative correlation.

The strong correlation of all the particle size groups to antecedent dry days indicates the increase in pollutant load with the increase in antecedent dry days. This further strengthens the conclusions relating to the characteristics of build-up as discussed in Section 5.4.2. However, in contrast to road surface build-up where particles less than 100 μm were subjected to a high degree of re-distribution, roof surface build-up does not indicate significant re-distribution of pollutants. This could be primarily due to the high elevation of roofs where vehicular-induced turbulence is limited.

The strong correlation of EC with particle size groups supports the increase in the ionic nature of build-up solids. The strong negative correlation of pH shows the increased of acidic nature of build-up solids. The acidic nature of the atmospheric depositions was confirmed by Novotny et al. (1985). The non correlation of TC and the relatively poor negative correlation of TOC and DOC with particle size groups indicate that there is no variation of these pollutants when the antecedent dry days increase. This was further confirmed by the relatively similar concentrations of TC, TOC and DOC for all the antecedent dry days. It was observed that 95% of the TC is organic and around 80% of the organic carbon is in soluble format. The high fraction of DOC and the high acidic nature of build-up samples confirm the strong capacity to enhance the solubility of other pollutants such as heavy metals and hydrocarbons (Hamilton et al., 1984; Pechacek, 1994; Tai, 1991; Warren et al., 2003).

5.5 Conclusions

The analysis of build-up samples from road and roof surfaces was critical to understand the processes involved in pollutant build-up and related influential parameters.

Build-up on road surfaces

- Rate of pollutant build-up is significantly high during the first two days and reduces as the dry period increases. This is in agreement with the already understood build-up process.
- It can be hypothesised that build-up load approaches a constant value over time.
- Significant variation in terms of build-up load was detected between the three road sites. This could be primarily due to the variation in urban-form and the population density.
- Pollutant build-up on road surfaces can be replicated by a power function in the form of:

  $$B = aD^b$$

  Where,

  B = Build-up load on road surface (g/m^2);

  D = Antecedent dry days; and

  a and *b* = Build-up coefficients.
- Though the rate of increase of build-up load reduces after about 21 days, the dynamic re-distribution of fine particles continues.
- Reduced re-distribution of larger particles and constant accumulation result in changes to the solids composition of build-up pollutants.
- The fraction of fine particles (<100 μm) dominates on road surfaces. The average road surface particle size composition demonstrates unique characteristics for residential catchments.
- The behaviour of fine particle (<100 μm) was completely different to that of coarse particles in terms of associated organic content. The fine particles were associated with a greater amount of organic matter compared to coarser particles.
- A reduced fraction of inorganic carbon content was detected on road surfaces compared to organic carbon. Furthermore, a significantly high fraction of organic compounds present in road surface pollutants were in soluble form.

Build-up on roof surfaces

- The rate of build-up is significantly high for up to around seven days and then reduces after that as the antecedent dry period progresses.
- Similar to build-up on road surfaces, it can be hypothesised that roof surface build-up approaches a constant value as the antecedent dry period progresses.
- Build-up on roof surfaces can be replicated by a power function similar to that used for road surfaces. However, a different set of build-up coefficients needs to be used.
- On average, 60% of the solids deposited on roof surfaces were less than 100 μm size.
- Only a small variation was detected in the particle size distribution of particulates belonging to different antecedent dry periods. This suggested that on roof surfaces there is only limited re-distribution with time.
- A significantly high amount of organic compounds was detected on roof surfaces. Most of these compounds were in soluble form.

Chapter 6 - Analysis of Pollutant Wash-off

6.1 Background

In the context of urban water quality research, an in-depth understanding of the two main pollutant processes, build-up and wash-off, is important. Due to the site specific nature and variability with a range of factors, extensive investigations are necessary to understand these processes. Chapter 5 discussed the outcomes of the in-depth investigation into pollutant build-up for residential road and roof surfaces. This chapter presents the outcomes of in-depth investigation into pollutant wash-off from road and roof surfaces.

Pollutant wash-off is a complex process that varies with a range of rainfall, runoff, and catchment variables. Vaze and Chiew (2002) and Mackay (1999) noted that wash-off is influenced by rainfall and runoff variables namely, rainfall intensity, duration, runoff volume and runoff rate. However, as explained by Chiew and McMahon (1999), it is difficult to discern the degree of influence of these variables on wash-off. Inter-correlation of these variables is the primary factor which causes such difficulty. Therefore, extra effort was made during the data analysis to understand the role of each variable in wash-off. Other than rainfall and runoff parameters, wash-off is influenced by the amount and characteristics of pollutants available on catchment surfaces, which in turn are a function of build-up during the antecedent dry period (Duncan, 1995). Representative pollutant samples were collected before the wash-off investigations and tested for physio-chemical parameters to understand the influence exerted on pollutant wash-off. Furthermore, Herngren et al. (2005a) noted that wash-off may be influenced by the characteristics of impervious surfaces. They observed variable characteristics of wash-off for road surfaces with road surface texture depth and slope. Therefore, the influence of these two primary road surface characteristic namely, texture depth and slope was also determined.

The highly variable nature of wash-off with a range of parameters and unpredictable occurrence of natural events can increase the complexity of the experimental design.

This was the main reason for using simulated rainfall for wash-off investigations. The use of simulated rainfall provided improved control over rainfall and runoff parameters. Furthermore, it was possible to generate a large amount of data during a short period of time (Herngren et al., 2005b). Detailed discussion on the use of simulated rainfall can be found in Section 3.3.

This chapter presents the analytical outcomes of the pollutant wash-off investigations described in Section 4.3. The investigations were undertaken on three road sites, namely, Gumbeel Court, Lauder Court and Piccadilly Place, and two roof surface types, namely, corrugated steel and concrete tile. The wash-off samples collected during investigations were tested for a range of water quality parameters as discussed in Section 4.6. Wash-off was separately analysed for road and roof surfaces. During the analysis, the primary focus was to understand the quantitative wash-off process, variation of particulate composition of washed-off pollutants and the variation of quality parameters. Prior to the analysis of wash-off data, analysis was performed to understand the primary characteristics of initially available pollutants which were collected before each field test.

6.2 Initially Available Pollutants

Duncan (1995) noted that the pollutant load originating from catchments is directly influenced by the amount of initially available pollutants on catchment surfaces. He further suggested that the initially available pollutants may be influenced by the antecedent dry period. This concept was confirmed by Sartor et al. (1974) noting that wash-off is highly influenced by the characteristics of initially available pollutants particularly the particle size distribution. They proposed a mathematical equation for the replication of pollutant wash-off and noted that the validity of the equation is improved if different sets of parameters were developed for different particle size ranges.

Initially available pollutant samples were collected prior to wash-off investigations from both road and roof surfaces. Road surface samples were collected from a 3 m^2 plot area at each site using the vacuum system. Roof surface samples were collected from a 1.5 m^2 area using a smooth brush. Further details on sample collection and testing can be found in Section 4.3 and Section 4.6.

6.2.1 Road Surfaces

A Pollutant Load

Table 6.1 – Amounts of initially available pollutants in road sites

Site	Weight of Particles (g/m^2)	Antecedent dry days
Gumbeel Court	10.89	77
Lauder Court	3.11	27
Piccadilly Place	3.54	36

The highest amount of initial pollutant availability was noted at the Gumbeel Court road site (see Table 6.1). The amount was almost three times higher than that from the Lauder Court and Piccadilly Place road sites. This is quite understandable as the sample from Gumbeel Court is the result of 77 antecedent dry days which is the highest among the three sites. Furthermore, Gumbeel Court is situated within a duplex townhouse region where the population density is comparatively high. These could be the primary reasons for having a high amount of particulate pollutants. The amount of pollutants noted in both the Lauder Court and Piccadilly Place sites was similar. This could be primarily attributed to the similar build-up characteristics in the two sites as noted in Section 5.3.1. The reduced rate of build-up for higher antecedent dry days would be the reason for similar build-up in the Lauder Court and Piccadilly Place sites, though the antecedent dry days are different. However, the amount of pollutants collected during the initial sampling was less compared to the samples collected by numerous other research studies. Deletic and Orr (2005) noted 5 to 25 g/m^2 of pollutants on residential road surfaces while Vaze and Chiew (2002) noted that there can be 8 to 40 g/m^2 of road surface pollutants depending on the site condition. Alhough different to the previous studies, the amount of pollutants noted is consistent with those amounts collected during the pollutant build-up study as discussed in Section 5.3.2.

B Particle Size Distribution

Each sample collected during the initially available pollutant investigation at the three road sites was tested for particle size distribution. This was undertaken to understand the composition of pollutants that could influence the characteristics of wash-off. Figure 6.1 shows the cumulative distribution of volumetric particle sizes for the samples collected. The particle size distribution curves were plotted for comparison along with the average particle size distribution curves for build-up samples that are discussed in Section 5.3.5. Comparisons of particle size distributions for each road site are given in Appendix D, Figures D.1 to D.3.

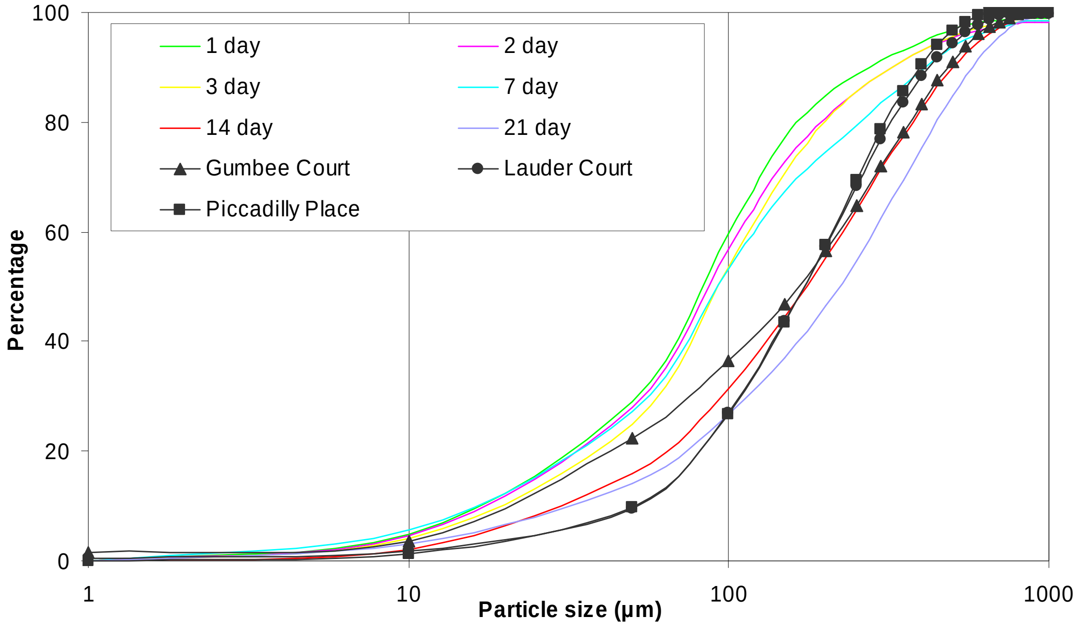


Figure 6.1 – Cumulative particle size distributions of initially available pollutant samples from road surfaces

As seen in Figure 6.1 and Appendix D, Figures D.1 to D.3, the particle size distribution of initially available pollutant samples was mostly within the size distribution envelope observed during pollutant build-up investigations. Furthermore, the particle size distribution curves for initially available pollutants are closely comparable with the 14 and 21 antecedent dry days particle size distribution curves which contain a high fraction of coarse particles. As the antecedent dry days for initially available pollutant samples were 77, 27 and 36 days for Gumbeel Court, Lauder Court and Piccadilly Place road sites respectively, it can be considered that the particle size composition of particulates is in the expected range. Furthermore, as seen in Figure 6.1, the distribution curve for the Gumbeel Court site is located to the right of the curves for Lauder Court and Piccadilly Place road sites, particularly for the coarser particle size ranges. This indicates a higher fraction of coarser particles in Gumbeel Court site compared to the other two sites. This further strengthens the argument developed regarding the change in particle size distribution of build-up samples when the antecedent dry days increase. As explained in Section 5.3.5, the composition of pollutants is subjected to continuous change with an increasing fraction of coarse particles when the antecedent dry days increase.

Figure 6.1 and Appendix D, Figures D.1 to D.3, further show that only around 30% of the total initially available pollutants were smaller than 100 μm particle size. As discussed in Section 5.3.6, this is the size range that has the capacity to adsorb other pollutants such as heavy metals and hydrocarbons. On the other hand, 40% of the particulate pollutants were larger than 200 μm, where very limited pollutant adsorption capacity exists. The samples collected during this investigation show significant deviations from the samples collected by Herngren et al. (2005). They have noted up to 90% of the solid particles being less than the 150 μm size. However, the antecedent dry periods for those samples were 1, 2 and 7 days, which is comparatively low when compared to this investigation.

6.2.2 Roof Surfaces

A Pollutant Load

Four samples of initially available pollutants were collected from each roof type prior to each rainfall simulation. The rainfall simulations were for 20, 40, 86 and 115 mm/hr intensities. Table 6.2 shows the average pollutant loads collected from each roof type. The collection of samples was generally for a seven day antecedent dry period apart from the sample collected prior to simulation of the 20 mm/hr intensity which was a three day period.

Table 6.2 – Amount of initially available pollutants in road sites

Site	Weight of Particles (g/m^2)	Antecedent dry days
Steel roof	0.39	3 and 7
Concrete roof	0.25	3 and 7

The average initial load of pollutants collected from the corrugated steel roof surface was high compared to the concrete tile roof surface. This was in agreement with the build-up observations noted in Section 5.4.1. It was further observed during sample collection that pollutants are strongly bound to the steel roof surface when compared to the concrete roof surface. This could be due to properties associated with the paints used for the different roofing products. The paint used in the corrugated steel roof could be developing chemical or electrostatic bonds with the pollutant particles, leading to a higher build-up load. However, it was not possible to confirm this hypothesis conclusively.

The amounts of pollutants collected during initial pollutant investigations on roof surfaces were less when compared to the amounts collected during build-up investigations. The pollutant amounts collected during build-up investigation for seven antecedent dry days were 0.86 and 0.66 g/m^2 for the corrugated steel and concrete tile roof surface respectively (see Figure 5.7). During sampling for initially available pollutants, 0.39 and 0.25 g/m^2 amounts were collected from the corresponding roof surfaces. Even the four samples collected prior to each rainfall simulation showed significant variation to each other with a CV of 11.9% and 13.6% for corrugated steel and concrete tile roofs respectively. The amounts of pollutants collected during investigations are shown in Appendix D, Table D.1. It is hypothesised that build-up on roof surfaces is subjected to high variation due to climatic factors when compared to road surfaces. The high degree of uncertainty involved in roof surface build-up was previously noted by Thomas and Greene (1993) and Van Metre and Mahler (2003).

B Particle Size Distribution

As samples were collected before each rainfall simulation, four data sets of particle size distributions were available for analysis. Figure 6.2 shows the particle size distribution curves for the concrete tile and corrugated steel roofs separately. The particle size distributions of build-up samples are also shown.

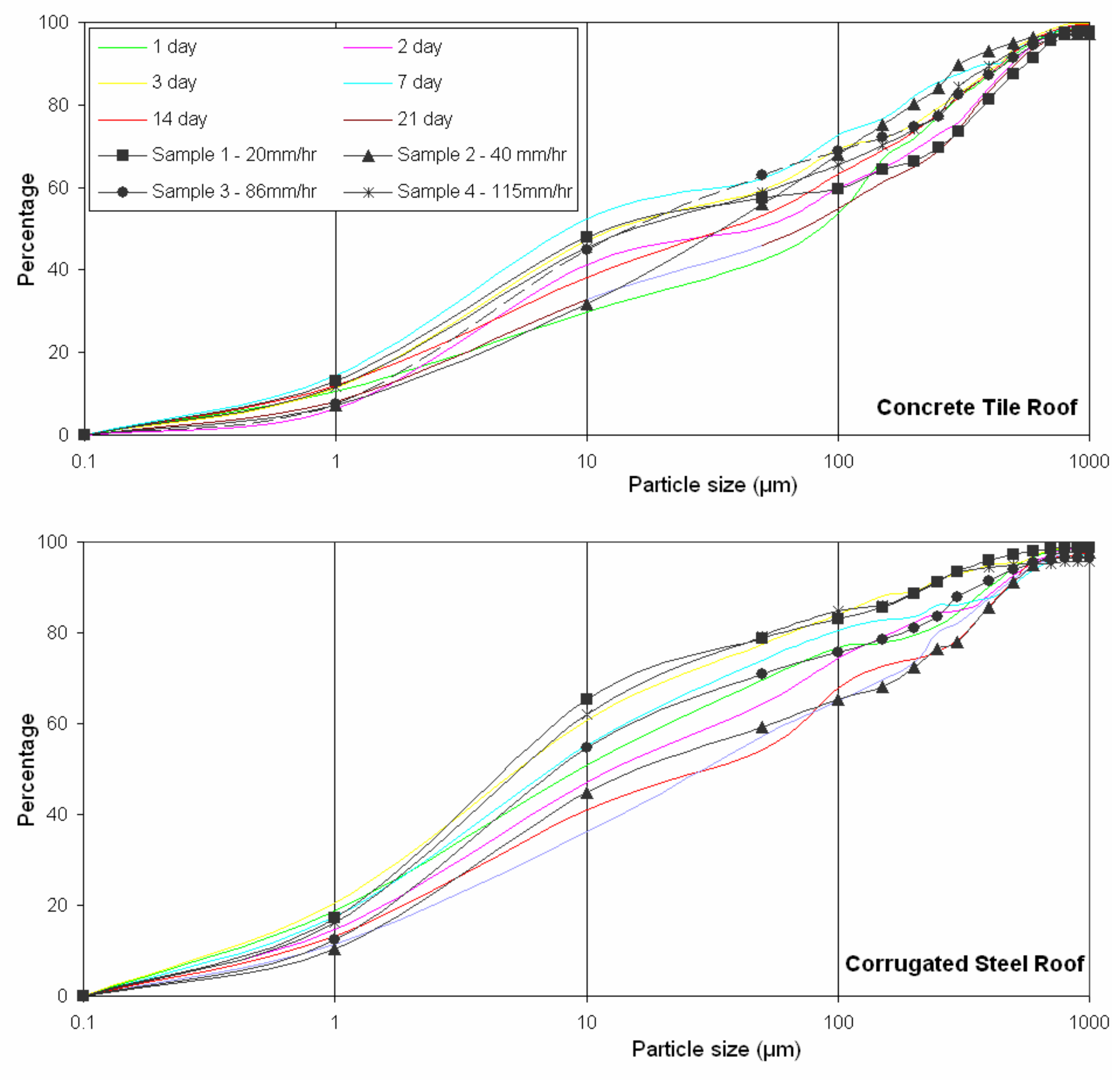


Figure 6.2 – Cumulative particle size distributions of initially available pollutant samples

As evident in Figure 6.2, the particle size distributions for samples collected from both concrete and steel roof surfaces are similar. For both surfaces, samples show fairly uniform distribution with dominant finer particles size ranges. On average, 75% of the total solids from the corrugated steel roof and 67% of the total solids from the concrete tile roof are less than 100 µm. However, the observed particle size distribution is significantly coarser when compared to the results reported by Van Metre and Mahler (2003). They noted a much smaller fraction of solids from roof surfaces which were larger than 63 µm. Anthropogenic activities and climatic conditions in the area adjacent to the study site could be a factor for such deviation in particle size. However, the fact that the size distributions for all the samples collected are within the particle size envelope generated during build-up investigations confirmed the consistency of the investigations.

6.3 Data and Variables

Pollutant wash-off was investigated using simulated rainfall. As noted in Sections 4.4.1 and 4.4.2, six rainfall intensities on road surfaces and four intensities on roof surfaces were simulated. The resulting runoff totalled 25 samples per road site and 27 samples per roof surface. These samples were tested for a range of water quality parameters as discussed in Section 4.6. The parameters included TSS, TDS, particle size distribution, pH, EC, TC, TOC and DOC.

6.3.1 Data Pre-processing

Total solids (TS) concentration was calculated by combining TSS and TDS. The TS concentration was multiplied by the runoff volume contained in each container in order to calculate the total weight of solids washed-off during a specific simulation event. The cumulative wash-off weight was calculated by adding the solids weight to the corresponding duration components. For example, in the case of the 20mm/hr intensity and 20 min duration event, TS weight was calculated by adding the weights belonging to the 0-10 min duration and the 10-20 min duration.

A Malvern Mastersizer was used to determining the particle size distribution of the suspended solids. The instrument software provided the percentage particle size distribution curve and it was possible to disaggregate the sample into any given size class at a later stage. However, the percentages are in volumetric form. For analytical purposes, it was converted to weight distribution assuming that all particles have the same density. It is understood that there can be particles such as tyre wear having relatively less density compared to road surface wear. Pre-processing of the other quality parameters was done in an exactly similar way to the pre-processing of build-up samples noted in Section 5.2.

6.3.2 Selection of Rainfall and Runoff Variables

The primary rainfall and runoff variables that influence pollutant wash-off are rainfall intensity, rainfall duration and runoff volume. Contradictory reporting has been noted on the degree of influence that these variables have on pollutant wash-off (Chiew and McMahon, 1999; Chui, 1997; Mackay, 1999). As explained by Chiew and McMahon (1999), these variables correlate with each other and therefore, it is difficult to discern the degree of influence. From an analytical point of view, it is difficult to analyse data with a range of correlating variables. It is important to eliminate variables that provide little information from the analysis.

Selection of appropriate variables was undertaken using a range of plotted graphs of TS with each variable and combination of variables. It was observed that very little information can be gained by relating wash-off to runoff volume. Therefore, it was decided to select rainfall intensity and duration as primary variables. Further analysis of wash-off was based on these two variables. The same two variables were also used by Sartor et al. (1974) to describe the wash-off process.

6.4 Analysis of Wash-off from Road Surfaces

The six rainfall intensities simulated on road surfaces were 20, 40, 65, 86, 115 and 133 mm/hr. Five runoff samples from 133 mm/hr rainfall intensity and four samples from each of the other intensities were collected. The rainfall durations from which these samples were collected are shown in Table 4.3. Further details on sample collection and testing were provided in Sections 4.4.1 and 4.6.

6.4.1 Variation of Wash-off with Influential Parameters

The analysis of wash-off data was carried out for the three road sites separately. Figure 6.3 shows the variations of wash-off with rainfall intensity and duration for the three sites. As evident in Figure 6.3, wash-off pollutant load is significantly influenced by initial pollutant availability on the road surfaces. The maximum pollutant load washed from the Gumbeel Court road site was around 29 g whereas it was 7.3 g and 9.2 g at Lauder Court and Piccadilly Place sites respectively. This was for the 133 mm/hr rainfall intensity and for 20 min duration. Similar comparisons can also be made for the other rainfall events. The relatively higher pollutant load washed-off from Gumbeel Court could be mainly attributed to the higher initial pollutant availability which was 32.7 g. It was found that only 9.3 and 10.6 g of pollutants were built-up at Lauder Court and Piccadilly Place sites respectively. However, the pattern of wash-off variations shows significant similarities among the three sites. For example, the ratio of the maximum wash-off to initial pollutant availability for the three sites was 0.9, 0.75 and 0.85. This confirms that irrespective of the amount of initial pollutant availability, similar fractions of pollutants are washed-off for the 133 mm/hr and 20 min duration event. This fraction was also consistently similar for other events. This indicated that though wash-off load is significantly influenced by initial pollutant availability, the influence it exerts on the wash-off process itself is not significant.

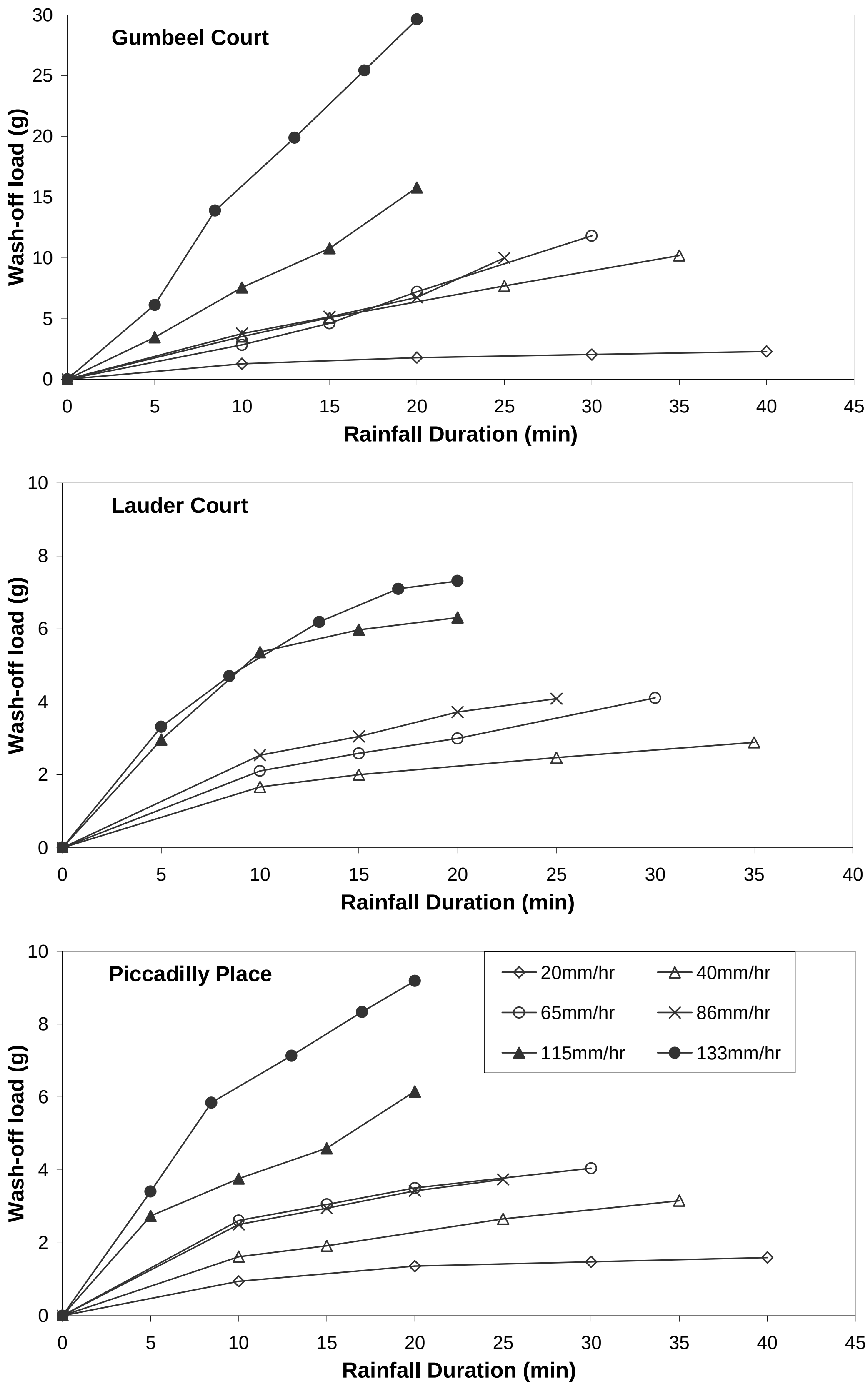


Figure 6.3 – Variation of wash-off with rainfall intensity and duration

In order to eliminate the influence of initial pollutant availability on the wash-off process, a parameter defined as 'fraction wash-off' was calculated. Fraction wash-off for a particular event is the ratio of washed-off pollutant load to the initially available load. In this way, it was possible to compare the wash-off of pollutants from the three road sites. Figure 6.4 shows the variation of fraction wash-off with rainfall intensity and duration for all three sites. Appendix D, Figure D.4 shows the variation of fraction wash-off with rainfall intensity and duration for the individual sites. Appendix D, Table D.2 shows the observed data for pollutant loads and calculated fraction wash-off for each site.

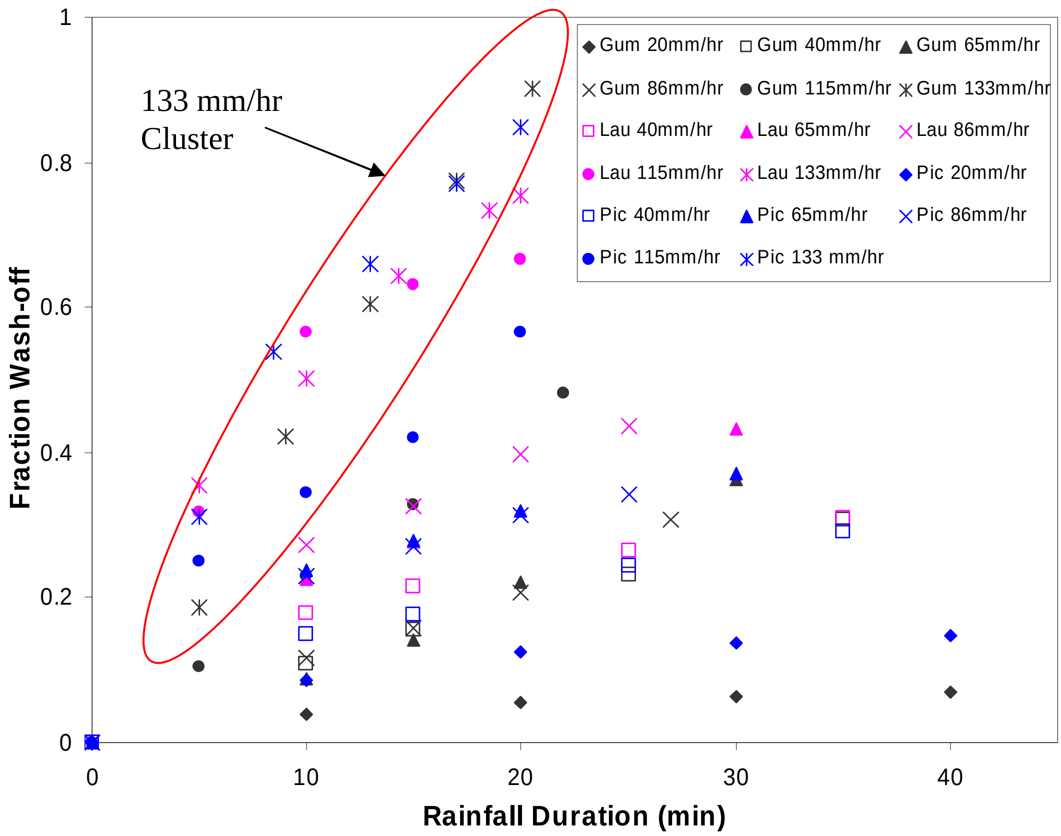


Figure 6.4– Variation of fraction wash-off with rainfall intensity and duration

From Figure 6.4 and Appendix D, Figure D.4, two main conclusions can be derived. Firstly, the largest fraction wash-off is in the range of 0.75 to 0.9 and these values belong to the 133 mm/hr intensity rainfall simulated for 20 min duration. In comparison to rain events in South-East Queensland, such an event is in the range of a ten year ARI event. This means that most of the general storm events are not capable of washing-off all the pollutants from road surfaces. Similar conclusions were noted by past researchers. Malmquist (1978) repeatedly simulated rain events on an urban road section. The resulting wash-off load decreased slowly in each simulation and multiple numbers of events were needed for significant reduction in wash-off load. Vaze and Chiew (2002) vacuumed road surfaces immediately after rain events and noted an appreciable fraction of pollutants still remaining on the surface.

Secondly, the variation of fraction wash-off for different road sites is closely related. For the 20 mm/hr rainfall intensity, fraction wash-off increases gradually up to around 0.2 as the duration increases. Similar variation is evident for other intensities. Furthermore, the gradient of the variation increases when the rainfall intensity increases. As seen in Figure 6.4, the data points belonging to each rainfall intensity are clustered into regions suggesting similar behaviour of wash-off for all three sites. As an example, the cluster for 133 mm/hr intensity is shown in Figure 6.4. Therefore, it can be concluded that wash-off is a common process and relatively independent from initial pollutant availability.

6.4.2 Mathematical Replication of Pollutant Wash-off

It is commonly accepted that wash-off from road surfaces can be replicated by an exponential equation. However, different forms of exponential equations have been suggested (Chiew et al., 1997; Sartor et al., 1974). The use of different rainfall and runoff parameters as exponents of the wash-off exponential equation is the most common difference among various equations that have been proposed. In some cases, runoff volume is used as the exponent and in some other cases the runoff rate is used (Chiew et al., 1997). However, it was concluded (see Section 6.3.2) from this research that wash-off is more closely related to rainfall intensity. Therefore, the equation proposed by Sartor et al. (1974) was selected as the conceptual basis for the replication of wash-off. The format of the selected equation is:

$$W = W_0(1 - e^{-kIt}) \qquad \text{Equation 6.1}$$

Where:

W Weight of the material mobilised after time t;

W_0 Initial weight of the material on the surface;

I Rainfall intensity; and

k Wash-off coefficient.

(Sartor et al., 1974)

Different derivations of this equation have been used in various stormwater quality models. For example, the US EPA's Stormwater Management Model (SWMM) and US Army Corps STORM model use similar exponential equations to replicate pollutant wash-off (Huber and Dickinson, 1988; USACE, 1977)

In this study the original exponential equation (Equation 6.1) proposed by Sartor et al. (1974) was tested in order to replicate the observed wash-off patterns. The equation was re-written in order to define fraction wash-off as:

$$Fw = \frac{W}{W_0} = (1 - e^{-kIt}) \qquad \text{Equation 6.2}$$

Where:

Fw Fraction wash-off.

The predictive capability of Equation 6.2 was tested by comparing observed data with the calculated fraction wash-off for corresponding rainfall intensities and durations. The comparisons were done separately for the three sites. In each case, the wash-off coefficient 'k' was estimated using the method of least squares so that the deviations of predicted values from the observed values were minimal. More details on the method of least squares was provided in Section 3.5.2. Appendix D, Figure D.5 shows the performance of optimum k generated for Equation 6.2. Analysis of the predictive capability of the equation was performed by calculating the mean and coefficient of variation (CV). The mean was calculated for the ratio between observed and predicted values. This makes the expected mean equal to one. The CV was calculated by dividing the standard deviation by the expected mean. More details on mean and CV were provided in Section 3.5.1. The means and CV obtained for the three sites are given in Table 6.3.

Table 6.3 – Predictive capability of Equation 2

Site	Mean	Coefficient of Variation (%)
Gumbeel Court	1.41	53.0
Lauder Court	1.04	22.7
Piccadilly Place	1.09	28.4

As evident from Appendix D, Figure D.5, predictions using Equation 6.2 do not provide adequate accuracy. As shown in Table 6.3, though the mean is close to one, which is the expected value, higher percentages of CV suggested a scattering of observed data with respect to predictions using Equation 6.2. Among the three road sites, the predictions were least accurate for the Gumbeel Court site, where the mean is 1.41 and CV is 53%.

It is evident from Figure 6.4 and Appendix D, Figure D.4, that the fraction wash-off approaches a finite value which is lower than one and this value varies with the rainfall intensity. This phenomenon was observed during the rainfall simulation. The latter part of most of the less intense rainfall events producesd relatively cleaner runoff. A similar observation was also reported by Herngren et al. (2005a). This suggested that a rainfall event has the capacity to mobilise only a fraction of particulate pollutants on the road surface and once it reaches that capacity relatively clean runoff results, even though a significant fraction of pollutants is still available for removal. The equation proposed by Sartor et al. (1974) is based on the assumption that every storm event has the capacity to remove all the available pollutants from a surface if it were to continue for an adequate period of time. The findings from this study confirmed the need to modify the wash-off equation.

The exponential pollutant wash-off equation was modified by introducing the ‘capacity factor’ (C_F) and can be written as:

$$Fw = \frac{W}{W_0} = C_F(1 - e^{-kIt}) \qquad \text{Equation 6.3}$$

Where:

C_F Capacity factor.

C_F indicates the rainfall event's capacity to mobilise pollutants. C_F will have a value ranging from 0 to 1 primarily depending on the rainfall intensity. However, other factors such as road surface condition, characteristics of the available pollutants and slope of the road may also have an influence on C_F.

6.4.3 Estimation of Wash-off Parameters

To use the modified wash-off equation (Equation 6.3), the parameters k and C_F must be estimated. The wash-off coefficient k is an empirical parameter with units (mm^{-1}) with no physical meaning. Water quality models such as SWMM use a constant value for k. However, there is evidence to claim that the k is site specific (Millar, 1999). The value k may vary with the pollutant type, rainfall intensity, catchment area and catchment slope (Alley 1981; Alley and Smith, 1981; Millar, 1999). However, the use of a constant value for k will reduce the complexity of the wash-off equation. It has been noted by Huber and Dickinson (1988) that a constant value is used in the SWMM model and it performs relatively well in estimation.

Estimation of wash-off parameters was done in three steps:

1) The approximate values were first estimated for C_F by plotting F_W versus rainfall duration. The curves were drawn freehand in order to obtain the best visual variation. Appendix D, Figure D.6 shows the plotted variations and estimated C_F values.
2) The best possible values for C_F and k were determined using the method of least squares. In this case, estimates obtained using plots were used as initial values.
3) A single value was determined for k so that the square of difference between estimated and observed values of F_W for one site is a minimum. Figure 6.5 illustrates the performance of the parameters developed for Equation 6.3, and Table 6.4 gives the C_F and k values determined for the different sites.

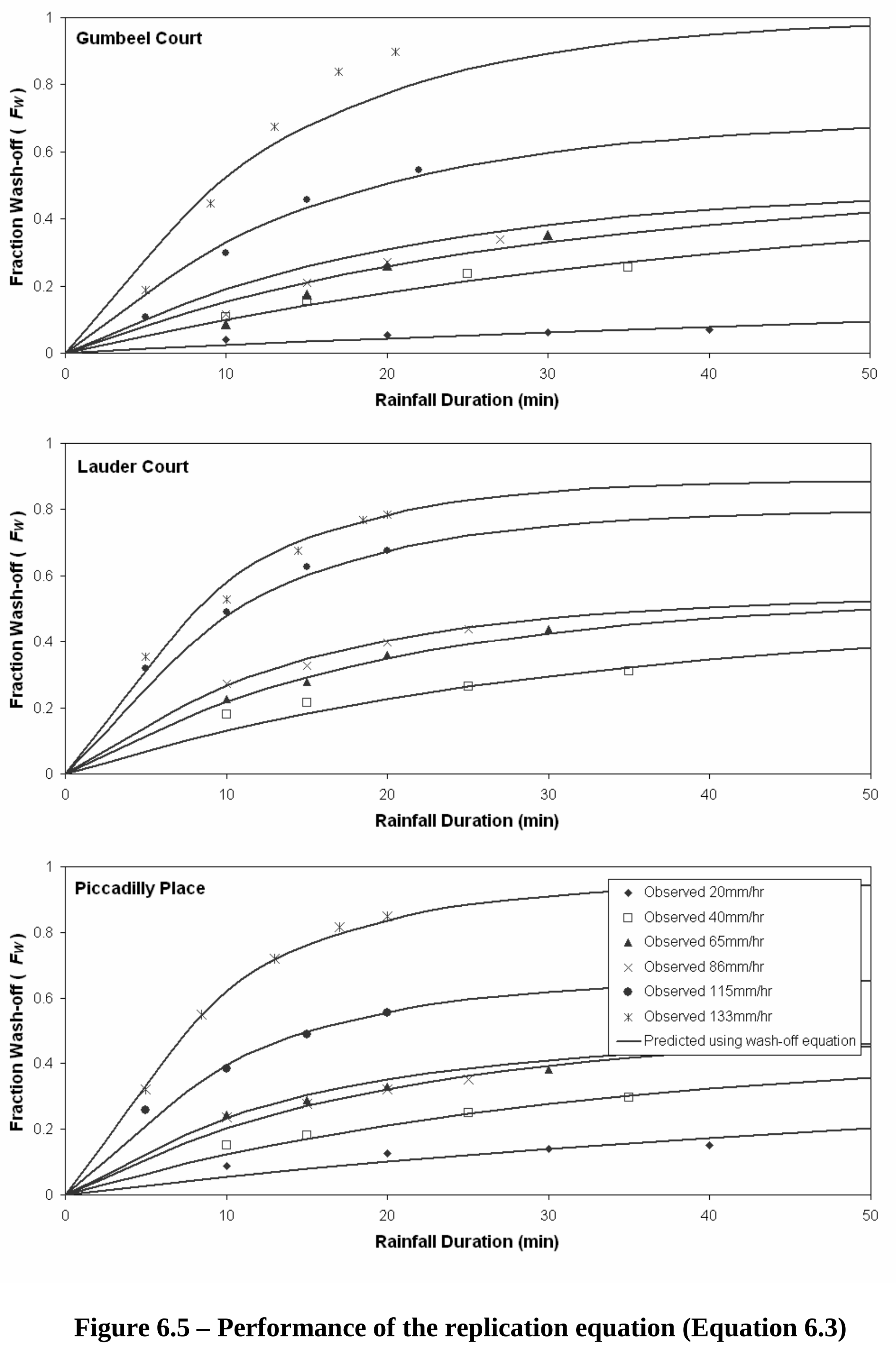


Figure 6.5 – Performance of the replication equation (Equation 6.3)

Table 6.4 - Estimated values for C_F and k

Site	Wash-off Coefficient *k*	Capacity Factor C_F					
		20 mm/hr	40 mm/hr	65 mm/hr	86 mm/hr	115 mm/hr	133 mm/hr
Gumbeel Court	5.6×10^{-4}	0.20	0.48	0.50	0.50	0.73	1.00
Lauder Court	8.0×10^{-4}	-	0.48	0.54	0.54	0.80	0.89
Piccadilly Place	8.0×10^{-4}	0.30	0.45	0.49	0.49	0.66	0.94

The validity of Equation 6.3 with estimated parameters of C_F and *k* was evaluated by analysing the mean and CV. The combination of mean and CV provides complete information on the validity of the predicted equation. The mean was calculated for the resultant of the predicted values divided by the observed value for each data point. CV was calculated by dividing the standard deviation from the expected return which was one. The mean and CV for each site are shown in Table 6.5.

Table 6.5 – Validity of replication of pollutant wash-off using parameters in Table 6.4

Parameter	Gumbeel Court	Lauder Court	Piccadilly Place
Mean	1.12	0.98	0.98
CV	27%	7%	12%

According to the results shown in Table 6.5, all three mean values are close to one and therefore, it can be argued that the overall performance of the prediction equation is satisfactory. However, the CV values indicate that there is a certain degree of error in estimating each data point. The performance of the wash-off equation for the Gumbeel Court data is poor whereas the performance of the equation for Lauder Court and Piccadilly Place are satisfactory. The variation between observed data and predicted data could be due to reasons such as the build-up data being non-representative for the site and errors in the calculation of the equation parameters. The Gumbeel Court site had a relatively high amount of pollutants. As such there can be a greater possibility of selecting a non-representative sample.

Considering the above, the most appropriate values for k would be the values obtained for the Lauder Court and Piccadilly Place road sites. The constant k value of 8.0×10^{-4} is proposed for use in the prediction equation. However, selection of a common value for k altered the performance evaluating parameters: the mean and CV as described in Table 6.5. A new set of performance evaluation parameters was calculated for the common parameter set as shown in Table 6.6. Common values for C_F were obtained so that the mean square of error for the complete set of data becomes minimal. The selected C_F values for different intensities were 0.3, 0.5, 0.5, 0.5, 0.75, 0.92 for 20, 40, 65, 86, 115 and 133 mm/hr rainfall events respectively. More discussion on the selection of C_F is included in Section 6.4.4.

Table 6.6 – Validity of replication of pollutant wash-off equation with the common set of parameters

Parameter	Gumbeel Court	Lauder Court	Piccadilly Place
Mean	1.4	0.95	1.02
CV	29%	9%	13%

As shown in Table 6.6, the use of a common set of parameters for wash-off altered the performance evaluating parameters. The highest change occurred for the Gumbeel Court site. This could be due to the increase of k from 5.6×10^{-4} to 8.0×10^{-4}. However, little change was noted for both the Lauder Court and Piccadilly Place sites. Furthermore, for those two sites, both the mean and CV is in a satisfactory range. Therefore, it can be considered that the common set of parameters performs adequately in replicating observed wash-off.

However, the variability in predicting observed data points in the Gumbeel Court site indicates the uncertainty involved in Equation 6.3 and of using a common set of parameters. Therefore, care should be taken when using these values particularly when the initial pollutant availability is comparatively high. Apart from the variation in initial pollutant availability, the Gumbeel Court road site was relatively flatter and rougher in texture depth. These factors could play a role in assigning factors for Equation 6.3.

6.4.4 Understanding the Wash-off Process

Apart from the mathematical replicating equation, understanding the mechanism of pollutant wash-off is important. Figure 6.6 shows the variation of C_F with rainfall intensity. The graph primarily consists of three parts. For an intensity less than about 40 mm/hr, C_F increases linearly to almost 0.5. It is hypothesised that this is due to the change in kinetic energy for different rainfall intensities. According to Rosewell (1986), the kinetic energy of sub-tropical rain events increases from 0 to around 25 J/m^2/mm for intensities from 0 to about 40 mm/hr, and beyond that, it is relatively constant at about 25 J/m^2/mm. The kinetic energy value noted by Rosewell (1986) for a 20 mm/hr intensity storm was able to be simulated using a flyscreen mesh as an energy dissipater. It is hypothesised that C_F varies linearly with kinetic energy within the 0 to 40 mm/hr intensity range.

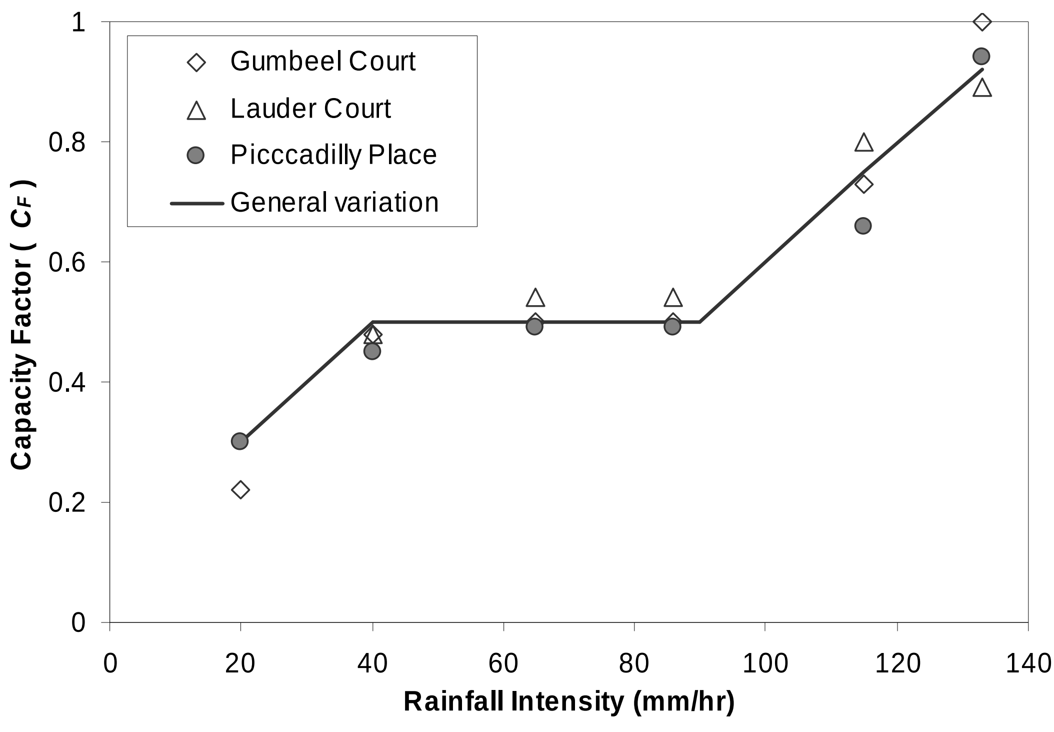


Figure 6.6 - Variation of C_F with rainfall intensity

For rainfall intensities ranging from 40 mm/hr to around 90 mm/hr, C_F has a relatively constant value of 0.5. This indicates that the rainfall intensities in this range have the capability to mobilise only around 50% of the pollutants available. It was observed that even more finer particles are washed-off during these rain events when compared to particle size distributions of initially available samples. Therefore, there is greater possibility of wash-off of most of the finer and lighter particle ranges during these events. It could be the case that these rainfall intensities are not capable of creating adequate turbulence to mobilise heavier and larger particles due to sheet flow on the surface. However, the upper limit of the constant C_F (90 mm/hr) could change with the texture depth of the road and particle size distribution of the pollutants available. Rainfall events with intensity of more than 90 mm/hr have a greater capability to mobilise particulate matter. It is hypothesised that this is due to the high degree of turbulence in the overland flow. The pollutant export study undertaken in the same urban catchment confirmed the higher mobilisation capacity of high intensity rainfall events which results in relatively higher pollutant concentrations and larger average size of the wash-off particles.

