Transmission of Nutrient in Urban Environment

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Certificate

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Abstract

Gross pollutant traps (GPT) are installed in many urban drainage systems in Australia to control stormwater pollutants from urban catchments. Stormwater pollutants (e.g. leaf litter) are trapped in the GPT during stormwater runoff events. If these devices are not managed properly, they may lead to deterioration of receiving water quality by introducing nutrients (phosphorus and nitrogen) from the leaf litter during dry weather periods between events. This study evaluated the release of nutrients from leaf litter in a GPT system and a novel conceptual model was developed for the prediction of phosphorus at the outlet of GPT. Catchment runoff and mathematical model were used to create an integrated model able to predict the phosphorus response from a GPT. The knowledge gained in this research is expected to contribute to improve understanding the impact of GPT on downstream water bodies.

Leaf litter collected from Centennial Park was found to be a significant source of nitrogen and phosphorus where the total nitrogen (TN) and total phosphorus (TP) content were 5.1 mg g^{-1} and 0.381 mg g^{-1} respectively. The releases of TN and TP from leaf litter were determined by considering a GPT environment. Initially, the phosphorus release declined exponentially with time. Consideration of the results indicated that the rate of phosphorus release was 0.0274 d^{-1} for the first 90 days and the release rate was 0.0195 d^{-1} for 180 days. Measured higher phosphorous release rate (90 days) was used to develop conceptual model. The quantity of TP loss from leaf litter was ~88% of the P in the leaf litter for the first 90 days and ~6% for the second 90 days. This suggests that the initial rapid TP release was due to higher rate of leaching of phosphorus. It was observed that the variation of phosphorus release from GPT is associated with the quantity of trapped leaf litter and

inter-event dry period. The study also found that longer retention time released more phosphorus confirming the degradation of leaf litter.

Results showed that the TP released from leaf litter was faster than the release of TN. About 54% of the total phosphorus was released while 20% of the total nitrogen was released within the same time frame (22 days). This suggests that nitrogen released at a slower rate. The change of pH, increase in electrical conductivity (EC) and decrease in dissolved oxygen (DO) further confirmed the decomposition of leaf matrix.

As part of this study, a model of catchment runoff quantity and quality was used. This model was based on the Stormwater Management Model (SWMM) and was used to consider different factors influencing stormwater quantity and quality from the catchment. In this study, different rainfall temporal patterns were used to investigate the influence of rainfall characteristics on catchment runoff. It was found that the predicted peak flow and loss varied significantly with rainfall temporal patterns. The rainfall loss increased and the rainfall loss rate decreased with storm duration. Furthermore, it was found that the runoff volume generated by 1 year ARI was enough to replace the volume of water stored within GPT. Therefore, rainfall events with 1 year ARI and durations of 5, 10, 20, 30, 45, 60 and 120 min were considered to determine the inlet hydrograph for the GPT.

Appropriate model was developed for quantification of phosphorus, in particular the TP released from leaf litter in GPT system. The SWMM model was applied to determine the catchment runoff flow in GPT which enabled estimating of phosphorus in the stormwater runoff. The catchment runoff was used as inflow to the GPT while the out flow was obtained from level pool routing of flow through the GPT. Model simulation results showed that the predicted total phosphorus load from decay of the leaf litter in the GPT was transported downstream for most storm events.

This confirmed that novel conceptual model developed in this study is capable to estimate outlet phosphorus concentration of GPT for different storm events. This information may be useful to recommend catchment management approaches to improve water quality and to set management priorities and thereby enhance the design of stormwater management systems. Hence, the results of this research have shown that catchment management need to consider leaf litter as a source of phosphorus and nitrogen in assessing downstream receiving water quality.

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Abbreviations

AHD	Australian Height Datum
APHA	American Public Health Association
ARE	Absolute Relative Error
ARI	Average Recurrence Interval
ARMCANZ	Agriculture and Resource Management Council of Australia and New Zealand
ARR	Australian Rainfall & Runoff
BMP	Best Management Practice
CDS	Continuous Deflective Separation
CV	Coefficient of Variance
EC	Electrical Conductivity
EMC	Event Mean Concentration
DIP	Dissolved Inorganic Phosphorus
DOP	Dissolved Organic Phosphorus
GPT	Gross Pollutant Trap
N	Nitrogen
P	Phosphorus
PP	Particulate Phosphorus
TN	Total Nitrogen
TP	Total Phosphorus
TSP	Total Soluble Phosphorus
SD	Standard Deviation
SWMM	Storm Water Management Model
USEPA	United States Environmental Protection Agency

Nomenclature

X	mass of dry matter remaining at time t
X_o	initial mass of dry matter
k	decomposition rate constant
Q_{GI}	inflow in GPT during time Δt, $m^3\ s^{-1}$
Q_{GO}	outflow in GPT during time Δt, $m^3\ s^{-1}$
Δt	time step, s
V	volume of water in GPT, m^3
Q_1^I	inflow in GPT at the beginning of time step Δt, $m^3\ s^{-1}$
Q_2^I	inflow in GPT at the end of time step Δt, $m^3\ s^{-1}$
Q_1^O	outflow in GPT at the beginning of time step Δt, $m^3\ s^{-1}$
Q_2^O	outflow in GPT at the end of time step Δt, $m^3\ s^{-1}$
V_1	volume of water in GPT at the beginning of time step Δt, m^3
V_2	volume of water in GPT at the end of time step Δt, m^3
C_1^G	concentration of P in GPT at the beginning of time step Δt, mg L^{-1}
C_2^G	concentration of P in GPT at the end of time step Δt, mg L^{-1}
C_1^I	concentration of P at inlet of GPT at the beginning of time step Δt, mg L^{-1}
C_2^I	concentration of P at inlet of GPT at the end of time step Δt, mg L^{-1}
C_1^O	concentration of P at outlet of GPT at the beginning of time step Δt, mg L^{-1}
C_2^O	concentration of P at outlet of GPT at the end of time step Δt, mg L^{-1}
P_{LL}	mass of P release from leaf litter in GPT at Δt, mg
P_{LL1}	P release from leaf litter at the beginning of time step Δt

P_{LL2}	P release from leaf litter at the end of time step Δt
ΔP	change in mass of P in GPT mg
P_{GI}	mass of P entering in GPT at Δt, mg
P_{GO}	mass of P leaving GPT at Δt, mg
S	storage, m^3
A	wetted cross-sectional area, m^2
R	hydraulic radius
n	Manning's roughness co-efficient

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CHAPTER 1

Introduction

1 Introduction

1.1Introduction

Urban cities have expanded both in Australia and in other parts of the world due to rapid population growth. Urbanisation increases the impervious areas including buildings, roads, parking areas, roofs and other facilities. It reduces the infiltration capacity, causes significant changes in surface runoff and increases peak flows in the catchment. Urban areas generate pollutants such as organic matter, heavy metals, nutrients and bacteria due to anthropogenic activities (Ballo et al., 2009; Priadi et al., 2011). Pollutants in urban waterways retained by a 5 mm mesh screen are termed as gross pollutants (Allison et al., 1998). These pollutants may be classified as litter, debris and sediments of which 80% is in organic in nature and primarily leaf litter (Ball, 2002). Stormwater collects these pollutants and transports them to receiving waters creating adverse impacts on the water environment. Urban stormwater runoff is considered one of the significant sources of receiving water quality deterioration (Davis and Birch, 2009). Many receiving water systems impacted by urban runoff due to mobilization of nitrogen and phosphorus at increasing concentrations and loadings causes eutrophication (Berretta and Sansalone, 2011). Eutrophication played a significant role to the deterioration of receiving water quality (Gray et al., 2008; Lewitus et al., 2008).

Management of water environments therefore requires management of the stormwater borne pollutants. However, field monitoring can provide information only for historic management approaches and cannot provide information about management approaches not yet implemented. Assessment of these future management approaches is feasible only through water quality models. Water quality models can be used to characterize urban runoff, estimate the appropriate size of the control structures, perform frequency analysis of quality parameters and quantification of stormwater pollutant loads (Huber, 1986). However, application of these models in many urban catchments is hindered by knowledge limitations about processes influencing both the quantity of stormwater and the pollutant loads being transported by the stormwater.