6.4.5 Particle Size Distribution Analysis

The factor C_F indicates a specific rainfall event's capacity to mobilise particulate pollutants from paved surfaces. C_F varies with rainfall characteristics and particularly with rainfall intensity. However, the nature of this relationship is not clearly known. For example, a 65 mm/hr rainfall event generally removes around 50% of the pollutants available on the road surface. The reasons for the remainder of the 50% to remain on the road surface needed to be understood. As noted by Mackay (1999), raindrop-induced turbulence is the primary factor that keeps the particulate pollutants in suspension. The kinetic energy in lateral flow is comparatively low compared to raindrop kinetic energy. However, this is sufficient to move the particles that are already in suspension.

A Variation of Particle Size Distribution with Rainfall Intensity

In order to better understand the regime governing pollutant wash-off, the particle size distribution of each sample was analysed. The particle size distribution data was in volumetric percentages and was converted to weights. More details on the pre-processing of particle size distribution data can be found in Section 6.3.1. However, the analysis was first undertaken to understand the variation of particle size distribution with rainfall intensity. For this, the particle size distribution of the total pollutant sample washed per each intensity was analysed. The weight-based particle size distribution developed from the analysis is shown in Figure 6.7. Figure 6.7 further shows the particle size distribution of the initially available pollutant sample so that a detailed comparison is possible.

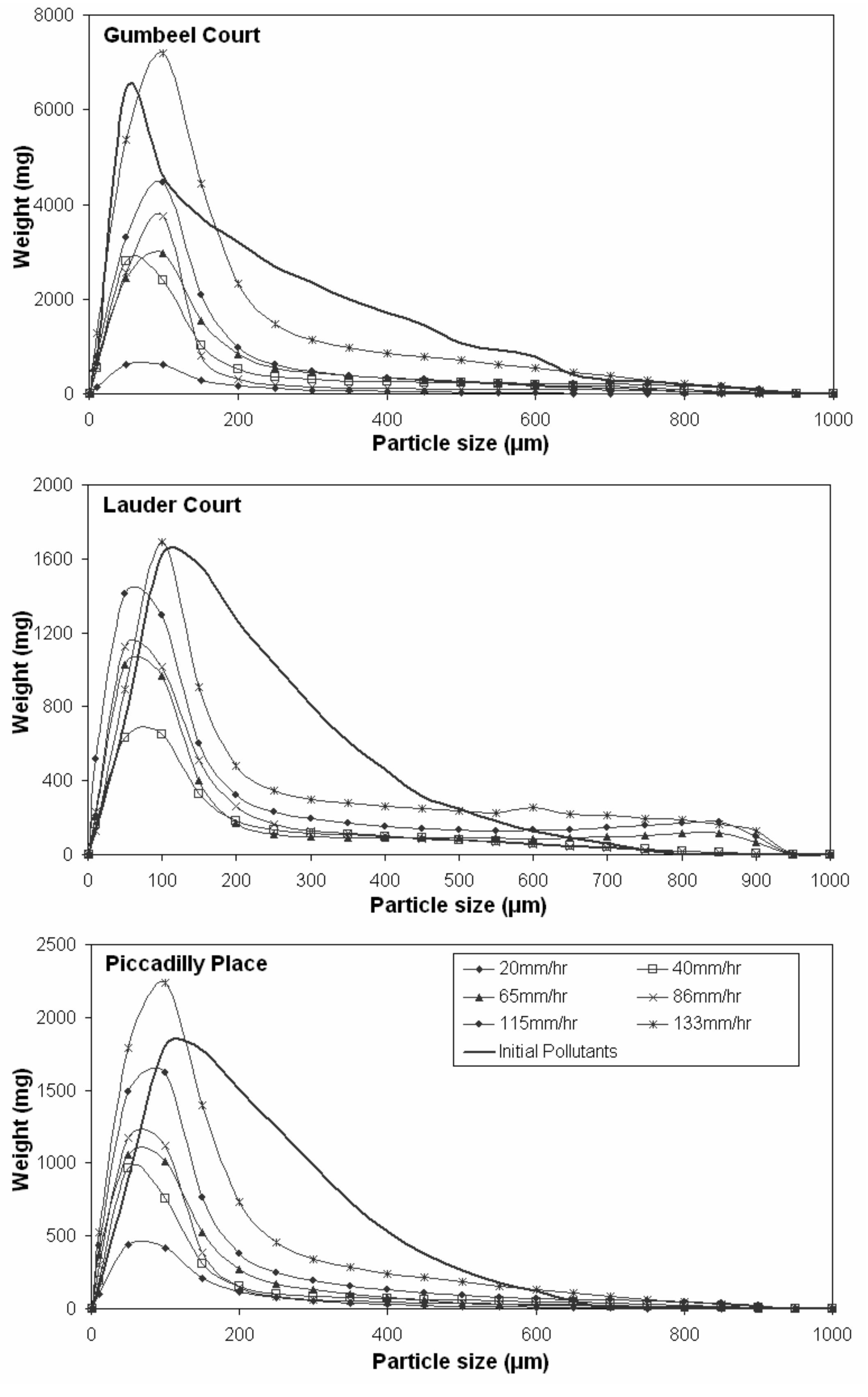


Figure 6.7 – Variation of particle size distribution

Figure 6.7 leads to several important observations on the physical process of wash-off. Firstly, it reveals that the higher fraction of wash-off particles is in the range of 0 to 200 μm. The average weight of washed-off particles less than 200 μm in size was 73%. The coarser range (>200 μm) shows only fractional increments in weight when the rainfall intensity increases. Therefore, it is not reasonable to argue that the increment in wash-off load with rainfall intensity is due to the increased capacity of the rainfall in mobilising coarser particles. It is true that the weight of coarser particles washed-off has increased with rainfall intensity. However, in comparison, weight increment of finer particles is most significant. This suggested that there is a fraction of finer particle size ranges which are not mobilised during less intense rain events. These particles are subsequently mobilised when the rainfall intensity increases. It is hypothesised that these finer particle size ranges remain on the road surface due to their relatively high particle density or adhesion to the road surface due to either physical or chemical bonding.

Secondly, as evident from Figure 6.7, the pattern of variation of average particle size distribution for all the intensities is similar. For example, the curve for the 86 mm/hr intensity is a close replicate of the 20 mm/hr curve with a multiplier. This suggests that there is a similar particulate composition for all the intensities. This further strengthens the influence of particle density in relation to wash-off. It would only be the lower density particles and those only lightly adhering to the surface being mobilised for smaller rainfall intensities. As the intensity increases, relatively higher density particles and those more strongly bound to the surface would be mobilised depending on the turbulence created by the rainfall.

Thirdly, in comparison to particle size distribution of initially available pollutants, wash-off resulted in a higher amount of finer particles. As seen in Figure 6.7, the weight of particles smaller than about 150 μm in wash-off samples is greater than that of the initially available pollutant sample. Furthermore, the weight of particles in the range of 150 to 600 μm in wash-off samples is significantly less compared to the initially available pollutant sample. These observations point to the possible break-up of coarser particles in this size range. This could occur due to the impact energy of raindrops and turbulence in surface runoff.

B Variation of Particle Size Distribution with Rainfall Duration

In order to understand the variation of particle size distribution for a continuous rainfall event, the pollutants in the wash-off belonging to each duration component were analysed separately. As discussed in Section 4.4.1, each intensity was simulated for a minimum of four duration components. The duration components can be found in Table 4.4. However, in order to obtain a general variation for three catchments, the particle size distributions belonging to similar rainfall intensity and duration components were averaged. For example, the particle size distribution data belonging to 40 mm/hr intensity and for the 0-10 min duration component from all three study sites was averaged. Figure 6.8 shows the average variation of wash-off for the 20 mm/hr intensity. The 20 mm/hr intensity was simulated in four duration components, 0-10, 10-20, 20-30, 30-40 min, and the corresponding particle size distribution for each component is separately shown. Appendix D, Figure D.7 shows the percentage particle size distributions for the other rainfall intensities.

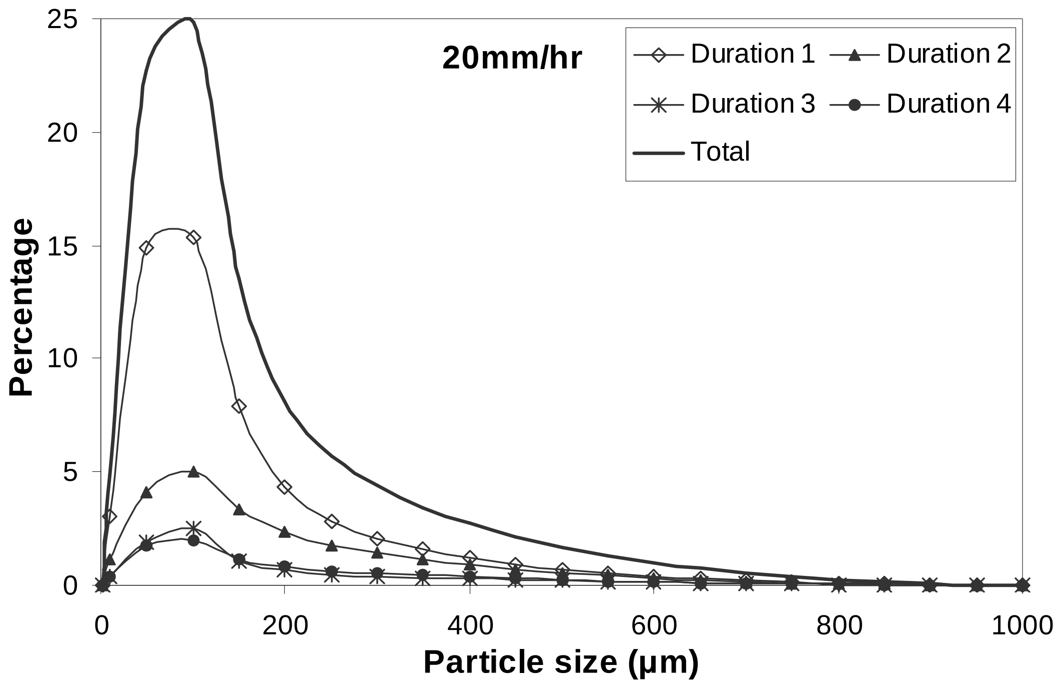


Figure 6.8 – Wash-off particle size distribution for four durations – 20mm/hr intensity

As evident in Figure 6.8 and Appendix D, Figure D.7, the variation of particle size distribution for different durations for any particular rainfall intensity shows similar characteristics. For all the durations, the highest weight percentage of particles is in the 0 to 150 μm range. Therefore, it can be argued that the particulate composition of wash-off throughout a constant intensity rain event is fairly uniform. This would mean that the influence of rainfall duration on wash-off particle size distribution is minimal.

It was further observed that a significant fraction of solids is being washed-off during the initial period of the rainfall simulations. Table 6.7 gives the weight percentages of washed-off particulates for different intensities and duration components. According to Table 6.7, the highest percentage of particulates is removed during the initial period of the storm for all rainfall intensities. This strengthens the concept of 'first flush' where the initial period of a runoff event produces a higher pollutant concentration and a concentration peak often preceding the runoff peak (Duncan, 1995; Lee et al., 2002).

Table 6.7 – Percentage wash-off for different intensities and durations

Intensity (mm/hr)	Pollutant Load Percentage (%)				
	1st Duration Component	2nd Duration Component	3rd Duration Component	4th Duration Component	5th Duration Component
20	56.6	23.8	9.0	9.1	-
40	42.2	21.2	19.2	16.1	-
65	36.9	19.5	21.9	20.2	-
86	39.8	18.1	21.1	18.6	-
115	37.9	27.1	15.1	18.3	-
133	29.3	25.0	17.5	14.8	12.5

It can be further noted from Table 6.7 that the fraction of pollutant contribution from the latter part of events increases when the rainfall intensity increases. The particles mobilised during the latter part could be the high density particles or those more strongly bound to the road surface. Therefore, it can be postulated that an appreciable fraction of pollutants in the latter part of high intensity events is high density particles and that the mobilisation of these high density particles along the road surface is comparatively slow. The slow movement would be due to the random motion of particles which suspend with raindrop splash and then deposit quickly when the turbulence reduces.

6.4.6 Physio-chemical Analysis

The quality impacts of stormwater are the most significant (Goonetilleke et al., 2005). This is primarily due to high concentrations of various pollutants such as hydrocarbons, heavy metals and nutrients in stormwater. However, this investigation did not focus on the characteristics of these pollutants. Instead, the parameters that influence the adsorption of these pollutants to particulate pollutants were investigated. This would enable the estimation of other pollutants using the predictive equations developed, with TS being considered as a surrogate parameter.

Many researchers have reported that physio-chemical parameters such as pH, EC, TC, TOC and DOC influence the adsorption of other pollutants to particulate pollutants. For example, Pechacek (1994) reported that the adsorption capacity of solid particles varies with size, structure and physio-chemical properties such as EC. Tai (1991), Hamilton et al. (1984) and Sansalone et al. (1995) noted that the desorption of heavy metals is primarily enhanced by lower pH ranges and the availability of DOC. Warren (2003) noted that the solubility of certain types of hydrocarbons is influenced by pH and organic carbon content.

The physio-chemical parameters in the form of concentrations were used for the analysis. This was due to the difficulty of converting parameters such as pH and EC to loads. Furthermore, the use of concentrations enables easy interpretation of outcomes. Other than the five physio-chemical parameters, TS was also employed in the analysis. This was to understand the behaviour of physio-chemical parameters with TS. In order to maintain the consistency of analysis, TS was also used in the form of concentration. Furthermore, TS concentrations were separated into six particle size categories for better understanding of processes and easy interpretations.

The analysis was performed using PCA techniques. PCA is one of the common techniques in water quality research that can be used to analyse multiple variables. A detailed discussion of PCA was set out in Section 3.5.3. The outcome of PCA provides an understanding of the degree of correlation between variables. However, the understanding gained is in relative terms. For example, if X correlates with Y, when X increases, Y increases. However, the exact behaviour of Y (whether it increases or decreases) is not known until the exact behaviour of X is known. Due to the nature of PCA outcomes, it was important to understand the variation of one variable with rainfall parameters prior to PCA analysis. In this case, TS was selected as the variable where primary understanding needed to be developed. The knowledge on variation of TS with rainfall intensity and duration is already known as discussed in Sections 6.4.1 to 6.4.4. However, this knowledge is based on TS in terms of loads.

The primary understanding on the variation of TS in terms of concentration was developed by plotting TS concentration with rainfall intensity and duration. Concentrations resulting from the laboratory testing were directly used in this analysis. The complete set of data used is available in Appendix D, Table D.3. The variation of TS concentrations with rainfall intensity and durations is shown in Figure 6.9.

As illustrated in Figure 6.9, TS concentration shows an exponential decay with the rainfall durations. The first duration component of the runoff event shows the highest TS concentration. The concentration reduces exponentially for the second, third and fourth components. The concentration increases marginally when the rainfall intensity increases. Such variation is clearly evident for the Lauder Court and Piccadilly Place sites whereas the Gumbeel Court site shows significant data scatter. Furthermore, the TS concentrations for the Gumbeel Court site were significantly high compared to the other two sites. This could be mainly due to the higher amount of initially available pollutants at the site. In the context of PCA, such data scatter and high concentration could influence the outcomes, if data from all the catchments is analysed together. PCA primarily analyses data variance and high concentrations of TC in Gumbeel Court could produce outcomes biased towards the Gumbeel Court site data. Therefore, PCA was undertaken for data from the three road sites separately. Figure 6.10 gives the resulting biplots from the analysis.

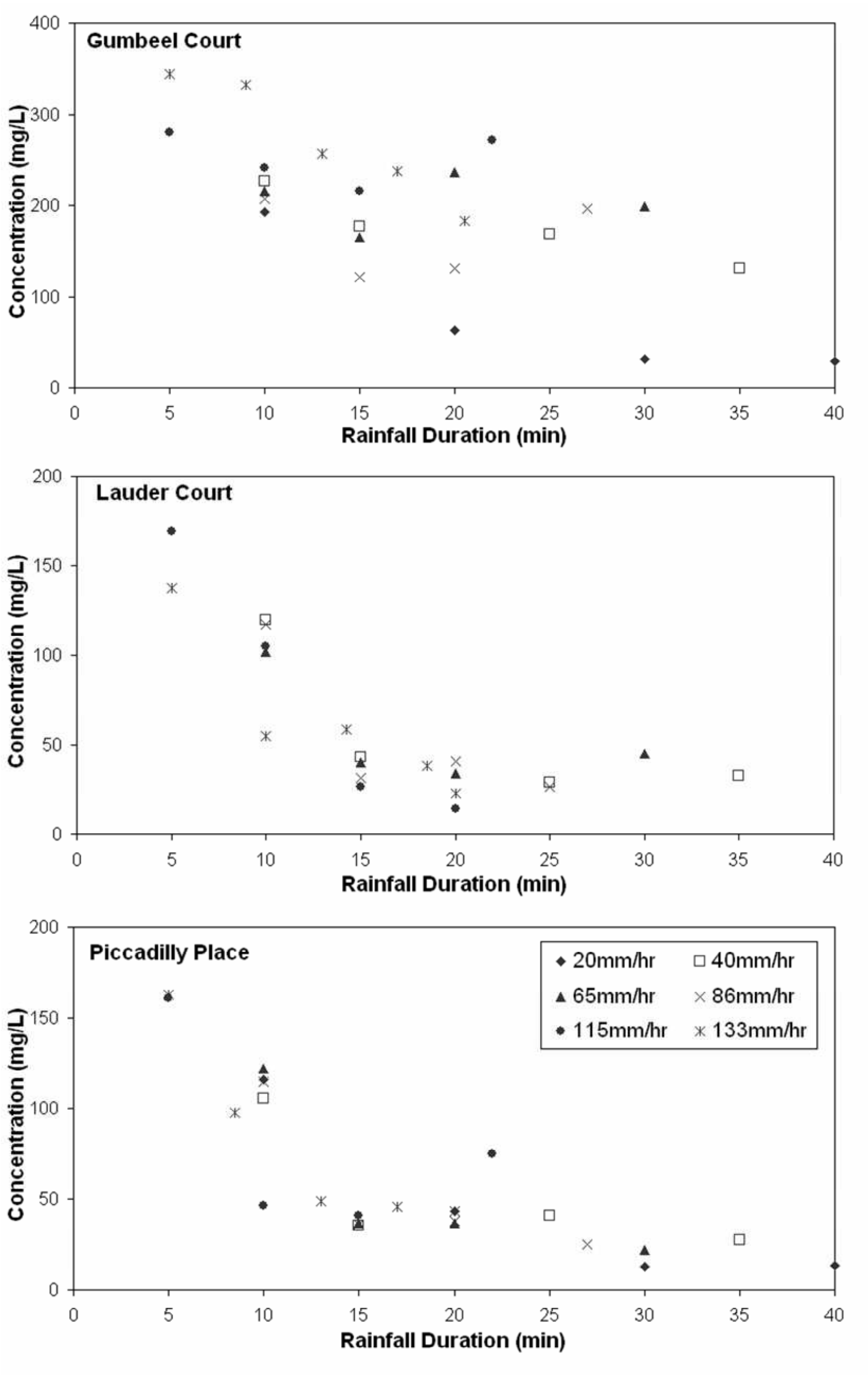


Figure 6.9 – Variations of TS concentrations

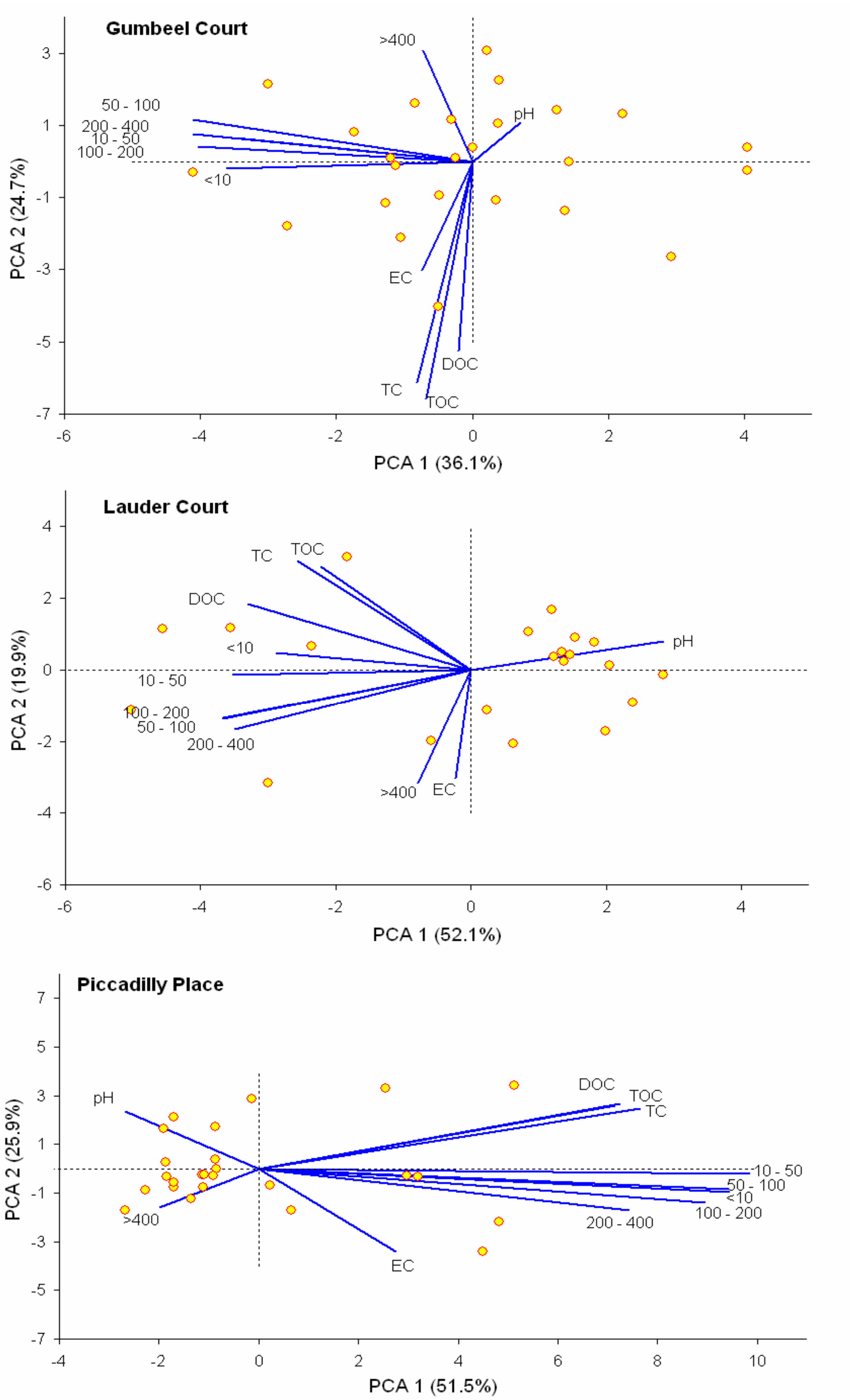


Figure 6.10 – Quality parameters for wash-off samples from Gumbeel Court road site: Biplot of data against the first two principal components

As evident from Figure 6.10, the biplots belonging to the Lauder Court and Piccadilly Place road sites show similar correlations whereas the biplot for the Gumbeel Court road site shows slightly different characteristics. The most significant deviation is in the degree of correlation shown between particle size groups less than 400 μm and quality parameters TC, TOC and DOC. For both the Lauder Court and Piccadilly Place sites, these two sets of parameters show good to partial correlation whereas Gumbeel Court shows no correlation. This could be due to the higher amount of initially available pollutant load which caused significant data scatter as observed in Figure 6.9. However, the relative correlation of parameters other than that between particle sizes less than 400 μm and quality parameters TC, TOC and DOC is mostly similar for all three biplots. Therefore, the following interpretations are primarily based on the observations of biplots belonging to the Lauder Court and Piccadilly Place road sites.

Figure 6.10 leads to the following observations:

1) Particle size classes less than 400 μm strongly correlate with each other, whereas particle size classes greater than 400 μm negatively correlate with other size classes.
2) Three water quality parameters: TC, TOC and DOC, strongly correlate with each other.
3) TC, TOC and DOC show correlations with particle size classes less than 400 μm.
4) Particle sizes greater than 400 μm show negative correlation with TC, TOC and DOC.

The strong correlation of the particle size classes less than 400 μm with each other suggested similar variation with rainfall intensity and duration. As these size ranges represent the highest fraction (around 90%) of the total solids, the concentrations of these size ranges should marginally increase when the rainfall intensity increases and reduce when the rainfall duration increases. These are the general understandings gained by the analysis of Figure 6.9. The negative correlation of particle sizes greater than 400 μm to other particle size ranges would illustrate the opposite behaviour to other particle size ranges. Therefore, the consequence would be the increase in concentration of solids with particle sizes greater than 400 μm as the rainfall duration increases. This could occur when coarser particles take a longer time to be transported through the plot surface.

The strong correlation of TC, TOC and DOC with each other indicates similar variations of these parameters with rainfall intensities and durations. As shown in Table 6.8, a significant fraction of carbon compounds is organic in nature and is in dissolved form. The amount of carbon compounds is significantly higher in the Lauder Court and Piccadilly Place road sites compared to the Gumbeel Court site. This could be mainly attributed to the re-distribution of organic material in Gumbeel Court site due to traffic-induced wind turbulence during the relatively longer antecedent dry conditions compared to other two sites. It is commonly known that organic materials would have a relatively lower density. In general, the average amount of organic carbon observed in runoff samples is closely comparable with previous findings. For example, Herngren et al. (2005a) noted significant variation in DOC concentrations during their study in residential, commercial and industrial land uses. The maximum limit of DOC they observed was 9.4 mg/L.

Table 6.8 – Average quality parameters and their variation

Parameter	Gumbeel Court		Lauder Court		Piccadilly Place	
	Average	Max/Min	Average	Max/Min	Average	Max/Min
pH	6.0	6.9 / 5.5	5.9	6.1 / 5.6	6.4	6.7 / 6.1
EC (µS/cm)	45.9	123 / 8.8	188	312 / 59	122.3	162 / 4.4
TC (mg/L)	8.2	13.2 / 5.3	8.0	17.8 / 4.2	10.6	21 / 6.5
TOC (mg/L)	6.7	10.8 / 3.9	7.1	17.7 / 4.1	10.0	21 / 6.0
DOC (mg/L)	4.4	9.6 / 0.0	6.1	11.1 / 3.4	6.7	20 / 3.2

The correlation of carbon compounds to particles sizes less than 400 µm and the fact that the highest correlation is shown by the finest size suggest that a significant fraction of the pollutants is associated with the finer particle size. This further strengthens the concept established by previous researchers such as Sartor et al. (1974), Vaze and Chiew (2002) and Herngren et al. (2005a). Due to the fact that concentrations of finer particles are significantly high during the initial part of the runoff event, there is a high probability of the washing-off of most of the associated pollutants during this period. This further confirms the concept of ‘first flush’ which results in relatively highly polluted runoff during the initial part of runoff events (Duncan, 1995; Lee et al., 2002). The correlation of carbon compounds to particle sizes less than 400 μm further confirms a decrease in pollutant concentration when the rainfall duration increases. The negative correlation of carbon compounds to particle sizes greater than 400 μm would mean that relatively few pollutants are associated with particles larger than 400 μm.

The negative correlation of pH with finer particle sizes and other quality parameters suggest that the runoff becomes less acidic as the rainfall progresses. As evident in Table 6.8, road surface runoff is acidic. The minimum pH shown in Table 6.8 mostly belongs to the first duration component suggesting acidic runoff during the initial period of flow. The lower pH values could be attributed to the higher amount of initially available pollutants on road surfaces. The lower pH in stormwater further enhances the solubility of other pollutants.

6.5 Analysis of Wash-off from Roof Surfaces

The characteristics of wash-off from roof surfaces are less well known than for road surfaces. Forster (1996) investigated runoff from different types of roofs for water quality parameters. As Forster (1996) noted, metal compounds were the most significant in roof runoff particularly from metal roofs. He also noted that most of the roof surface pollutants were removed during the initial period of storm events and he suggested an exponential equation with negative exponent to replicate the dissolved component of pollutants whilst little attention was given to understanding wash-off of particulate pollutants.

The analysis of wash-off data from roof surfaces was done based on the assumption that it is similar to wash-off from road surfaces. The assumption was strengthened by the recommendation by Forster (1996) of an exponential equation (in the form of Equation 6.3). Further, it can be argued that wash-off processes, as discussed in

Section 6.4, will not change in its original form as a result of the change in surface type.

The investigation of pollutant wash-off from roof surfaces was conducted for four rainfall intensities: 20, 40, 86 and 115 mm/hr. The intensities of 65 and 133 mm/hr were not simulated on roofs. The durations of rainfall simulations were selected on site so that the latter part of the events washed virtually no pollutants. More details of the rainfall simulations on roof surfaces can be found in Section 4.4.2. Five to seven samples were collected from each rainfall simulation.

6.5.1 Variation of Wash-off with Influential Parameters

The primary data analysis revealed that the fundamental characteristics of wash-off from roof surfaces are very similar to the observations made during road runoff data analysis. Figure 6.11 shows the variation of F_W with rainfall intensity and duration. It is clearly seen that the variation is close to an exponential relationship in the form of Equation 6.3. Figure 6.11 further shows data points with $F_W > 1$. This could be primarily due to sampling errors and non uniform pollutant distribution.

As evident in Figure 6.11, wash-off patterns for both types of roof surfaces show similar characteristics. Therefore, it can be surmised that the characteristics of wash-off for both roof surfaces are similar. This led to the development of a single replication equation for roof surface wash-off. For the 115 mm/hr rainfall events, all of the initially available pollutants were washed-off from roofs as F_W approaches unity at the end of the six minute duration. This intensity was considered as the upper limit of intensity in wash-off investigations in roofs. Technically, it is not possible to have a F_W value greater than one. However, it is possible to remove the complete amount of pollutants on the surface earlier than six minutes for a rain event greater than 115mm/hr intensity. Due to the short timeframe and difficulty of increasing sampling frequency, it was not possible to investigate such variation. It was considered that the intensities greater than 115 mm/hr would result in the same outcomes as for the 115 mm/hr intensity rainfall simulation. For both the 40 and 86mm/hr rain events, F_W is approximately 0.9. This indicates that a similar wash-off pattern exists for the rainfall intensity range from 40 to around 90 mm/hr. Similarities in wash-off pattern for this rainfall intensity range were observed for wash-off investigations on road surfaces. However, the F_W value was around 0.5. This could be primarily due to variation in surfaces texture. Due to the smooth surface texture of roof surfaces, less kinetic energy would be needed to suspend particulate pollutants.

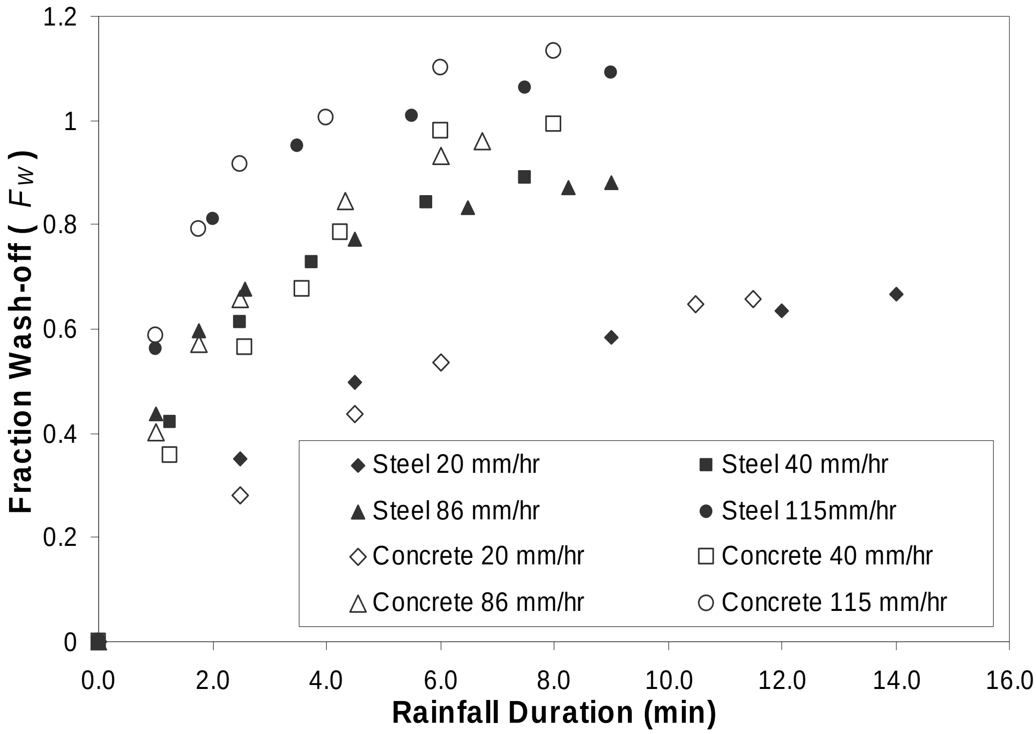


Figure 6.11 – Observed fraction wash-off (F_W) from roof surfaces

6.5.2 Mathematical Replication of Pollutant Wash-off

The exponential pollutant wash-off equation in the form of Equation 6.3 was used as the basis of wash-off replication from roofs. Equation 6.3 is re-stated below.

$$Fw = C_F(1 - e^{-kIt})$$

The parameters C_F and k were estimated based on the observed wash-off pattern. Similar to the estimation of parameters for road surfaces, the parameter estimation process was based on minimising the square of difference between observed and predicted values. The initial values for C_F were determined by careful observation of wash-off variation in Figure 6.11. It was intended to develop a range of C_F values according to rainfall intensity whilst keeping k as a constant. Table 6.9 shows the values obtained for C_F while k is at its optimum value of 9.33 x 10^{-3}.

Table 6.9 – Optimum parameters for Equation 6.3

Roof Type	Wash-off Coefficient k	Capacity Factor C_F			
		20 mm/hr	40 mm/hr	86 mm/hr	115 mm/hr
Steel	9.33 x 10^{-3}	0.75	0.97	0.87	1.01
Concrete	9.33 x 10^{-3}	0.76	0.99	0.86	1.03

As shown in Table 6.9, the parameter C_F obtained for both roof types is similar. This suggests the possibility of generating a common set of parameters for both roof types. Further, it is possible to develop a constant C_F value for the rainfall intensity range of 40 to 90 mm/hr. This is due to the similarities of C_F for this range as noted in Table 6.9. Therefore, as for road surface wash-off, it can be assumed that C_F varies linearly from 0.75 to 0.91 for the 20 to 40 mm/hr intensity range, it is constant at 0.91 between 40 to 90 mm/hr intensities and varies linearly from 0.91 to 1 for 90 to 115 mm/hr rainfall intensities. C_F was considered to be constant at 1.00 for all the intensities greater than 115 mm/hr. The values for C_F were obtained based on the method of least squares. The rainfall intensity ranges are exactly the same as the wash-off process for road surfaces (see Section 6.4.4).

Figure 6.12 shows the performances of the parameters developed for Equation 6.3 in replicating wash-off from roof surfaces. Performance of the developed parameters was further verified by obtaining the mean for the ratio between predicted and observed values and CV ,as given in Table 6.10.

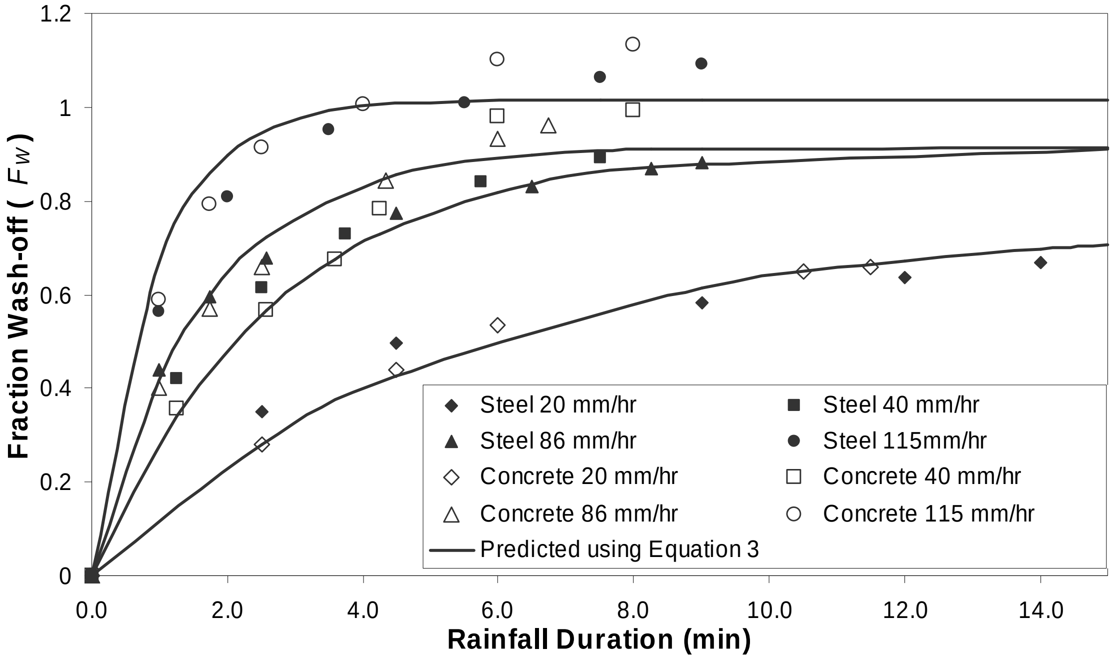


Figure 6.12 – Performances of the replication equation for roof surface wash-off

Table 6.10 – Performance of Equation 3 with common set of optimum parameters

Parameter	Corrugated Steel	Concrete Tile
Mean	1.01	1.00
CV	10.3%	10.0%

As evident from Figure 6.12, the visual performance of the replication equation is satisfactory. As shown in Table 6.10, the mean for both roof surfaces is close to one and the CV is around 10%. This confirmed the ability to reproduce with adequate accuracy the observed wash-off data set using Equation 6.3. Therefore, it can be considered that the replication equation in the form of Equation 6.3 and the common set of parameters as described above can be used to replicate pollutant wash-off from roof surfaces.

It was possible to develop a replicating equation in the form of Equation 6.3 for all the investigated impervious surface types. The two types of surfaces investigated, namely, roads and roofs, are vastly different in their primary characteristics including, surface texture and slope. The ability to use a similar equation for these surfaces suggested the possibility of using the equation for all the other impervious surfaces such as driveways.

The wash-off coefficient k also shows significant variation with surface type and characteristics of pollutants. For wash-off from road surfaces it was 8.0 x 10^{-4} whereas for roof surface wash-off it was 9.33 x 10^{-3}. The parameter k primarily defines the shape of the wash-off curve which is more closely related to the surface type rather than the characteristics of pollutants.

6.5.3 Particle Size Distribution Analysis

The particle size distribution of individual samples was tested in order to understand the physical processes governing pollutant wash-off and to identify the reasons for the variation of C_F with rainfall intensities. Figure 6.13 shows the average particle size distribution for both roof surfaces.

As shown in Figure 6.13, the variation in weight for 40 and 86 mm/hr rainfall shows similarities, whereas the particle size distribution for 115 mm/hr is relatively high when compared to the other two. The primary cause for this is the variation in initially available pollutants. Table 6.11 shows the initially available pollutants for the two roof surfaces.

Table 6.11 – Initially available pollutants prior to rainfall simulations

Roof Type	Pollutant load (g)			
	20(mm/hr)	40(mm/hr)	86(mm/hr)	115(mm/hr)
Steel	0.264	0.647	0.624	0.810
Concrete tile	0.288	0.386	0.339	0.461

As shown in Table 6.11, initially available pollutants before the 115 mm/hr intensity simulation is comparatively high when compared to the other three intensities. This could lead to significant variation in wash-off load. Further to this, it is clearly evident in Table 6.11 that the amount of initially available pollutants on the steel roof is significantly higher than for the concrete tile roof except prior to the 20 mm/hr rainfall simulation. This would be the reason for the relatively higher amount of pollutant wash-off from steel roofs.

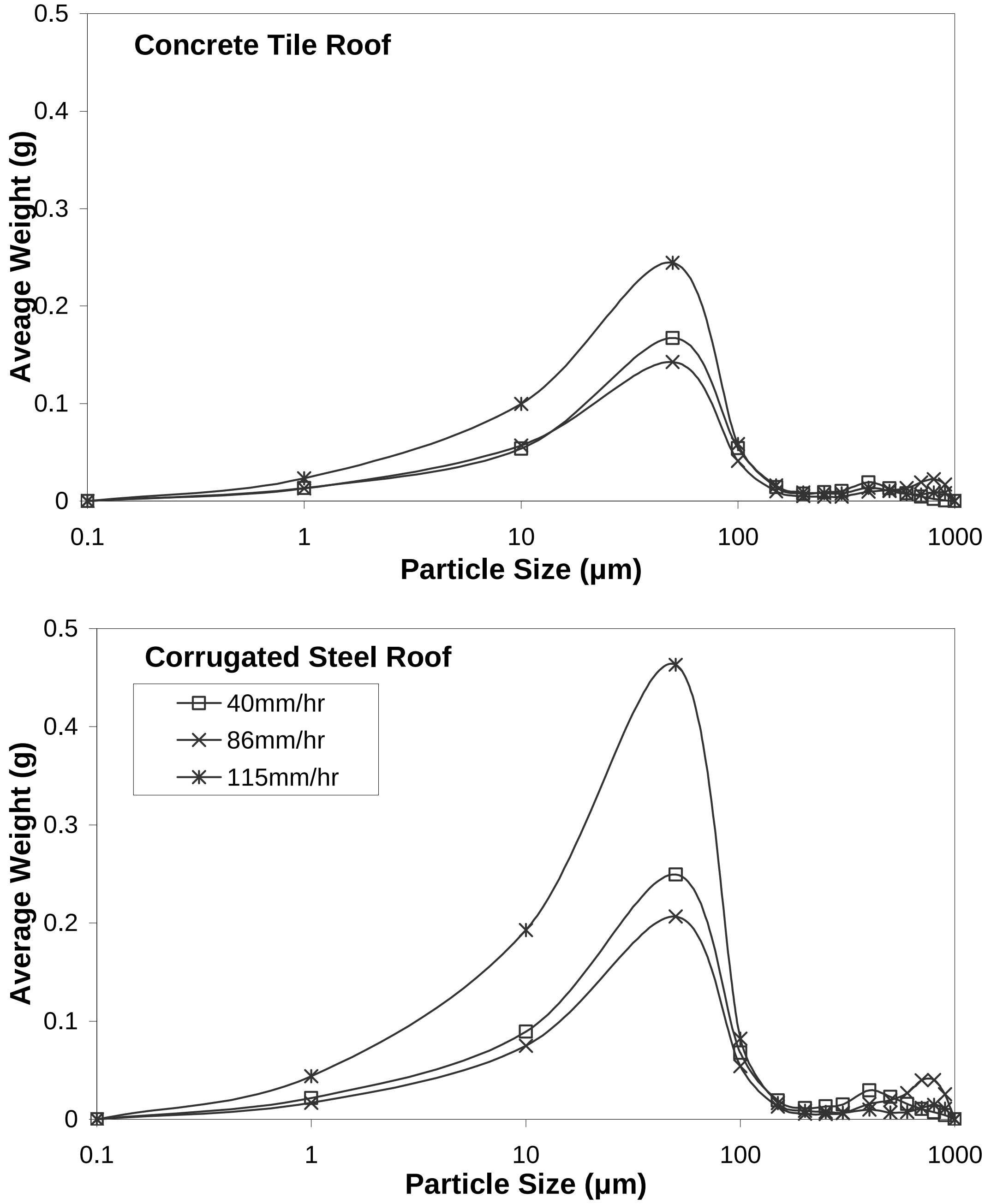


Figure 6.13 – Averaged particle size distribution for two roof surface types

It was understood that both the 40 and 86 mm/hr rainfall events are not capable of washing-off all the pollutants from roofs. Since the fraction retained is low, it was not possible to distinguish which particle size category was retained on the surface. As evident from Figure 6.13, there are no significant differences in the pattern of particle size distribution. The majority of the solids are in the range of 1 to 100 μm with the median around 50 μm for all the samples from the two roofs. It would alter the wash-off particle size distribution if the additional amount of pollutants washed-off during the 115 mm/hr rain event belonged to a particular particle size range. As this was not the case, it can be surmised that the additional amount of pollutant retained on the roof surface is a well distributed sample.

Due to the fineness of the particles, it is more possible to retain particles on roof surfaces by chemical bonds rather than gravity. The finer particles are more likely to be polar and create electrostatic bonds with the roof surfaces. On the other hand, roofs are angled at 20^0 and therefore, a significant fraction of the gravity force is in the direction of the roof slope. Additionally, the low roughness of roofs compared to road surfaces provides fewer pores within the texture to trap pollutants. This would mean relatively low resistance against wash-off. Therefore, it can be surmised that the retention of particles on the surface during low rainfall intensities would be due to their strong chemical bonds. The less intense rain events would not be able to supply adequate energy to overcome these bonds thereby allowing the particles to be retained on the surface.

In comparison to road surface wash-off, particles washed-off from roof surfaces are significantly fine. This is primarily due to the fineness of the initial pollutants which are mainly sourced from atmospheric sources. The fineness of the particles on roofs may create significant differences in terms of gravitational forces and chemical bonds when compared to road surface pollutants. However, the kinetics of the wash-off observed from the two surface types were similar. Furthermore, it was possible to develop a replication equation of similar form for both surface types. Therefore it can be surmised that rainfall parameters rather than surface type and pollutant characteristics exert the higher degree of influence on wash-off. The rainfall parameters are the only unchanged parameters used during the analysis of wash-off for the two surface types.

6.5.4 Physio-chemical Analysis

The analysis of the water quality parameters obtained from the laboratory testing was undertaken using PCA. Similar to the analysis of water quality data from road surface runoff, detailed understanding of the variation of TS concentrations was needed for better interpretation of PCA outcomes. This entailed the analysis of variation of TS concentrations with rainfall intensity and duration as shown in Figure 6.14.