Within the greater Sydney urban area, the many ponds within Centennial Park provide examples of receiving waters impacted by stormwater borne pollution (Ball, 2002). In most small to medium size winter flood events, significant amounts of phosphorus (60%) and suspended sediments are deposited in this pond (Shatwell and Cordery, 1999). The Centennial Park ponds including Musgrave pond and other large downstream ponds have experienced blue-green algal blooms (Shatwell and Cordery, 1999).

Nutrients are transported by stormwater in a variety of forms. Abustan and Ball (1995) reported typical ranges of particulate, soluble and organic forms. The primary organic form in which nutrients are transported is leaf litter. Therefore, one management approach is to capture leaf litter and other gross pollutants. For this purpose, a Gross Pollutant Trap (GPT) was installed on the Musgrave Avenue Stormwater Channel upstream of Musgrave pond. This GPT formed part of stormwater management strategy for the restoration of water quality of the ponds within the ground of Centennial Park.

The GPT installed immediately upstream of Musgrave pond in Centennial Park trapped gross pollutants greater than 5 mm and stored these gross pollutants within the GPT and below the water surface; in other words the gross pollutants were stored in a saturated environment. A consequence of storing the gross pollutants in this manner is the nutrients are not removed from the stormwater system until such time as they are physically removed by cleaning of the GPT. Hence, the leaf litter trapped in the GPT will be subjected to decay processes with subsequent changes to the form of the nutrients and their bioavailability.

1.2 Research objectives

The focus of the research undertaken was to provide a greater understanding of the interaction between a physical stormwater drainage system and the nutrients within leaf litter. To investigate this problem, both laboratory and modelling approaches were necessary.

Due to the absence of information regarding the decay of leaf litter sourced from Australian vegetation that may be captured by a GPT, laboratory techniques needed to be used to provide information suitable for application in any catchment. These laboratory techniques included the collection of field samples of leaf litter and analysis of their decay and subsequent nutrient release.

For the data developed from the laboratory techniques to be useful for more than the catchment considered in this study, a model of leaf litter decay in a GPT was developed in a manner where it could be linked to existing catchment models. This model was used to assess the significance of leaf litter as a source of nutrients.

There are many hydrologic factors that influence the volume of stormwater runoff and hence the significance of nutrients from the decay of leaf litter. To assess some of the factors, the variability in runoff volume, peak flow, rainfall losses and inter-event period were investigated. While techniques for collection and removal of gross pollutants constitute a viable research area, the focus herein is on the collected leaf litter and its decay.

1.3 Novel aspects of study

There are many novel aspects of this study. These include:

i) nutrient release from leaf litter from Australian vegetation

ii) assessment of the importance of these nutrients

iii) development of leaf litter decay model for a GPT

iv) linkage of hydrologic factors to nutrient release

1.4 Thesis outline

This dissertation is divided into eight chapters:

Chapter 1 is an introduction to the study and describes the background, significance of the research study, aim and objectives.

Chapter 2 provides a literature review related to this study includes stormwater pollutants, gross pollutant traps (GPTs) and catchment modelling techniques. This chapter explains phosphorus and nitrogen as stormwater pollutants in a GPT system and their significant impact on water bodies. Catchment modelling concept and fundamental theory are also discussed.

Chapter 3 describes the Centennial Park, Sydney which is used as the study catchment that influences the water quality and quantity. Therefore the physical and hydrological characteristics of the catchment and the available data are focused in this chapter.

Chapter 4 presents the overview of stormwater management model (SWMM) structure and key data requirements for water quantity simulation.

Chapter 5 presents the experimental design, methodology and detailed leaf litter leaching experimental procedures. Nutrient release from leaf litter was estimated. It was used for the determination of phosphorus mass in GPT.

Chapter 6 investigates the effect of temporal rainfall variability on catchment runoff prediction for study catchment.

Chapter 7 presents the GPT modelling for phosphorus quantification. This includes the development of GPT conceptual model and simulation of phosphorus transportation to downstream and correlation with catchment runoff volume.