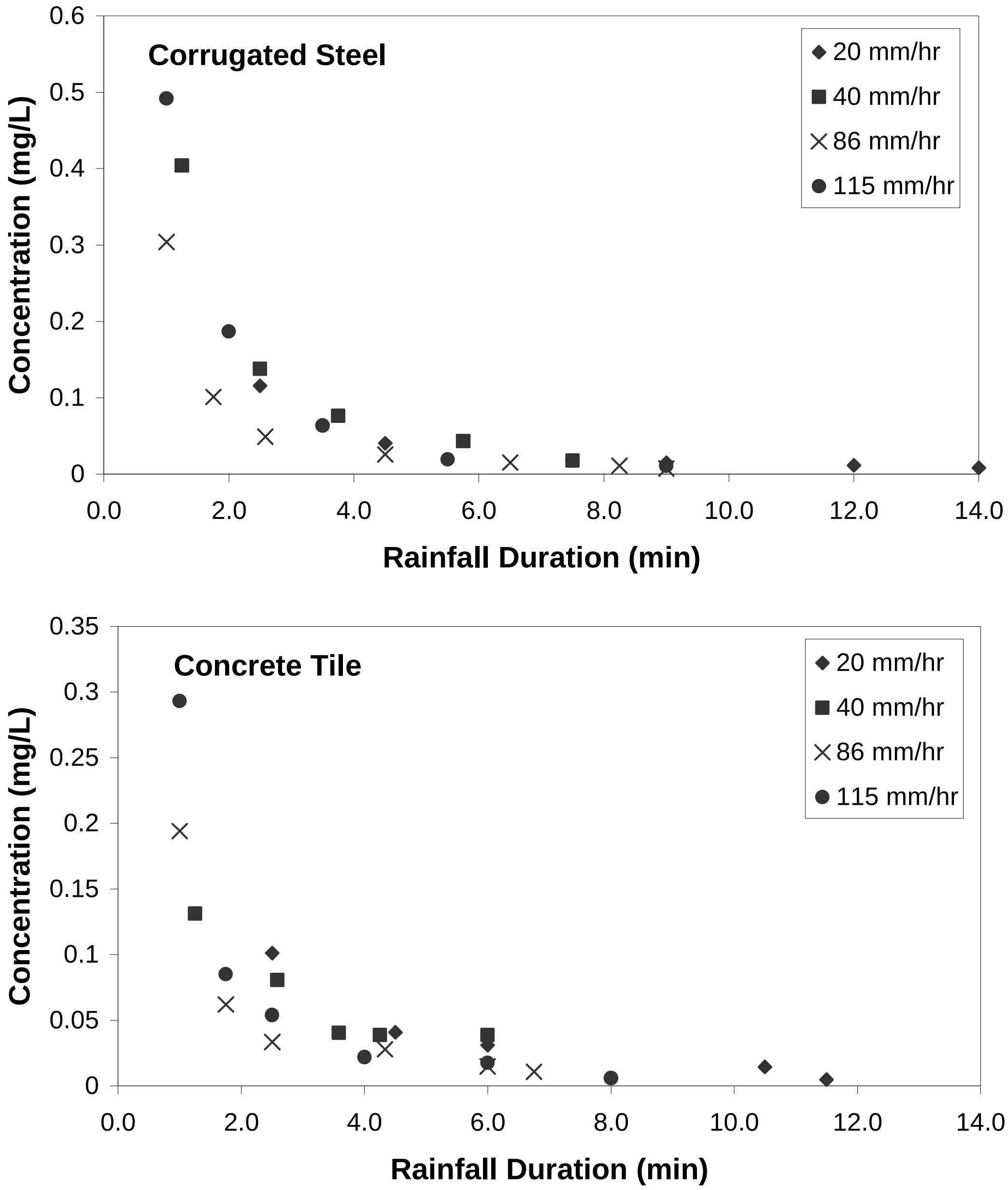


Figure 6.14 – Variation of TS concentration with rainfall intensity and duration

As illustrated in Figure 6.14, the concentration shows an exponential decay when the investigated duration components move from the first to the fourth. Furthermore, it shows an increase in TS concentration particularly for the first duration component when the intensity increases. This observation is very similar to the variations of TS concentration in road surface runoff. Therefore, the interpretation of the PCA outcomes was undertaken using a similar approach.

Figure 6.15 shows the biplot resulting from PCA. Due to the similarities in the variation of concentrations and comparatively less data scatter, a combined analysis was done for both roof types.

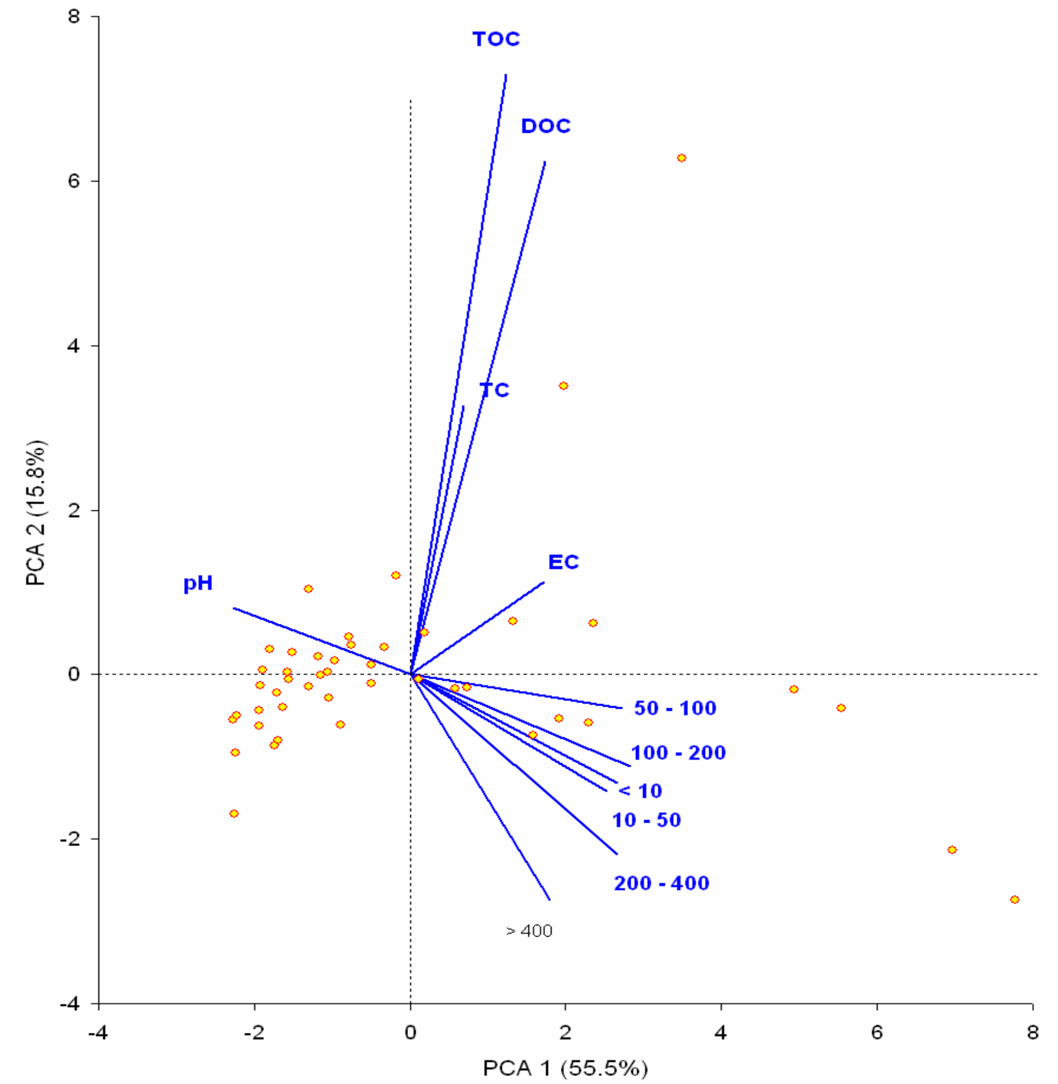


Figure 6.15 – Quality parameters for wash-off samples from roof surfaces: Biplot of data against the first two principal components

Figure 6.15 leads to the following conclusions:

1) All the particle size classes strongly correlate with each other;
2) TC, TOC and DOC strongly correlate with each other; and
3) All the particle size classes show virtually no correlation with TC, TOC and DOC.

The strong correlation of all the particle size classes with each other would mean similar variation of all particle sizes during wash-off. As the variation of TS with rainfall duration was understood as an exponential decay (see Figure 6.14), the concentration of all the particle size classes should have similar variation with rainfall parameters.

The strong correlation of TC, TOC and DOC with each other indicates similar variations of these parameters during rainfall events. However, the higher vectorial length of TOC and DOC suggested a higher variation compared to TC. As shown in Table 6.12, both TOC and DOC concentrations are significantly high when compared to road surfaces. Higher organic carbon content could be due to the significant fraction of surrounding unpaved land.

Table 6.12 - Average quality parameters and their variation

Parameter	Steel Roof		Concrete Roof	
	Value	Max/Min	Value	Max/Min
pH	6.6	7.9 / 4.9	6.6	7.3 / 5.4
EC (μS/cm)	193	371 / 61	160	351 / 61
TC (mg/L)	17.0	38.7 / 4.2	16.5	32.9 / 6.5
TOC (mg/L)	6.3	33.7 / 1.2	7.2	18.9 / 3.2
DOC (mg/L)	5.1	15.2 / 0.9	5.9	11.9 / 2.7

The negative correlation of pH to particle size classes indicates that the acidic nature of roof surface runoff decreases when the duration of simulations increase. The average pH for all the initial duration components was 5.67 while it was 6.18, 6.67 and 7.18 respectively for the next consecutive duration components. The lower pH in the initial part of the runoff events and its increase when the duration increases means that the acidic nature can be primarily attributed to particulate pollutants.

Lower pH and higher fraction of DOC in roof surface runoff increases the likelihood of having other pollutants in dissolved form (Herngren et al., 2006; Warren et al., 2003). This can be significant for steel roofs where high concentrations of heavy metals is a distinct possibility (Bannerman et al., 1993).

6.6 Conclusions

This chapter discussed the analytical outcomes of the extensive investigations into pollutant wash-off from road and roof surfaces. The analysis primarily focussed on understanding the characteristics of wash-off of particulate pollutants. This was due to the fact that particulate pollutants were adopted as the indicator pollutant in the research study. Additionally, efforts were made to understand the factors that influence the adsorption of other pollutants to solids.

The outcomes of the analyses are as follows:

1) Wash-off of particulate pollutants can be replicated using an exponential equation in the form of:

   $$Fw = C_F(1 - e^{-kIt})$$

   Where;

   I Rainfall intensity;

   k Wash-off coefficient;

   Fw Fraction wash-off;

   C_F Capacity factor; and

   t Rainfall duration

   C_F and k are parameters that need to be estimated in order to use the wash-off equation. Parameter estimation was undertaken for roads and roofs separately as these are the primary types of impervious surfaces in urban areas.

2) Analysis was undertaken to understand the characteristics of each parameter. C_F was defined as the rainfall capacity to mobilise pollutants. However, it was found that C_F is not purely a property of rainfall characteristics alone. C_F shows a strong relationship to rainfall intensity, particle size distribution of pollutants and impervious surface type. For simplicity of calculations, C_F was estimated for three rainfall intensity classes. For the 20 to 40 mm/hr intensity range, C_F increased linearly, for the 40 to 90 mm/hr intensity range C_F is a constant and for above the 90 mm/hr intensity it varied linearly to a maximum of one. The values of C_F obtained for these rainfall intensity ranges differ for the two impervious surface types: roads and roofs. This is due to the differences in the characteristics of the surfaces and particle size distribution of available pollutants. Wash-off coefficient *k* was estimated as a constant for each impervious area type. It was 8.0×10^{-4} for road surfaces and 9.33×10^{-3} for roof surfaces.

3) On average, 73% of road surface wash-off pollutants belong to the 0 – 200 μm particle size range. Furthermore, it was observed that this particle size range is dominant for all the rainfall intensities. The average particle size distribution curves for samples from different rainfall intensities show closely similar characteristics.

4) Up to 90% of the particles washed-off from roof surfaces belong to the 0 – 100 μm size range. The particle size distribution showed consistent similarities when both rainfall intensity and duration varied. Only a small fraction of particles were retained on the roof surface even after the simulation of the lowest rainfall intensity.

5) For both roof surface types, the highest amount of wash-off occurred during the initial period of rainfall simulations. This strengthens the first flush concept noted by many researchers.

6) It was noted that higher fractions of organic carbon are in dissolved form and are associated with the finer particle size ranges. The amount of organic carbon reduces when the concentration of particulate pollutants reduces.

Chapter 7 - Catchment Modelling

7.1 Introduction

Chapter 5 and 6 provided extensive information on processes involved in particulate build-up and wash-off from impervious urban surfaces. The understanding gained from these investigations enabled the estimation of the amount of particulate pollutant build-up on different impervious surface types for a given antecedent dry period and the particulate load removed during a known storm event. In order to relate the estimated solids load to catchment water quality, detailed knowledge is needed relating to how discrete plot surfaces are hydrologically connected. The hydrologic information that is needed is not only the amount of runoff volume that a particular surface generates, but also the time taken for that particular volume to transfer to the catchment outlet.

The most feasible approach to generate the requisite hydrologic information that is needed is to use a calibrated hydrologic model. Hydrologic modelling is commonly used to estimate runoff from catchments. However, in this case, the use of a hydrologic model was not for typical use in relation to runoff predictions. The primary use of a hydrologic model in this research study was to facilitate the translation of pollutant concentrations from catchment sub-areas to the catchment outlet.

This chapter discusses in detail the hydrologic modelling used to develop runoff information. The modelling software used was Mike STORM which was developed by the Danish Hydraulic Institute (DHI) (Mike STORM, 2004). The chapter first discusses the basic architecture of Mike STORM and its simulation techniques. Then the setting up of three catchment models and details of model calibration for a range of storm events are outlined. The calibrated models were then used for the estimation of water quality.

7.2 Model Setup

7.2.1 Model Architecture

Mike STORM is an advanced and comprehensive surface runoff, open channel flow, pipe flow and water quality modelling package for urban drainage systems (Mike STORM, 2004). It is a combination of mathematical modelling procedures developed for hydrologic, hydraulic, and water quality simulations. Table 7.1 shows the different mathematical procedures embedded within Mike STORM for different types of mathematical simulations. Most importantly, Mike STORM provides a highly efficient platform for these mathematical procedures to operate with the same input data and to link each type of routine as a chain of action.

Table 7.1 – In-build mathematical routines in Mike STORM

Hydrologic Procedure	Hydraulic Procedure	Water Quality Routing Procedure
Time area method	Dynamic wave method	Advection
Kinematic wave analysis method	Diffusive wave method	Dispersion
Linear reservoir method	Kinematic wave method	Combination of advection and dispersion

Mike STORM needs three categories of input data for simulations. These are network, catchment and boundary data. Each input data file is linked to a 'project' file which is a dynamic file that updates information as each file is modified. Figure 7.1 shows the routine for linking each file and the sequence of simulations.

Network inputs are primarily of two types: nodes and links. Nodal information is spatial location, dimension and elevation of nodal structures such as manholes, basins and outlets. These nodal structures are connected by links which are primarily pipes and channels. The primary link inputs are type of link, their hydraulic properties such as roughness and information on upstream and downstream nodes.

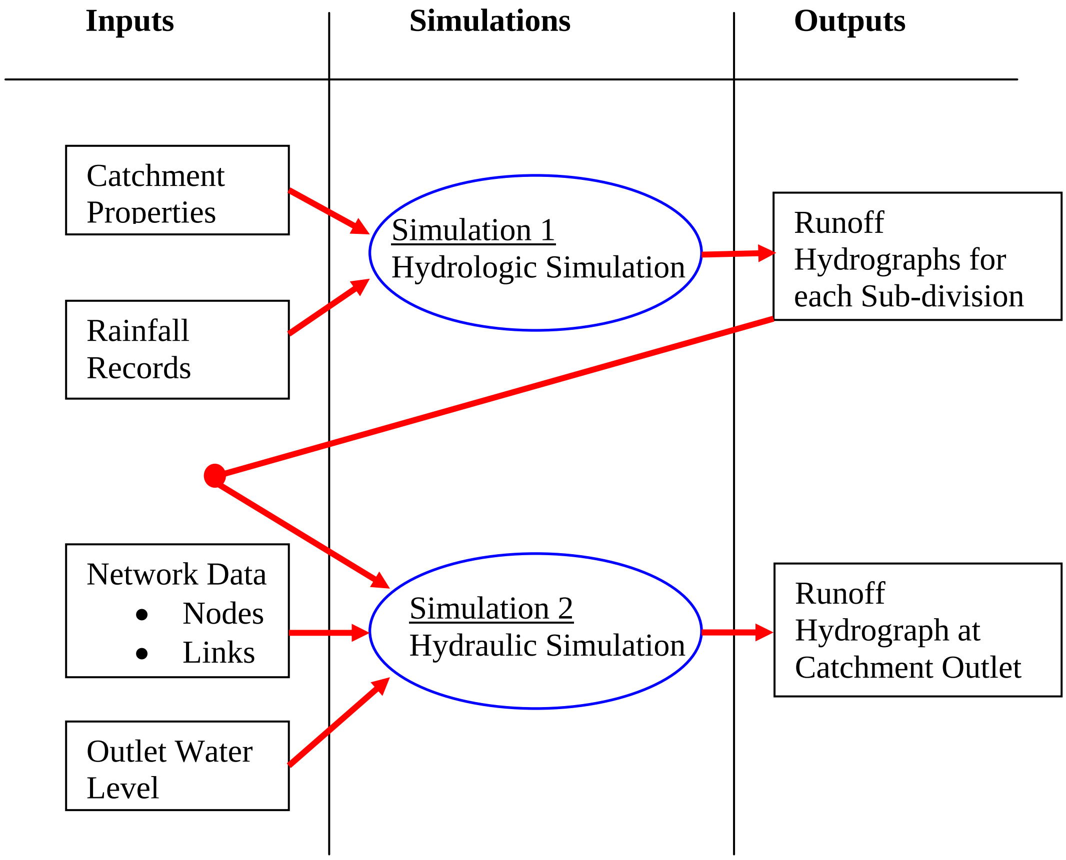


Figure 7.1 – File structure and simulation sequence in Mike STORM.

Catchment inputs primarily consist of catchment area and the node at which the catchment drains. The catchment should drain to a pre-defined node from nodal inputs. The same catchment input dialog box is used to define hydrologic parameters. Separate windows are available to define variables for different hydrologic methods.

Two types of boundary inputs are used in Mike STORM: rainfall boundary and water level boundary. Details of the rainfall event in the form of intensity time series should be inserted as a rainfall boundary. There are options to insert several time series for different rain gauges and to use distributed rainfall patterns for simulations. The time series of the catchment outlet water level is used as a water level boundary. This is used to calculate the back-water curve when limited drainage facilities are available at the catchment outlet.

7.2.2 Alextown Catchment

Alextown is a tenement townhouse development, 1.7 ha in area. The percentages of impervious surfaces are 10.5%, 38.1% and 8.6% for roads, roofs and driveways respectively. Further details of the catchment characteristics can be found in Section 4.3.1. The catchment consists of an efficient drainage system with rectangular gully pits with steel mesh lids placed at the middle of the road to collect road runoff. Detailed maps of the drainage network including sizes of gully pits and pipe diameters were provided by the Gold Coast City Council (GCCC). These maps can be found in Appendix B, Figures B.1 to B.4. Runoff from roofs is directly connected to the drainage pipe network.

For the modelling, the catchment was divided into 16 sub-areas so that its distributed nature can be adequately represented. The subdivisions were done after careful investigation of the catchment contours and drainage network. The sub-areas were demarcated such that each gully pit accounts for the surrounding drainage area. Figure 7.2 shows the details of the drainage network and catchment subdivisions. Appendix E, Figures E.1 to E.3 show the data input to Mike STORM for model setup. The primary data inputs were location coordinates of gully pits, their surface and invert elevations, properties of connecting pipes such as diameter and type, extent of sub-areas and impervious percentages.

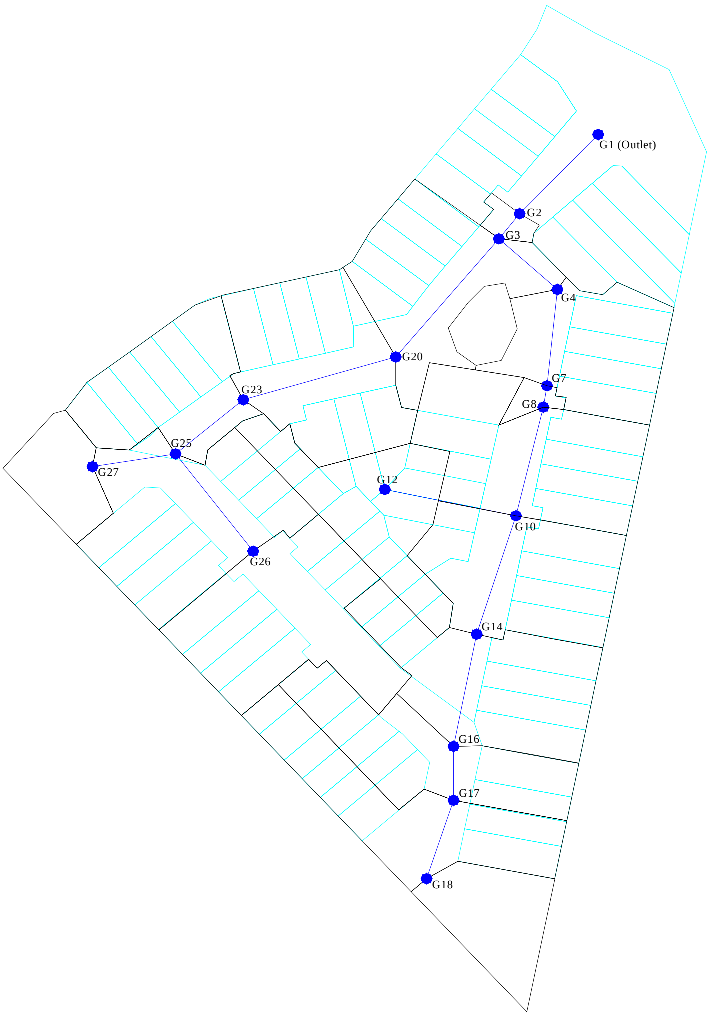


Figure 7.2 – Drainage network and catchment sub-divisions for Alextown

Most of the input data as shown in Appendix E, Figures E.1 to E.3 was measured data or obtained from GCCC data sets. However, there was information which needed further investigation. Firstly, a constant value was used for impervious percentages based on the average value measured for the Alextown catchment as discussed in Section 4.3.1. It was assumed that impervious surfaces were distributed equally over the catchment surfaces. Secondly, Mike STORM considers the gully pits to be cylindrical shaped and a diameter is assigned as the primary dimension parameter. However, physically all gully pits have a rectangular shape. An equivalent diameter which was considered as the diagonal length of the rectangular manhole was adopted for catchment modelling. Representation of gully pits in different shapes would not introduce error to the modelling outcomes (Mike STORM, 2004).

7.2.3 Gumbeel Catchment

Gumbeel is a duplex housing development of 2.1 ha. The impervious percentages are 10.3%, 19.2% and 11.2% for roads, roofs and driveways respectively. The catchment is located in a typical ridge shape area. However, most of the runoff from roads and roofs is artificially directed to the drainage network. The length of the drainage network is comparatively short compared to the other study catchments. The total catchment was divided into two sub-areas and the required parameters were obtained as for the Alxetown catchment. Figure 7.3 shows the drainage network and catchment sub-areas and Appendix E, Figures E.4 to E.6 gives the input data for the Mike STORM model.

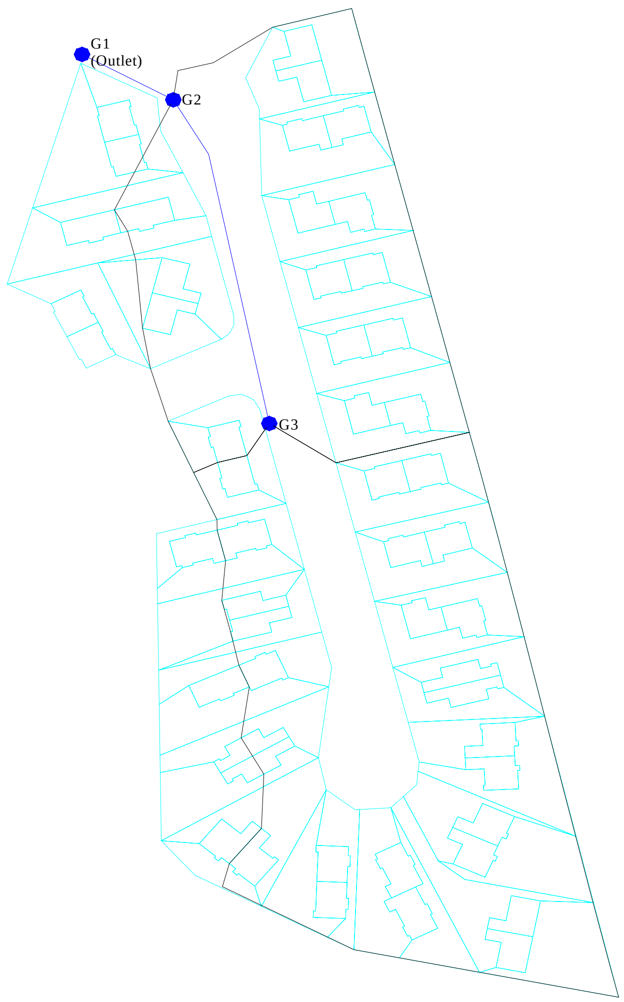


Figure 7.3 – Drainage network and catchment sub-divisions for Gumbeel

7.2.4 Birdlife Park Catchment

Birdlife Park is a high socio-economic single detached dwelling area of 8.6 ha area. The catchment is in a valley, with a relatively greater slope when compared to the other catchments. All the roof runoff in the catchment is directed to road gutters and then collected by side manholes along with road runoff. Furthermore, any runoff generated in pervious areas or driveways is accumulated with road runoff. The total catchment was divided into 54 sub-areas. The parameters for each sub-area were obtained in the same way as for the Alextown catchment. Figure 7.4 shows the drainage network and catchment sub-areas and Appendix E, Figures E.7 to E.9 gives the input data which was used for Mike STORM modelling.

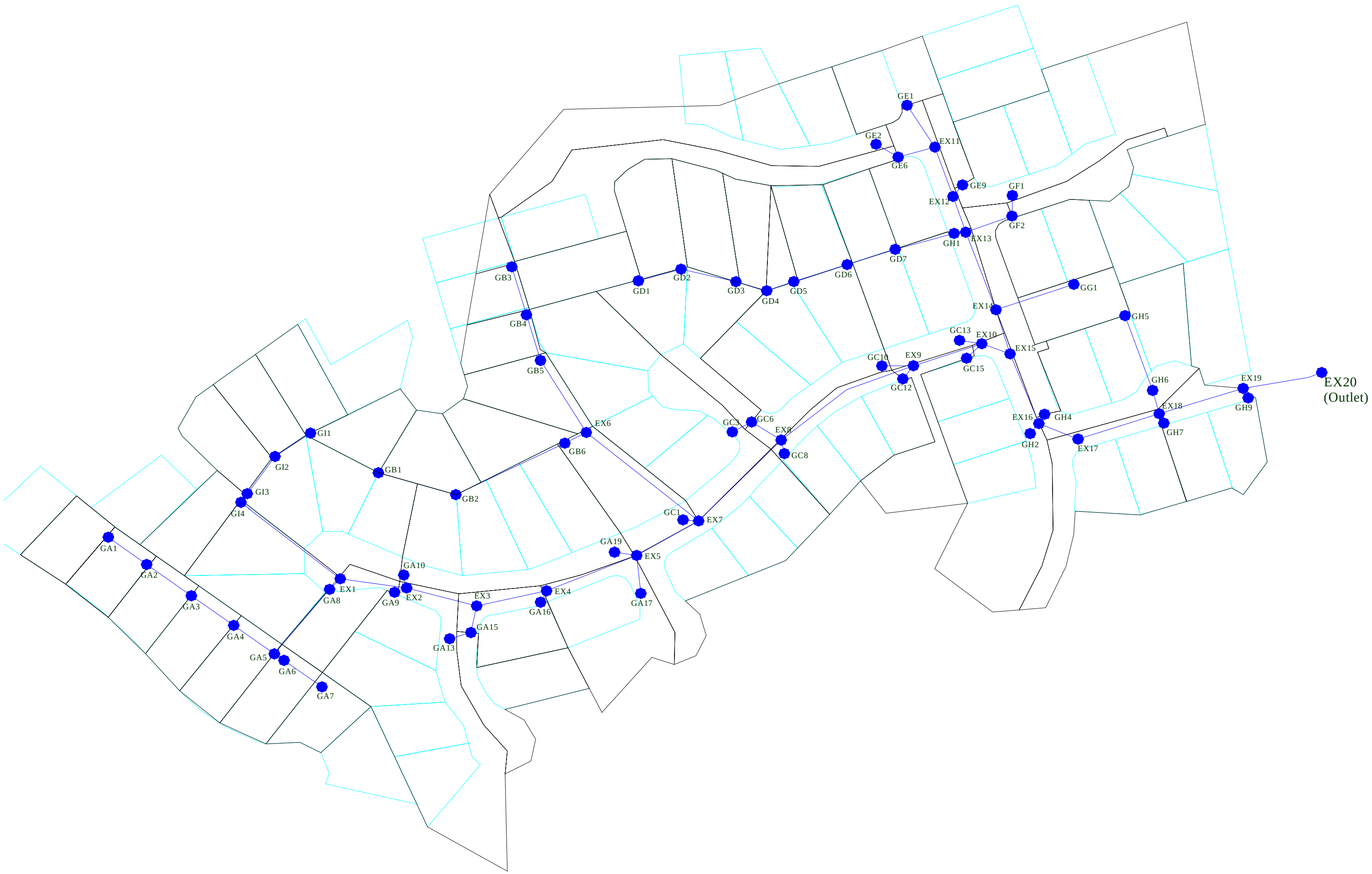


Figure 7.4 – Drainage network and catchment sub-divisions for Birdlife Park

7.3 Model Calibration

Model calibration is one of the more important requirements in hydrologic modelling. Calibration involves the estimation of model parameters which in turn enables the model to closely match the behaviour of the natural system which it is meant to represent. There are situations where the model parameters can be estimated using physically-based measurements. However, in most cases, the model parameters need to be estimated by trial-and-error processes (Gupta and Sorooshian, 1998).

Even after a model is calibrated to a high level of accuracy, there can be significant uncertainty involved in its predictions (Pilgrim et al., 1981). However, hydrologic modelling is the most reliable and accurate method of runoff estimation based on the current state of knowledge, provided that the model is calibrated and used with care. The primary uncertainty of hydrologic model prediction is due to the lack of measured data for calibration. Generally, hydrologic models are calibrated using a number of rain events that cover only a limited range of possible variations in rainfall characteristics. Therefore, it is hard to justify the accuracy of prediction, particularly for those rain events outside the calibrated range.

As noted by Beven and Binley (1992), further uncertainties associated with calibration of models arise due to structural errors in the model and errors in measurements and observations. The calibration procedure compensates for such structural, measurement and observational errors by varying model parameters. Therefore, the parameter set obtained during calibrations may not be the true set of parameters. It is hard to eliminate such errors, but they can be minimised by using quality measurements and observations. As discussed in Section 4.3, measurements were obtained using reliable measuring systems and equipment. However, the quality of measurements alone does not eliminate the problems associated with the calibrated model parameters. It is essential to have a systematic calibration procedure to develop more reliable model parameters (Gupta and Sorooshian, 1998).

Various numerical procedures have been developed in order to assist model calibration (Madsen, 2000; Seibert et al., 2000). These procedures, commonly referred to as 'automatic calibration', use different types of optimisation techniques to generate a set of parameters so that the model output closely matches the measured response. However, the useability of these techniques is still limited to reduce the parameter space for manual calibration (Mike STORM, 2004). Mike STORM has an automatic option that can be used to assist model calibration. However, it is recommended to confirm the outcome manually. As noted by Beven and Binley (1992), automatic calibration procedures can often lead to error due to inter-correlation of parameters and an excessive number of parameters. Therefore, in this study it was decided to use the automatic calibration procedure only to estimate the initial parameters and the final calibration was done manually.

7.3.1 Measured Data for Calibration

Data for model calibration was obtained from the procedure explained in Section 4.3.2. As explained, state-of-the-art technology was used to obtain both rainfall and runoff data. The rainfall data was obtained from a tipping bucket rain gauge which was situated within a 2 km proximity to the study catchments. It is acknowledged that the spatially distributed nature of rainfall events could influence the accuracy of predictions (Shah et al., 1996). In order to account for such variability, the recommended method is to include data from surrounding rain gauges. However, the available rain gauges in the region were further apart from the study catchments. Inclusion of data from these surrounding gauges, therefore, was not considered to be feasible. It was hypothesised that an accurate model can be developed using records from the closest rain gauge. Consequently, the spatial distribution of rainfall was not considered.

The runoff from each catchment outlet has been measured for a range of storm events since 2002. Measurements have been primarily done for runoff depth and later converted to runoff rate using rating tables. The runoff data was in 15 min time intervals.

The model calibration was based on selected rainfall events where measured rainfall, runoff and water quality data is available. These events were selected by careful inspection of the available data. The same events were used for the calibration and verification of hydrologic models. Therefore, the error of calibration due to the selection of non-representative data was minimal. Table 7.2 shows the number of events selected for calibration and verification.

Table 7.2 – Number of events used for calibration and verification

Model Name	Number of Events for Calibration
Alextown	7
Gumbeel	7
Birdlife Park	13

7.3.2 Methods and Parameters

Mike STORM consists of a range of hydrologic and hydraulic analytical models as noted in Table 7.1. It is totally at the discretion of the user to decide which combination of models is suitable for the task. The nature of the research and outcomes required are decisive factors in such selection. For this study, the model was developed using the 'time area method' to simulate catchment hydrologic behaviour. The 'dynamic wave' model was used for pipe flow modelling. The hydrologic model based on the time area method was used since the same procedure was to be used in pollutant translation as a part of the water quality estimations. The method was first developed by Laurenson (1962) and is used in a range of models such as ILSAX and DRAINS (O'Loughlin and Stack, 2004). Further discussion on the time area method and other catchment modelling approaches can be found in Section 2.5.2(D).

Altogether five parameters are needed for the calibration of the Mike STORM model. Those parameters are:

1) Time of concentration (Tc);

2) Reduction factor (Rf);
3) Initial loss (IL);
4) Time area coefficient (*a*); and
5) Manning's roughness (n).

Time of concentration (Tc) is one of the most critical parameters which govern the efficiency of the drainage system. The parameter primarily varies with slope, drainage length and a range of other factors. However, to maintain simplicity, effort was made to obtain constant Tc for the sub-areas in each catchment. Variable Tc values were used when the quality of the calibration became poor. In such cases, Tc was selected based on the size of the sub-area. Catchment area is one of the primary measures that influences the time of concentration (Askew, 1970; Boyd et al., 1979). The calibrated constant values for Tc for Gumbeel and Birdlife Park sub-areas were 20 and 10 min respectively. For Alextown catchment a range of Tc values were used depending on the extent of the sub-areas. The values were 2, 8, 20 and 25 min for <100, 100 – 1200, 1200 – 1400 and greater than 1400 m^2 extents respectively.

Reduction factor (Rf) is primarily a measure of the ratio of directly connected impervious surfaces and the total impervious surfaces. As noted in Section 4.3, the total impervious surfaces was measured using aerial photographs. However, it was difficult to identify the directly connected impervious surfaces visually. Boyd and Milevski (1996) suggested the analysis of volume ratio between runoff and rainfall would be the most feasible approach to obtain the fraction of directly connected impervious surfaces. The study they did on 29 catchments revealed that only about 75% of the impervious surfaces measured from aerial photographs were directly connected. A similar analysis conducted for the study catchments found that around 90% of the impervious surfaces were directly connected. Consequently, 0.9 was initially used as Rf for all three catchments and was subsequently refined during the calibration process. The final values obtained were 0.95, 0.82 and 0.70 for Alextown, Birdlife Park and Gumbeel catchments respectively.

Impervious surface initial loss (IL) was one of the more important parameters that was decisive in determining runoff volume. IL was determined by calibration and commenced with the default value of 0.6 mm. As noted by Boyd et al. (1994) and Boyd and Milevski (1996), the impervious area initial loss can vary from 0 to 5 mm depending on the surface type and initial moisture content on the surface. IL can vary from event to event depending on the initial moisture content of the catchment surface. However, for simplicity of this study, a common value of IL was used for all events per catchment. After calibration using the selected storm events, the common IL values selected were 3, 0.3, and 5 mm for Alextown, Birdlife Park and Gumbeel catchments. The values obtained for IL could be influenced by the selected range of storm events for the calibration. Furthermore, the difference in IL for the three catchments could be due to factors such as variation of directly connected impervious fraction and variation in road surface condition.

The time area coefficient (*a*) primarily represents the shape of the catchment sub-area. As stated in the Mike STORM user manual (Mike STORM, 2004), the coefficient '*a*' can vary from 0.5 to 2. Physically, 0.5 and 2 denote convergent and divergent triangular shapes. The coefficient for a rectangular catchment shape is 1 and it makes the time area diagram linear. During the demarcation, all effort was made to maintain similar length width ratio for sub-areas. Additionally, several hydrologic models, for example ILSAX use a linear time area diagram which means *a* has a constant value of 1. Therefore, *a* was considered to be 1 for all the catchments and for all the events for this study.

Manning's roughness is the primary parameter used for pipe and channel flow routing. The drainage networks of all three study catchments were predominantly precast reinforced concrete pipes. Typical Manning's roughness coefficients for such pipes are in the range of 0.012 to 0.015 (Mike STORM, 2004; O'Loughlin and Stack, 2004). However, the roughness coefficients may vary from the default range due to various reasons. Firstly, a pipe network consists of joints and gully pots which typically have high flow resistance when compared to pipes. This makes the overall flow resistance higher for the drainage network and should be compensated from pipe roughness.

Secondly, pipe roughness may alter from its original value due to erosion and depositions. However, due to comparatively shorter drainage networks, the influence of Manning's roughness was not clearly visible for the simulated hydrograph. Therefore, the default value for smooth concrete (0.012) was used for all the models.

7.3.3 Calibration Sequence

As a range of parameters was available for calibration and some of them were correlated to each other, extra care was needed during calibration. For example, both initial loss (IL) and reduction factor (Rf) theoretically alter the runoff volume in model response and it was difficult to decide which parameters were to be adjusted in order to calibrate runoff volume with the measured response.

To avoid the correlation of adjusted parameters in model response, a definite sequence of calibration was used. The first step was to adjust Tc so that the peak discharge from model response and observed runoff coincides. For Alextown catchment, multiple combinations of Tc were used for calibration since different Tc values were assigned for different area categories. The second step was to adjust Rf and IL so that the simulated runoff volume is closely comparable with the measured runoff volume. These two steps were repeatedly adjusted so that the model response was closely similar to the measured hydrographs. Default values of *a* and n were used during the calibration.

During the calibration, optimum parameter sets were first obtained for each calibration event. After careful investigation of parameter sets, common values were selected to represent models for each catchment. Using the common values obtained, simulations were done for each event and the performance was evaluated. Evaluations were done for both peak discharge and runoff volume. Figure 7.5 shows the variation of ratio between simulated and observed peak discharges, and Figure 7.6 shows the variation of ratio between simulated runoff volume and observed runoff volume.

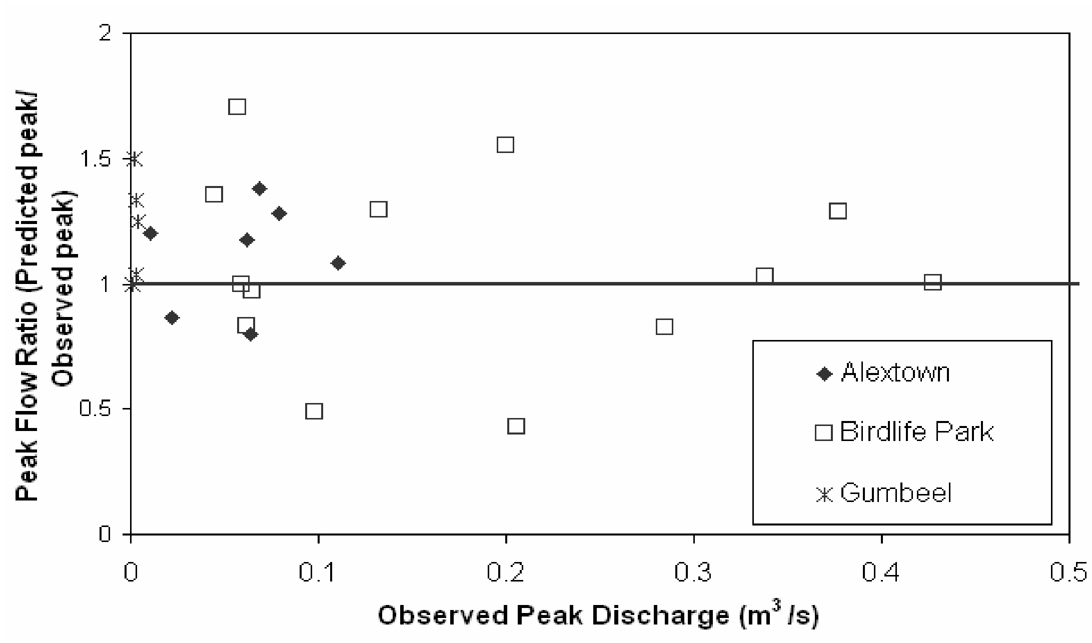


Figure 7.5 – Variation of peak flow ratio with observed peak discharges

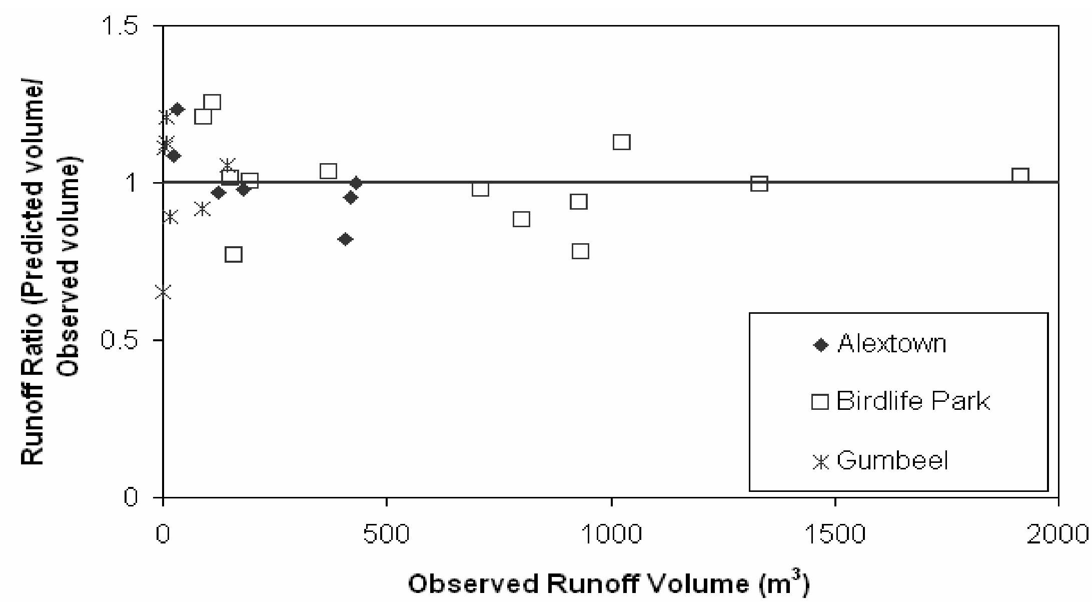


Figure 7.6 – Variation of Runoff volume ratio with observed runoff volume

As seen in Figures 7.5 and 7.6, though significant data scatter is noted, it can be considered that both simulated peak discharge and runoff volume are closely similar to the observed peak discharges and runoff volumes. The averages of the peak flow ratio and runoff volume ratio are 1.13 and 1.0 respectively. The peak flow prediction illustrates less consistency with CV being 30%. However, due to the low runoff rates noted for all the catchments, the accuracy obtained for peak flow predictions was considered to be in an acceptable range. The CV for volumetric predictions was 14%. This suggested consistently accurate simulation of correct volumes by calibrated models. Since the models were only used to facilitate the estimation of water quality by translating pollutant concentrations from sub-areas to catchment outlets, the predictive ability for this range was considered adequate.

7.4 Conclusions

Three models were developed to simulate hydrologic features of three urban catchments, Alextown, Gumbeel and Birdlife Park. These three models were calibrated for a range of storms so that they replicate catchment hydrologic features. The same storm events which the models were intended to simulate were also used for calibration. In this way, it was possible to develop the best calibrated models for the intended use.

The parameter set obtained for each model was the optimal for selected storm events. Therefore, some of the calibrated parameters such as IL were different for the three catchments. It was considered that this is due to the differences in selected storm events, differences in the percentage of directly connected impervious surfaces of catchments and differences in road surface conditions. With optimum parameter sets, notable differences in prediction were observed for the three catchments. This was in comparison to the measured peak discharge and runoff volume.

Chapter 8 - Development of Translation Procedure

8.1 Background

Accurate and reliable estimation of stormwater quality is highly valued in urban planning, catchment management and the design of stormwater treatment measures. Water quality modelling is the primary tool used for such estimations. Water quality models are typically based on the understanding gained about key pollutant processes. The primary understanding of pollutant processes has been gained by detailed investigations into small-plot surfaces (Letcher et al., 2002). For example, Sartor et al. (1974) carried out a comprehensive investigation to understand key pollutant processes on road surfaces. This investigation led to a better understanding of two key pollutant processes namely, build-up and wash-off, and formed the base for a significant number of water quality estimation models. Similar investigations for different land-uses and regions have strengthened the knowledge base on these processes (for example Ball et al., 1998; Deletic and Orr, 2005; Sartor et al., 1974; Vaze and Chiew, 2002).

Although an in-depth understanding of small-plot pollutant processes is used, stormwater quality modelling is highly complex. This is primarily attributed to three factors. Firstly, the understanding gained on small-plot pollutant processes is not totally adequate to fully account for highly variable urban conditions. It can lead to inaccuracies in estimations, and mismatches in the pollutant process used. Therefore, further understanding on pollutant processes and associated physical parameters is needed. Secondly, the estimation approach used in water quality models based on these processes is complex. Typical water quality models are replications of both pollutant and hydrologic processes in sequential order similar to natural occurrence. In order to achieve higher accuracy, these replications are typically integrated into one platform and simulated in small time steps. Thirdly, in order to use such complex and highly detailed models, a large array of data is needed. The data requirement is primarily for the setting up of the model and for calibration and verification purposes. Due to resource constraints, such data is difficult to obtain (Grayson et al., 1999; Letcher et al., 2002; Letcher et al., 1999).

This research is intended to create further knowledge relating to the inherent complexities that arise in stormwater quality modelling. Chapters 5 and 6 developed a detailed understanding of the build-up and wash-off processes. This chapter focuses on the development of a simplified but robust procedure to estimate catchment scale water quality using the knowledge developed on small-plot pollutant processes. It is hypothesised that the difficulties highlighted are primarily associated with the complex approach of using knowledge of small-plot pollutants processes in water quality modelling. The complexities that arise in modelling do not diminish the validity of the understanding gained on small-plot pollutant processes. Though the understanding is not necessarily comprehensive, it provides fundamental scientific explanations on pollutant processes. This concept strengthens the validity of the use of small-plot pollutant processes in water quality modelling. However, the approach adopted in the application of this knowledge in water quality modelling should not be complex and should have reduced data and resource requirements.

This chapter reports on the development of the approach to translate knowledge on small-plot pollutant processes to catchment scale, leading to a simplified stormwater quality estimation procedure. Initially, as part of the development of this procedure, the degree of validity of small-plot pollutant processes for catchment scale water quality was investigated. This was done by comparing the predicted water quality at the study catchment outlets to measured water quality. The predictions were done by simultaneously replicating pollutant and hydrologic processes which is the typical approach adopted in simulation procedures in water quality models.

8.2 Estimation of Pollutant Build-up

Pollutant build-up was estimated using the build-up replication equations developed in Chapter 5. As discussed in Chapter 5, build-up primarily varies with antecedent dry days, land-use and impervious surface type. Although build-up is subjected to such variability, it was possible to develop a single replication equation. The variability of build-up was accounted for by using different sets of coefficients for the build-up equation.

A Road Surfaces

The pollutant build-up equation as discussed in Chapter 5 is in the form of:

$$B = aD^b$$

The corresponding build-up coefficients for the equation are multiplication coefficient *a* and power coefficient *b*. Values for these coefficients were developed for two residential urban forms, as noted in Section 5.3.2. The coefficient values are as shown in Table 8.1.

Table 8.1 – Parameters for build-up on road surfaces

Urban Form	*a*	*b*
Townhouse regions (high population density)	2.90	0.16
Single detached housing regions (low population density)	1.65	0.16

However, it was noted in Section 5.3.3 that the estimations obtained from using Equation 5.1 give only the lower limit of the build-up. The total amount of pollutant build-up further depends on the pollutant load remaining after a removal event such as a stormwater runoff event. The most appropriate way to incorporate the pollutant existing after such an event into the estimation is explained in Section 5.3.3 as a hypothesis. However, the primary mathematical parameters defining the hypothesis are not well known. Therefore, a simplified approach to the hypothesised build-up mechanism was developed as illustrated in Figure 8.1.

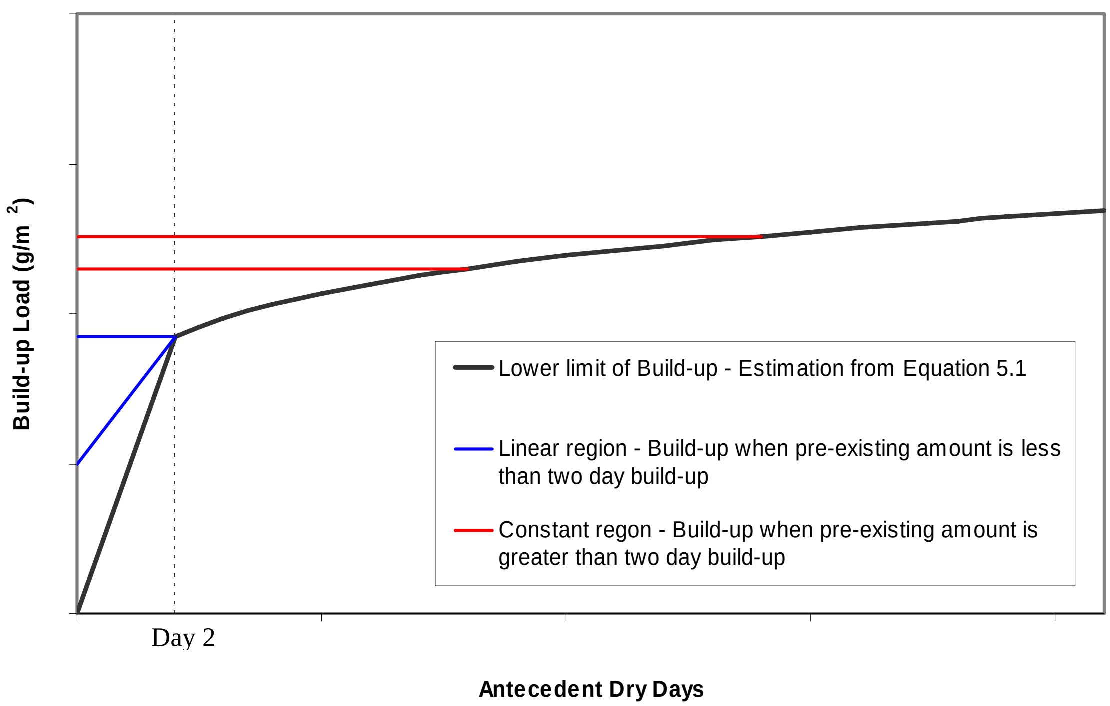


Figure 8.1 – Simplified Build-up model

A simplified curve of build-up was developed based on two facts. Firstly, as noted in Section 5.3.3, the influence of the pollutant amount remaining after a wash-off event (or pre-existing pollutants) is limited when the number of antecedent dry days is high. This is based on the understanding that the build-up asymptotes to a constant value irrespective of the amount of pre-existing pollutants. Therefore, the estimation based on Equation 5.1 is closely accurate when the number of antecedent dry days is high. Secondly, the high build-up rate is limited to the first two days. This is the region where the influence of pre-existing pollutants is significant. However, the variation of build-up for this region when the pre-existing pollutants are available is not directly known. It was assumed that the variation is linear. A linear variation is acceptable in defining build-up even when no pre-existing pollutants are available on the surface.

In order to estimate total build-up on roads, the antecedent dry period was first obtained by investigation of rainfall records. Dry days were counted from the time of the end of the previous storm. During the count, storms with less than 5 mm rainfall were disregarded. It was found that the storms with less than 5 mm rainfall produce little runoff and are not capable of creating significant wash-off. Equation 5.1 was directly applied if the antecedent dry days are greater than 21 days. For antecedent dry days less than 21 days, the amount of pre-existing pollutants was estimated by analysing the previous storm and the simplified variation (as shown in Figure 8.1) was used to estimate build-up. The estimation procedure is further explained in Section 8.6.2. Appendix F, Table F.1 shows the estimated build-up for sample storm events for the three study catchments.

B Roof Surfaces

Equation 5.1 with a different set of coefficients was used to estimate the pollutant build-up on roof surfaces. The coefficient set is given in Table 8.2.

Table 8.2 – Build-up coefficients for roof surfaces

Impervious surface type	*a*	*b*
Roof surfaces	0.43	0.266

As observed in wash-off investigations, a high fraction of pollutants are washed-off from roof surfaces even for relatively small storm events. This means that there are very limited pollutants remaining on roof surfaces after most frequent storm events. Therefore, additional approaches to account for pollutants remaining after a wash-off event would not be required. The estimates derived from Equation 5.1 with appropriate coefficients were considered adequate for the analysis. Appendix F, Table F.1 gives the estimated pollution build-up for the three study catchments.

8.3 Estimation of Fraction Wash-off (F_W)

As noted in Chapter 6, fraction wash-off can be replicated using an exponential equation in the form of:

$$Fw = C_F(1 - e^{-kIt})$$

The variability accounted for in Equation 6.3 is rainfall intensity and duration. Though the variability of rainfall intensity and duration was included, the equation was originally developed for continuous and uniform rainfall events. However, most of the natural storm events show significant temporal variation. Equation 6.3 was not designed to account for such temporal variability. Therefore, an appropriate strategy was needed to account for the temporal variability of rainfall.

8.3.1 Wash-off Model

In order to account for the temporal variability of rainfall events, a conceptual wash-off model was developed. The wash-off model was primarily a strategy to select an appropriate wash-off curve depending on rainfall intensity, and an appropriate time of simulation depending on the fraction washed-off. It was required to change over between curves to calculate total F_W when the rainfall is temporally variable. The basis for such changeover was to select the starting point of the wash-off curve corresponding to the given rainfall intensity based on the fraction of pollutants left on the surface after the previous burst. Figure 8.2 illustrates the graphical interpretation of the wash-off model. As an example, it explains the wash-off prediction for a hypothetical event with 20, 65 and 40 mm/hr intensities of 25 min duration.

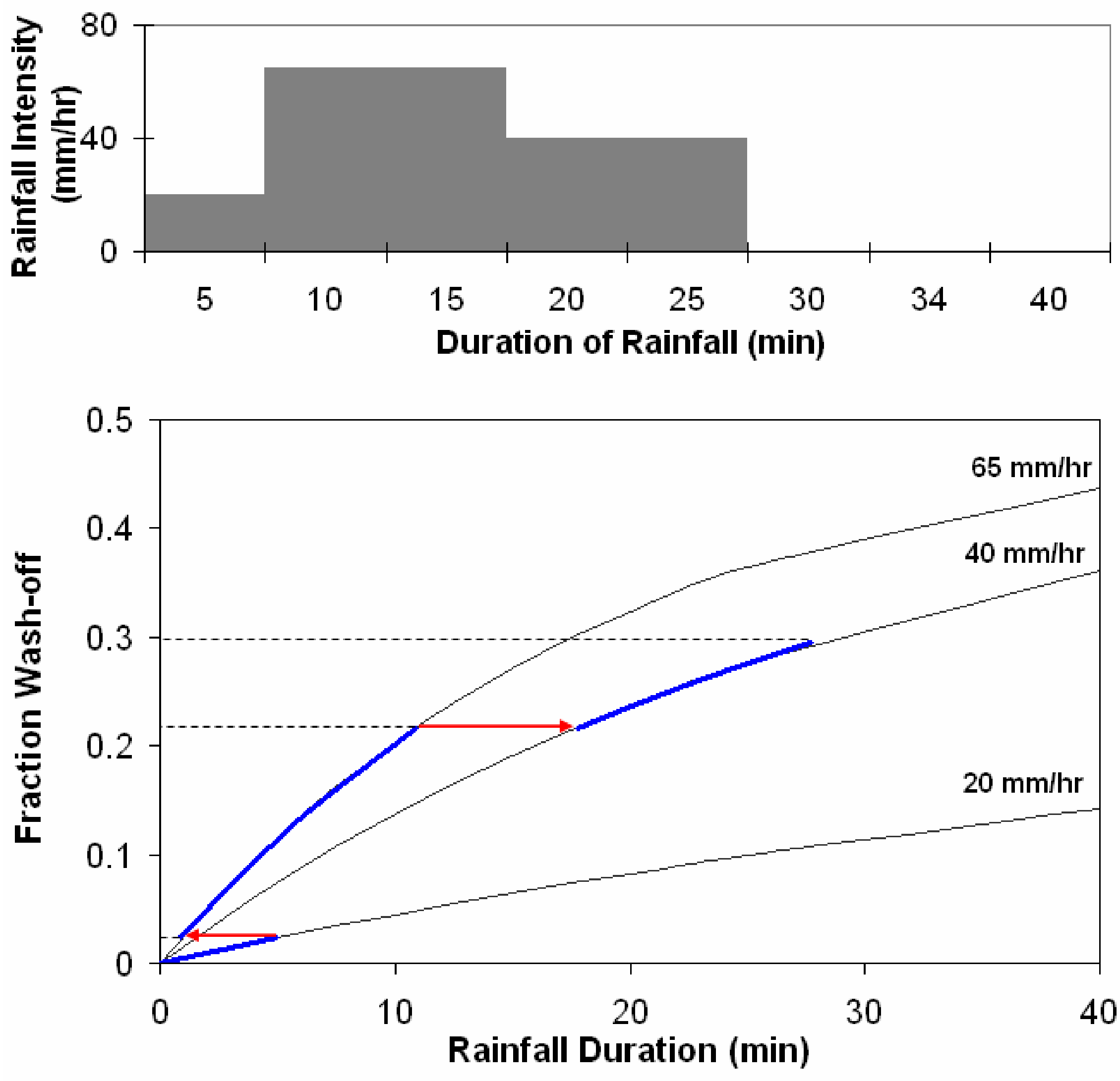


Figure 8.2 – Conceptual wash-off model

Figure 8.2 explains the methodology adopted to calculate total F_W for an event when the intensities are temporally variable. For the initial 5 min duration (20 mm/hr intensity), F_W is estimated using the original wash-off equation. Then, for the second 10 min duration (65 mm/hr) F_W is determined commencing from an initial value equivalent to the previously determined F_W for 20 mm/hr intensity. This is done by drawing a line parallel to the horizontal axis to intersect the 65 mm/hr intensity curve as shown. Accordingly, it is possible to account for the continuity of the event and calculate the F_W for the next 10 min duration based on the fraction of pollutants available on the surface. In simple terms, the wash-off model assumes that the 5 min continuation of 20 mm/hr intensity is equivalent to approximately 1 min continuation of the 65 mm/hr event. This is based on the fact that both events result in the same F_W. Then the second 10 min duration starts from the time determined, which is approximately 1 min. The calculations then continue as illustrated in Figure 8.2. The final value of F_W represents the total fraction of pollutant wash-off for the complete rainfall event. The main features of the wash-off model are:

1) The method automatically calculates F_W based on the remaining fraction of pollutants on the surface.
2) The model considers rainfall time series as a continuous event and estimates the overall capacity to mobilise pollutants depending on a range of intensities. This means that it is possible to generate zero wash-off for a low intensity rainfall time step preceded by a high intensity rainfall time step. The primary reason for this is that the capacity of the rainfall event is already reached prior to the low intensity time step. The capacity of the event is therefore considered as a reflection of all the previous rainfall time-steps continued up to a particular time step.
3) The model does not necessarily replicate the exact rainfall duration. The starting point for a rainfall time step is the F_W value corresponding to the previous time step.

Calculation of the fraction wash-off based on the above methodology was done using Visual Basic Macros in Microsoft XL. Appendix F, Figure F.1 shows the sample calculation undertaken for road surfaces.

8.3.2 Parameters and Estimation Procedure

Other than the rainfall intensity and duration, F_W is influenced by parameters such as surface type, texture depth of the surface, and slope of the surface. Variability of these parameters is accounted for by specifying different parameter sets for Equation 6.3. As noted in Chapter 6, two parameter sets were developed for road and roof surfaces.

A Road Surfaces

Prediction of fraction wash-off from road surfaces was conducted using the parameters developed in Chapter 6. The parameters used for prediction are given in Table 8.3.

Table 8.3 – Wash-off parameters for road surfaces

Parameter	Range	Value
Capacity factor C_F	5 to 40 mm/hr	(0.01 x **I**) + 0.1
	40 to 90 mm/hr	0.5
	90 to 133 mm/hr	(0.0098 x **I**) – 0.38
Wash off coefficient *k*	All intensities	8×10^{-4}

I - Rainfall intensity

As seen in Table 8.3, linear variation of C_F for the intensity ranges 5 to 40 mm/hr and 90 to 133 mm/hr were adopted. These variations are based on observations and analytical outcomes as noted in Chapter 6.

For the prediction of fraction wash-off, all the selected rainfall events were converted into temporal patterns of 5 min time steps. Rainfall events with a time step of 5 min are in the typical format used for hydrologic modelling. This conversion resulted in a significant number of time steps with relatively less intense rainfall. However, the calculations revealed that most of these small intensity time steps are not capable of producing a significant F_W value. This led to the adoption of a threshold value for rainfall intensity where the intensities lower than threshold is not considered for the calculations. The threshold rainfall intensity value adopted was 5 mm/hr.

Although the threshold for rainfall intensities was 5 mm/hr, the lowest rainfall intensity simulated was 20mm/hr. This means that in order to calculate the F_W for intensities less than 5 mm/hr, extrapolated parameter values needed to be used. Therefore, the possibility exists that this approach can introduce errors in the estimation. However, due to comparatively low F_W values resulting for less intense rainfall events, the magnitude of these errors would be limited. Furthermore, the presence of high rainfall intensity time steps in rainfall events, which results in high F_W values would further reduce the impact of such errors.

B Roof Surfaces

A different set of parameters was developed for the estimation of F_W from roof surfaces. These parameters are given in Table 8.4.

Table 8.4 – Parameters used for the fraction wash-off estimations from roof surfaces

Parameter	Range	Value
Capacity factor C_F	5 to 40 mm/hr	(0.008 x **I**) + 0.59
	40 to 90 mm/hr	0.91
	90 to 133 mm/hr	(0.0036 x **I**) + 0.59
Wash off coefficient *k*	All intensities	9.33×10^{-3}

I - Rainfall intensity

Similar to road surfaces, the variations of C_F were defined by analysing the outcomes from Chapter 6. An approach similar to that for road surfaces was employed to estimate the fraction wash-off time series.

8.4 Estimation of Stormwater Quality

It is well known that impervious surfaces are not the only pollutant sources in the urban environment. Other sources such as pervious surfaces, channel beds and previously deposited sediments in the drainage network can also contribute to the urban stormwater pollutant load. However, contributions from these sources are highly variable. For example, Bannerman et al. (1993) noted that the pollutant contribution from pervious surfaces is highly dependent on the rainfall depth. For storm events with low rainfall depth, the pollutant contribution from pervious surfaces could be relatively very little due to low runoff, high rate of infiltration and pollutant trapping within rough surfaces. For storms events with large rainfall depth, pervious surfaces can be a large pool of pollutants, particularly sediments. However, many researchers have noted that the pollutant contribution from impervious surfaces is the major component in stormwater runoff. Most researchers have specifically focused on road surfaces due to their critical role in contributing stormwater pollutants (Bannerman et al., 1993; Bertrand-Krajewski et al., 1998; Deletic and Orr, 2005; Sartor et al., 1974; Shaheen, 1975).

These observations suggest that the pollutant contribution from impervious surfaces can be either major or minor depending on the nature of the storm event, characteristics of the drainage network and the catchment management practices. This means that for a given catchment with known catchment and drainage characteristics and for common regional rainfall characteristics, the relative fraction of pollutants originating from impervious surfaces could be within a constant range. Based on the above argument, it is important to understand the relative fraction of pollutant contribution from impervious surfaces. Furthermore, outcomes of such analysis provide important information as to how representative small-plot pollutant processes are in catchment scale water quality predictions.

The pollutant contribution from urban impervious surfaces was estimated based on pollutant build-up and wash-off processes. The methodology adopted when using these pollutant processes is discussed in Sections 8.2 and 8.3. Apart from these processes, both hydrologic and hydraulic processes were also simulated to estimate the runoff. This was to calculate the pollutant concentrations. The comparison of estimated pollutant concentration with the observed value was done in two stages. Firstly, the comparison was 'event based', which compared the event mean concentrations (EMCs) of estimated and observed water quality. Secondly, instantaneous concentrations extracted from the estimated pollutographs were compared with the corresponding instantaneous observations.

8.4.1 Event Based Water Quality Comparison

The estimations of pollutant amounts washed-off from road and roof surfaces were done separately. These were later added together in order to determine the total amount of pollutants washed-off. Calculation of pollutants washed-off from each impervious surface type was determined by multiplying the amount of build-up per unit area by the total area of impervious surface and fraction wash-off. The outcomes of the calculations are presented in Appendix F, Table F.1. The total area of road and roof surfaces for each catchment was determined using aerial photographs. Greater details of impervious area calculations can be found in Section 4.3.1. Mean pollutant concentration for each event was calculated by dividing the estimated load by runoff volume. The mean concentration calculated for each rain event was compared with the measured event mean concentrations for each catchment as shown in Figure 8.3.

It was found that driveways represent a significant fraction of impervious areas in urban catchments and hence could have an appreciable influence on runoff quality. For the three study catchments: Alextown, Birdlife Park and Gumbeel, the fraction of driveway area to total catchment area are 8.6%, 11.2% and 11.2% respectively. For the analysis, driveways were considered to have similar build-up and wash-off properties to road surfaces. This assumption is more applicable for build-up estimations since driveways are subjected to similar traffic-related and atmospheric depositions and pollution re-distribution. However, due to relatively low texture depth of concrete driveways, the wash-off could be different to roads. Nevertheless, due to greater variability of primary surface characteristics such as texture depth, slope and porosity, the wash-off characteristics of driveways can be significantly different to that of roof surfaces. Hence, the adoption of wash-off replications of road surfaces for driveways was considered to lead to less error.

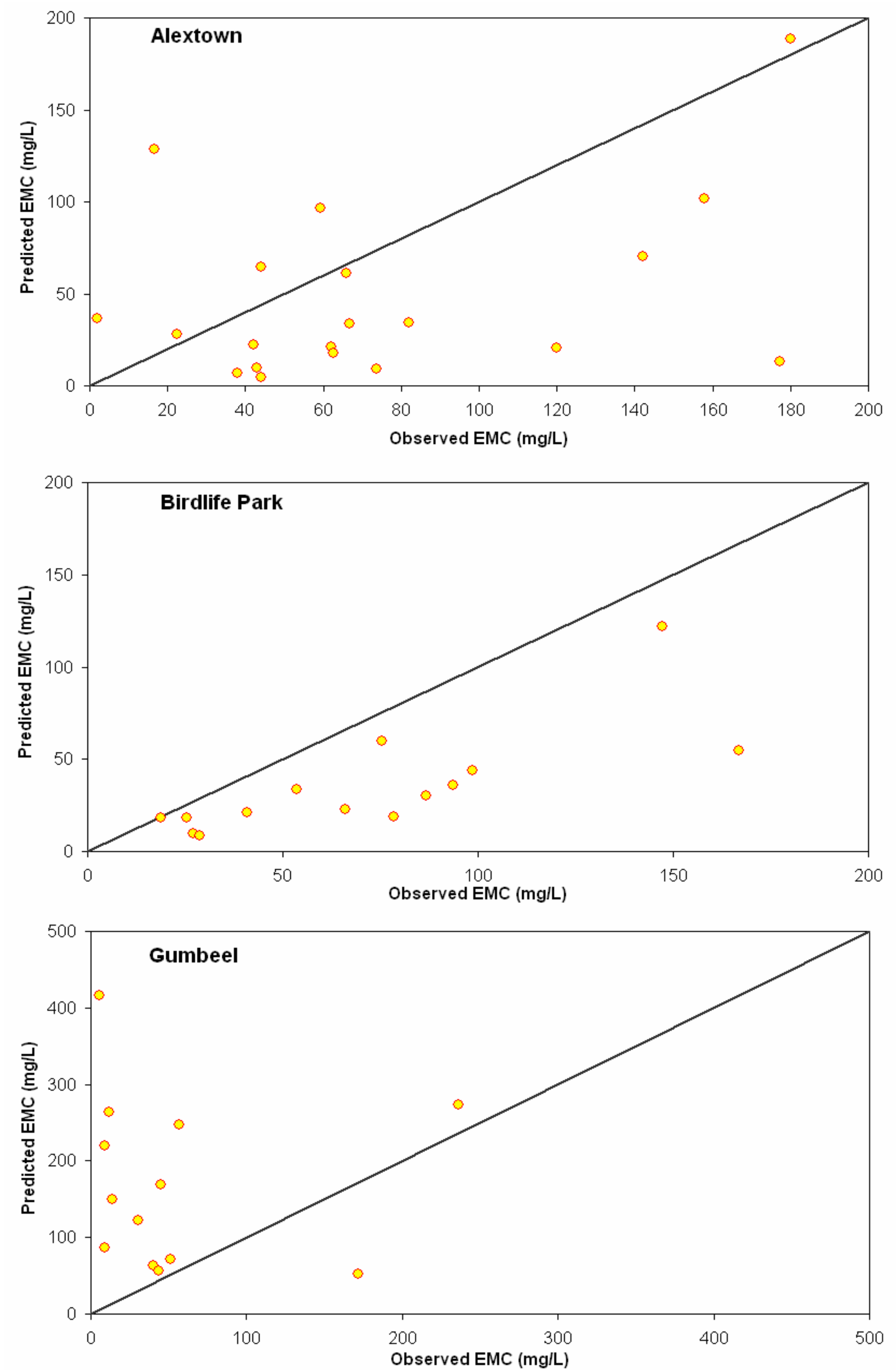


Figure 8.3 – Comparison of predicted and observed EMCs

In the analysis it was noted that a relatively higher amount of pollutants was originating from roof surfaces. For a significant number of events, the contribution from roof surfaces is even higher than the contribution from road surfaces (see Appendix F, Table F.1). This is due to the higher fraction wash-off from roof surfaces which can be primarily attributed to the relatively smoother surface texture and higher slopes when compared to road surfaces. This highlights the significance of roof surfaces as an urban water pollutant source. The significance is particularly important for low intensity storm events where a higher fraction of pollutants is washed-off from roofs when compared to roads.

As seen in Figure 8.3, event based estimation of water quality using small-plot pollutant processes is relatively unsuccessful. The estimated EMCs deviate significantly from the observed EMCs for most of the storm events. For the Alextown catchment, predictions are scattered compared to observed EMCs. The estimates relatively under-predict the water quality at Birdlife Park catchment whereas they over-predict the Gumbeel catchment water quality. The deviations between predicted and observed EMCs can be primarily attributed to the following factors:

1) The predicted mean concentrations represent pollutants from impervious surfaces only. Therefore, for the events where a significant fraction of pollutants originates from other sources, the observed and predicted water quality would be different.
2) Sampling from storm events was done by pumping from a constant height from the channel bed, irrespective of the flow depth. This could result in collecting non-representative samples.
3) EMC samples were prepared from the runoff samples typically collected 30 min apart. Due to the relatively smaller size of catchments and the 'flashy' nature of storm events, water quality can vary significantly during this time interval. This can lead to non-representative EMC results for events.
4) The predicted water quality was based on a number of assumptions and conceptual pollutant processes. This may introduce errors to the predictions.

The unsatisfactory correlation of predicted and observed EMCs suggested that the replication of small-plot pollutant processes is not satisfactory for predicting the event based water quality. However, due to the fact that non-correlation could arise from non-representative EMC measurements, comparison of instantaneous water quality was undertaken.

8.4.2 Comparison of Instantaneous Water Quality

Estimation of instantaneous water quality was undertaken by simulating pollutant build-up and wash-off processes along with hydrologic processes. The simulations were done so that the outcomes of each simulated process were temporally compatible. The technique used for simulation was similar to the techniques used in typical stormwater quality estimation models. Instantaneous water quality was then extracted from the predicted pollutographs and compared with the corresponding observed water quality. The estimated pollutographs were in 1 min time steps. The detailed procedure used for simulations and the estimation of pollutographs is discussed below.

A Pollutant wash-off time series

The pollutant load washed-off from a unit area of each surface type was calculated in 5 min time steps. This was done by multiplying the time series of fraction wash-off by build-up pollutant load. More details on the methodologies adopted to estimate build-up load and fraction wash-off time series are given in Sections 8.2 and 8.3 respectively. The resulting values for both road and roof surfaces were multiplied by their corresponding surface area in the catchment and added together in order to calculate the total amount of pollutants removed at each time step.

B Translation from Catchment Surfaces to Sub-area Outlet

Translation of estimated wash-off pollutant time series from catchment surfaces to sub-area outlets was done using a routing procedure. For this, each catchment was subdivided into sub-areas similar to the catchment subdivisions in Section 7.2. A routing procedure was developed based on the concept of the time-area method (see Section 2.5.2). When routing, each sub-area was considered to consist of strips with equal area, having different times of concentration. The pollutants originating from each strip were considered to arrive at the sub-area outlet at time periods according to their pre-assigned time of concentration. During the routing, the pollutant load belonging to each strip was calculated by multiplying each time step of the pollutant wash-off time series by the ratio between the strip area to total catchment area and impervious fraction. For ease of calculations, the routing procedure was coded as a Visual Basic Macro in Microsoft XL interface. Consequently, it was possible to use a Microsoft XL spreadsheet as the platform for rainfall and catchment data input and to obtain the resulting output. Appendix F, Figure F.2 gives the Microsoft XL spreadsheet and Figure F.3 gives the Visual Basic code.

The accuracy of the routing procedure was tested using a series of rainfall events instead of pollutant loads. This was done due to the similarities of the routing procedure to hydrologic routing. As the procedure is very similar to the method adopted in Mike STORM, the outcomes of the routing were compared with simulated runoff using this model. Furthermore, the primary parameters for the routing procedure were obtained from the calibrated Mike STORM models as noted in Section 7.3. A sample comparison is shown in Figure 8.4.

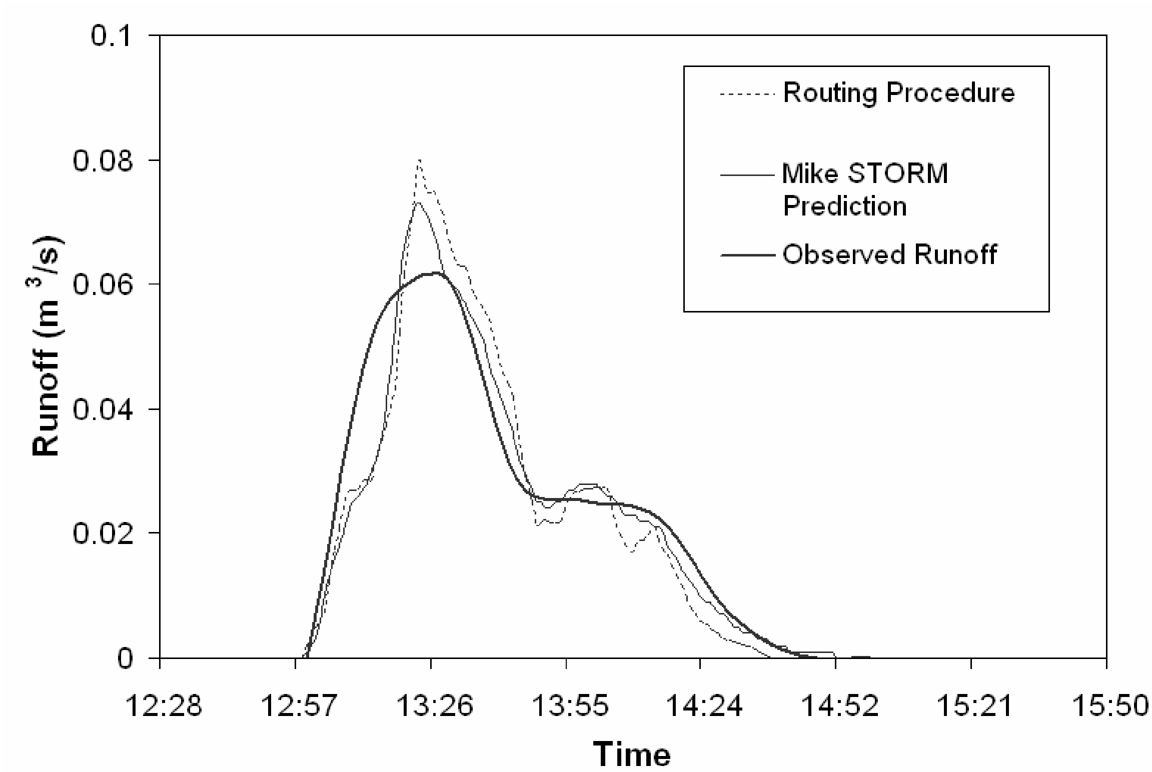


Figure 8.4 – Performance of the routing procedure

As evident in Figure 8.4, the prediction from the developed routing procedure is closely similar to the Mike STORM output. Considering the magnitude of the runoff rates, both predictions can be considered as replications of the observed runoff hydrograph. This indicates an appropriate level of accuracy from the developed routing procedure.

The use of the procedure for pollutant routing was based on the important assumption that the transportation of pollutants in overland flow occurs only by advection. The assumption is justified for suspended solids transport in highly turbulent overland flow. As noted in Chapter 6, overland flow is highly turbulent and pollutants are kept in suspension due to raindrop impact energy. The other means of pollutant transport such as dispersion are dominant only for the dissolved fraction and for low turbulent situations. Furthermore, the assumption is also justified for suspended solids transport in gutter flow due to the inherent high velocity and turbulence (Francos et al., 2001; Freyberg, 1986).

C Translation from Sub-area Outlet to Catchment Outlet

In order to obtain the pollutograph at the catchment outlet, the resulting pollutant load time series for sub-area outlets needed to be translated to the catchment outlet. This was done using the Mike STORM advection-dispersion (AD) routing model. However, the AD model is designed only to rout average pollutant concentrations from nodes to the catchment outlet. Therefore, the average pollutant concentration was calculated for each event. This was done by dividing the total pollutant load at each time step by the corresponding runoff volume. The total pollutant load time series was obtained by adding all the sub-area pollutant load time series together. The use of average concentration in pollutant translation provides sufficient accuracy.

Apart from the average concentration time series, Mike STORM (AD) also needs both hydrologic and hydraulic simulation results for each storm event. This was obtained by simulating calibrated Mike STORM models for each catchment, as explained in Chapter 7. In order to establish the accuracy of estimations, both estimated runoff and water quality were compared with the observed values. Figure 8.5 shows sample comparisons for the three study catchments.

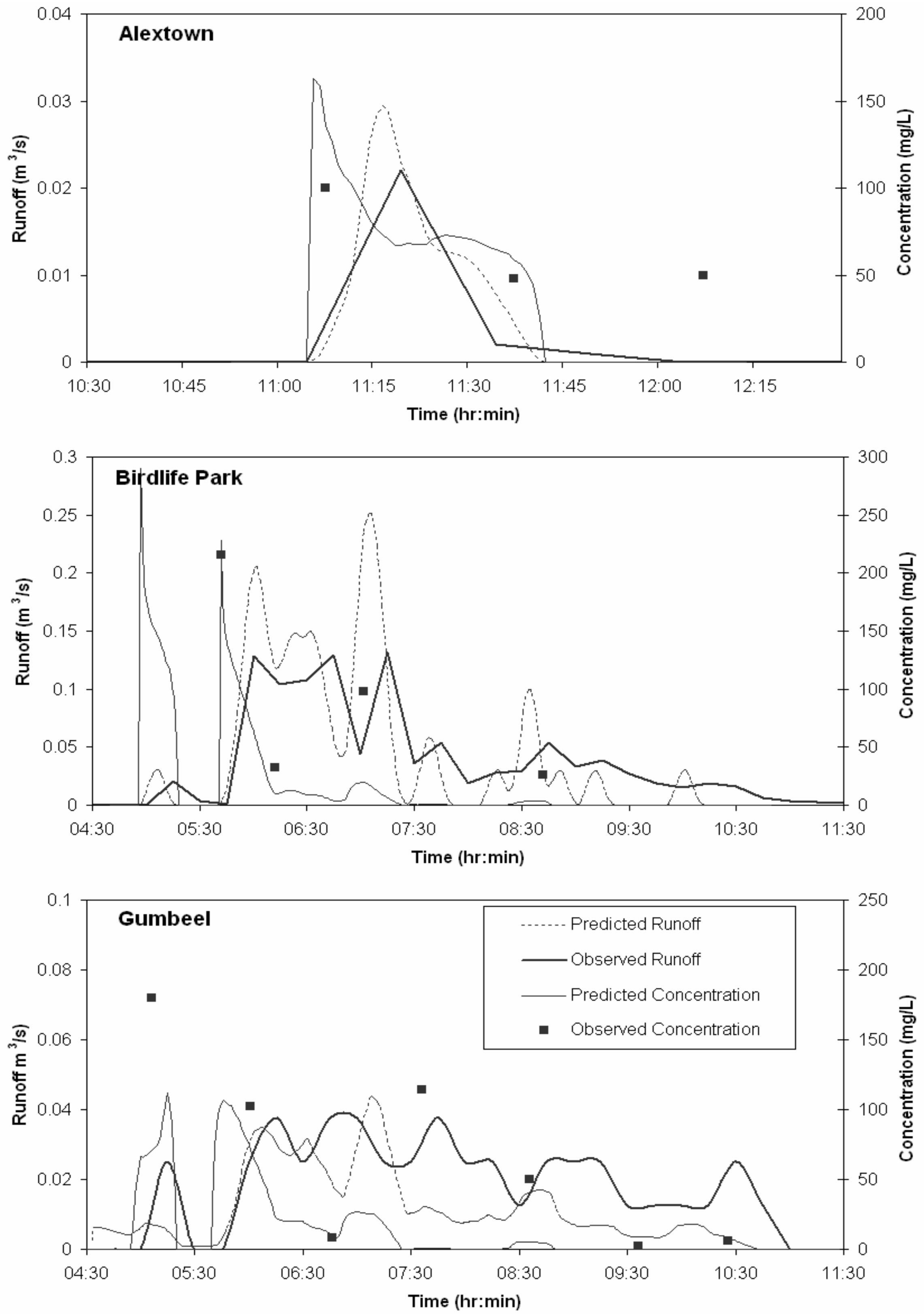


Figure 8.5 – Comparison of continuous water quality estimations with observed water quality

D Comparison of Predicted and Observed Water Quality

As noted in Section 4.3.2, runoff samples have been collected from the study catchment outlets and tested for a range of quality parameters. Apart from the quality parameters, the exact date and time where each sample was collected was also available. These data are referred to as instantaneous quality observations. From the estimated pollutographs, the instantaneous water quality records corresponding to the exact collection time of observed water quality records were extracted. However, prior to extraction, the time scale of predicted measurements was adjusted so that the predicted hydrograph peaks and starting points coincide with the peaks and starting points of observed hydrographs. In this way, it was possible to eliminate the non-synchronised data logging between the water sampling/flow measuring device and the rain gauge. The extracted data from the predicted pollutographs and observed instantaneous data was compared to understand the predictive capability. Figure 8.6 shows the comparison of observed and predicted instantaneous water quality for all catchments. Appendix F, Figure F.4 gives the comparisons for individual catchments.

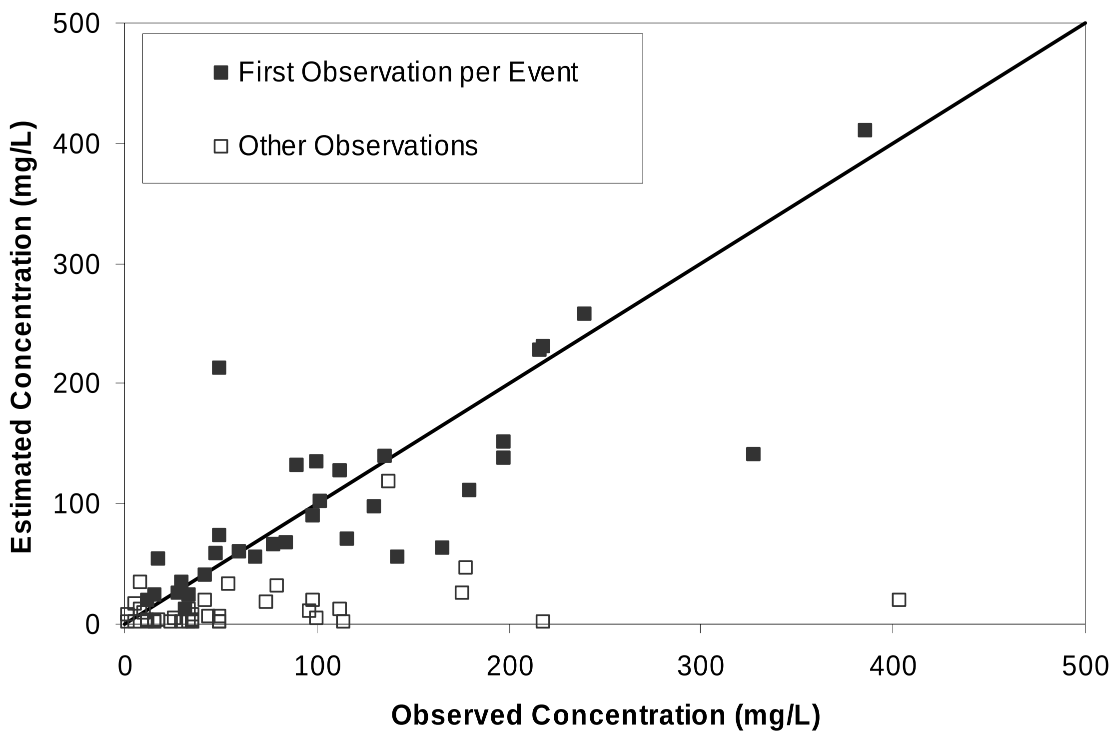


Figure 8.6 – Comparison of observed and predicted instantaneous concentration

As seen in Figures 8.5 and 8.6, the variation of predicted water quality with respect to observed water quality illustrates a common pattern. However, it is quite clear that the predictions do not give perfect accuracy. It is commonly accepted that the prediction of water quality is subjected to a high degree of variability. Consequent to the range of simplifying assumptions used in predictions, the water quality estimations are subjected to a high degree of uncertainty (Ahyerre et al., 1998; Huber, 2001). Additionally, non-representative water sampling can lead to errors in observed water quality which in turn reduces reliability when used for comparison. Considering these facts, it can be concluded that the results obtained from the continuous water quality prediction are within an accuracy range typical of those described in numerous research studies (for example Ahyerre et al., 1998; Huber, 2001; Im et al., 2003; Leon et al., 2001; Supriyasilp et al., 2003; Tsihrintzis and Hamid, 1998; Zug et al., 1999).

In the analysis of observed and predicted water quality, the initial water quality observation of each event and the corresponding extracted quality from the predicted pollutograph were noted. This was to distinguish the predictive capability for various stages of the storm event. As seen in Figure 8.6, the accuracy of estimations is high for the initial observation of each event. In statistical terms, the mean of the ratio between predicted and observed instantaneous water quality is 1.2 for the initial observation and 15.2 for the others. For highly accurate estimations, the mean should be close to 1. Furthermore, the initial observations show less data scatter compared to others. The CV for the initial observation is 60% whereas for others it is 200%. This confirms that the methodology adopted to estimate water quality is relatively more accurate for the initial period of storm events.

It was noted during the analysis that estimated pollutant concentration is significantly high during the initial part of runoff events. This can be particularly noted in Figure 8.5. This could be primarily attributed to wash-off behaviour from impervious surfaces where a higher fraction of pollutants is washed-off during the initial part of rainfall events. Higher fraction wash-off is particularly common for roof surfaces where a significant number of selected events resulted in 100% wash-off during the initial period of the rainfall event. The high concentrations of pollutants in the initial part of the runoff event can also be noted in observed water quality. As noted in Figure 8.6, most of the initial water quality observations are relatively high compared to others. Such high concentration of pollutants is termed as ‘first flush’ and has been reported by many researchers (for example: Duncan, 1995; Lee et al., 2002). This revealed that the initial part of the runoff is the most critical in terms of deterioration of receiving water quality.

The above discussion leads to two primary conclusions. Firstly, the initial part of the runoff event is the most critical as a pollutant source to receiving water bodies. Secondly, the methodology adopted to estimate the stormwater quality is reasonably accurate in estimating the initial part of the runoff event. These two observations suggest that pollutant build-up and wash-off measurements used for the estimation procedure are representative in estimating water quality in the most critical part of the runoff event. Therefore, the intended translation procedure based on pollutant build-up and wash-off processes would result in estimations of acceptable accuracy.

8.5 Simplified Wash-off Estimation

Although the estimation procedure described in Section 8.4.2 provides reasonably accurate results, the method is too complex to be used in simple water quality estimations. The complexity can be primarily attributed to the procedure for simulating pollutant wash-off and to the procedure used to translate the wash-off time series to the catchment outlet. Simulation of wash-off is particularly complex due to the procedure adopted to account for the temporal variability of rainfall events. In order to eliminate this complexity, it was felt that a simplified method was needed. However, it was clear that the use of a simplified method could reduce the accuracy of estimation. Consequently, every effort was made to obtain the highest possible accuracy using a simplified method.

The primary approach to simplify the simulations was to obtain an equivalent constant rainfall intensity that results in a similar fraction wash-off. By this way, it is possible to eliminate the simulation of rainfall events with high temporal variability. However, it is noted in Section 6.4.3 that F_W is subjected to a higher degree of variability with rainfall intensity. According to Equation 6.3, the variability is primarily attributed to capacity factor, C_F, which has different values for several ranges of rainfall intensity. This highlighted the difficulty of obtaining a constant rainfall intensity to represent a temporally variable rainfall event.

Instead of one constant rainfall intensity, several constant rainfall intensities for different intensity ranges would be the most appropriate to represent a temporally variable rainfall event. The rainfall intensity ranges used for defining values for C_F would be the most appropriate. Intensity ranges of 5 to 40 mm/hr, 40 to 90 mm/hr and 90 to 133 mm/hr were adopted to develop the simplified rainfall event. The average intensity for each range was calculated by dividing the rainfall depth in each range by the cumulative rainfall duration for the range. It was assumed that this average intensity continues for the cumulative duration. The average intensities were arranged in ascending order to facilitate easy manual estimation of F_W. This eliminates the possibility of giving non-significant wash-off results for smaller average intensities if they were used at the end of intensity time series. Figure 8.7 shows an illustration of the procedure used to obtain the simplified rainfall intensity. The detailed calculations for Figure 8.7 are given in Appendix F, Table F.2.

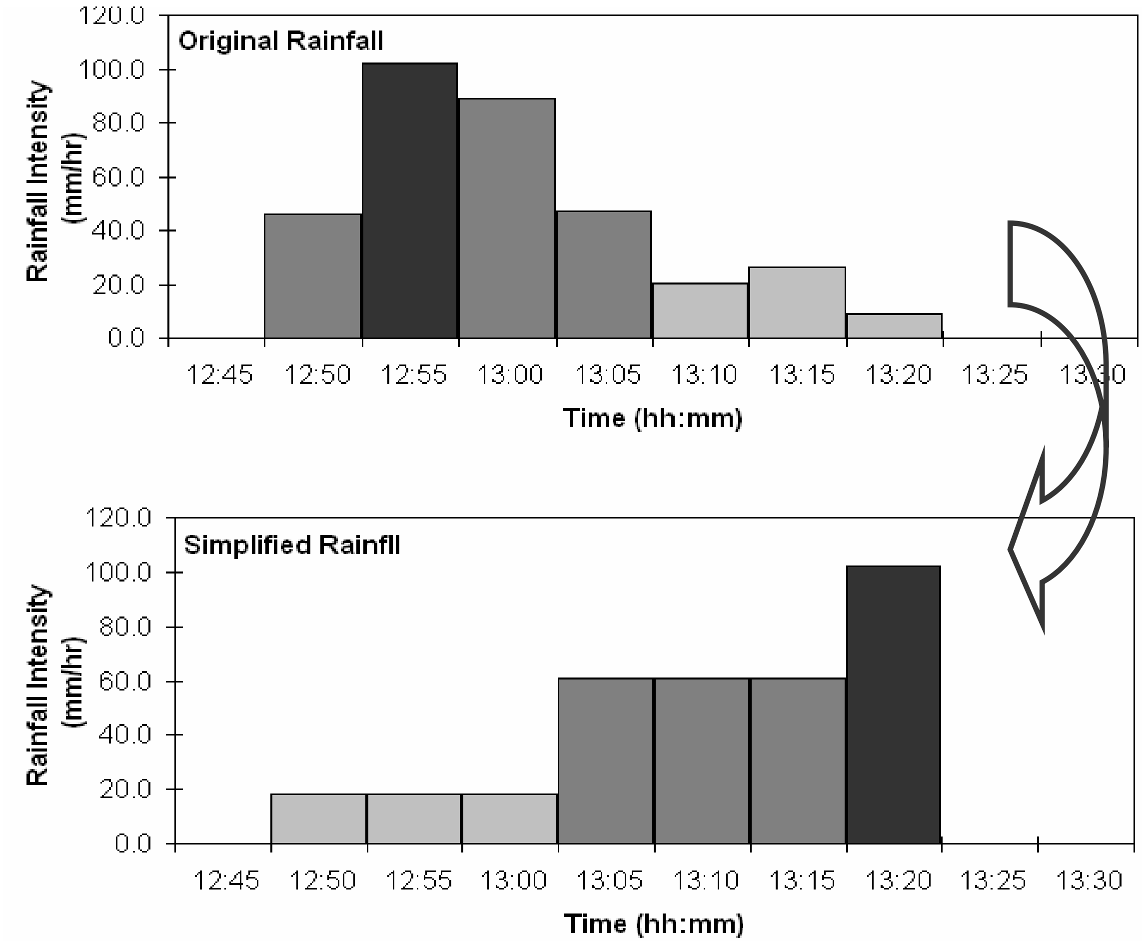


Figure 8.7 – Method to obtain simplified rainfall event

In order to determine the degree of error involved in using the simplified rainfall events, the resulting F_W was compared to the F_W calculated for the original rainfall events. This was done for road and roof surfaces separately. Figure 8.8 shows the variation of the two sets of F_W values. The events analysed were those selected for the three study catchments.