Chapter 8 provides conclusions of the research.

CHAPTER 2

Literature Review

2 Literature Review

2.1 Introduction

This chapter reviews the significance of stormwater pollutants, their transportation, their presence in a Gross Pollutant Trap (GPT) and their impacts on receiving waters. To determine the quantity of pollutant discharge, its control within a GPT and its impact on receiving waters, a number of closely related topics are reported and reviewed. Therefore, one of the aims of this review was to understand urban stormwater runoff and its influence on urban water quality. In addition the influence of catchment and rainfall characteristics were considered to understand the behaviour of pollutant transportation in an urban drainage system that includes a GPT. To develop conceptual models this review of literature therefore includes urban catchment modelling and GPT devices.

2.2 Urban stormwater runoff

Stormwater runoff is defined as water flowing over ground surfaces to natural streams and drains as a direct result of rainfall over a catchment (ARMCANZ/ANZECC, 2000). The impact of stormwater runoff is a major problem in urban areas due to increase of impervious surfaces. The impervious surfaces are covered by stone and concrete or asphalt. The infiltration capacity of these materials is low (Barnes et al., 2001). Therefore, rainfall in these surfaces produces higher rate of runoff (Shuster et al., 2005) and consequently a higher velocity. This runoff with significant nutrient and pollutant loads accumulated on the catchment surfaces and enters the stormwater drainage system (Kang et al., 1998; Lehner et al., 1999). There are two characteristics of storm water runoff that influences the water environment; these are quantity (primarily the peak flow and runoff depth) and quality (inclusive of total suspended solids and total phosphorus) (Tsihrintzis and Hamid, 1997). Both are important because a large volume of water can cause erosion, flooding and sediment deposits in streams and the pollutants carried in stormwater can deteriorate receiving waters.

2.2.1 Runoff quantity

Urbanised land, leads to decrease in surface roughness and infiltration which reduces the time required for runoff to flow from the source area of the catchment to the drainage system. This increases the peak runoff (Changnon et al., 1996; Zoppou, 1999) and the rate of hydrograph rise and recession (Burns et al., 2005). The peak flow can increase by 30% to more than 100% greater compared to less urbanised and non-urbanised catchments (Rose and Peters, 2001).

In addition, Barron et al. (2011) concluded that urbanisation led to an apparent expansion in the area of the catchment due to the stormwater drainage system which leads to increase in runoff volume. The increased runoff volume leads to reduce the time to peak flow and an increase in runoff peak flow (Moscrip and Montgomery, 1997; Moon et al., 2004). Thus the hydrologic changes due to urbanisation in the catchments are correlated with runoff volume, runoff peak and time to peak flow. A typical hydrograph of urban runoff before and after urbanisation is shown in Figure 2.1.

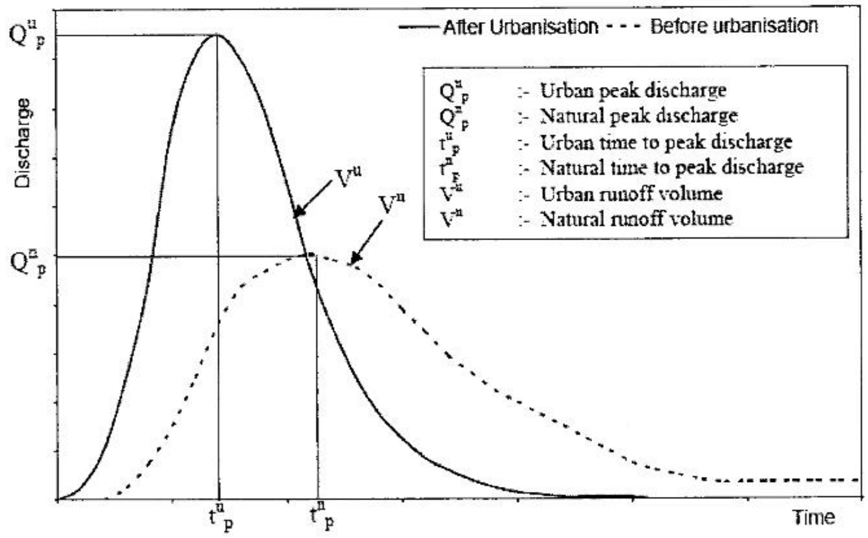

Figure 2.1 Runoff hydrograph before and after urbanisation (adapted from Kibler, 1982)