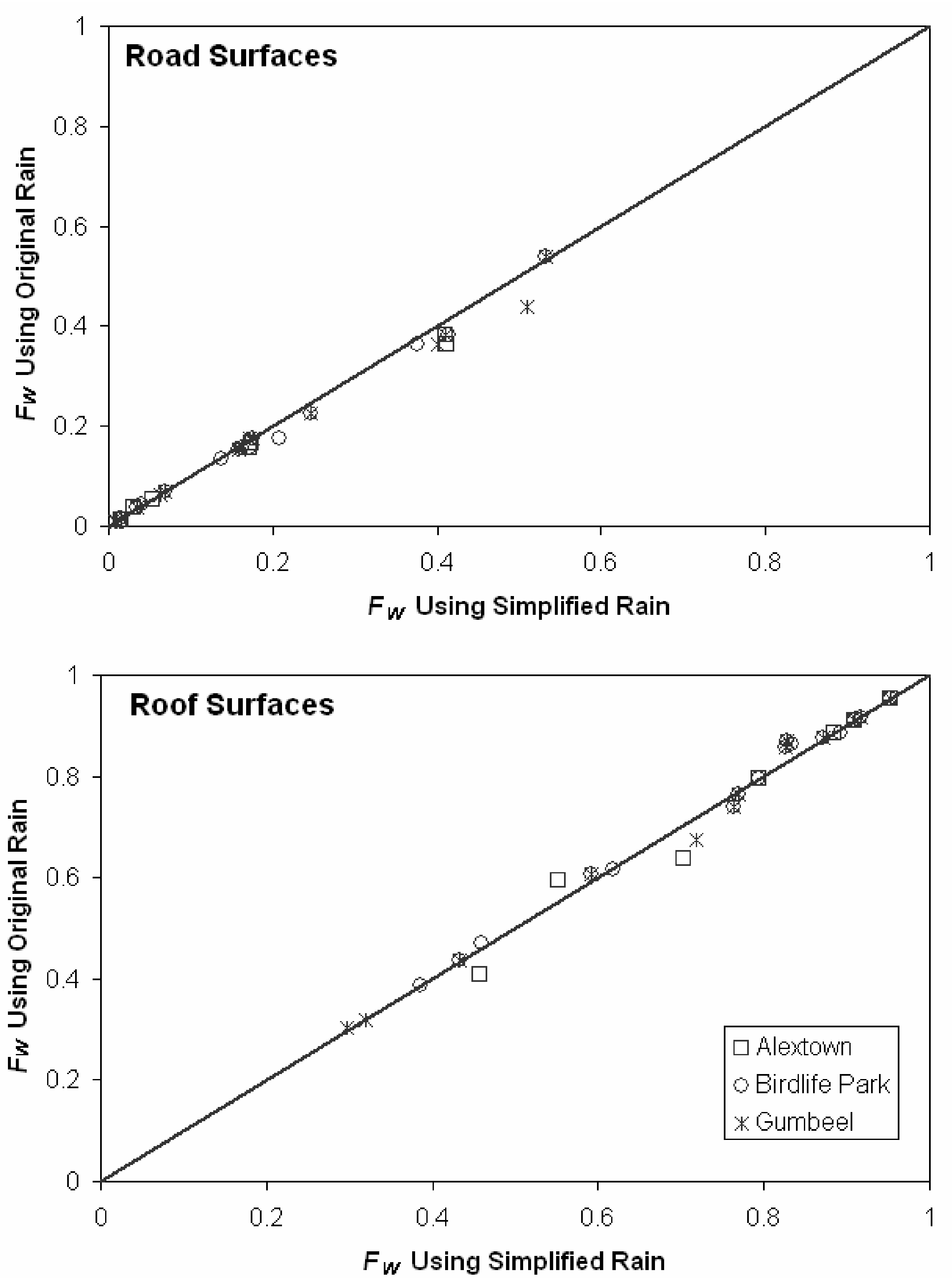


Figure 8.8 – Analysis of estimation accuracy using simplified rainfall events

As seen in Figure 8.7, the difference between the estimation of F_W values using original rainfall events and simplified rainfall events is minimal for both road and roof surfaces. The mean of the ratio between the two sets of F_W values estimated using original and simplified rainfall events is 0.97 for road surfaces and 1.01 for roof surfaces. The CV for road and roof surfaces is 9.3% and 3.8% respectively. This suggests that the estimations resulting from using simplified rainfall events are consistently similar to those obtained using original rainfall events. Therefore, it can be considered that the use of simplified rainfall events in F_W estimation is accurate enough to be used in water quality predictions.

8.6 Translation Procedure

A simple tool such as a translation procedure is useful to calculate the amount of suspended solid pollutants washed-off from urban impervious surfaces. The method can be based on the knowledge of small-plot pollutant processes, namely, pollutant build-up and wash-off from road and roof surfaces. The predictions are limited to the amount of pollutants originating from impervious surfaces. However, as discussed in Section 8.4.2, urban impervious surfaces are the dominant pollutant source during the initial period of runoff events. Therefore, the method is valid for prediction for more common storm events where other sources such as pervious surfaces and erosion are not significant.

For better understanding and simple use, the translation procedure is described in tabular form below. Table 8.5 shows the estimation procedure. The estimation procedure requires a typical set of catchment and rainfall data that common water quality modelling tools often require. This data includes catchment area, impervious percentage, and temporal distribution of rainfall. The values relating to small-plot pollutant processes that needed to be obtained from the charts are shown in the following sections. The methods of using these charts are discussed in Sections 8.2 and 8.3.

Table 8.5 - Estimation of Event Based Suspended Solid Pollutants from Urban Catchments by Translating Small-plot Pollutant Processes to Catchment Scale

Storm No.	Catchment Area **(A)** (m^2)	Impervious Percentage **(Im)** (%)		Build-up on Roads **(B)** (g/m^2) (Figure 8.9& 8.10)	Build-up on Roofs **(B)** (g/m^2) (Figure 8.11)	F_W **(Ro)** from Roads (Figure 8.12)	F_W **(Rf)** from Roofs (Figure 8.13)	Wash-off from Roads (g) **(C)**	Wash-off from Roofs (g) **(D)**	**Total Wash-off**
		Roads and Driveways	Roofs							
Method	See Section 8.6.1			See Section 8.6.2		See Section 8.6.3		A x Im x B x F_{W-} (Ro)	A x Im x B x F_{W-} (Rf)	C + D

8.6.1 Data for Translation Procedure

The data required for the translation procedure is of two types; catchment data and rainfall data. The required primary catchment data is catchment area and impervious surface percentages. The required rainfall data is rainfall temporal pattern for the study events and dry days prior to the rainfall event. Relevant considerations in relation to these data requirements are:

1) Catchment demarcation is one of the most important parts of pollutant load estimation. Since the research was conducted in relatively small urban catchments with areas of 1.7 to 8.6 ha, it is recommended to demarcate catchments in similar size. Use of small catchments also mean that pollutants from impervious surfaces only are washed-off during the initial part of the runoff event.

2) The translation procedure requires percentages of impervious area for two surface types. Due to similarities of small-plot pollutant processes, roads and driveways were considered one surface type and roofs were considered a different type. The percentage of impervious surfaces was measured using aerial photographs. Further details on the method used are discussed in Section 4.3.1.

3) For the research study, data from the tipping bucket rain gauge situated within a 2 km distance to all sites was used for obtaining the temporal patterns for the rainfall. However, depending on the aerial variability of rainfall and the accuracy required by the user, commonly available rainfall data can be used. The same data can be used to obtain the number of antecedent dry days. During the study, dry days were counted from the end of the previous storm event to the start of the next storm. Rainfall events less than 5 mm were disregarded during the count.

8.6.2 Estimation of Build-up

The amounts of pollutant build-up on both road and roof surfaces have to be estimated separately using the charts provided in Figures 8.9, 8.10 and 8.11. The first two figures are for two different residential population density categories of low and high. The low population density is equivalent to typical single detached housing. The high population density is equivalent to townhouses. Most residential urban land-uses commonly belong to these two categories. However, for any other conditions where these two land-uses are not considered suitable, it is possible to develop specific curves by modifying the relevant parameters. It is recommended to change the multiplication coefficient '*a*' for such instances. For mixed residential urban form, selection of an appropriate *a* is recommended. Changing the power coefficient '*b*' is only recommended if the surface type is different from typical residential road surfaces. A similar approach to obtaining the necessary parameters for roof surfaces is recommended. The typical build-up variation for residential catchments is shown in Figure 8.11.

For the simplicity of predictions, charts for road surface build-up were separated into two regions. The region up to two antecedent dry days is where the build-up is assumed to vary linearly. For this region, the starting point for the build-up is considered to be dependent on the pre-existing pollutant amount after the previous rain event. This pollutant amount needs to be estimated by analysing the previous rain event. A linear variation is then considered from the pre-existing amount at day zero to typical two day build-up at day two. In the case where the pre-existing pollutant amount is more than the two day equivalent build-up, no variation is considered. For the region beyond a two day antecedent dry period, build-up is considered to be a power function. The estimation resulting from the power variation is considered to be accurate if the pre-existing pollutant load is less than the two day equivalent build-up. No variation is considered, if the pre-existing pollutant load is greater than a two day equivalent build-up.

For the roof surfaces, a pre-existing amount is not considered to be available after a rain event. This is due to the relatively high wash-off from roof surfaces which leads to near zero build-up remaining for most rain events. Therefore, only the linear variation up to two days and the power variation beyond that would be appropriate to estimate the build-up on roofs.

Line projections can be used to estimate the amount of pollutant build-up using these charts. However, the first step would be to estimate the pre-existing amount of pollutants that provides the starting point for using the chart. This can be determined when a series of consecutive rain events have been analysed.

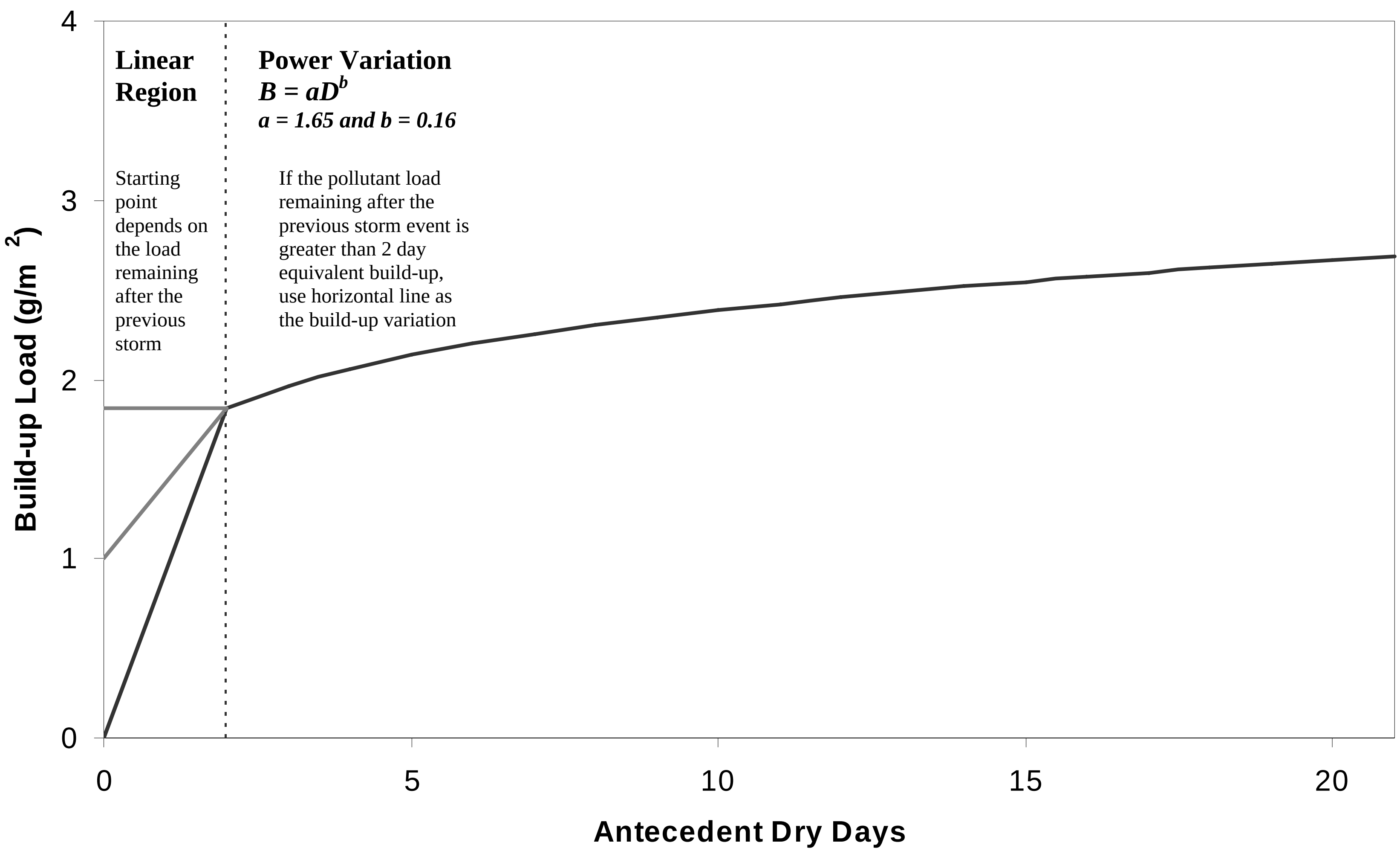


Figure 8.9 - Build-up on road surfaces: residential roads in low population density residential forms (equivalent to single detached housing regions)

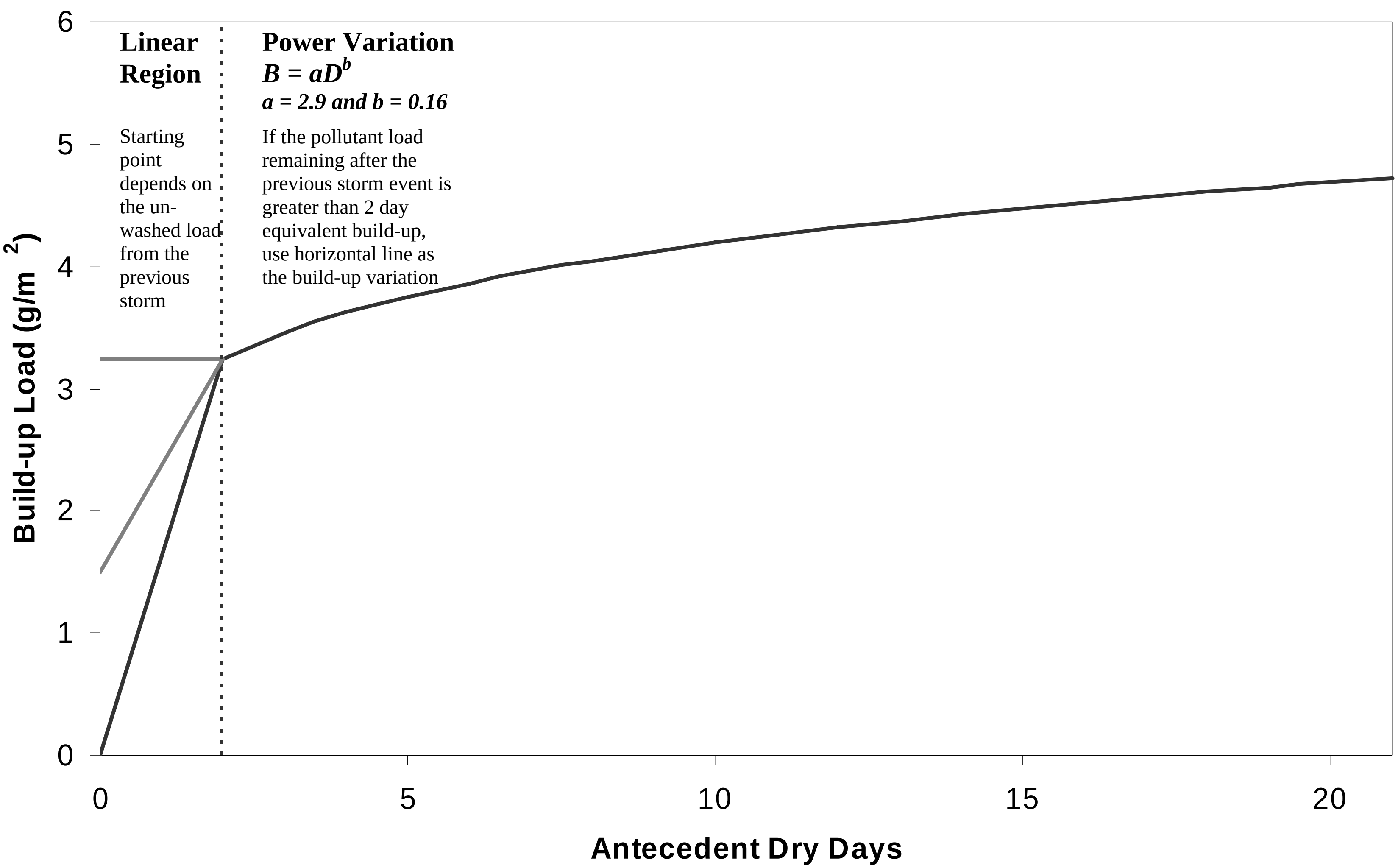


Figure 8.10 - Build-up on road surfaces: residential roads in high population density residential forms (equivalent to townhouse regions)

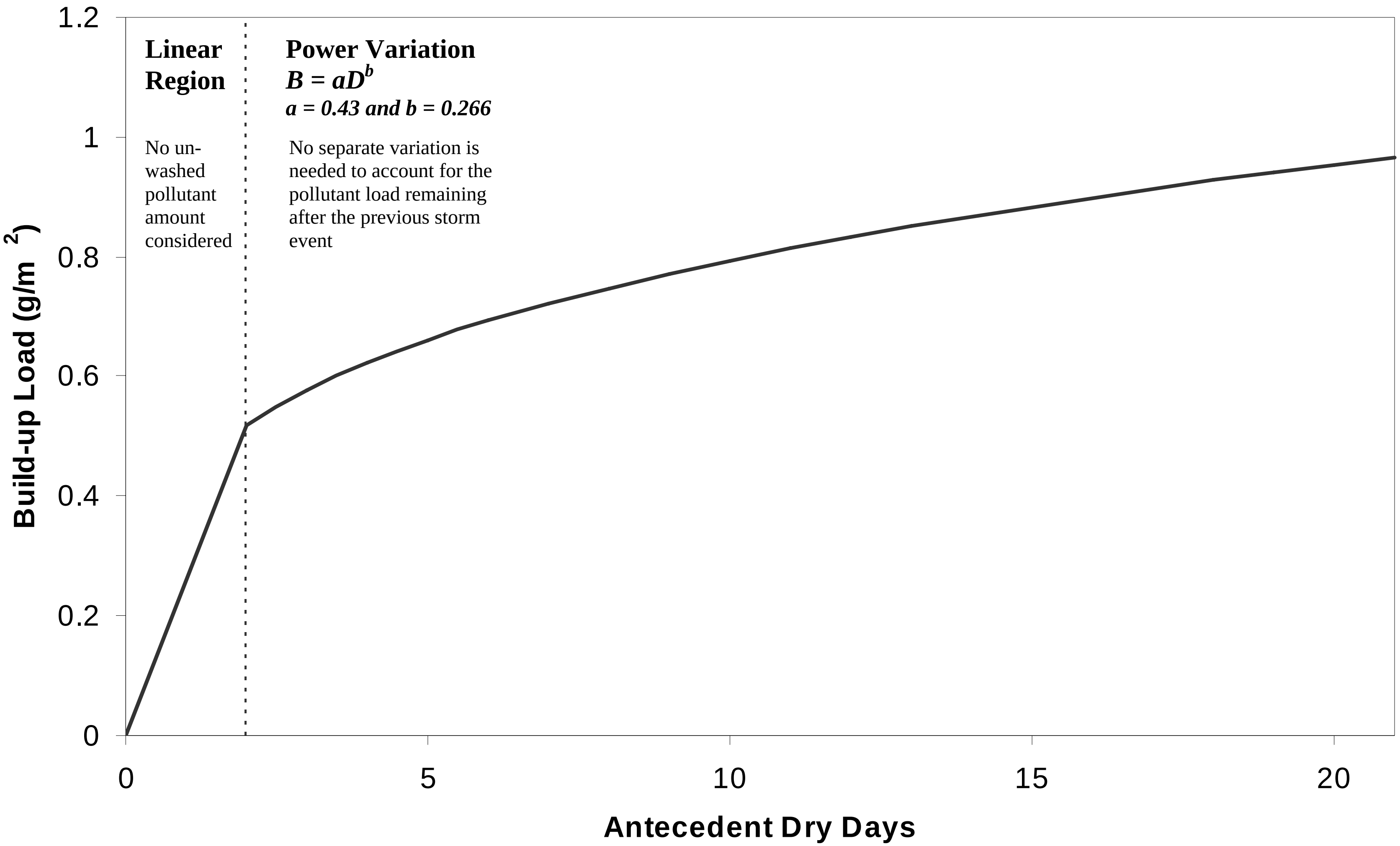


Figure 8.11 - Build-up on roof surfaces: common residential roofs (variation developed for corrugated steel and concrete tile roofs with 20^0 roofing angle)

8.6.3 Estimation of F_W

F_W for both road and roof surfaces has to be determined using Figures 8.12 and 8.13 respectively. Figure 8.12, which represents the wash-off from road surfaces was developed for roads with 0.66 to 0.92 mm texture depth and 7.2 to 10.8% longitudinal slopes. However, the variation of F_W as noted in Figures 8.12 and 8.13 would be applicable to most of the common residential road surfaces. As similar pavement methods are commonly used in road construction, the variation of texture depth would not deviate significantly from the investigated range. Furthermore, no significant variation of wash-off characteristics is expected due to changes in the longitudinal slope. Figure 8.13, which represents wash-off from roof surfaces was developed for corrugated steel and concrete tile roofs with 20^0 roofing angle. However, the outcomes are considered to be satisfactory for most of the common roofing types and for different roofing angles.

For the estimation of F_W, it is recommended to use simplified rainfall events. It was noted in Section 8.5 that simplified rainfall events are capable of providing estimations close to those obtained using the original rain events. The procedure to be adopted to obtain a simplified rainfall event is given in Section 8.5 and illustrated in Appendix F, Table F.2. The original rainfall events used in the analysis should be obtained from measured data as explained in Section 8.6.1.

The variation of F_W for intensities other than those illustrated in the charts should be interpolated and plotted. The interpolations would be valid only for the intensities greater than 5 mm/hr and less than 133 mm/hr. Intensities less than 5 mm/hr can be disregarded from the analyses due to relatively low F_W. It is recommended that the curve for 133 mm/hr (as shown in Figure 8.12) should be used for any greater rainfall intensity. The upper limit of intensity for Figure 8.13 is 115 mm/hr. The procedure for the estimation of F_W for other intensities can be carried out in a way similar to that for the wash-off model discussed in Section 8.3.1 and illustrated in Figure 8.2.

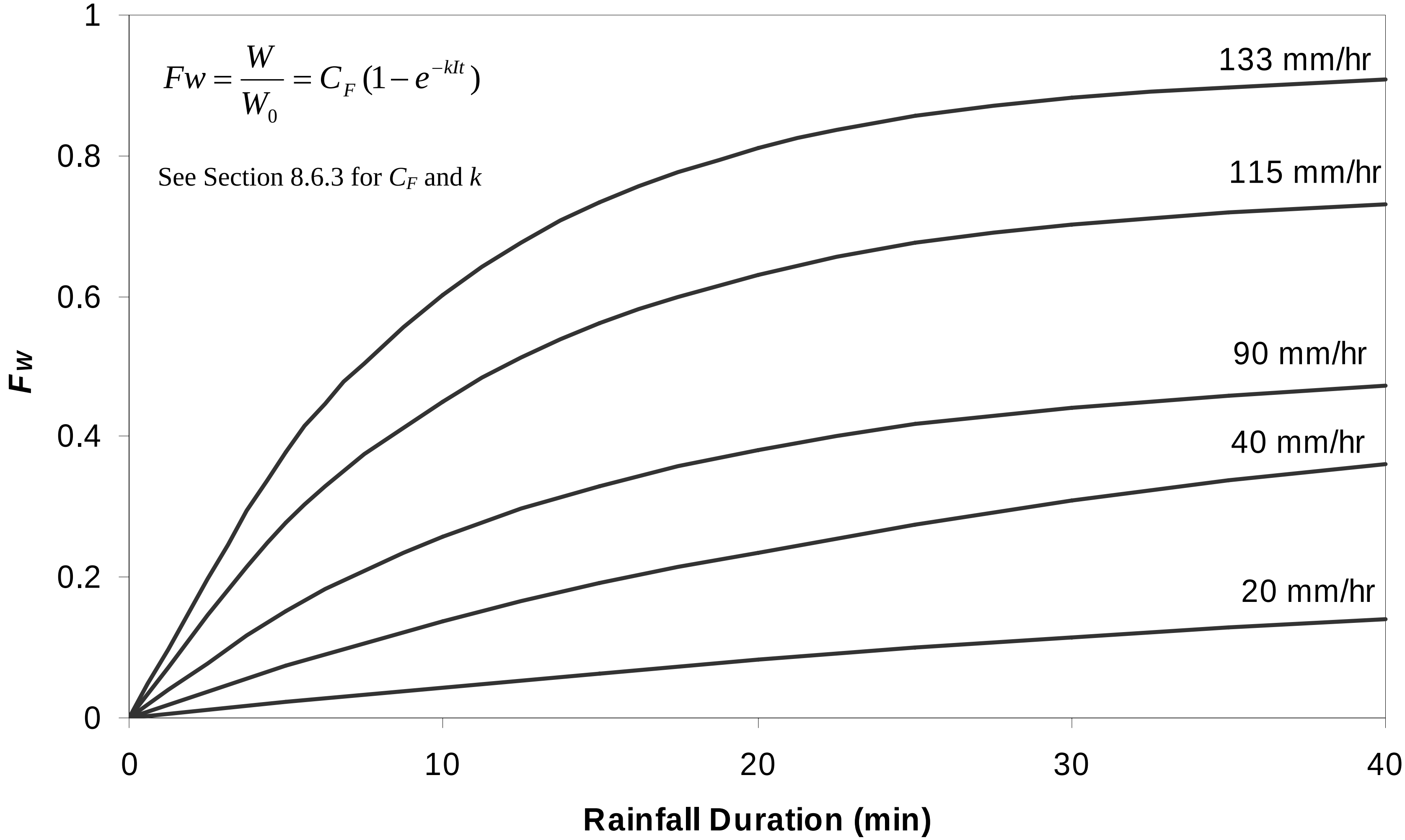


Figure 8.12 - Wash-off from road surfaces: typical residential roads (variation developed for roads with 0.66 to 0.92 mm texture depth and 7.2 to 10.8 % longitudinal slope)

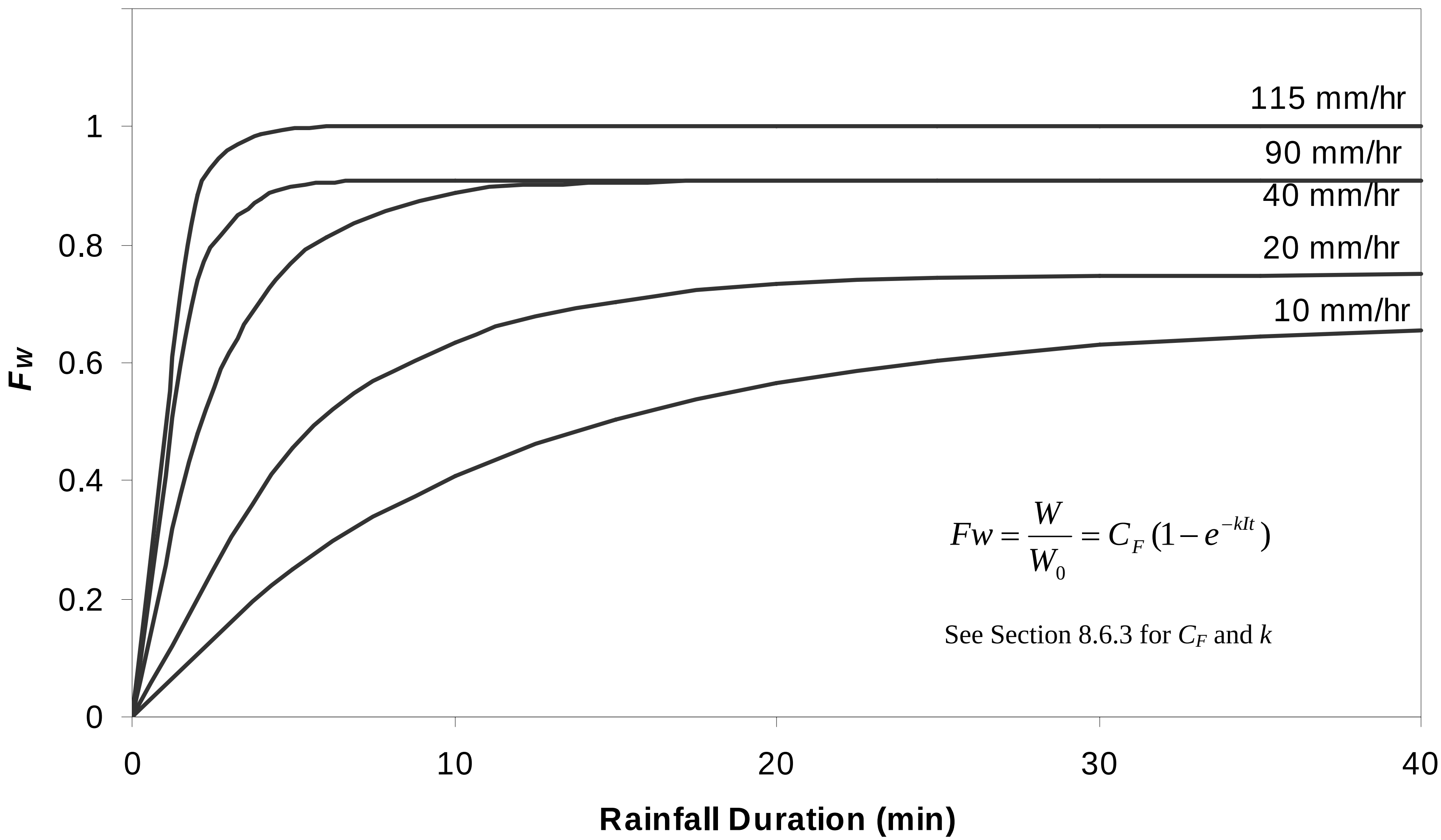


Figure 8.13 – Wash-off from roof surfaces: typical residential roofs (variation developed for roofs with corrugated steel and concrete tile roofs with 20^0 roofing angle)

8.6.4 Issues in Using the Translation Procedure

A Validity of the Translation Procedure to Other Geographical Regions

The translation procedure is a simplified approach to estimate the amount of pollutants washed-off from urban catchments. With the use of appropriate build-up and wash-off data to best suit the characteristics of a given catchment, the procedure would be as accurate as a typical stormwater quality modelling tool.

As discussed in Chapter 6, the variation of build-up on both road and roof surfaces is parameterised by the multiplication coefficient '*a*' and power coefficient '*b*'. It was understood that *b* varies with the surface type, where two values were obtained for road and roof surfaces. The values obtained for *b* would be appropriate for any common road and roof surface types. However, investigations are needed if a high fraction of other surfaces such as parking lots is present within the catchment.

The coefficient *a* defines the pollutant accumulation potential of the catchment surfaces which would vary with population density, land-use, traffic volume and other regional factors. Two coefficient values for road surfaces, specifically for high and low population density residential urban form, and one coefficient value for common residential roof surfaces have been derived. For catchments with characteristics other than these urban forms, values for *a* can be obtained based on the amount of pollutant availability on road surfaces. However, this would require experience and judgement. Furthermore, a field investigation to justify the assumed values would be advisable.

As discussed in Chapter 6, the primary characteristics that influence pollutant wash-off other than rainfall parameters are surface type and condition. The parameter values defining wash-off from most common road and roof surfaces have already been developed. Therefore, the curves shown in Figures 8.12 and 8.13 are applicable for most of the road and roof surfaces in urban catchments with common land-uses. Furthermore, it can be considered that driveways are equivalent to road surfaces. However, these values would not be appropriate for surfaces such as brick pavements and further investigations are recommended.

B Interpretation of Outcomes

Since the translation procedure is based on pollutant build-up and wash-off, the outcomes only reflect the pollutant amount originating from catchment impervious surfaces. However, impervious surfaces are not the only pollutant sources in the urban environment. Depending on the requirement, other methods can be used to estimate the amount of pollutants originating from other sources such as pervious surfaces. Though not comprehensive, the translation procedure estimates the most critical fraction of pollutants which causes the most significant impact on receiving waters.

8.7 Conclusions

Prior to the development of the translation procedure the validity of small-plot pollutant processes being representative of catchment impervious surfaces was evaluated. This was done by replicating pollutant build-up and wash-off processes for a range of selected rainfall events for the three study catchments where water quality observations were available. Predicted and measured water qualities were compared using two approaches.

Comparison of event EMCs of predicted and observed water quality showed limited correlation. Therefore, it was considered that the validity of estimating event based water quality using small-plot pollutant processes is not appropriate. It is hypothesised that this is primarily due to pollutant contributions from pervious surfaces, non-representative EMC observations and errors in water quality estimations.

The comparison of instantaneous water quality observations with quality data from predicted pollutographs resulted in close correlations. The error associated with such comparisons was considered to be in the acceptable range for water quality predictions which are generally highly variable. Therefore, small-plot pollutant processes can be representative of catchment scale water quality particularly for the initial part of runoff events. The translation procedure developed is limited to pollutants originating from impervious surfaces which are the predominant source during the initial period of runoff events.

The translation procedure is a simplified tool that can be used to estimate suspended solid loads washed-off by a particular rainfall event. The method uses knowledge build-up and wash-off processes developed for road and roof surfaces. However, the knowledge developed relating to small-plot processes is limited to the specific land-uses and surface types.

Chapter 9 - Conclusions and Recommendations

9.1 Conclusions

The research project primarily developed a simplified procedure to estimate urban stormwater quality by developing an in-depth understanding of pollutant build-up and wash-off processes in small plots. The procedure was based on the hypothesis that the translation of pollutant build-up and wash-off knowledge from small plots using rainfall simulator can be used for predicting catchment scale water quality. However, build-up and wash-off data is not readily available for various land-uses and climatic conditions. This led to the development of fundamental knowledge on these processes as part of the research study.

The data needed for the development of fundamental knowledge on pollutant build-up and wash-off and the data for validation of the model were generated from in-depth investigations undertaken on selected residential road and roof surfaces. Altogether, three road sites and two roof surface types were investigated. Investigations were based on small-plot areas. This was to eliminate difficulties inherent in the use of non-homogeneous areas. Wash-off investigations were undertaken using simulated rainfall events. This was to eliminate constraints inherent in the dependency of natural rainfall events and their unpredictable nature. Data for the validation of the model was generated by collecting runoff samples from three urban catchment outlets, namely, Alextown, Gumbeel and Birdlife Park. Samples from a significant number of storm events have been collected from these catchment outlets. Samples generated from all field investigations were tested for a range of standard water quality parameters.

Data analysis was undertaken to develop mathematical replication equations and to develop understanding on the underlying physical processes of build-up and wash-off. The analysis further extended to an estimation of water quality of the three catchments for a selected number of storm events. The accuracy of the estimations was tested by comparison with the measured water quality at the catchment outlets. Based on the accuracy of prediction, the simplified water quality estimation procedure was developed.

9.1.1 Pollutant Build-up

Analysis of build-up data revealed rapid build-up during the initial period after site cleaning. However, the build-up observed on roof surfaces was gradual compared to road surfaces where the rate was 2.3 g/m^2/day for first two days and account for around 66% of the total build-up. Rapid variation in build-up during the initial period was considered to be due to the higher impact of anthropogenic activities on road surfaces such as traffic. The rapid reduction in the rate of build-up with the equilibrium condition attained for the latter period was considered to be due to the influence of pollutant re-distribution. This concept is justified by the gradual build-up pattern observed on roof surfaces. Roof surface pollutants are mostly from atmospheric sources and re-distribution would be relatively limited.

Although the pattern of pollutant build-up is common, the build-up loads observed for the three road surfaces were different. The build-up load on the Gumbeel Court site was significantly high compared to the Lauder Court and Piccadilly Place sites. The build-up loads observed at the Lauder Court and Piccadilly Place sites were similar. The differences in urban form and population density were considered as the primary cause for such variation. Notable variation of build-up load was also evident on two roof surface types. It was hypothesised that this is due to differences in the properties of coatings used on the roofing products. However, this difference in build-up load was not considered significant in water quality modelling.

It was possible to develop mathematical replication equations for build-up on roads and roofs in a common format. A power equation was the most suitable. The variation of build-up on roads due to urban form and population density was accounted for by using two sets of parameters. A separate set of parameters was also developed for roof surfaces. The proposed build-up equation is in the form of:

$$B = aD^b$$

Where,

B = Build-up load on road surface (g/m^2);

D = Antecedent dry days; and

a and b= Build-up coefficients.

The parameter values for the build-up replication equation are shown in Table 9.1.

Table 9.1 – Parameters values for build-up replication equation

Surface Type	Characteristics	*a*	*b*
Road	Townhouse region with high population density	2.90	0.16
Road	Single detached housing regions with low population density	1.65	0.16
Roof	All residential land-use	0.43	0.266

According to observations of build-up and the analytical outcomes, the power coefficient *b* varies primarily with surface type. This confirmed the applicability of values generated for *b* for other geographical regions. The multiplication coefficient primarily replicates the polluted nature of the impervious surface and varies with parameters such as land-use and traffic volume. Values for *a* can be assumed accordingly. However, verification of the selected value by using field data is recommended.

Investigations into pollutant build-up further resulted in detailed understanding of the underlying physical processes. For this, analysis was conducted to understand the variation of particle size distribution and variation of physio-chemical parameters. Different particle size distribution curves were noted for different antecedent dry days. It was observed that the average particle size becomes coarser when the antecedent dry period increases. It was hypothesised that this is due to pollutant re-distribution. This would be the result of the removal of finer particles from the surface and the accumulation of coarser particles due to wind and vehicular-induced turbulence. Analysis of physio-chemical data for these samples suggested that particles less than 100 μm are highly susceptible to re-distribution. The analysis noted relatively limited change in sample load for this range, whilst particles coarser than this range progressively accumulate. However, the high degree of pollutant re-distribution was not evident on roof surfaces. This would be due to the lack of influence of vehicle-induced wind turbulence in the vicinity of roof surfaces.

The pollutants observed on both road and roof surfaces were significantly finer compared to results reported in previous research. On average, 50% of the road surface solid pollutants and 60% of the roof surface solid pollutants were finer than the 100 μm size range. The fineness of the road surface pollutants could be due to the low traffic volumes in residential roads which formed the study sites. It was observed that a high amount of soluble organic carbon is associated with the finer fraction of solids from both road and roof surfaces. Hence, there is significant potential of having a relatively high amount of other pollutants such as heavy metals and hydrocarbons being adsorbed to the finer particles or in dissolved form when there is a wash-off event.

9.1.2 Pollutant Wash-off

Investigations into pollutant wash-off were conducted to understand the behaviour for a range of influential factors and to measure the specific wash-off rates from impervious surfaces. It was found that wash-off load is influenced by the initially available pollutant amount on the surface. However, the wash-off process was found to be independent of initial pollutant availability. This conclusion was based on the consistently similar variation patterns of 'fraction wash-off' for the three road sites despite differences in pollutant availability. Although a range of rainfall and runoff variables can be related, it was found that the wash-off process is most adequately defined by two rainfall variables: intensity and duration. These two variables were used in the mathematical replication of wash-off.

The mathematical replication equation developed is a modified version of the original exponential equation proposed by Sartor et al. (1974). The modification is primarily in terms of an additional parameter referred to as the 'capacity factor', C_F. The study results showed that a storm event has the capacity to wash-off only a fraction of pollutants available and this fraction varies primarily with rainfall intensity, kinetic energy of raindrops and particle size distribution of the pollutants. The C_F is defined to incorporate this capacity in the replication equation. The modified wash-off equation is in the form of:

$$Fw = C_F(1 - e^{-kIt})$$

Where,

I	Rainfall intensity;
k	Wash-off coefficient;
Fw	Fraction wash-off;
C_F	Capacity factor; and
t	Rainfall duration.

The modification made to the common pollutant wash-off equation is an improvement to the current usage. The parameters developed are shown in Table 9.2.

Table 9.2 – Parameter values for wash-off replication equation

Parameter	Range	Value
For Road Surfaces		
Capacity factor C_F	5 to 40 mm/hr	(0.01 x **I**) + 0.1
	40 to 90 mm/hr	0.5
	90 to 133 mm/hr	(0.0098 x **I**) – 0.38
Wash off coefficient k	All intensities	8×10^{-4}
For Roof Surfaces		
Capacity factor C_F	5 to 40 mm/hr	(0.008 x **I**) + 0.59
	40 to 90 mm/hr	0.91
	90 to 133 mm/hr	(0.0036 x **I**) + 0.59
Wash off coefficient k	All intensities	9.33×10^{-3}

I - Rainfall intensity

The particle size distribution of washed-off pollutants from both road and roof surfaces was significantly finer. From road and roof surfaces around 90% of the pollutants were less than 200 μm and less than 100 μm respectively. It was further noted that there is mismatch of these wash-off size range with the particle size distribution of initially available pollutants. This could be the result of the fragmentation of larger particles due to raindrop-induced turbulence.

The study further noted little variation in particle size distribution of suspended solids with the variation in rainfall parameters such as rainfall intensity and duration. This would mean that there is no variation of the underlying physical processes that govern pollutant wash-off. These findings would help to enhance the current conceptual understanding into wash-off processes.

The analysis of wash-off showed that the inherent processes led to relatively higher concentrations of pollutants during the initial part of runoff events. This implies that there should be a significant focus on the initial part of the runoff events for the design of treatment systems.

Very limited research has been undertaken in the past on roof surface wash-off. This research has contributed to the fundamental understanding of roof surface wash-off and also developed a mathematical replication equation. It was found that the wash-off behaviour is not different to road surfaces though the surface characteristics and particle size distribution of the particulates are different. This confirmed that a common form of wash-off behaviour could be assumed for most urban impervious surfaces. A high fraction wash-off was observed during the initial part of rain events even when the intensity was low. This could significantly increase the first flush effect. Furthermore, this indicates that roof runoff is cleaner for most of the latter part of storm events.

In the data analysis, it was noted that a relatively high amount of pollutants was originating from roof surfaces. Particularly for low intensity rainfall events, the load originating from roofs exceeded the load from roads. These findings question the general understanding of the role of road surfaces as the primary pollutant contributor to stormwater runoff. The higher contribution from roof surfaces is primarily attributed to the large surface area and low surface texture that causes most of the pollutants to wash-off even in low intensity rain. Therefore, the significance of roof surfaces arises in the case of low intensity rain events where road surface contribution could be significantly less. Also, low intensity rainfall events are the most frequent and therefore it is possible that a relatively significant amount of pollutants would be generated from roof surfaces when compared to roads.

9.1.3 Translation Procedure

Translation of small-plot pollutant processes to catchment scale is based on the hypothesis that measured parameters can be used for direct estimation of catchment scale water quality. Therefore, the translation procedure is a unique estimation tool that shows significant conceptual differences to the common water quality modelling tools. Water quality models replicate commonly known pollutant processes to predict water quality. The translation procedure was based on the measured pollutant processes for representative catchment surfaces. Therefore, the calculation is a direct estimation of the water quality and there is no requirement for calibration. Hence, this reduces the complexities commonly associated with urban stormwater quality modelling. The translation procedure is simple to use and straightforward in calculations. Furthermore, the procedure is reliable when compared to the empirical methods used in lumped estimations.

The translation procedure was developed for residential land-uses in the Gold Coast region. However, the procedure is applicable for other land-used in other regions with appropriate coefficients for build-up and wash-off replications. Most of the coefficients are applicable to other geographical regions with little modification needed. However, the estimation of the multiplication coefficient '*a*' in the build-up replication equation requires attention. Apart from the appropriate coefficients, data on catchment characteristics such as surface area, percentage impervious and rainfall records is needed as input data. These data requirements are typical for most water quality models. The translation procedure estimates the amount of the pollutants washed from catchment impervious surfaces which are the most critical in receiving water quality degradation. Furthermore, the estimation represents the pollutant load generated during the initial part of the storm event.

9.2 Recommendations for Further Research

The outcomes of this research have contributed to the current knowledge base in relation to pollutant build-up and wash-off from road and roof surfaces. Furthermore, this research developed a stormwater quality estimation tool based on an innovative conceptual approach. Apart from these research outcomes, several areas were identified where further detailed investigations are warranted as discussed below.

- During the research study, the high variability of pollutant build-up was noted. This was primarily in terms of pollutant load, rate and composition variation mainly with antecedent dry period, land-use, urban form and traffic related parameters. A significant amount of past research has focused on identifying the variability induced by these parameters. However, further research is still needed particularly in order to identify the variability of pollutant composition with the increase of antecedent dry days.

- The understanding gained on pollutant build-up by this research is limited to residential roads and roofs. Further investigations are needed to understand the build-up on other surfaces types, such as driveways and parking lots where such areas are significant.

- Further investigation into pollutant wash-off is essential in order to strengthen the existing knowledge base. The understanding gained from this research is limited to typical residential roads and roofs. There are other impervious surface types common to urban areas such as concrete pavements, driveways and parking lots where characteristics of wash-off were not investigated.

- Pollutant contribution from urban pervious surfaces and its characteristics are not adequately understood. It is accepted that pervious surfaces can contribute significantly depending on the storm characteristics. However, further investigations are needed to understand the contribution and to develop appropriate mathematical replications.

- Impacts of stormwater pollution are due to a range of pollutant types. This research specifically focussed on suspended solids as it is an indicator pollutant. However, further research is needed to understand the adsorption of other common pollutants in urban stormwater. Such understanding provides valid platform to translate the knowledge gained and estimation techniques developed, for other pollutants.

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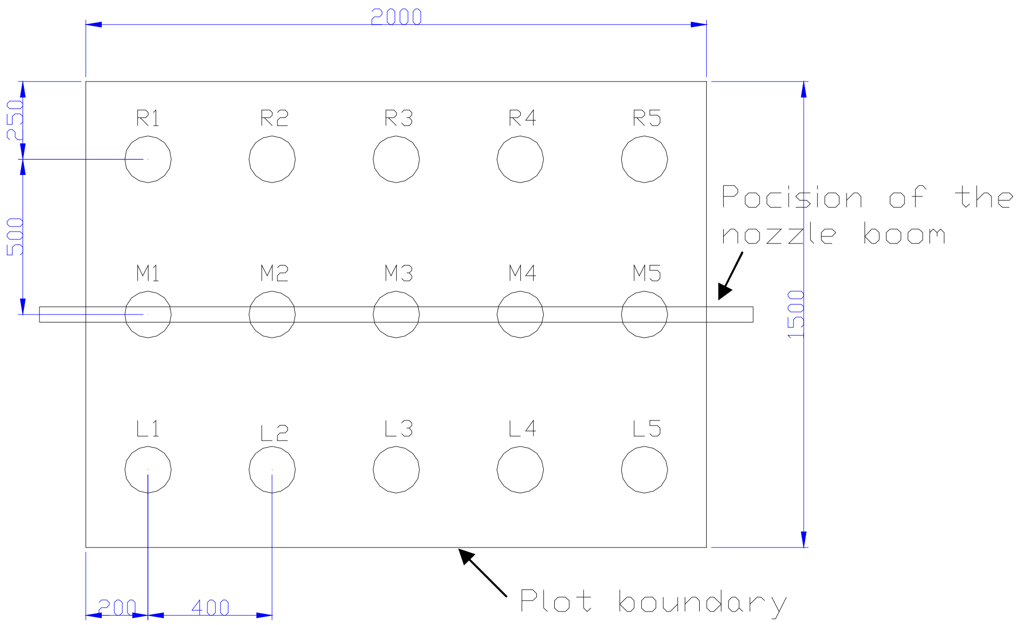
APPENDIX A

CALIBRATION OF STUDY TOOLS

Calibration of the rainfall simulator was done by collecting water in fifteen containers which were placed under the simulator in a grid pattern for a five minute period. The containers were positioned as shown in Figure A 3.1.



The volume of water collected in each container was measured for each control box setting. Table A3.1 shows the volume of water collected and calculated average rainfall intensity. A sample calculation for control box setting '1 – A' and for a 20mm/hr rainfall intensity is shown below.

Sample Calculation - Calculation of rainfall intensity

For container position R1

Volume of water collected	= 9mL.
Area of the container opening	= 5541.8mm^2
Depth of water	= 9 x 1000/5541.8
Depth of water per hour	= 9 x 1000 x 60/(5541.8 x 5)
	= 19.5mm/hr

Table A.1 Calculation of rainfall intensity from the measured water volume (1 of 2)

Control Box Setting	Position	Volume (mL)			Intensity (mm/hr)			Uniformity Coefficient
		R	M	L	R	M	L	
1-A	1	9	12	7	19.5	26.0	15.2	81.4
	2	8	11	8	17.3	23.8	17.3	
	3	9	14	10	19.5	30.3	21.7	
	4	8	12	9	17.3	26.0	19.5	
	5	7	11	7	15.2	23.8	15.2	
1-C	1	11	13	10	23.8	28.1	21.7	87.8
	2	12	15	10	26.0	32.5	21.7	
	3	13	14	13	28.1	30.3	28.1	
	4	12	15	10	26.0	32.5	21.7	
	5	11	13	10	23.8	28.1	21.7	
1-E	1	13	17	12	28.1	36.8	26.0	86.7
	2	14	18	12	30.3	39.0	26.0	
	3	14	18	13	30.3	39.0	28.1	
	4	14	18	13	30.3	39.0	28.1	
	5	12	15	12	26.0	32.5	26.0	
1-G	1	15	20	15	32.5	43.3	32.5	84.8
	2	15	20	14	32.5	43.3	30.3	
	3	16	20	19	34.6	43.3	41.1	
	4	15	21	14	32.5	45.5	30.3	
	5	14	19	13	30.3	41.1	28.1	
1-I	1	20	25	19	43.3	54.1	41.1	85.9
	2	23	29	20	49.8	62.8	43.3	
	3	28	29	25	60.6	62.8	54.1	
	4	23	27	19	49.8	58.5	41.1	
	5	19	24	18	41.1	52.0	39.0	
1-J	1	24	30	23	52.0	65.0	49.8	87.2
	2	25	32	22	54.1	69.3	47.6	
	3	26	32	29	56.3	69.3	62.8	
	4	26	32	23	56.3	69.3	49.8	
	5	21	26	19	45.5	56.3	41.1	
1-K	1	30	38	28	65.0	82.3	60.6	85.2
	2	30	43	30	65.0	93.1	65.0	
	3	32	42	37	69.3	90.9	80.1	
	4	31	43	29	67.1	93.1	62.8	
	5	27	34	26	58.5	73.6	56.3	
1-L	1	44	62	49	95.3	134.3	106.1	84.6
	2	47	70	47	101.8	151.6	101.8	
	3	53	67	60	114.8	145.1	129.9	
	4	52	69	47	112.6	149.4	101.8	
	5	42	55	39	90.9	119.1	84.4	
1-H	1	16	21	15	34.6	45.5	32.5	82.9
	2	17	23	18	36.8	49.8	39.0	
	3	20	26	22	43.3	56.3	47.6	
	4	18	23	17	39.0	49.8	36.8	
	5	14	16	12	30.3	34.6	26.0	
2-I	1	25	30	22	54.1	65.0	47.6	85.7
	2	26	33	22	56.3	71.5	47.6	
	3	27	34	27	58.5	73.6	58.5	
	4	26	33	21	56.3	71.5	45.5	
	5	22	27	17	47.6	58.5	36.8	

Table A.1 Calculation of rainfall intensity from the measured water volume (2 of 2)

Control Box Setting	Position	Volume (mL)			Intensity (mm/hr)			Uniformity Coefficient
		R	M	L	R	M	L	
2-J	1	33	41	28	71.5	88.8	60.6	86.2
	2	33.5	43	28	72.5	93.1	60.6	
	3	34.5	42.5	35.5	74.7	92.0	76.9	
	4	34	44	27	73.6	95.3	58.5	
	5	33	33	23	71.5	71.5	49.8	
2-K	1	42.5	52	37	92.0	112.6	80.1	84.5
	2	44.5	55	35.5	96.4	119.1	76.9	
	3	45	53.5	45	97.4	115.8	97.4	
	4	45	58	35	97.4	125.6	75.8	
	5	31.5	42	30	68.2	90.9	65.0	
2-L	1	62	77	55	134.3	166.7	119.1	85.1
	2	65	83	53	140.7	179.7	114.8	
	3	66	82	71	142.9	177.6	153.7	
	4	67	86.5	54	145.1	187.3	116.9	
	5	55	67	42.5	119.1	145.1	92.0	
1-M	1	41	57.5	40	148.0	207.5	144.4	83.2
	2	44.5	60.5	37	160.6	218.3	133.5	
	3	47	60	50.5	169.6	216.5	182.3	
	4	46	60.5	36.5	166.0	218.3	131.7	
	5	38	49	31	137.1	176.8	111.9	
2-M	1	45.5	59	43.5	164.2	212.9	157.0	84.8
	2	49	64	40	176.8	231.0	144.4	
	3	48	62	52	173.2	223.8	187.7	
	4	50	65	40	180.4	234.6	144.4	
	5	41	52	33.5	148.0	187.7	120.9	
3-L	1	39.5	49	36	142.6	176.8	129.9	84.6
	2	40	52.5	35	144.4	189.5	126.3	
	3	43	52.5	44.5	155.2	189.5	160.6	
	4	43	54.5	32.5	155.2	196.7	117.3	
	5	33.5	42	27	120.9	151.6	97.4	
3-I	1	35	40.5	30	75.8	87.7	65.0	84.6
	2	38.5	48	34	83.4	103.9	73.6	
	3	46	55	45	99.6	119.1	97.4	
	4	40	50	32	86.6	108.3	69.3	
	5	34	39	30	73.6	84.4	65.0	
3-J	1	42	52	49	90.9	112.6	106.1	89.7
	2	50	58	52	108.3	125.6	112.6	
	3	57	70	63	123.4	151.6	136.4	
	4	56	56	54	121.3	121.3	116.9	
	5	40	52	48	86.6	112.6	103.9	
3-K	1	54	64	52	116.9	138.6	112.6	89.4
	2	58	74	56	125.6	160.2	121.3	
	3	64	75	64	138.6	162.4	138.6	
	4	58	74	57	125.6	160.2	123.4	
	5	53	62	53	114.8	134.3	114.8	

Table A.2 – Calculation of median drop size and kinetic energy

Sieve Size Class	Weight of Pellets (mg)	Weight of Single Pellet (mg)	Number of Pellets	Calibration Ratio	Mass of a Water Drop (mg)	Total Masss (mg)	Terminal velocity of drops (m/s)	Kinetic Energy of Individual Droplets (J)	Volume of Water (mm^3)
>4.75	249.8	83.27	3	1.27	105.75	317	9.17	0.0133	0.318
4.75 - 3.35	1739.4	36.78	47	1.27	46.71	2209	9	0.0895	2.213
3.35 - 2.36	7279.1	18.99	383	1.27	24.12	9244	8.6	0.3419	9.261
2.36 - 1.68	10395.4	6.50	1599	1.23	8.00	12786	4.42	0.1249	12.809
1.68 - 1.18	5646.9	2.83	1993	1.18	3.34	6663	6.09	0.1236	6.675
1.18 - 0.85	2252	0.86	2622	0.96	0.82	2162	4.64	0.0233	2.166
<0.85	270.9	0.33	815	0.76	0.25	206	3.27	0.0011	0.206
Total			**7463**			**33588**		**0.7175**	**33.649**

Calculation of Median Diameter

Total mass of water collected in the flour tray = 33,588 mg

Total number of pellet (drops) counted = 7463

Average mass of a rain drop = 33588 / 7463 = 4.5 mg

Volume of a median diameter rain drop = $4.5 \times 10^{-6} / 998.2\ m^3$ = $4.508\ mm^3$

Median diameter = $(4.508 \times 6 / \pi)^{1/3}$ = **2.05 mm**

APPENDIX B

STUDY AREA

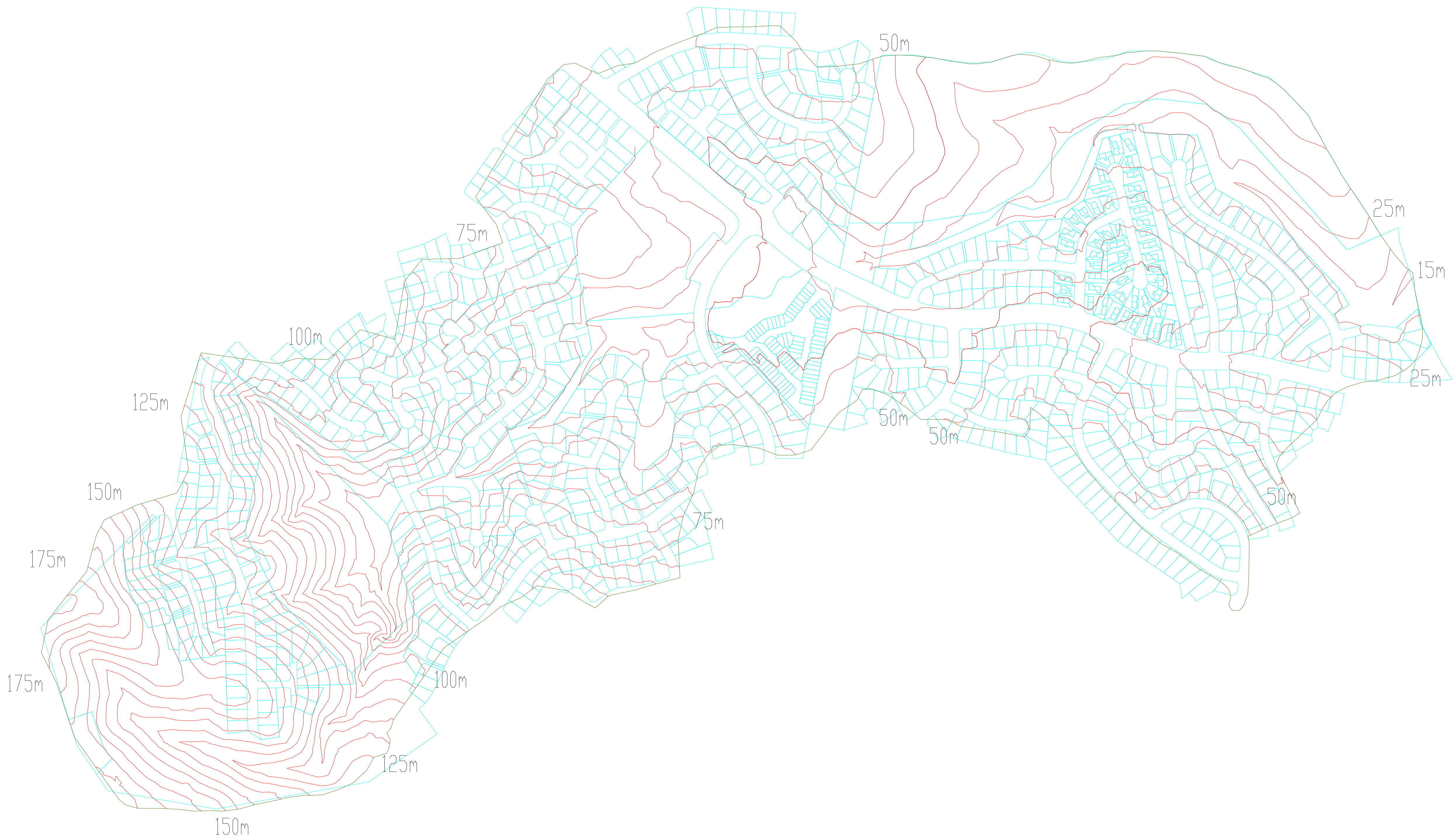


Figure B.1 – Contour map for Highland Park residential area – contours are 5 m intervals

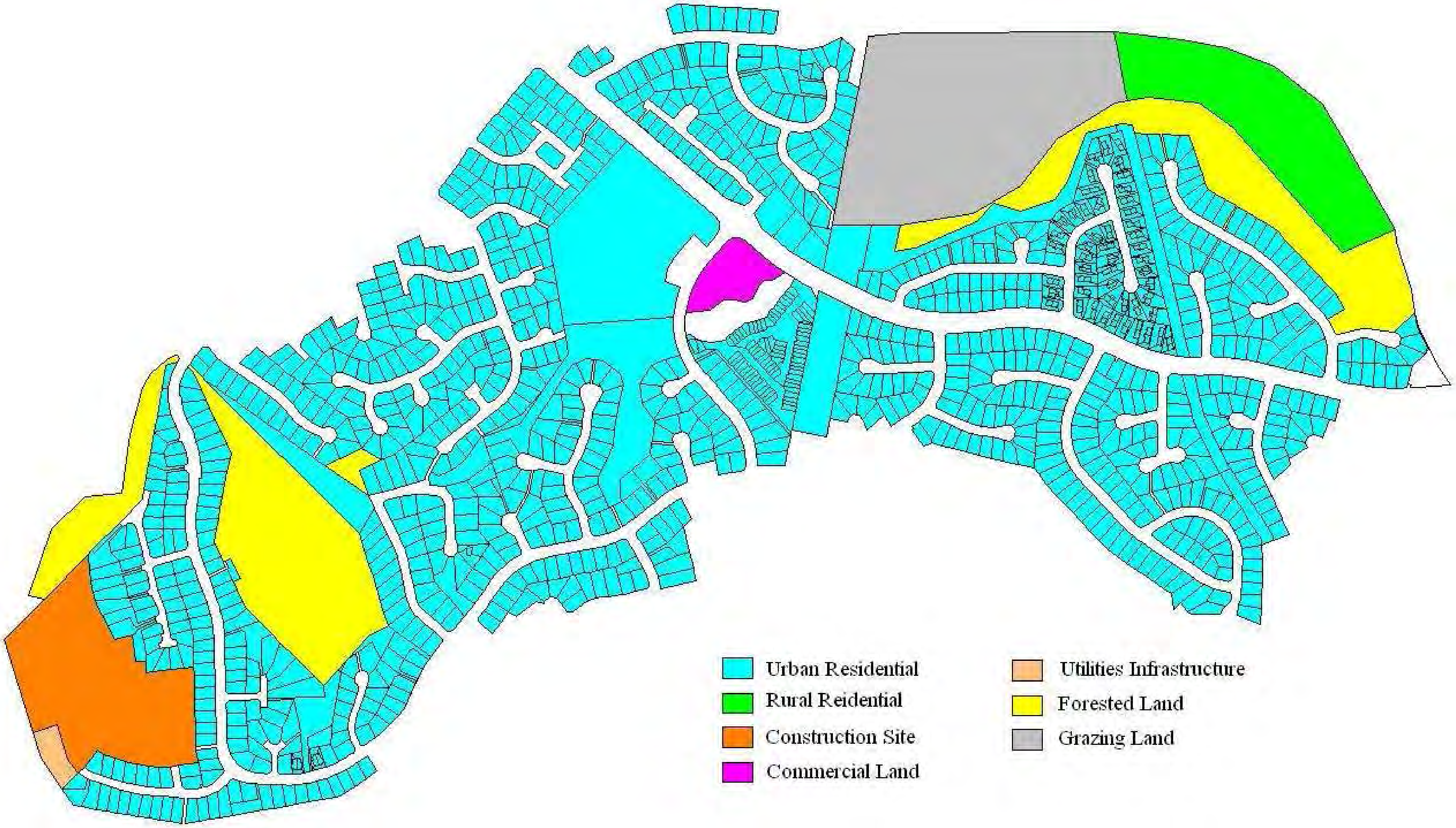


Figure B.2 – Land-use map for Highland Park residential area

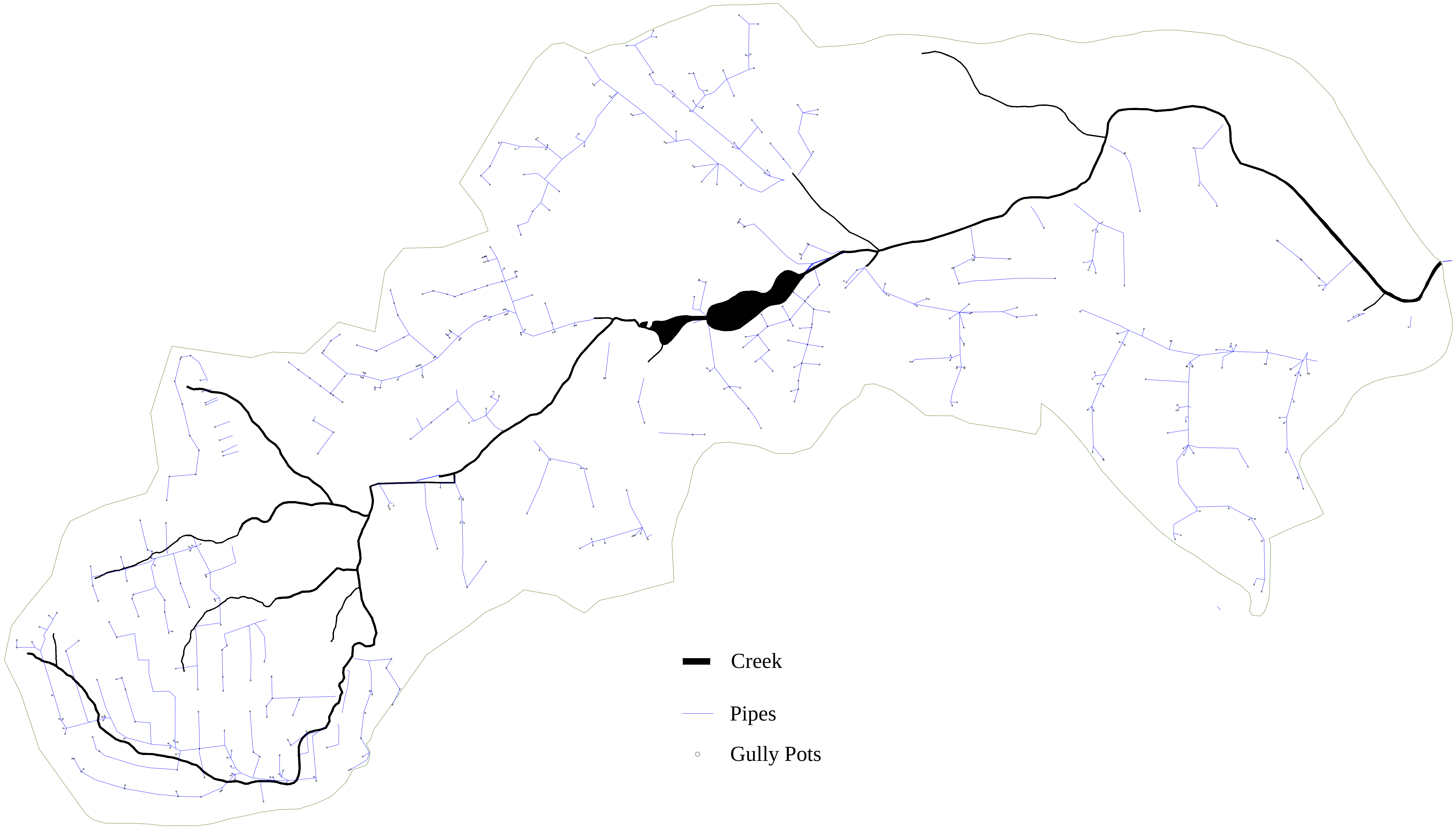


Figure B.3 – Drainage network for Highland Park residential area

Figure B.4 – Aerial photograph of Highland Park residential area (The electronic version is in high resolution)

APPENDIX C

POLLUTANT BUILD-UP DATA

Table C.1 – Unprocessed data matrix for road surface build-up

Road Site	Antecedent Dry Days	Total Solids (g)	Particle Size Distribution µm						pH	EC (µS)	Original Sample (mg/L)		Filtrate (mg/L)	
			0-10	10-50	50-100	100-200	200-400	>400			TC	IC	TC	IC
Gumbeel	1	2.43	7.13	28.14	30.69	19.96	8.86	3.33	6.02	22.39	7.21	0	5.46	0
Gumbeel	1	1.69	3.26	19.6	25.77	31.97	13.52	5.22	6.42	21.87	6.701	0	5.18	0
Gumbeel	2	3.14	7.12	27.52	26.08	20.17	11.49	5.09	5.91	19.6	8.19	0	6.35	0
Gumbeel	2	2.60	2.72	18.48	30.28	26.85	14.6	6.16	6.31	27.1	10.09	0	5.21	0
Gumbeel	3	3.81	3.99	20.08	24.14	27.6	15.99	6.13	5.54	17.6	8.21	0	6.41	0
Gumbeel	7	4.04	3.3	12.35	14.69	21.73	25.98	21.47	5.6	15.2	7.93	0	5.21	0
Gumbeel	14	3.82	2.36	8.51	11.59	21.92	31.91	23.58	5.72	15.1	8.21	0	6.14	0
Gumbeel	14	5.10	1.03	10.83	9.69	19.52	32.53	26.06	5.74	15.3	5.199	0	4.85	0
Gumbeel	23	5.26	3.83	13	9.22	13.58	27.66	31.01	5.62	14.9	5.511	0	5.25	0
Louder	1	1.98	4.23	20.77	35.1	26.71	8.01	4	5.65	18.16	6.23	0	5.18	0
Louder	1	1.63	1.59	20.61	29.27	29.11	12.21	6.43	6.35	19.58	6.13	0	4.85	0
Louder	2	1.70	5.73	25.88	31.73	22.33	8.82	3.99	5.67	16.02	6.78	0	5.91	0
Louder	2	1.94	1.64	22.22	26.44	27.83	13.52	5.97	5.98	14.48	6.39	0	4.65	0
Louder	3	2.07	4.36	21.66	32.48	25.91	10.04	4.36	5.92	25.66	7.13	0	6.04	0
Louder	7	2.09	5.29	20.61	25.3	22.94	17.06	7.09	5.76	22.26	7.35	0	5.92	0
Louder	14	2.20	0.6	14.74	20	26.28	26.3	12.09	6.05	16.78	6.93	0	6.21	0
Louder	14	2.63	1.6	13.12	12.81	25.49	29.15	17.44	5.72	16.22	5.38	0.88	4.93	0
Louder	23	2.72	2.71	8.27	12.46	24.43	31.34	19.83	5.69	15.93	4.46	0	4.85	0
Piccadilly	1	1.91	8.4	31.38	32.53	17.49	6.72	2.49	5.73	21.89	5.21	0	4.93	0
Piccadilly	2	2.01	5.94	23.15	29.05	23.04	12.31	4.97	5.77	19.8	5.34	0	4.23	0
Piccadilly	7	2.36	5.36	22.25	31.49	22.75	10.35	6.1	5.86	19.7	6.39	0	5.61	0
Piccadilly	7	2.02	8.4	31.38	32.53	17.49	6.72	1.37	5.84	18.5	6.21	0	5.39	0
Piccadilly	14	2.48	4.15	22.25	23.81	25.62	17.2	6.6	6.57	17.23	7.21	0	4.98	0
Piccadilly	21	2.60	2.38	12.29	15.92	21.34	27.69	20.7	6.2	17.53	6.52	0	5.87	0

Table C.2 – Unprocessed data matrix for roof surface build-up

Road Site	Antecedent Dry	Total Solids (g)	Particle Size Distribution μm						pH	EC (μS)	Original Sample		Filtrate (mg/L)	
			0-10	10-50	50-100	100-200	200-400	>400			TC	IC	TC	IC
Concrete t	1	0.44	2.47	23.82	27.56	18.12	15.09	11.54	6.81	53.4	17.94	16.82	0.92	0.45
Concrete t	2	0.46	3.19	19.32	22.06	20.31	19.31	14.81	6.21	28.4	9.86	9	1.5	1.3
Concrete t	3	0.54	3.43	27.12	26.47	18.07	13.17	11.54	6.43	42.1	9.92	9.6	1.96	1.77
Concrete t	7	0.66	2.84	23.32	25.06	17.31	18.31	13.37	5.98	54.2	8.74	6.71	1.7	1.66
Concrete t	14	0.68	4.21	24.12	22.47	22.74	14.06	11.72	6.42	39.7	8.23	6.66	1.93	1.73
Concrete t	21	0.84	3.49	17.82	21.82	19.86	20.31	14.81	6.01	34.2	10.96	10.49	3.26	2.81
Corrugatec	1	0.38	3.25	30.28	24.89	16.61	15.04	8.5	6.89	60.2	13.17	12.04	0	0
Corrugatec	2	0.48	3.94	33.47	25.21	13.75	12.07	10.17	6.34	62.4	6.4	5.27	0.07	0
Corrugatec	3	0.66	4.44	31.29	25.59	15.61	14.04	7.84	6.49	57.1	9.06	8.5	1.25	0.68
Corrugatec	7	0.86	3.14	29.49	26.21	13.75	12.89	11.65	5.84	72.4	9.37	7.21	1.96	1.89
Corrugatec	14	1.01	2.14	29.29	23.21	13.91	17.28	11.69	6.71	69.2	4.58	4.45	0	0
Corrugatec	21	1.07	3.09	24.47	23.21	22.75	14.07	10.17	6.12	74.6	11.59	10.66	3.31	3.15

Table C.3 – Data matrix used for physico-chemical analysis of road surface build-up data

Site	Days	pH	EC (µS)	TC (mg)	TOC (mg)	DOC (mg)	Fraction build-up for each particle size class					
							0-10	10-50	50-100	100-200	200-400	>400
Gumbeel	1	6.02	22.39	50.47	50.47	38.22	0.17	0.68	0.75	0.49	0.22	0.08
Gumbeel	1	6.42	21.87	30.15	30.15	23.31	0.06	0.33	0.44	0.54	0.23	0.09
Gumbeel	2	5.91	19.60	57.33	57.33	44.45	0.22	0.86	0.82	0.63	0.36	0.16
Gumbeel	2	6.31	27.10	51.46	51.46	26.57	0.07	0.48	0.79	0.70	0.38	0.16
Gumbeel	3	5.54	17.60	57.47	57.47	44.87	0.15	0.76	0.92	1.05	0.61	0.23
Gumbeel	7	5.60	15.20	55.51	55.51	36.47	0.13	0.50	0.59	0.88	1.05	0.87
Gumbeel	14	5.72	15.10	57.47	57.47	42.98	0.09	0.33	0.44	0.84	1.22	0.90
Gumbeel	14	5.74	15.30	31.19	31.19	29.10	0.05	0.55	0.49	1.00	1.66	1.33
Gumbeel	23	5.62	14.90	33.07	33.07	31.50	0.20	0.68	0.49	0.71	1.46	1.63
Lauder	1	5.65	18.16	43.61	43.61	36.26	0.08	0.41	0.69	0.53	0.16	0.08
Lauder	1	6.35	19.58	29.42	29.42	23.28	0.03	0.34	0.48	0.48	0.20	0.11
Lauder	2	5.67	16.02	47.46	47.46	41.37	0.10	0.44	0.54	0.38	0.15	0.07
Lauder	2	5.98	14.48	30.67	30.67	22.32	0.03	0.43	0.51	0.54	0.26	0.12
Lauder	3	5.92	25.66	49.91	49.91	42.28	0.09	0.45	0.67	0.54	0.21	0.09
Lauder	7	5.76	22.26	51.45	51.45	41.44	0.11	0.43	0.53	0.48	0.36	0.15
Lauder	14	6.05	16.78	48.51	48.51	43.47	0.01	0.33	0.44	0.58	0.58	0.27
Lauder	14	5.72	16.22	34.97	29.25	32.05	0.04	0.34	0.34	0.67	0.77	0.46
Lauder	23	5.69	15.93	26.76	26.76	29.10	0.07	0.22	0.34	0.66	0.85	0.54
Piccadilly	1	5.73	21.89	36.47	36.47	34.51	0.16	0.60	0.62	0.33	0.13	0.05
Piccadilly	2	5.77	19.80	37.38	37.38	29.61	0.12	0.47	0.58	0.46	0.25	0.10
Piccadilly	7	5.86	19.70	44.73	44.73	39.27	0.13	0.53	0.74	0.54	0.24	0.14
Piccadilly	7	5.84	18.50	43.47	43.47	37.73	0.17	0.64	0.66	0.35	0.14	0.03
Piccadilly	14	6.57	17.23	50.47	50.47	34.86	0.10	0.55	0.59	0.63	0.43	0.16
Piccadilly	21	6.20	17.53	45.64	45.64	41.09	0.06	0.32	0.41	0.55	0.72	0.54

Table C.4 – Data matrix used for physico-chemical analysis of road surface build-up data

Surface type	Days	pH	EC	TC	TOC	DOC	Fraction build-up for each size class					
							0-10	10-50	50-100	100-200	200-400	>400
Concrete	1	6.81	53.4	53.82	51.06	49.11	0.011	0.104	0.121	0.079	0.066	0.051
Concrete	2	6.21	28.4	34.51	29.26	26.95	0.015	0.088	0.101	0.093	0.088	0.068
Concrete	3	6.43	42.1	34.72	27.86	27.405	0.018	0.146	0.142	0.097	0.071	0.062
Concrete	7	5.98	54.2	52.44	42.24	30.3	0.019	0.154	0.166	0.115	0.121	0.089
Concrete	14	6.42	39.7	32.92	25.2	19.72	0.029	0.165	0.153	0.155	0.096	0.080
Concrete	21	6.01	34.2	49.32	34.65	34.56	0.029	0.150	0.183	0.167	0.171	0.124
Steel	1	6.89	60.2	39.51	39.51	36.12	0.012	0.115	0.095	0.063	0.057	0.032
Steel	2	6.34	62.4	22.4	22.155	18.445	0.019	0.161	0.121	0.066	0.058	0.049
Steel	3	6.49	57.1	36.24	31.24	31.28	0.029	0.206	0.169	0.103	0.092	0.052
Steel	7	5.84	72.4	42.165	33.345	23.94	0.027	0.253	0.225	0.118	0.111	0.100
Steel	14	6.72	69.2	20.61	20.61	20.025	0.022	0.295	0.234	0.140	0.174	0.118
Steel	21	6.12	74.6	46.36	33.12	30.04	0.033	0.262	0.248	0.243	0.150	0.109

APPENDIX D

POLLUTANT WASH-OFF DATA

Table D.1 – Amount of pollutants collected during initially available pollutant investigation on roof surfaces

Sampling Description	Amounts (g/m^2)	
	Concrete tile	Corrugated steel
Sample 1 – before 40mm/hr rainfall simulation	0.26	0.43
Sample 2 – before 65mm/hr rainfall simulation	0.31	0.54
Sample 3 – before 86mm/hr rainfall simulation	0.23	0.41
Average	0.27	0.46
CV	13.4 %	12.0 %

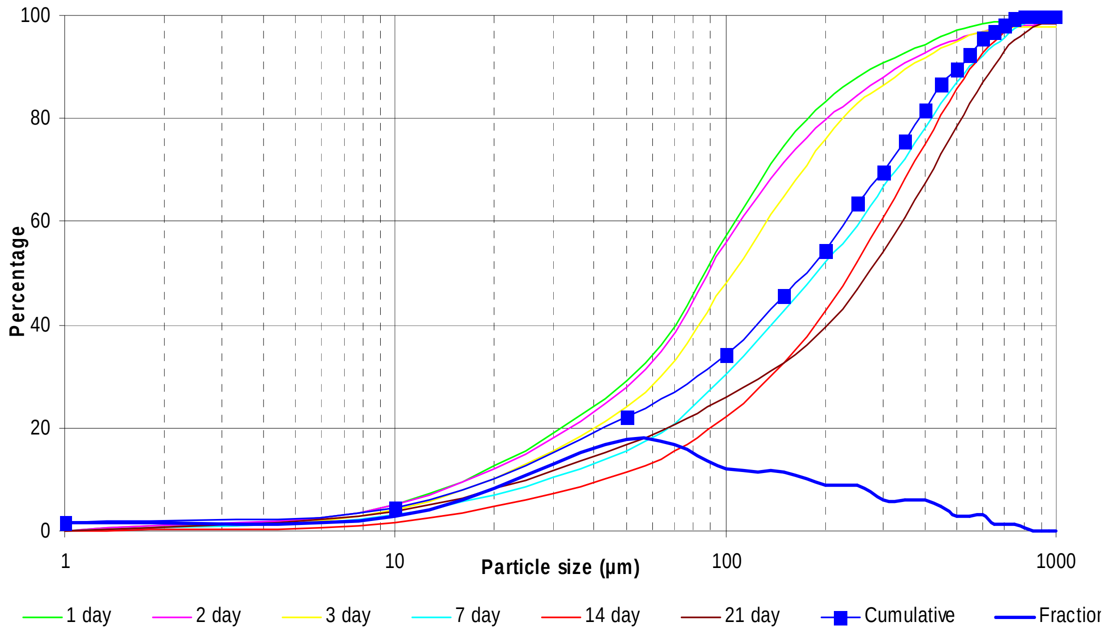


Figure D.1 – Cumulative particle size distribution: Comparison of Initially available pollutant sample with build-up samples for Gumbeel Court road site

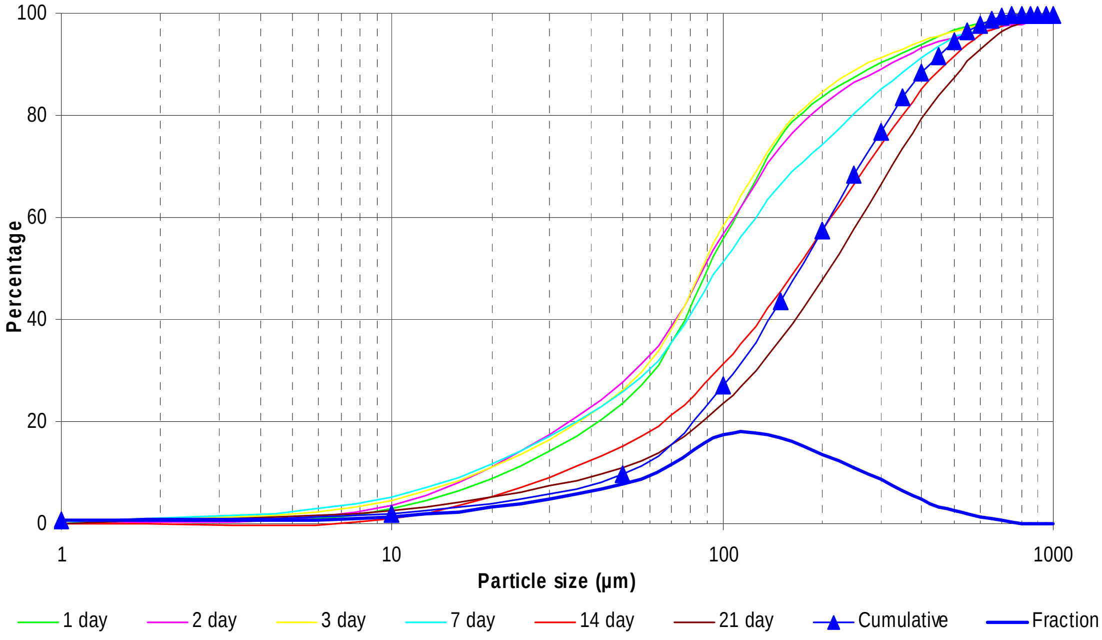


Figure D.2 – Cumulative particle size distribution: Comparison of Initially available pollutant sample with build-up samples for Lauder Court road site

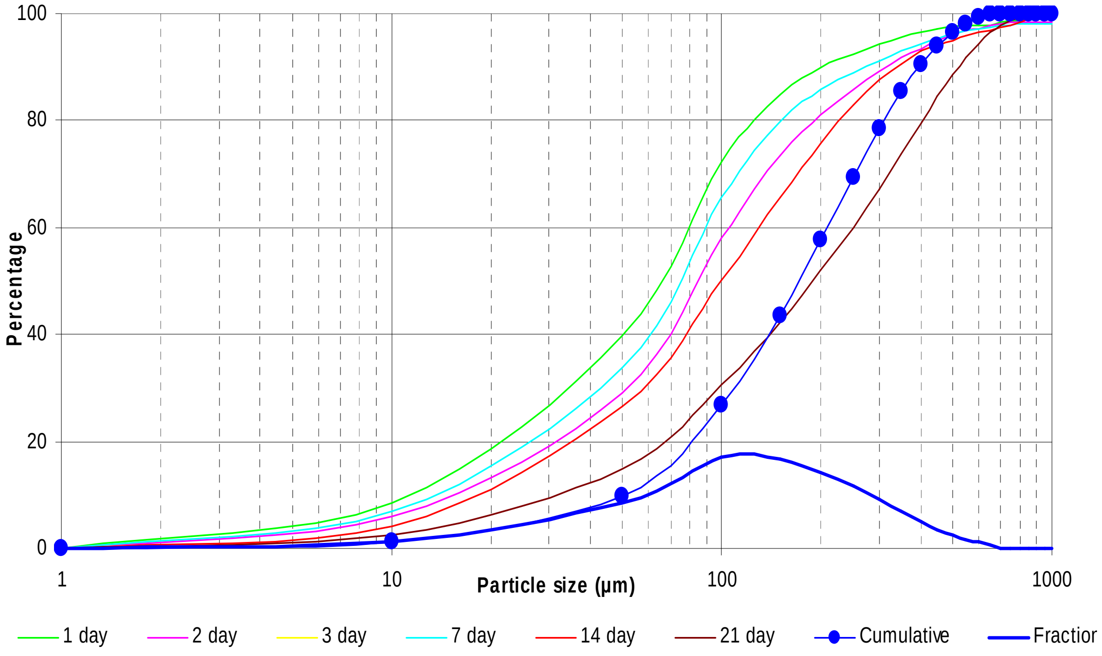


Figure D.3 – Cumulative particle size distribution: Comparison of Initially available pollutant sample with build-up samples for Piccadilly Place road site

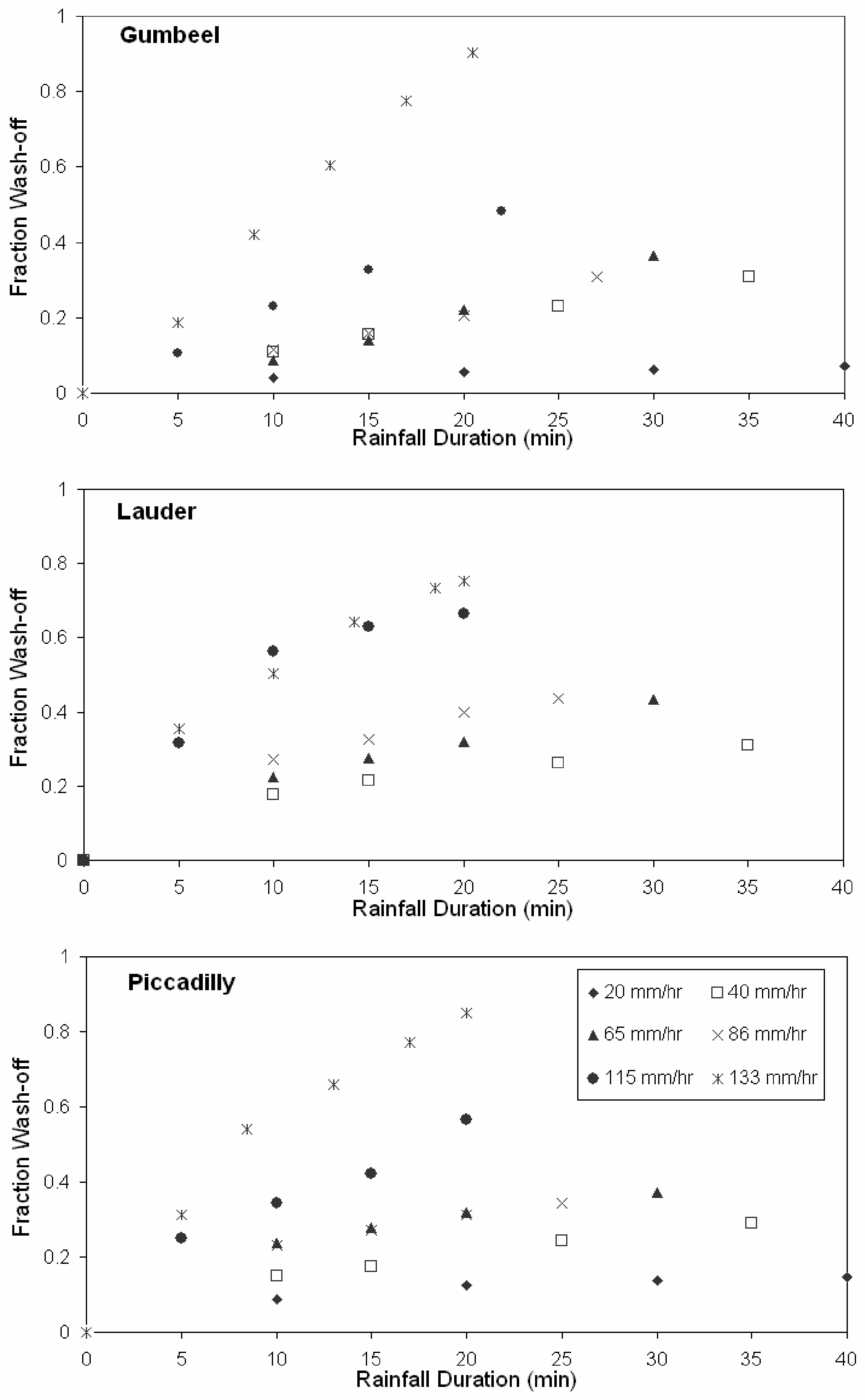


Figure D.4 – Variation of fraction wash-off with rainfall intensity and duration for three road sites

Table D.2 – Observed wash-off data and calculation of fraction wash-off

Site / Sampling	Intensity (mm/hr)	Duration (min)	TSS Concentration (mg/L)	Wash-off Pollutant Load (mg)	Cumultive Wash-off Load (mg)	Fraction Wash-off
Gumbeel - wash-off	20	10	189.8	1267.9	1267.9	0.04
Gumbeel - wash-off	20	20	62.4	507.9	1775.8	0.06
Gumbeel - wash-off	20	30	31.2	237.1	2012.9	0.06
Gumbeel - wash-off	20	40	28.8	255.2	2268.1	0.07
Gumbeel - wash-off	40	10	224.8	3484.4	3484.4	0.11
Gumbeel - wash-off	40	15	175.2	1531.2	5015.6	0.16
Gumbeel - wash-off	40	25	155.2	2421.1	7436.8	0.23
Gumbeel - wash-off	40	35	129	2458.7	9895.5	0.31
Gumbeel - wash-off	65	10	213.6	2806.7	2806.7	0.09
Gumbeel - wash-off	65	15	162.8	1756.6	4563.3	0.14
Gumbeel - wash-off	65	20	233.6	2560.3	7123.6	0.22
Gumbeel - wash-off	65	30	197.2	4582.9	11706.5	0.36
Gumbeel - wash-off	86	10	205	3735.1	3735.1	0.12
Gumbeel - wash-off	86	15	119.6	1356.3	5091.4	0.16
Gumbeel - wash-off	86	20	128.8	1566.2	6657.6	0.21
Gumbeel - wash-off	86	27	193.6	3221.5	9879.1	0.31
Gumbeel - wash-off	115	5	273.4	3390.2	3390.2	0.11
Gumbeel - wash-off	115	10	236.2	4006.0	7396.1	0.23
Gumbeel - wash-off	115	15	211.8	3177.0	10573.1	0.33
Gumbeel - wash-off	115	22	267.4	4925.5	15498.6	0.48
Gumbeel - wash-off	133	5	336.4	5987.9	5987.9	0.19
Gumbeel - wash-off	133	9	326	7595.8	13583.7	0.42
Gumbeel - wash-off	133	13	253.6	5908.9	19492.6	0.61
Gumbeel - wash-off	133	17	233.6	5456.9	24949.5	0.77
Gumbeel - wash-off	133	20.5	178.2	4095.0	29044.5	0.90
Gumbeel - Initial pollutant load			5209.4	32694.1		
Lauder - wash-off	40	10	117.6	1665.2	1665.2	0.18
Lauder - wash-off	40	15	42.8	335.6	2000.8	0.21
Lauder - wash-off	40	25	28.8	459.6	2460.4	0.26
Lauder - wash-off	40	35	32.4	419.3	2879.7	0.31
Lauder - wash-off	65	10	100.2	2104.2	2104.2	0.23
Lauder - wash-off	65	15	39	474.2	2578.4	0.28
Lauder - wash-off	65	20	33.6	408.6	2987.0	0.32
Lauder - wash-off	65	30	42.2	1053.3	4040.3	0.43
Lauder - wash-off	86	10	115.4	2538.8	2538.8	0.27
Lauder - wash-off	86	15	30.6	508.0	3046.8	0.33
Lauder - wash-off	86	20	40.2	668.1	3714.9	0.40
Lauder - wash-off	86	25	26.2	365.2	4080.1	0.44
Lauder - wash-off	115	5	165.8	2961.2	2961.2	0.32
Lauder - wash-off	115	10	100	2308.0	5269.2	0.56
Lauder - wash-off	115	15	26.6	611.3	5880.5	0.63
Lauder - wash-off	115	20	14.2	333.7	6214.2	0.67
Lauder - wash-off	133	5	135.8	3305.4	3305.4	0.35
Lauder - wash-off	133	10	54.6	1381.4	4686.8	0.50
Lauder - wash-off	133	14.4	52	1322.9	6009.6	0.64
Lauder - wash-off	133	18.5	34.8	827.5	6837.2	0.73
Lauder - wash-off	133	20	21.8	204.0	7041.2	0.75
Lauder - Initial pollutant load			1340.8	9332.0		

Table D.2 – Observed wash-off data and calculation of fraction wash-off (Continued)

Site / Sampling	Intensity (mm/hr)	Duration (min)	TSS Concentration (mg/L)	Wash-off Pollutant Load (mg)	Cumultive Wash-off Load (mg)	Fraction Wash-off
Piccadilly wash-off	20	10	113.2	923.7	923.7	0.09
Piccadilly wash-off	20	20	42.6	407.3	1331.0	0.13
Piccadilly wash-off	20	30	12.8	122.6	1453.6	0.14
Piccadilly wash-off	20	40	13	114.1	1567.7	0.15
Piccadilly wash-off	40	10	103.2	1583.1	1583.1	0.15
Piccadilly wash-off	40	15	34.6	289.9	1873.0	0.18
Piccadilly wash-off	40	25	40.2	723.6	2596.6	0.24
Piccadilly wash-off	40	35	27	489.2	3085.9	0.29
Piccadilly wash-off	65	10	118.2	2531.8	2531.8	0.24
Piccadilly wash-off	65	15	35.8	436.0	2967.9	0.28
Piccadilly wash-off	65	20	36	437.0	3404.9	0.32
Piccadilly wash-off	65	30	21.8	535.8	3940.8	0.37
Piccadilly wash-off	86	10	111.8	2443.9	2443.9	0.23
Piccadilly wash-off	86	15	35.4	435.4	2879.4	0.27
Piccadilly wash-off	86	20	36.8	459.3	3338.6	0.31
Piccadilly wash-off	86	25	24.6	309.5	3648.1	0.34
Piccadilly wash-off	115	5	157	2665.9	2665.9	0.25
Piccadilly wash-off	115	10	45.4	1003.3	3669.2	0.35
Piccadilly wash-off	115	15	39.6	805.5	4474.7	0.42
Piccadilly wash-off	115	20	73.6	1533.8	6008.5	0.57
Piccadilly wash-off	133	5	158.6	3314.7	3314.7	0.31
Piccadilly wash-off	133	10	96.8	2425.8	5740.5	0.54
Piccadilly wash-off	133	13	47.8	1265.7	7006.3	0.66
Piccadilly wash-off	133	17	45.4	1187.7	8194.0	0.77
Piccadilly wash-off	133	20	42.2	838.1	9032.0	0.85
Piccadilly - Initial pollutant load			1303.2	10634.1		

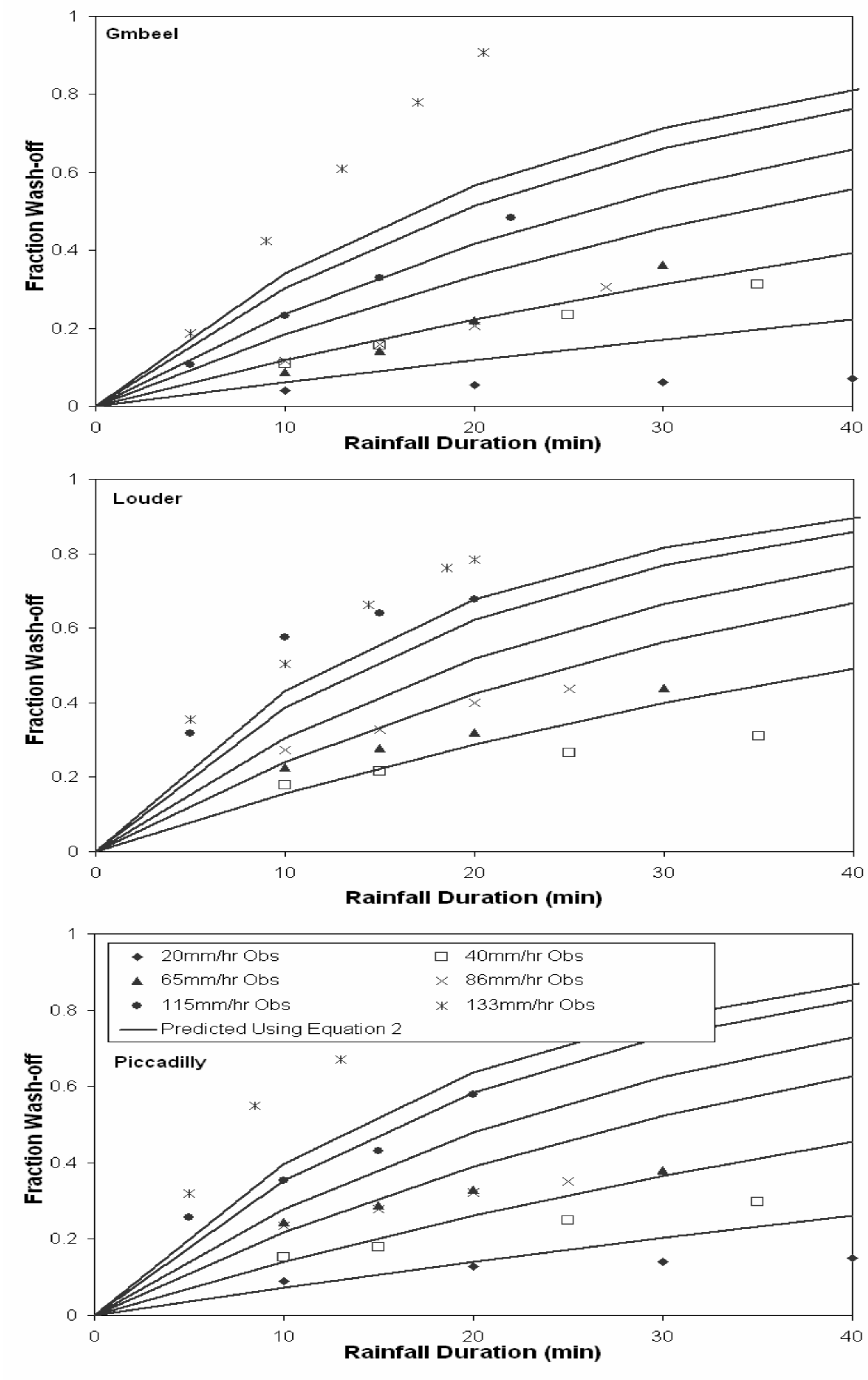
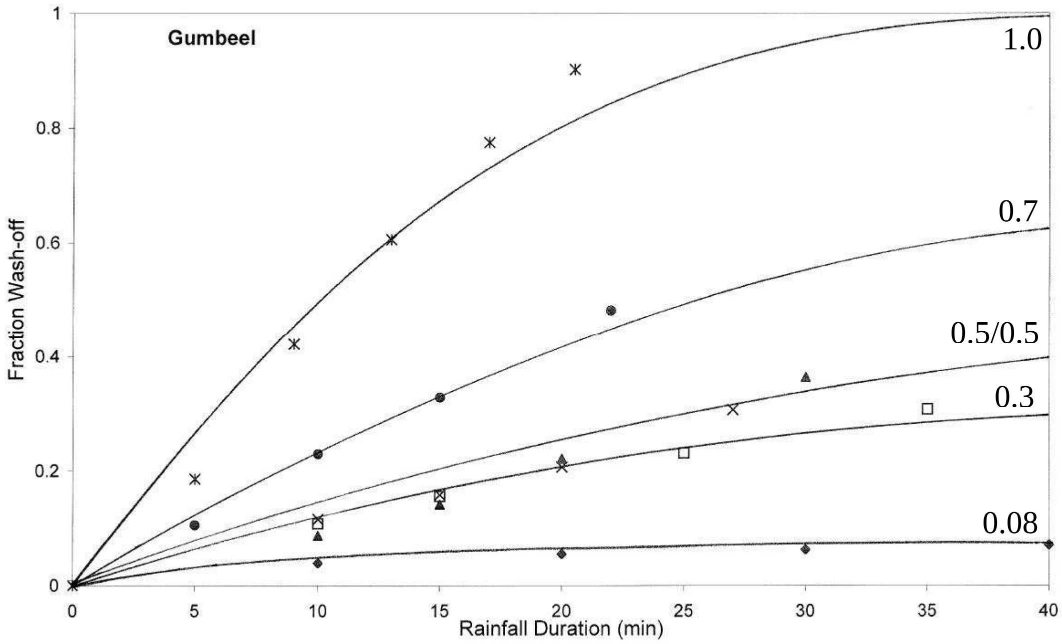
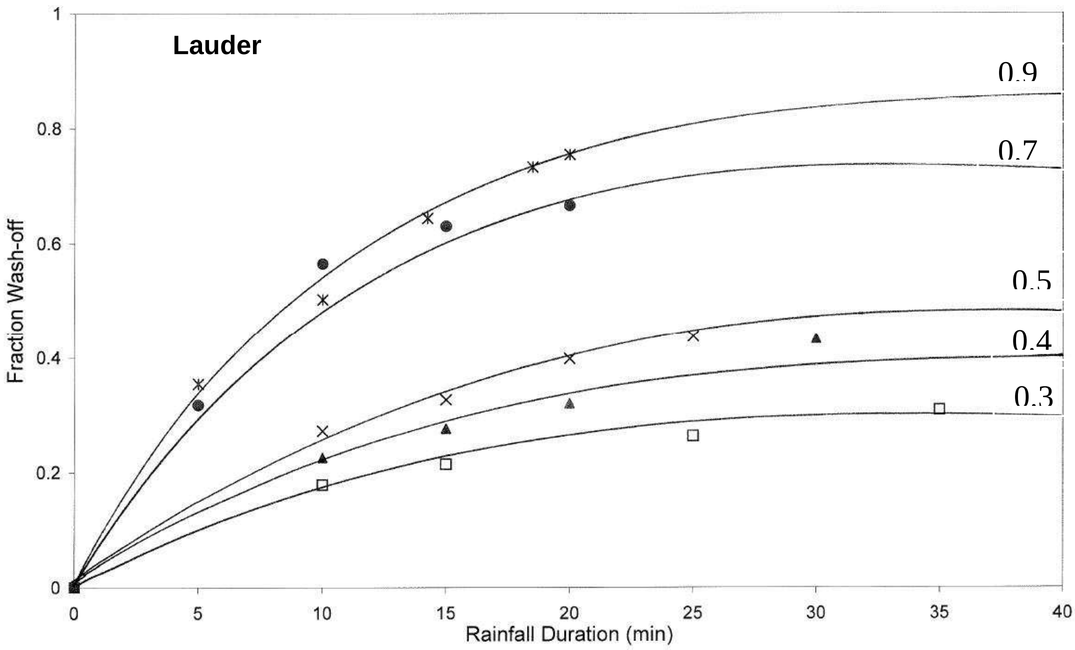


Figure D.5 – Comparison of observed data with predicted using Equation2



Gumbeel
1.0
0.7
0.5/0.5
0.3
0.08
Fraction Wash-off
Rainfall Duration (min)
0
0.2
0.4
0.6
0.8
1
0
5
10
15
20
25
30
35
40



Lauder
0.9
0.7
0.5
0.4
0.3
Fraction Wash-off
Rainfall Duration (min)
0
0.2
0.4
0.6
0.8
1
0
5
10
15
20
25
30
35
40

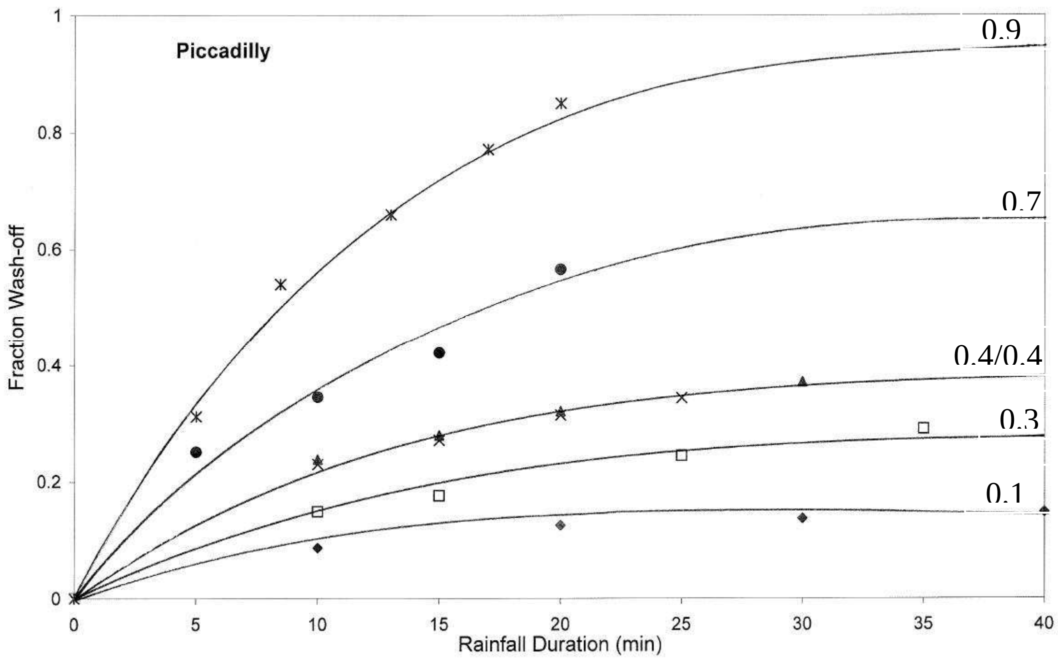


Figure D.6 – Initial estimates for C_F using freehand sketches

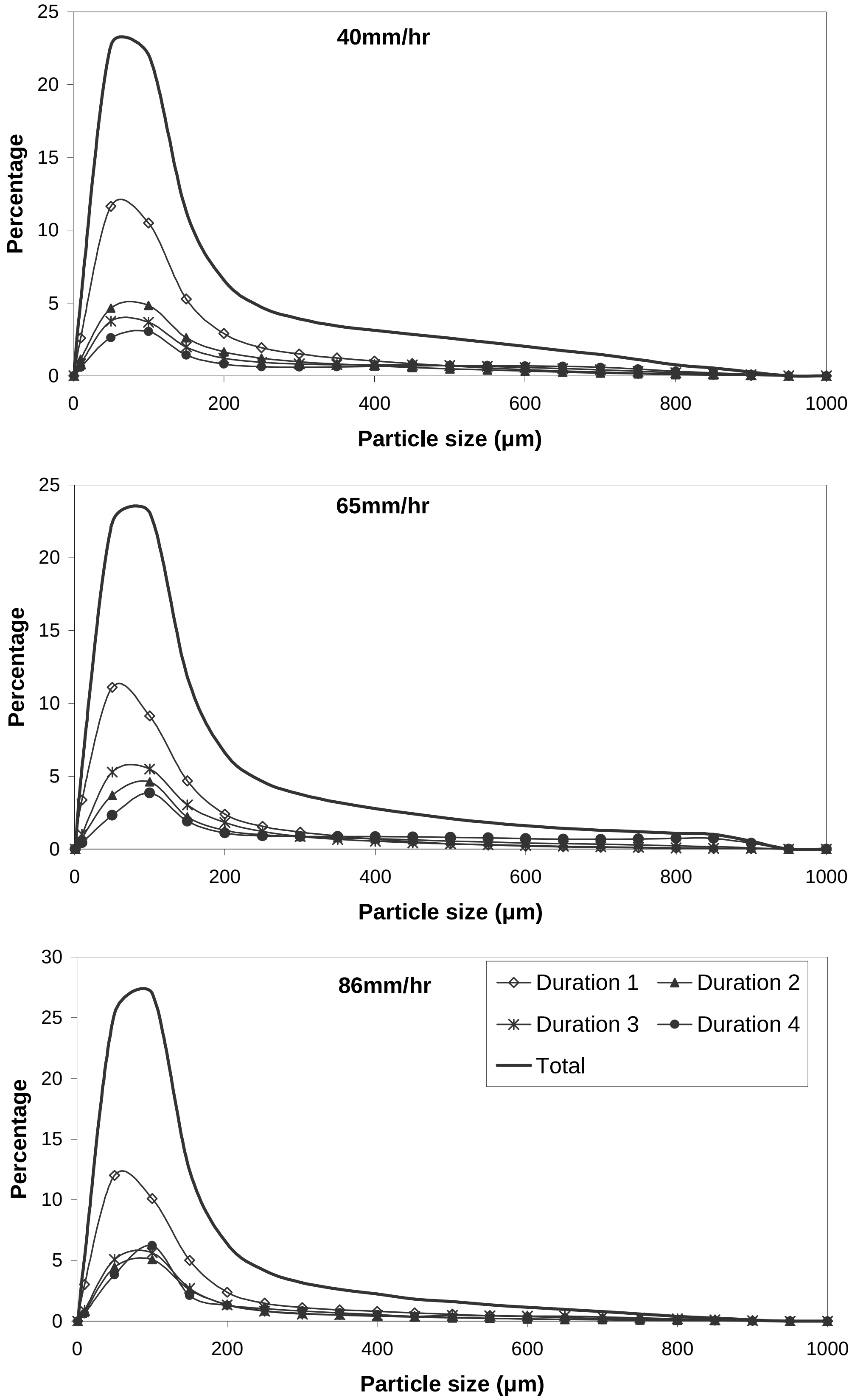


Figure D.7 – Variation of wash-off particle size distribution with rainfall duration

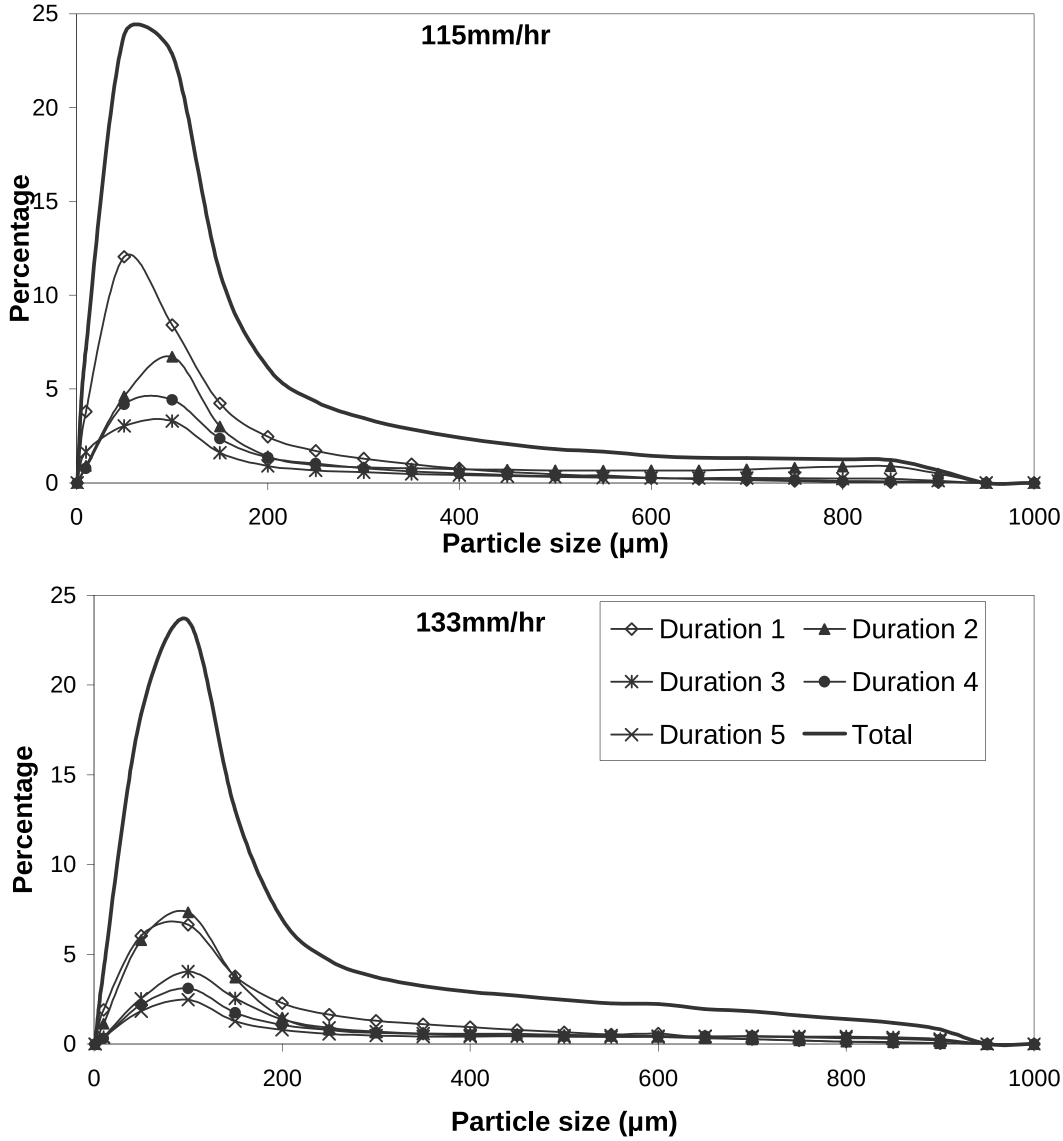


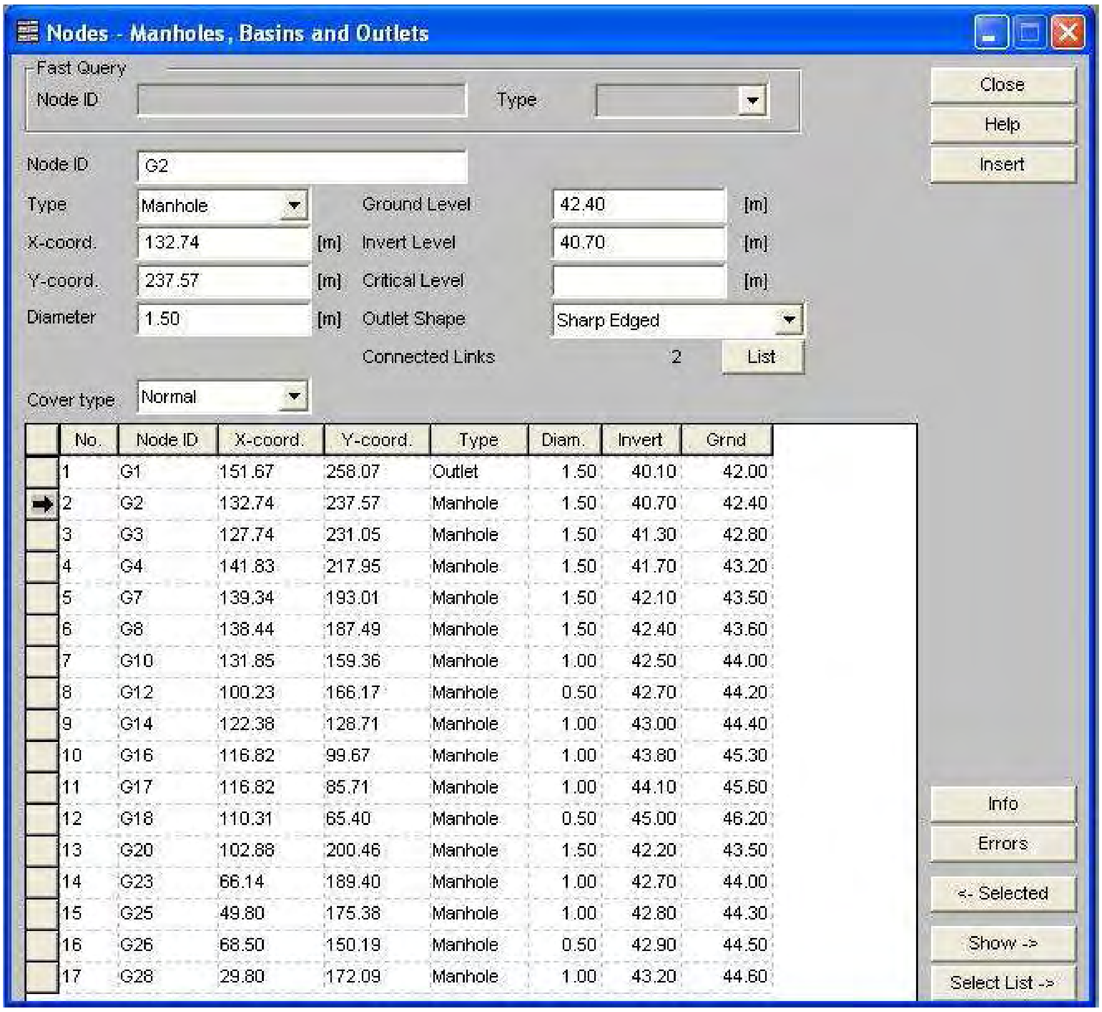
Figure D.7 – Variation of wash-off particle size distribution with rainfall duration - Continued

Table D.3 – Data matrix used for analysis of quality parameters resulted from road surface investigations

ID	pH	EC	TC	TOC	DOC	Particulate Concentrations (mg/L)					
						<10 µm	10 - 50 µm	50 - 100 µm	100 - 200 µm	200 - 400 µm	>400 µm
G11	6.3	54.9	13.2	10.8	9.6	6.2	36.0	47.9	44.0	36.1	19.8
G12	6.1	22.3	9.8	9.6	8.2	2.0	9.7	13.4	15.1	13.4	8.9
G13	6.1	19.7	6.4	5.3	4.7	1.6	6.1	6.9	7.4	6.1	3.0
G14	6.2	15.3	8.3	6.5	3.9	0.9	5.0	6.4	6.8	6.2	3.6
G21	5.6	26.2	9.6	8.4	5.8	9.3	40.1	52.1	57.8	43.7	22.1
G22	5.8	28.6	9.5	7.1	-0.1	7.8	33.2	40.1	46.4	36.9	10.8
G23	5.8	28.7	5.3	5.3	5.1	5.2	23.7	29.7	29.4	33.0	46.7
G24	5.7	64.7	6.3	4.7	3.2	3.5	17.0	20.6	17.7	22.2	49.0
G31	5.8	77.0	10.7	8.5	6.6	10.4	45.8	48.0	48.7	39.4	21.6
G32	5.7	123.0	8.9	6.8	4.1	5.5	26.1	32.9	35.5	36.4	26.7
G33	6.9	75.5	9.4	6.5	2.8	8.5	52.8	67.9	62.7	32.8	9.0
G34	6.1	46.5	8.0	6.0	3.2	3.9	21.0	27.4	34.0	55.3	56.4
G41	5.6	53.5	9.4	7.7	4.9	9.4	43.1	49.0	43.9	32.0	25.9
G42	6.1	63.5	8.3	8.1	5.5	4.2	24.9	32.0	34.2	21.3	3.1
G43	6.3	62.0	8.5	6.1	3.0	3.0	25.3	33.8	33.9	23.5	9.3
G44	6.3	80.0	8.8	6.1	2.9	5.7	38.9	45.6	45.9	40.9	16.6
G51	5.8	66.0	9.8	8.1	7.2	27.9	86.7	57.8	47.3	40.0	13.6
G52	5.7	66.1	8.1	7.0	4.6	11.4	53.1	50.0	44.4	43.3	34.4
G53	6.2	37.4	5.5	5.5	5.0	11.8	56.0	51.8	44.2	29.5	18.7
G54	6.2	38.2	8.2	6.6	3.2	12.2	61.9	62.5	54.8	45.2	31.1
G61	5.7	36.7	8.6	7.7	5.2	39.6	105.1	71.2	54.5	43.0	23.3
G62	6.1	22.8	5.6	4.8	3.8	19.1	98.1	93.2	59.8	36.2	20.0
G63	6.2	18.5	7.7	5.9	2.8	7.8	50.3	54.7	48.6	42.9	50.3
G64	6.2	10.5	5.7	4.0	2.7	6.3	39.0	47.3	40.2	36.9	65.8
G65	6.2	8.8	5.5	3.9	2.7	9.3	43.6	49.9	44.9	27.6	4.0
L21	5.8	219.0	14.2	13.9	11.1	6.5	25.8	30.0	25.0	18.3	12.1
L22	5.6	182.0	17.9	17.7	8.2	2.9	9.5	9.9	6.7	5.8	8.1
L23	5.9	174.3	8.5	7.9	7.6	1.8	6.5	4.5	3.0	4.5	8.6
L24	6.0	171.8	6.7	4.1	6.5	1.7	7.0	5.9	4.7	6.0	7.3
L31	5.8	114.8	9.3	8.8	7.6	7.0	32.6	24.1	16.8	11.8	8.1
L32	6.0	92.3	6.4	4.5	6.2	1.3	7.9	11.2	4.6	3.2	11.1
L33	6.1	90.6	6.0	5.5	4.9	2.1	10.0	7.4	5.7	4.7	3.8
L34	6.1	75.9	7.1	6.2	4.3	0.9	4.9	9.4	3.7	2.1	23.5
L41	5.7	66.4	12.6	10.1	8.2	7.0	33.6	28.2	23.3	14.4	8.9
L42	6.0	50.8	6.4	4.4	6.1	1.1	7.7	8.5	5.5	3.5	4.3
L43	6.0	113.4	7.2	5.9	4.9	2.2	9.9	8.6	6.0	5.0	8.3
L44	6.0	149.6	11.1	9.0	5.4	1.4	6.7	7.7	4.7	3.7	2.0
L51	5.8	226.0	8.9	6.2	8.5	13.0	52.5	36.7	30.9	20.0	12.8
L52	5.9	229.6	7.0	7.0	6.4	2.7	14.8	22.8	11.5	9.0	43.2
L53	6.0	249.1	6.3	6.3	5.3	9.4	4.1	1.6	2.3	5.6	3.7
L54	6.1	254.0	5.3	5.3	4.0	0.3	1.7	3.2	2.2	2.3	4.6
L61	5.7	296.0	7.5	5.4	5.9	2.5	19.8	33.0	28.1	26.9	27.4
L62	5.7	311.0	7.1	7.1	5.2	1.2	8.4	13.4	7.8	8.7	15.3
L63	5.7	312.0	4.9	4.9	4.8	0.8	4.1	12.6	13.0	7.3	20.8
L64	5.9	312.0	4.2	4.2	3.8	0.4	3.2	7.8	6.1	4.2	16.3
L65	5.9	252.2	4.4	4.4	3.8	0.4	2.3	4.2	3.1	2.3	10.7
P11	6.3	107.3	21.0	21.0	19.5	8.3	38.0	33.0	22.8	9.5	1.6
P12	6.7	81.2	13.6	13.2	9.5	2.6	8.1	8.9	10.0	9.5	3.5
P13	6.4	79.2	11.1	10.8	7.6	0.4	3.0	4.5	1.7	1.4	1.8
P14	6.3	74.4	10.8	9.9	5.6	0.6	2.8	2.7	2.4	2.7	1.8
P21	6.7	81.2	16.0	15.9	13.1	8.5	41.5	26.2	13.7	7.8	5.7
P22	6.5	96.2	11.5	11.1	8.5	1.8	9.2	7.7	5.6	5.7	4.7
P23	6.3	100.4	9.9	9.7	6.9	1.7	9.5	9.4	8.0	6.4	5.2
P24	6.3	105.1	9.8	9.0	4.7	0.9	4.4	6.5	3.8	2.9	8.7
P31	6.4	137.4	11.8	11.5	9.8	14.6	38.1	31.1	23.7	11.0	1.0
P32	6.3	124.8	9.7	8.9	4.4	1.9	7.7	8.2	7.2	7.2	3.7
P33	6.4	125.8	6.5	6.4	5.7	1.9	7.8	7.6	6.7	6.2	5.9
P34	6.3	125.4	6.6	6.0	4.0	0.6	3.2	6.3	4.8	3.2	3.7
P41	6.3	151.4	12.6	12.6	11.7	11.8	40.1	30.0	17.2	7.7	5.0
P42	6.3	139.5	10.7	10.3	5.2	1.8	10.0	10.5	6.6	3.7	2.9
P43	6.3	137.6	10.1	10.0	4.7	1.6	10.3	12.3	5.7	1.8	5.6
P44	6.4	135.1	7.8	7.6	4.6	0.3	3.4	14.9	2.3	1.9	1.5
P51	6.2	162.3	13.4	11.5	8.9	19.3	50.2	35.9	26.5	18.7	6.5
P52	6.4	131.5	9.7	9.0	4.9	1.2	6.5	17.2	10.9	4.2	5.5
P53	6.5	136.3	9.4	8.6	3.8	0.7	5.3	11.8	6.3	3.7	12.8
P54	6.4	127.9	10.3	9.2	4.9	3.2	18.4	18.8	15.6	11.2	6.4
P61	6.1	154.5	11.5	10.7	5.2	16.3	37.1	34.7	37.5	25.0	8.0
P62	6.4	139.4	8.9	7.4	3.8	4.6	21.1	31.9	25.4	6.4	7.7
P63	6.5	134.5	8.5	7.3	3.2	1.2	8.4	13.4	13.4	7.9	3.6
P64	6.4	133.5	6.5	6.0	4.3	1.1	8.3	10.3	11.2	10.6	3.9
P65	6.5	135.3	6.6	6.1	3.7	0.3	2.4	4.4	3.2	7.8	24.6

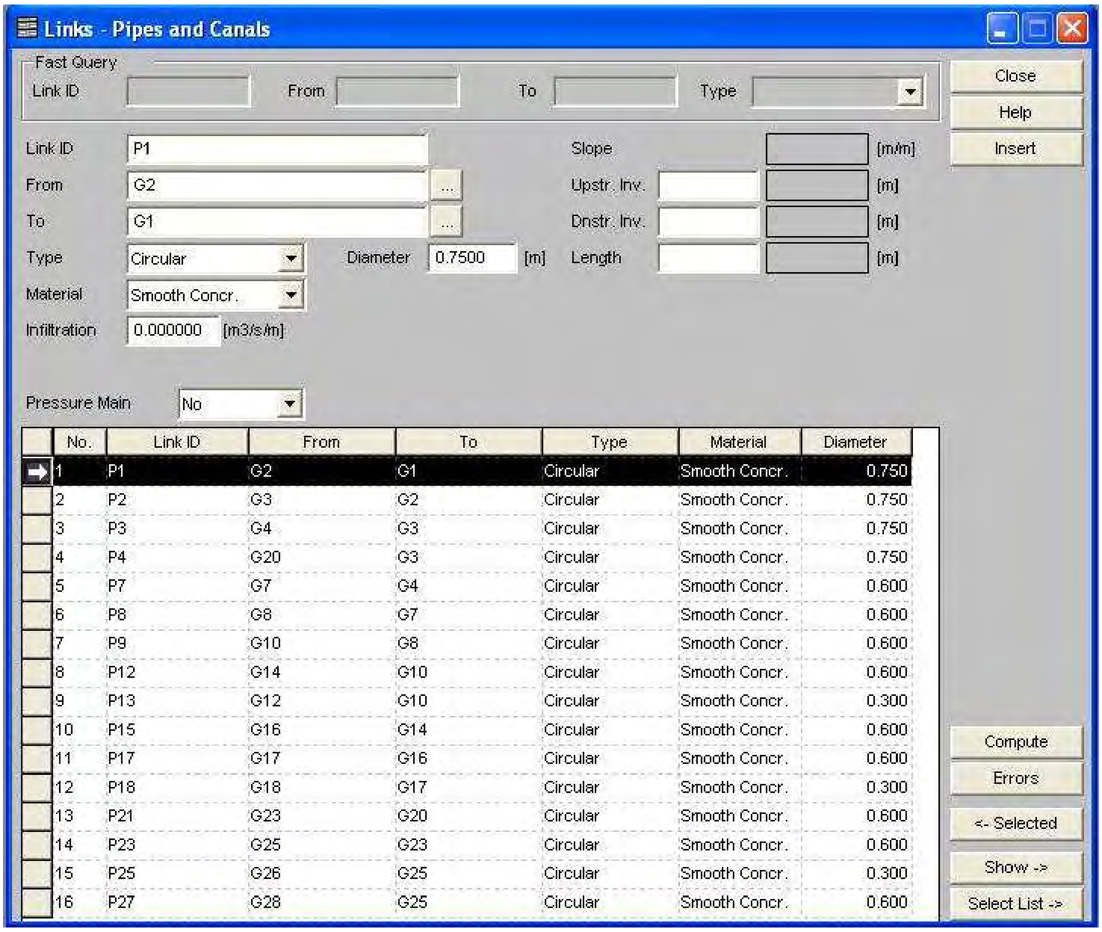
APPENDIX E

CATCHMENT MODELLING



No.	Node ID	X-coord.	Y-coord.	Type	Diam.	Invert	Grnd
1	G1	151.67	258.07	Outlet	1.50	40.10	42.00
2	G2	132.74	237.57	Manhole	1.50	40.70	42.40
3	G3	127.74	231.05	Manhole	1.50	41.30	42.80
4	G4	141.83	217.95	Manhole	1.50	41.70	43.20
5	G7	139.34	193.01	Manhole	1.50	42.10	43.50
6	G8	138.44	187.49	Manhole	1.50	42.40	43.60
7	G10	131.85	159.36	Manhole	1.00	42.50	44.00
8	G12	100.23	166.17	Manhole	0.50	42.70	44.20
9	G14	122.38	128.71	Manhole	1.00	43.00	44.40
10	G16	116.82	99.67	Manhole	1.00	43.80	45.30
11	G17	116.82	85.71	Manhole	1.00	44.10	45.60
12	G18	110.31	65.40	Manhole	0.50	45.00	46.20
13	G20	102.88	200.46	Manhole	1.50	42.20	43.50
14	G23	66.14	189.40	Manhole	1.00	42.70	44.00
15	G25	49.80	175.38	Manhole	1.00	42.80	44.30
16	G26	68.50	150.19	Manhole	0.50	42.90	44.50
17	G28	29.80	172.09	Manhole	1.00	43.20	44.60

Figure E.1 – Information of nodes for Alextown catchment



No.	Link ID	From	To	Type	Material	Diameter
1	P1	G2	G1	Circular	Smooth Concr.	0.750
2	P2	G3	G2	Circular	Smooth Concr.	0.750
3	P3	G4	G3	Circular	Smooth Concr.	0.750
4	P4	G20	G3	Circular	Smooth Concr.	0.750
5	P7	G7	G4	Circular	Smooth Concr.	0.600
6	P8	G8	G7	Circular	Smooth Concr.	0.600
7	P9	G10	G8	Circular	Smooth Concr.	0.600
8	P12	G14	G10	Circular	Smooth Concr.	0.600
9	P13	G12	G10	Circular	Smooth Concr.	0.300
10	P15	G16	G14	Circular	Smooth Concr.	0.600
11	P17	G17	G16	Circular	Smooth Concr.	0.600
12	P18	G18	G17	Circular	Smooth Concr.	0.300
13	P21	G23	G20	Circular	Smooth Concr.	0.600
14	P23	G25	G23	Circular	Smooth Concr.	0.600
15	P25	G26	G25	Circular	Smooth Concr.	0.300
16	P27	G28	G25	Circular	Smooth Concr.	0.600

Figure E.2 – Information of links for Alextown catchment

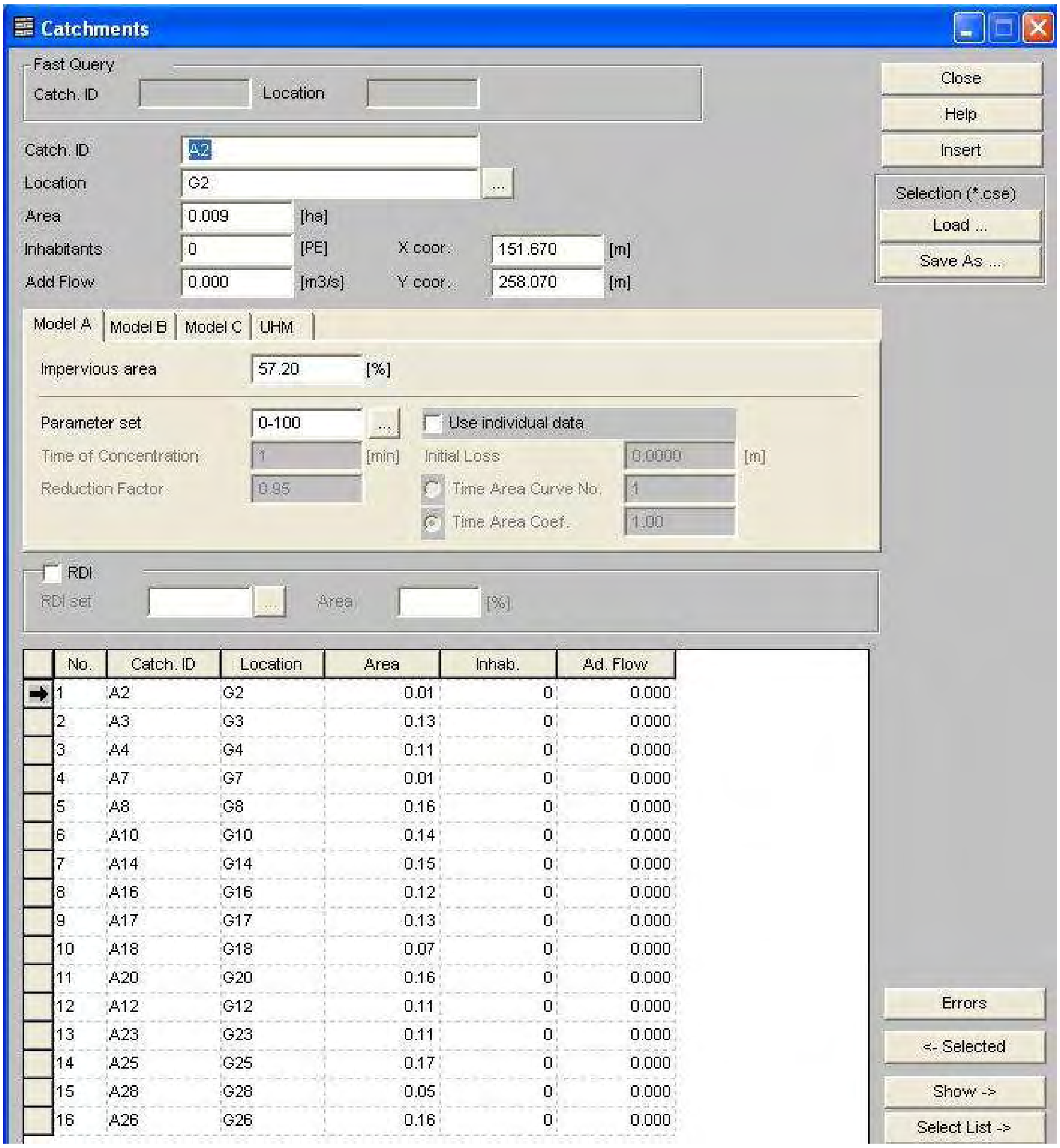


Figure E.3 – Information of sub-areas for Alextown catchment

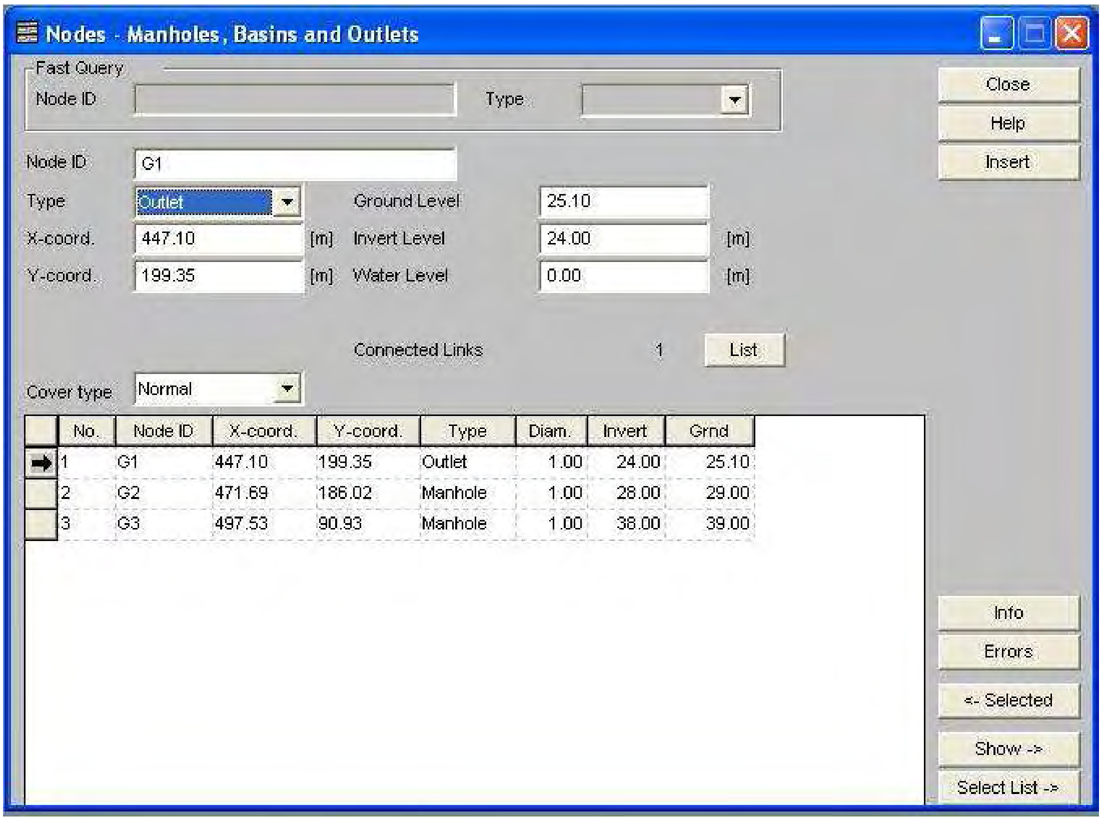


Figure E.4 – Information of nodes for Gumbeel catchment

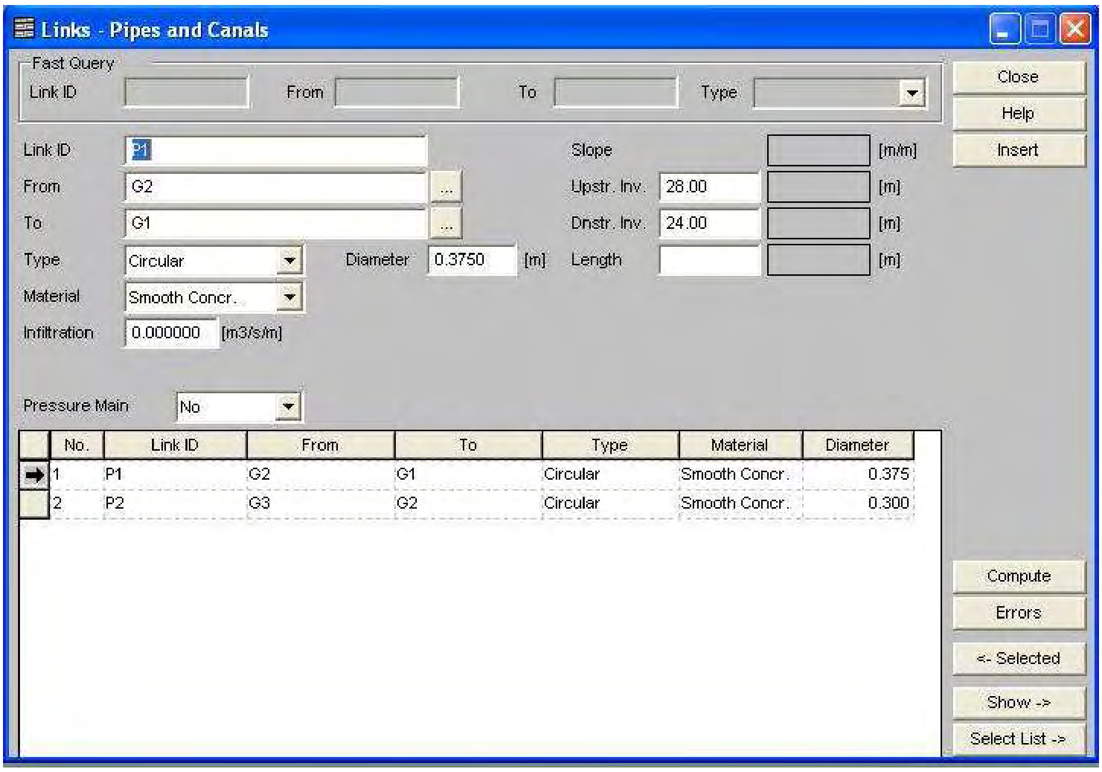


Figure E.5 – Information of links for Gumbeel catchment

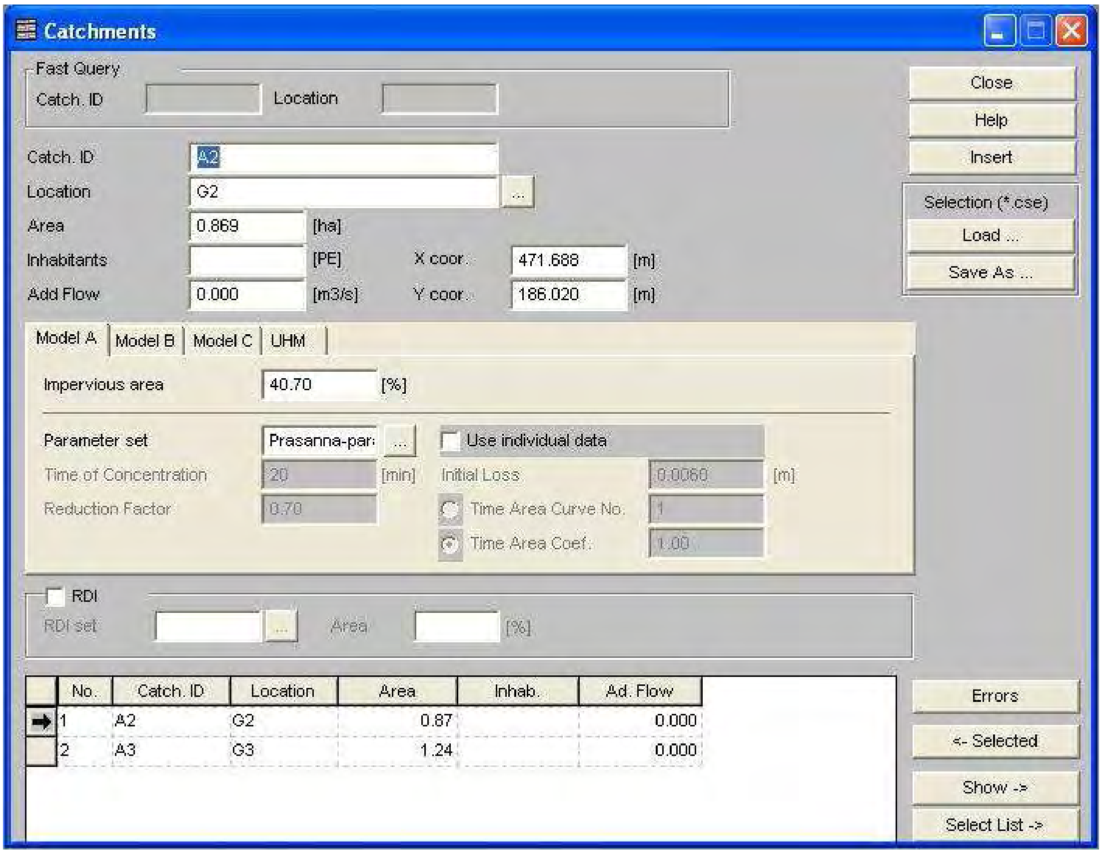
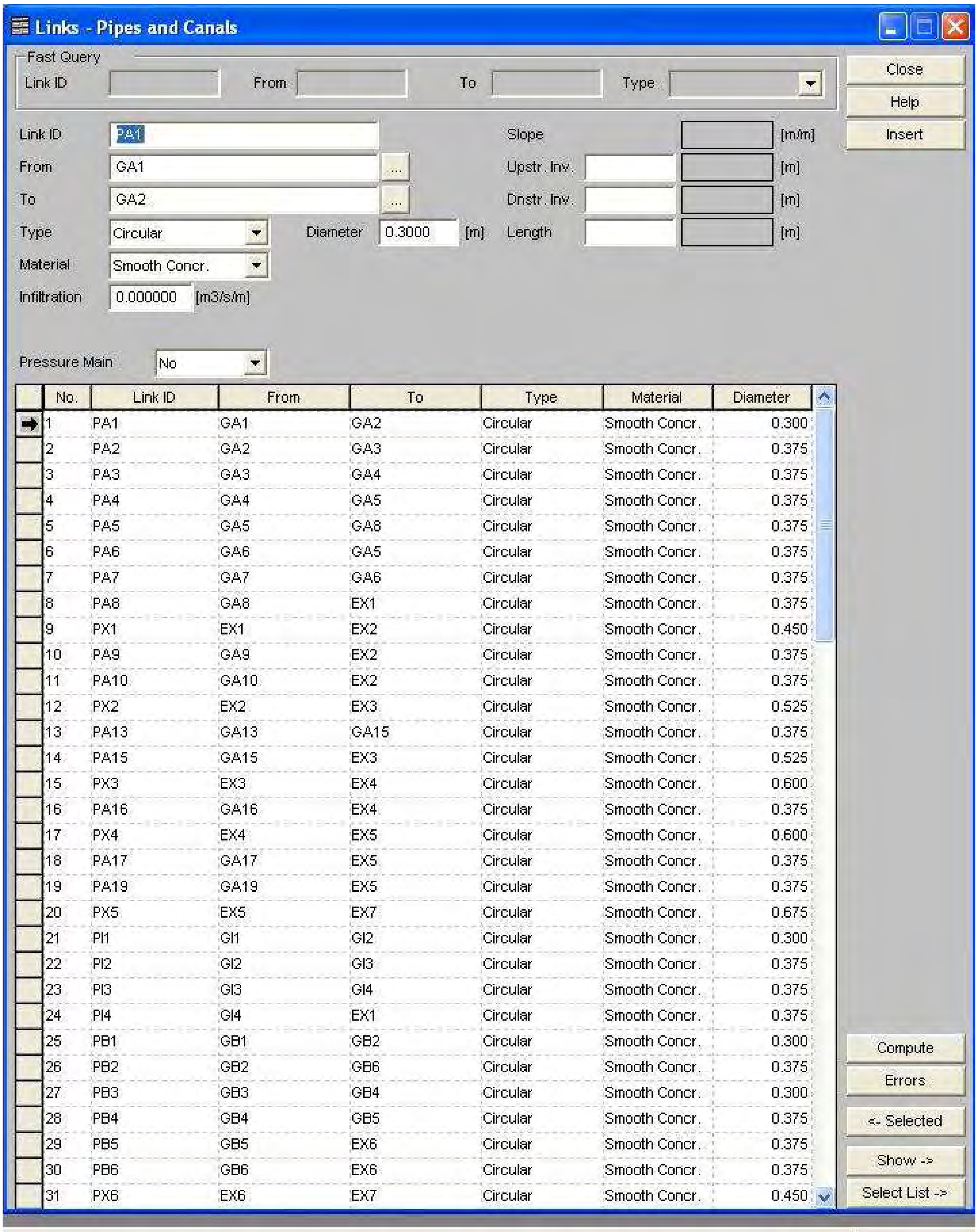
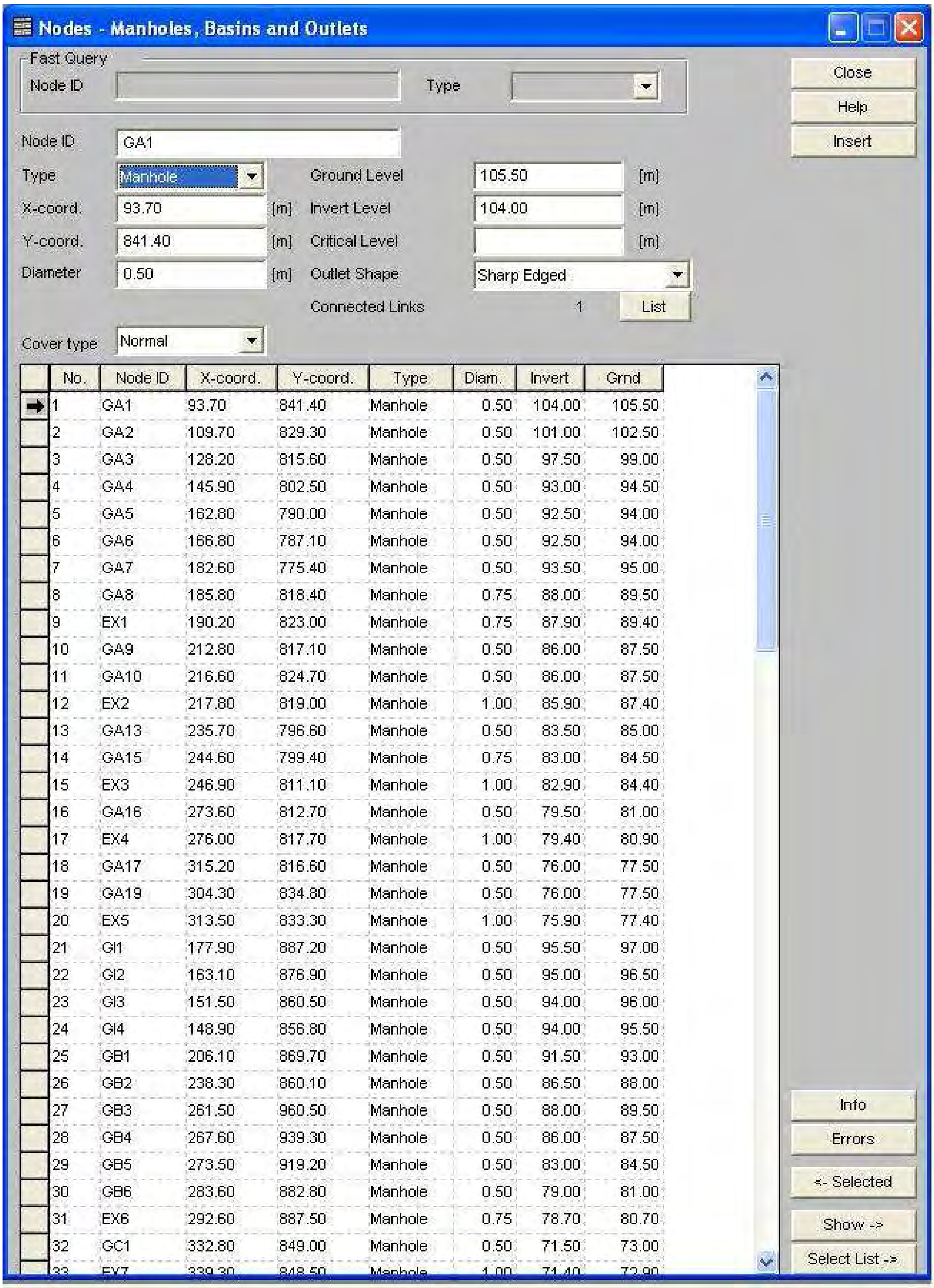


Figure E.6 – Information of sub-areas for Gumbeel catchment



No.	Link ID	From	To	Type	Material	Diameter
1	PA1	GA1	GA2	Circular	Smooth Concr.	0.300
2	PA2	GA2	GA3	Circular	Smooth Concr.	0.375
3	PA3	GA3	GA4	Circular	Smooth Concr.	0.375
4	PA4	GA4	GA5	Circular	Smooth Concr.	0.375
5	PA5	GA5	GA8	Circular	Smooth Concr.	0.375
6	PA6	GA6	GA5	Circular	Smooth Concr.	0.375
7	PA7	GA7	GA6	Circular	Smooth Concr.	0.375
8	PA8	GA8	EX1	Circular	Smooth Concr.	0.375
9	PX1	EX1	EX2	Circular	Smooth Concr.	0.450
10	PA9	GA9	EX2	Circular	Smooth Concr.	0.375
11	PA10	GA10	EX2	Circular	Smooth Concr.	0.375
12	PX2	EX2	EX3	Circular	Smooth Concr.	0.525
13	PA13	GA13	GA15	Circular	Smooth Concr.	0.375
14	PA15	GA15	EX3	Circular	Smooth Concr.	0.525
15	PX3	EX3	EX4	Circular	Smooth Concr.	0.600
16	PA16	GA16	EX4	Circular	Smooth Concr.	0.375
17	PX4	EX4	EX5	Circular	Smooth Concr.	0.600
18	PA17	GA17	EX5	Circular	Smooth Concr.	0.375
19	PA19	GA19	EX5	Circular	Smooth Concr.	0.375
20	PX5	EX5	EX7	Circular	Smooth Concr.	0.675
21	PI1	GI1	GI2	Circular	Smooth Concr.	0.300
22	PI2	GI2	GI3	Circular	Smooth Concr.	0.375
23	PI3	GI3	GI4	Circular	Smooth Concr.	0.375
24	PI4	GI4	EX1	Circular	Smooth Concr.	0.375
25	PB1	GB1	GB2	Circular	Smooth Concr.	0.300
26	PB2	GB2	GB6	Circular	Smooth Concr.	0.375
27	PB3	GB3	GB4	Circular	Smooth Concr.	0.300
28	PB4	GB4	GB5	Circular	Smooth Concr.	0.375
29	PB5	GB5	EX6	Circular	Smooth Concr.	0.375
30	PB6	GB6	EX6	Circular	Smooth Concr.	0.375
31	PX6	EX6	EX7	Circular	Smooth Concr.	0.450

Figure E.7 – Information of nodes for Birdlife Park catchment



No.	Node ID	X-coord.	Y-coord.	Type	Diam.	Invert	Grnd
1	GA1	93.70	841.40	Manhole	0.50	104.00	105.50
2	GA2	109.70	829.30	Manhole	0.50	101.00	102.50
3	GA3	128.20	815.60	Manhole	0.50	97.50	99.00
4	GA4	145.90	802.50	Manhole	0.50	93.00	94.50
5	GA5	162.80	790.00	Manhole	0.50	92.50	94.00
6	GA6	166.80	787.10	Manhole	0.50	92.50	94.00
7	GA7	182.60	775.40	Manhole	0.50	93.50	95.00
8	GA8	185.80	818.40	Manhole	0.75	88.00	89.50
9	EX1	190.20	823.00	Manhole	0.75	87.90	89.40
10	GA9	212.80	817.10	Manhole	0.50	86.00	87.50
11	GA10	216.60	824.70	Manhole	0.50	86.00	87.50
12	EX2	217.80	819.00	Manhole	1.00	85.90	87.40
13	GA13	235.70	796.60	Manhole	0.50	83.50	85.00
14	GA15	244.60	799.40	Manhole	0.75	83.00	84.50
15	EX3	246.90	811.10	Manhole	1.00	82.90	84.40
16	GA16	273.60	812.70	Manhole	0.50	79.50	81.00
17	EX4	276.00	817.70	Manhole	1.00	79.40	80.90
18	GA17	315.20	816.60	Manhole	0.50	76.00	77.50
19	GA19	304.30	834.80	Manhole	0.50	76.00	77.50
20	EX5	313.50	833.30	Manhole	1.00	75.90	77.40
21	GI1	177.90	887.20	Manhole	0.50	95.50	97.00
22	GI2	163.10	876.90	Manhole	0.50	95.00	96.50
23	GI3	151.50	860.50	Manhole	0.50	94.00	96.00
24	GI4	148.90	856.80	Manhole	0.50	94.00	95.50
25	GB1	206.10	869.70	Manhole	0.50	91.50	93.00
26	GB2	238.30	860.10	Manhole	0.50	86.50	88.00
27	GB3	261.50	960.50	Manhole	0.50	88.00	89.50
28	GB4	267.60	939.30	Manhole	0.50	86.00	87.50
29	GB5	273.50	919.20	Manhole	0.50	83.00	84.50
30	GB6	283.60	882.80	Manhole	0.50	79.00	81.00
31	EX6	292.60	887.50	Manhole	0.75	78.70	80.70
32	GC1	332.80	849.00	Manhole	0.50	71.50	73.00
33	EX7	339.30	848.50	Manhole	1.00	71.40	72.90

Figure E.8 – Information of links for Birdlife Park catchment

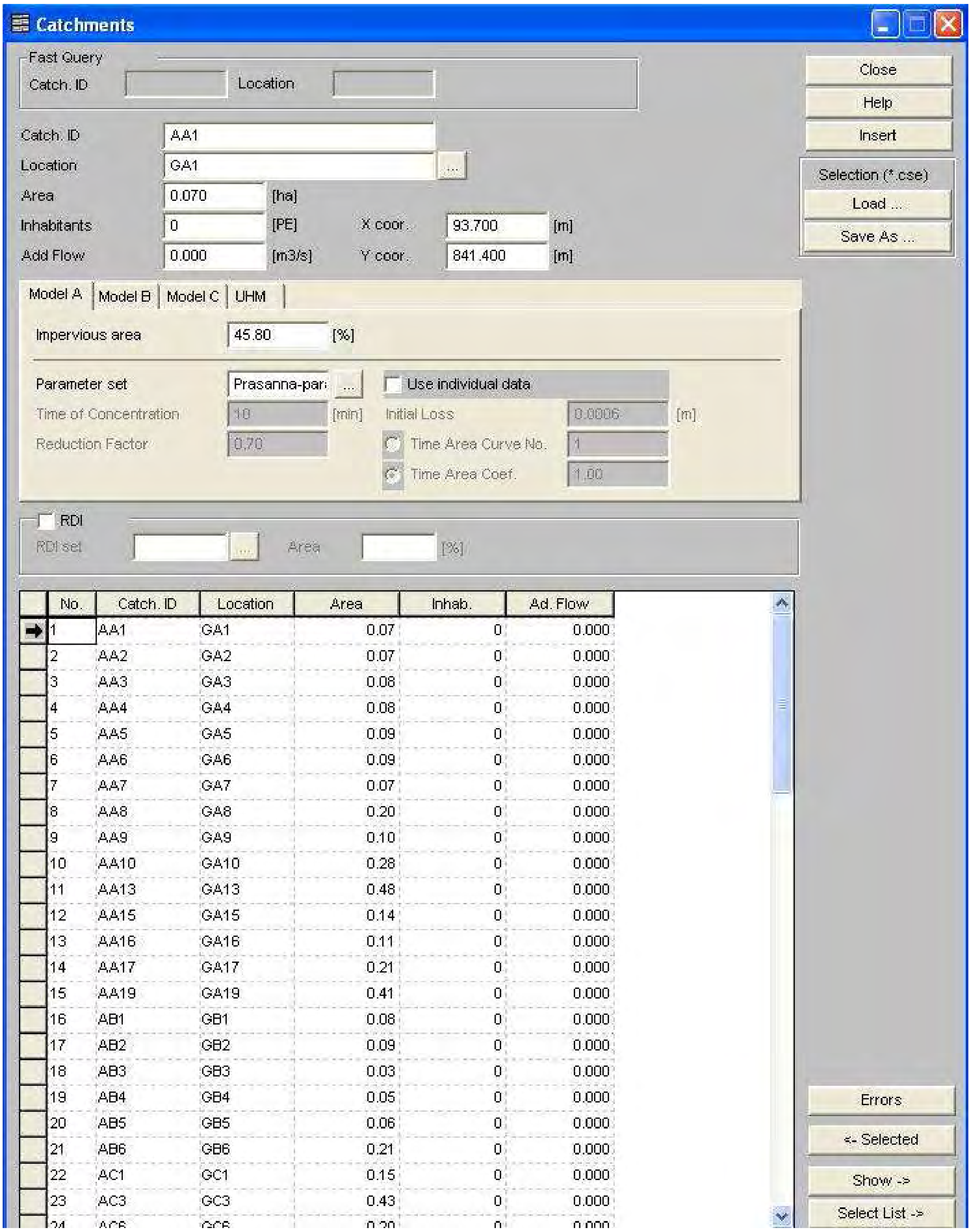


Figure E.9 – Information of sub-areas for Birdlife Park catchment

APPENDIX F

DATA ANALYSIS

Table F.1 – Estimated build-up on impervious surfaces for selected storm events (1/3 – Alextown)

Event Date	Build-up Load (g/m2)			Fraction Wash-off (Fw)		Wash-off Load (g/m^2)		Total Wash-off (g)	
	Gumbeel	Louder / Piccadilly	Roof	Road	Roof	Road	Roof	Road	Roof
2002-08-21	6.75	2.95	1.29	0.166	0.887	1.121	1.141	3803	7725
2002-08-25	2.66	1.86	0.46	0.037	0.594	0.098	0.272	331	1841
2002-11-13	5.86	2.75	1.10	0.384	0.910	2.249	1.001	7632	6774
2002-11-15	4.75	2.48	0.87	0.363	0.953	1.726	0.830	5856	5619
2002-12-10	2.73	1.89	0.47	0.158	0.796	0.432	0.376	1467	2543
2002-12-26	4.20	2.33	0.76	0.053	0.639	0.222	0.486	752	3291
2003-02-02	3.16	2.03	0.55	0.013	0.407	0.042	0.226	141	1529
2003-02-03	2.10	1.66	0.35	0.098	0.681	0.206	0.240	699	1624
2003-02-01	2.40	1.77	0.41	0.024	0.526	0.058	0.215	196	1457
2003-03-01	5.37	2.63	1.00	0.162	0.895	0.869	0.894	2949	6049
2003-03-07	2.64	1.86	0.45	0.098	0.844	0.259	0.383	878	2594
2003-03-12	3.14	2.02	0.55	0.131	0.131	0.410	0.072	1392	487
2003-03-13	3.51	2.14	0.62	0.178	0.857	0.625	0.534	2122	3613
2003-10-24	2.10	1.66	0.35	0.440	1.012	0.923	0.357	3133	2416
2003-12-14	4.72	2.47	0.87	0.382	0.910	1.805	0.788	6126	5335
2003-12-16	3.51	2.14	0.62	0.153	0.898	0.537	0.559	1822	3786
2004-01-16	3.89	2.24	0.70	0.086	0.720	0.335	0.502	1137	3399
2004-02-24	2.60	1.84	0.45	0.469	0.910	1.217	0.406	4128	2746
2002-10-27	2.10	1.66	0.35	0.125	0.786	0.262	0.277	890	1876
2003-04-27	5.38	2.64	1.00	0.201	0.872	1.084	0.874	3679	5913

Table F.1 – Estimated build-up on impervious surfaces for selected storm events (2/3 – Birdlife Park)

Event Date	Build-up Load (g/m2)			Fraction Wash-off (Fw)		Wash-off Load (g/m^2)		Total Wash-off (g)	
	Gumbeel	Louder / Piccadilly	Roof	Road	Roof	Road	Roof	Road	Roof
2002-04-28	4.75	2.48	0.87	0.158	0.765	0.392	0.667	7384	13628
2002-04-29	2.60	1.84	0.45	0.069	0.740	0.127	0.330	2394	6740
2002-05-04	3.46	2.12	0.61	0.152	0.876	0.323	0.537	6095	10975
2002-05-04	2.10	1.66	0.35	0.037	0.606	0.062	0.214	1168	4368
2002-06-02	5.50	2.66	1.02	0.010	0.320	0.026	0.327	499	6692
2002-06-04	2.73	1.89	0.47	0.016	0.436	0.031	0.206	580	4204
2002-06-16	4.49	2.41	0.82	0.226	0.917	0.545	0.750	10283	15329
2002-08-21	6.78	2.95	1.29	0.174	0.887	0.514	1.146	9693	23416
2002-08-27	2.66	1.86	0.46	0.014	0.387	0.027	0.177	505	3618
2002-09-21	5.86	2.75	1.10	0.175	0.870	0.480	0.957	9052	19560
2002-10-27	5.37	2.63	1.00	0.043	0.617	0.112	0.616	2115	12582
2002-11-15	2.93	1.95	0.51	0.363	0.953	0.710	0.486	13387	9925
2002-11-13	4.82	2.50	0.89	0.384	0.910	0.958	0.807	18073	16483
2002-12-10	5.09	2.56	0.94	0.158	0.796	0.405	0.748	7645	15294
2002-12-10	2.18	1.69	0.37	0.538	1.079	0.909	0.396	17148	8099
2003-03-13	2.48	1.80	0.42	0.174	0.857	0.314	0.363	5922	7424
2003-04-27	2.10	1.66	0.35	0.136	0.865	0.225	0.305	4243	6233

Table F.1 – Estimated build-up on impervious surfaces for selected storm events (3/3 – Gumbeel)

Event Date	Build-up Load (g/m2)			Fraction Wash-off (Fw)		Wash-off Load (g/m^2)		Total Wash-off (g)	
	Gumbeel	Louder / Piccadilly	Roof	Road	Roof	Road	Roof	Road	Roof
2002-04-28	4.75	2.48	0.87	0.158	0.765	0.751	0.667	3382	2684
2002-04-29	2.60	1.84	0.45	0.069	0.740	0.179	0.330	806	1327
2002-05-04	3.46	2.12	0.61	0.152	0.876	0.527	0.537	2376	2161
2002-05-04	2.10	1.66	0.35	0.037	0.606	0.078	0.214	353	860
2002-03-05	2.23	1.71	0.38	0.009	0.303	0.019	0.114	87	460
2002-06-02	5.50	2.66	1.02	0.010	0.320	0.055	0.327	246	1318
2002-06-04	2.73	1.89	0.47	0.016	0.436	0.045	0.206	201	828
2002-06-16	4.49	2.41	0.82	0.226	0.917	1.015	0.750	4576	3019
2002-09-21	5.86	2.75	1.10	0.175	0.870	1.024	0.957	4613	3852
2002-11-13	4.82	2.50	0.89	0.384	0.910	1.852	0.807	8343	3246
2002-11-15	2.93	1.95	0.51	0.363	0.953	1.064	0.486	4795	1954
2002-12-10	2.18	1.69	0.37	0.538	1.079	1.173	0.396	5285	1595
2003-02-25	4.41	2.39	0.80	0.062	0.673	0.272	0.540	1224	2174
2003-03-13	2.48	1.80	0.42	0.174	0.857	0.433	0.363	1949	1462
2003-10-24	2.10	1.66	0.35	0.440	1.012	0.923	0.357	4161	1436

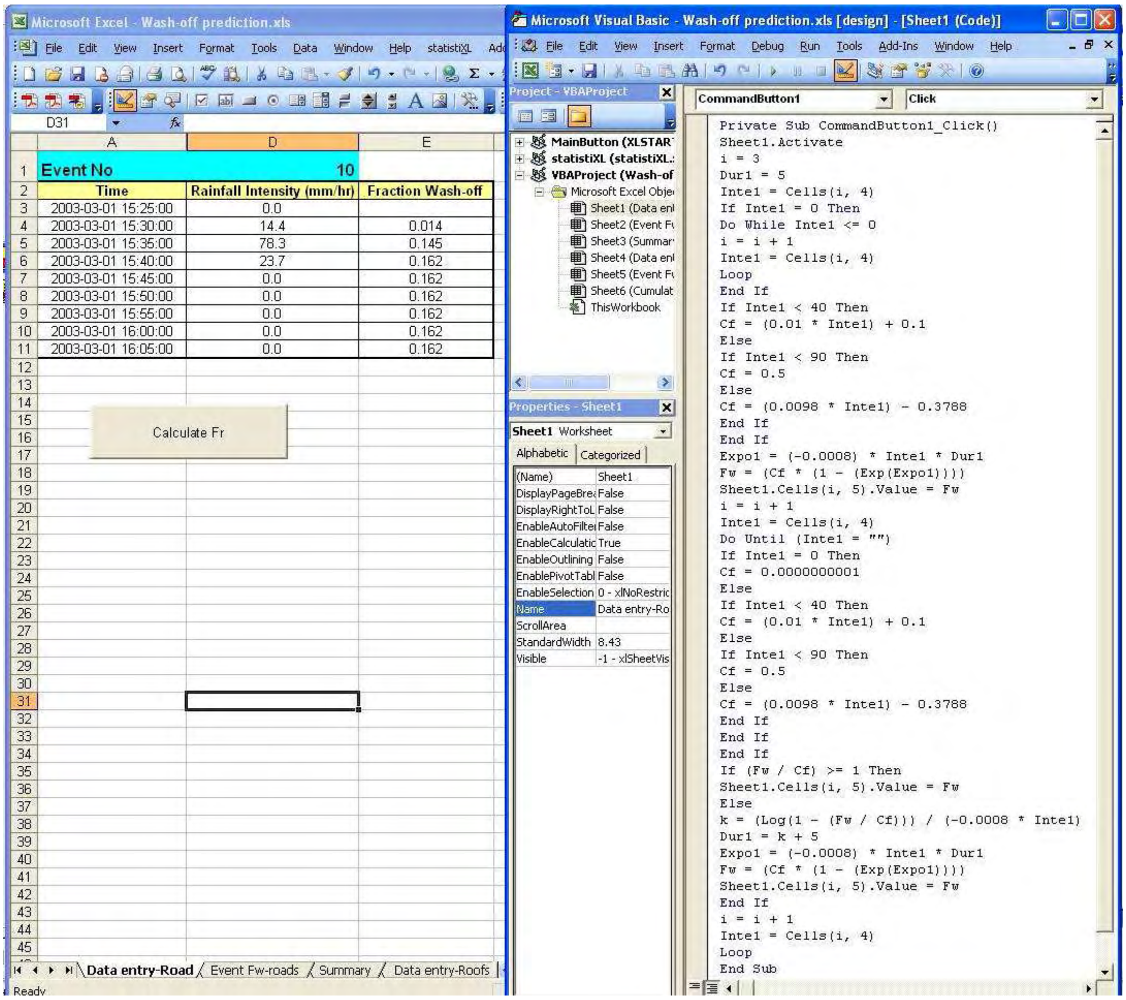
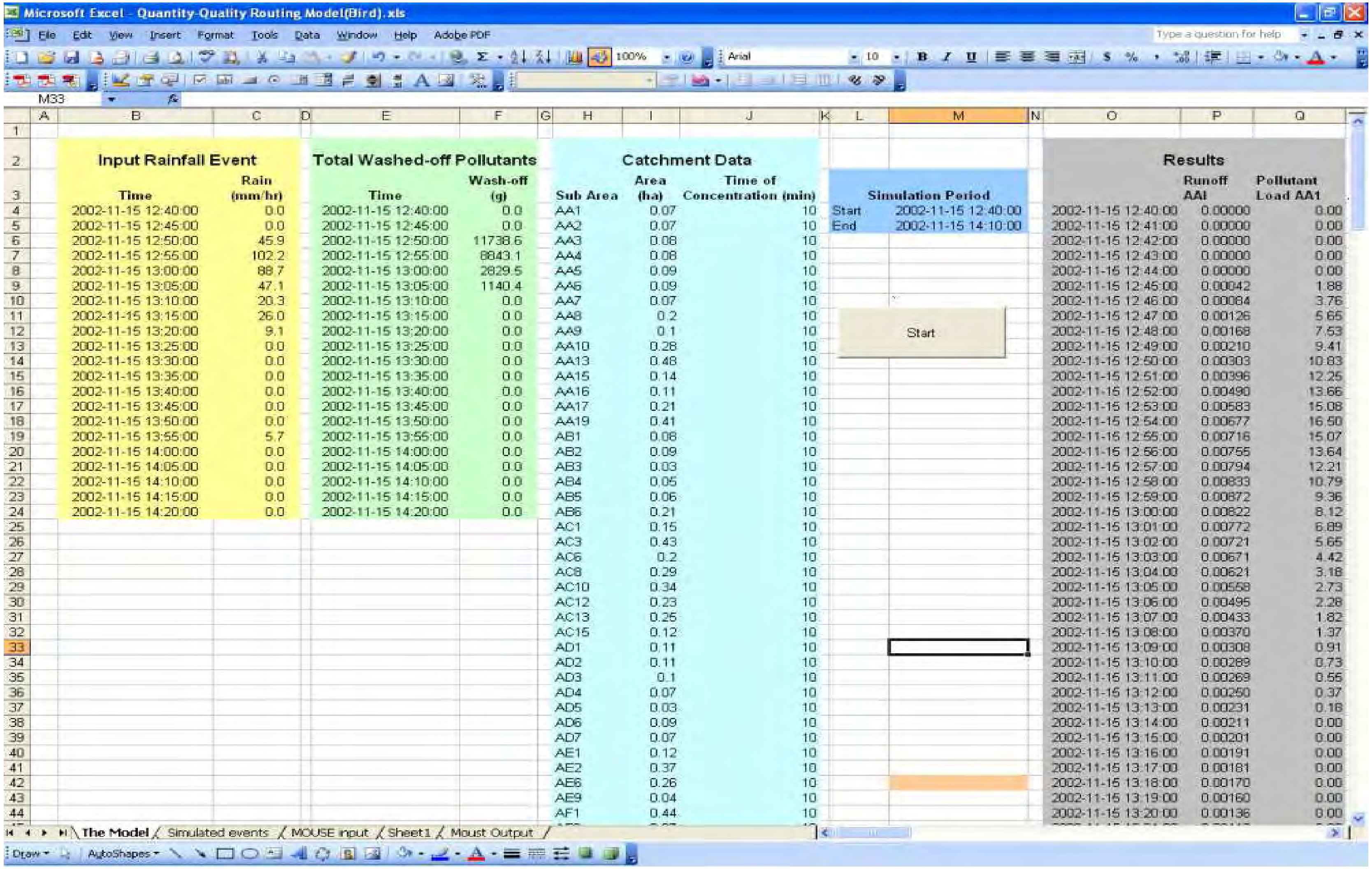


Figure F.1 – Conceptual Wash-off model: Sample calculation and Visual Basic coding

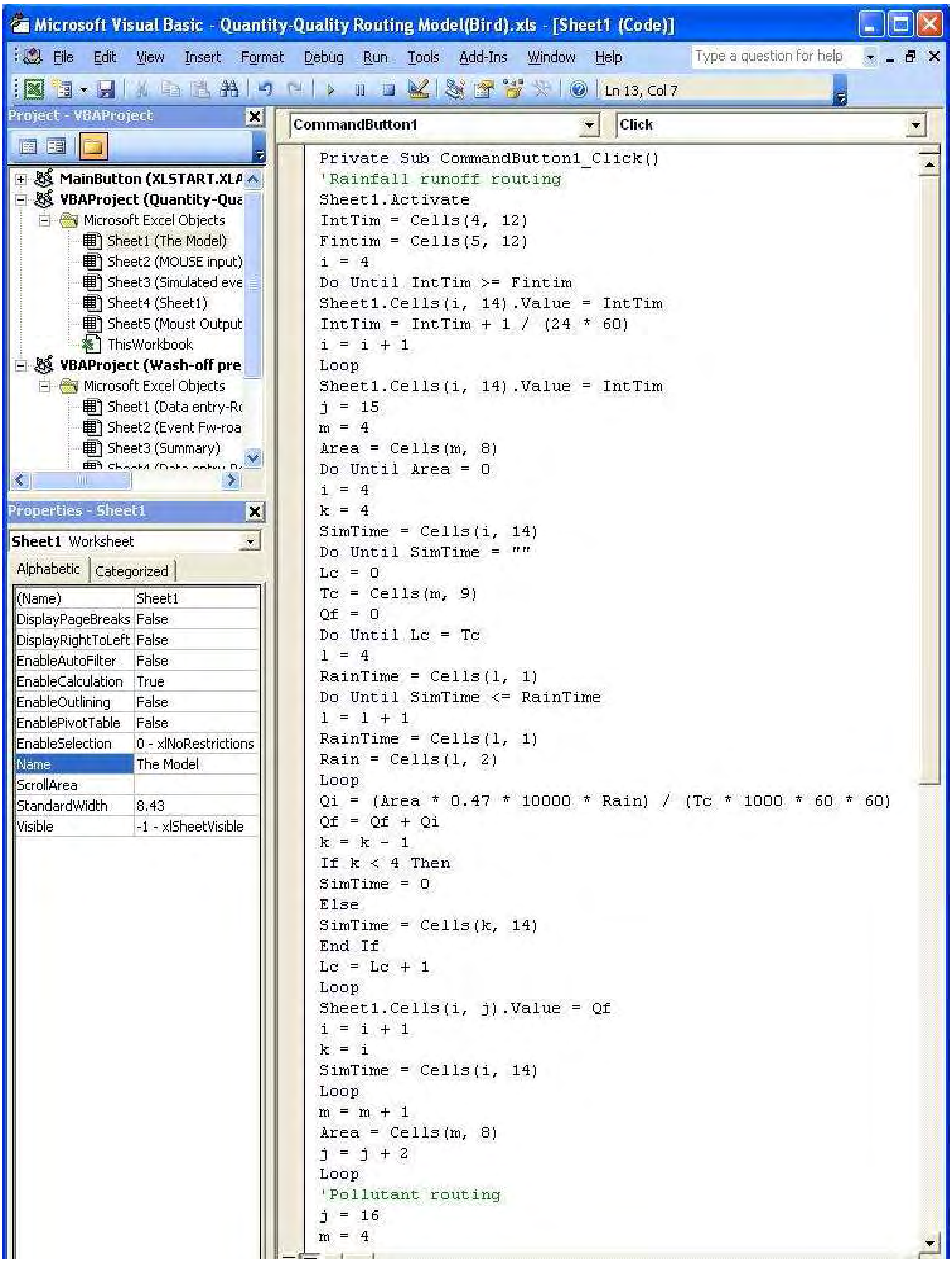


Input Rainfall Event: Time	Rain (mm/hr)	Total Washed-off Pollutants: Time	Wash-off (g)
2002-11-15 12:40:00	0.0	2002-11-15 12:40:00	0.0
2002-11-15 12:45:00	0.0	2002-11-15 12:45:00	0.0
2002-11-15 12:50:00	45.9	2002-11-15 12:50:00	11738.6
2002-11-15 12:55:00	102.2	2002-11-15 12:55:00	8843.1
2002-11-15 13:00:00	88.7	2002-11-15 13:00:00	2829.5
2002-11-15 13:05:00	47.1	2002-11-15 13:05:00	1140.4
2002-11-15 13:10:00	20.3	2002-11-15 13:10:00	0.0
2002-11-15 13:15:00	26.0	2002-11-15 13:15:00	0.0
2002-11-15 13:20:00	9.1	2002-11-15 13:20:00	0.0
2002-11-15 13:25:00	0.0	2002-11-15 13:25:00	0.0
2002-11-15 13:30:00	0.0	2002-11-15 13:30:00	0.0
2002-11-15 13:35:00	0.0	2002-11-15 13:35:00	0.0
2002-11-15 13:40:00	0.0	2002-11-15 13:40:00	0.0
2002-11-15 13:45:00	0.0	2002-11-15 13:45:00	0.0
2002-11-15 13:50:00	0.0	2002-11-15 13:50:00	0.0
2002-11-15 13:55:00	5.7	2002-11-15 13:55:00	0.0
2002-11-15 14:00:00	0.0	2002-11-15 14:00:00	0.0
2002-11-15 14:05:00	0.0	2002-11-15 14:05:00	0.0
2002-11-15 14:10:00	0.0	2002-11-15 14:10:00	0.0
2002-11-15 14:15:00	0.0	2002-11-15 14:15:00	0.0
2002-11-15 14:20:00	0.0	2002-11-15 14:20:00	0.0

Simulation Period	
Start	2002-11-15 12:40:00
End	2002-11-15 14:10:00

Catchment Data: Sub Area	Area (ha)	Time of Concentration (min)	Results: Time	Runoff AAI	Pollutant Load AA1
AA1	0.07	10	2002-11-15 12:40:00	0.00000	0.00
AA2	0.07	10	2002-11-15 12:41:00	0.00000	0.00
AA3	0.08	10	2002-11-15 12:42:00	0.00000	0.00
AA4	0.08	10	2002-11-15 12:43:00	0.00000	0.00
AA5	0.09	10	2002-11-15 12:44:00	0.00000	0.00
AA6	0.09	10	2002-11-15 12:45:00	0.00042	1.88
AA7	0.07	10	2002-11-15 12:46:00	0.00084	3.76
AA8	0.2	10	2002-11-15 12:47:00	0.00126	5.65
AA9	0.1	10	2002-11-15 12:48:00	0.00168	7.53
AA10	0.28	10	2002-11-15 12:49:00	0.00210	9.41
AA13	0.48	10	2002-11-15 12:50:00	0.00303	10.83
AA15	0.14	10	2002-11-15 12:51:00	0.00396	12.25
AA16	0.11	10	2002-11-15 12:52:00	0.00490	13.66
AA17	0.21	10	2002-11-15 12:53:00	0.00583	15.08
AA19	0.41	10	2002-11-15 12:54:00	0.00677	16.50
AB1	0.08	10	2002-11-15 12:55:00	0.00716	15.07
AB2	0.09	10	2002-11-15 12:56:00	0.00755	13.64
AB3	0.03	10	2002-11-15 12:57:00	0.00794	12.21
AB4	0.05	10	2002-11-15 12:58:00	0.00833	10.79
AB5	0.06	10	2002-11-15 12:59:00	0.00872	9.36
AB6	0.21	10	2002-11-15 13:00:00	0.00822	8.12
AC1	0.15	10	2002-11-15 13:01:00	0.00772	6.89
AC3	0.43	10	2002-11-15 13:02:00	0.00721	5.65
AC6	0.2	10	2002-11-15 13:03:00	0.00671	4.42
AC8	0.29	10	2002-11-15 13:04:00	0.00621	3.18
AC10	0.34	10	2002-11-15 13:05:00	0.00558	2.73
AC12	0.23	10	2002-11-15 13:06:00	0.00495	2.28
AC13	0.25	10	2002-11-15 13:07:00	0.00433	1.82
AC15	0.12	10	2002-11-15 13:08:00	0.00370	1.37
AD1	0.11	10	2002-11-15 13:09:00	0.00308	0.91
AD2	0.11	10	2002-11-15 13:10:00	0.00289	0.73
AD3	0.1	10	2002-11-15 13:11:00	0.00269	0.55
AD4	0.07	10	2002-11-15 13:12:00	0.00250	0.37
AD5	0.03	10	2002-11-15 13:13:00	0.00231	0.18
AD6	0.09	10	2002-11-15 13:14:00	0.00211	0.00
AD7	0.07	10	2002-11-15 13:15:00	0.00201	0.00
AE1	0.12	10	2002-11-15 13:16:00	0.00191	0.00
AE2	0.37	10	2002-11-15 13:17:00	0.00181	0.00
AE6	0.26	10	2002-11-15 13:18:00	0.00170	0.00
AE9	0.04	10	2002-11-15 13:19:00	0.00160	0.00
AF1	0.44	10	2002-11-15 13:20:00	0.00136	0.00

Figure F.2 – Rainfall and pollutant routing model: Inputs, catchment characteristics and outputs



```
Private Sub CommandButton1_Click()
'Rainfall runoff routing
Sheet1.Activate
IntTim = Cells(4, 12)
Fintim = Cells(5, 12)
i = 4
Do Until IntTim >= Fintim
Sheet1.Cells(i, 14).Value = IntTim
IntTim = IntTim + 1 / (24 * 60)
i = i + 1
Loop
Sheet1.Cells(i, 14).Value = IntTim
j = 15
m = 4
Area = Cells(m, 8)
Do Until Area = 0
i = 4
k = 4
SimTime = Cells(i, 14)
Do Until SimTime = ""
Lc = 0
Tc = Cells(m, 9)
Qf = 0
Do Until Lc = Tc
l = 4
RainTime = Cells(l, 1)
Do Until SimTime <= RainTime
l = l + 1
RainTime = Cells(l, 1)
Rain = Cells(l, 2)
Loop
Qi = (Area * 0.47 * 10000 * Rain) / (Tc * 1000 * 60 * 60)
Qf = Qf + Qi
k = k - 1
If k < 4 Then
SimTime = 0
Else
SimTime = Cells(k, 14)
End If
Lc = Lc + 1
Loop
Sheet1.Cells(i, j).Value = Qf
i = i + 1
k = i
SimTime = Cells(i, 14)
Loop
m = m + 1
Area = Cells(m, 8)
j = j + 2
Loop
'Pollutant routing
j = 16
m = 4
```

Figure F.3 – Rainfall and pollutant routing model: Visual Basic coding

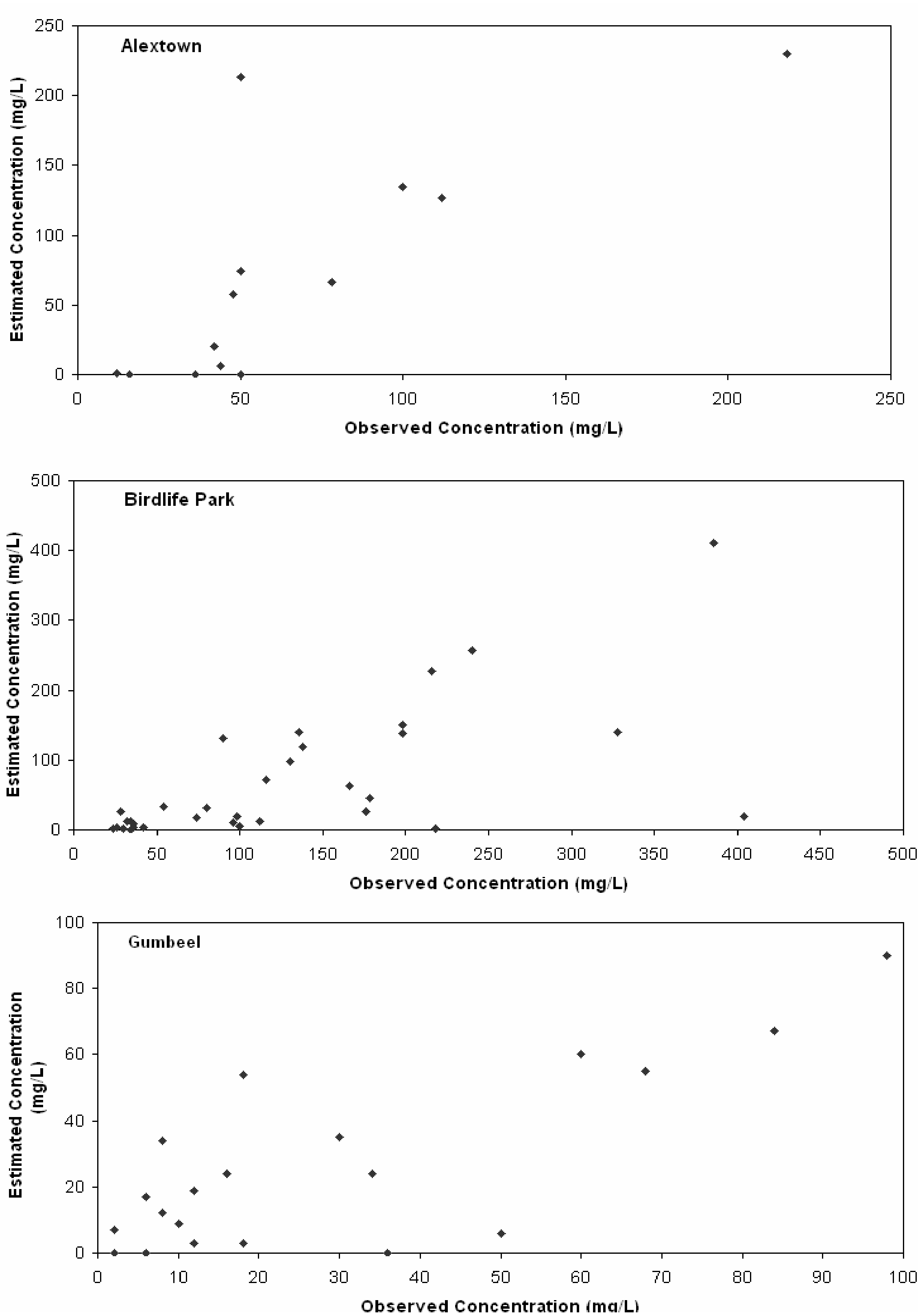


Figure F.4 - Comparison of observed and predicted instantaneous concentrations: Individual catchment basis

Table F.2 – Sample simplification of rainfall events

Original Rainfall Event

Date - Time	Rainfall Intensity (mm/hr)	Intensity Catogary (mm/hr)
2002-11-15 12:45:00	0.0	
2002-11-15 12:50:00	45.9	40 - 90
2002-11-15 12:55:00	102.2	90 - 133
2002-11-15 13:00:00	88.7	40 - 90
2002-11-15 13:05:00	47.1	40 - 90
2002-11-15 13:10:00	20.3	5 - 40
2002-11-15 13:15:00	26.0	5 - 40
2002-11-15 13:20:00	9.1	5 - 40
2002-11-15 13:25:00	0.0	
2002-11-15 13:30:00	0.0	

Analysis

Rainfall Intensity Category	Average Rainafall Intensity (mm/hr)	Number of Timesteps
5 - 40	18.4	3
40 - 90	60.6	3
90 - 133	102.2	1

Simplified Rainfall Event

Date - Time	Rainfall Intensity (mm/hr)
2002-11-15 12:45:00	0.0
2002-11-15 12:50:00	18.4
2002-11-15 12:55:00	18.4
2002-11-15 13:00:00	18.4
2002-11-15 13:05:00	60.6
2002-11-15 13:10:00	60.6
2002-11-15 13:15:00	60.6
2002-11-15 13:20:00	102.2
2002-11-15 13:25:00	0.0
2002-11-15 13:30:00	0.0