2.2.2 Runoff quality

Urbanisation influences urban stormwater quality. Stormwater quality deterioration in urban areas involves chemical, physical and biological activities leading to degradation of receiving water. Urban runoff transports various pollutants into receiving water and alters the natural characteristics of their ecosystem (House et al., 1993; Tsihrintzis and Hamid, 1998) which can have a significant impact on human health risk. Major water quality problems associated with stormwater runoff due to urbanisation are sedimentation, higher water temperature, salinity, low dissolved oxygen concentration, biological effects, introduction of toxic substances (herbicides, pesticides, heavy metals and radioactive substances) and excess nutrients (Zoppou, 1999).

Stormwater also introduces pollutants from various anthropogenic activities common to urban areas such as residential, industrial and commercial areas (Pegram et al., 1999). Pollutants from these areas are accumulated on both impervious and pervious surfaces.

The mobilization of surface materials through urban runoff may result in significant discharge of pollutants into the receiving water (Lee et al., 2002). From Cordery (1977), a study of three urban catchments in Sydney, Australia suggested that the pollutant load resulting from surface runoff was higher than the secondary sewage treatment plant effluent. According to Pitt (1987), pollutants are transported from urban area to receiving waters easily and quickly by stormwater runoff since urban area have elaborate and efficient drainage systems. Numerous studies (Sonzogni et al., 1980; Line et al., 2002) have reported that the average loads of sediments, total nitrogen and phosphorus from urban areas were 10–100 times greater than rural areas.

Pollutant buildup and washoff is associated with runoff quality. Pollutant buildup is the accumulation of pollutants on catchment surfaces whilst pollutant washoff is the process of removing the accumulated pollutants from the catchment surfaces by stormwater runoff during rainfall events (Vaze and Chiew, 2002). Pollutant buildup on catchment surfaces depends on several factors such as urban area location, urban form, antecedent dry period and land use (Sator and Boyd, 1972; Bradford, 1977; Pitt, 1979). Washoff process is affected with variation in rainfall events in relation to duration and intensity (Egodawatta et al., 2007). Pollutant generation is responsible to buildup and transportation to washoff processes. The rainfall over the catchment passes through the different hydrologic processes and hydraulic system (Nix, 1994). The resulting urban runoff moves through the drainage system and concentrates into larger and larger flow streams (Nix, 1994). This brings the various pollutants in the process and transported to the receiving waters.

2.3 Stormwater pollutants

Stormwater runoff from urban areas can contains significant quantity of harmful pollutants that degrades water quality. Common pollutants are solids, oil and grease, heavy metals, organic micro pollutants, nutrients and pathogens originating from road surfaces, car washing areas, vegetation and fertilisers (USEPA, 2004). The stormwater pollutants can be categorized into following main groups: 1) gross pollutants, 2) heavy metals and 3) suspended sediments. Nutrients and organic matter originating from gross pollutants were identified as the major stormwater pollutants in urban catchment management for water quality improvement (Allison et al., 1997). Stormwater transport pollutants, leading to the deterioration of receiving water quality (House et al., 1993; Fletcher et al., 2013). The quantity of pollutant load varies with location, duration, frequency and intensity of different storm events. The rate of degradation depends on the characteristics of pollutants. It is necessary to identify the characteristics of stormwater pollutants before entering the aquatic environment and therefore require management. In this study the gross pollutants including nutrients (nitrogen and phosphorus) are discussed in terms of their impacts on urban receiving water quality.

2.3.1 Gross pollutants

Gross pollutants are a class of pollutants such as leaves, debris, litter, trash and coarse sediment that are flushed through urban catchments and stormwater system (ASCE, 2010). It carries harmful pollutants such as oxygen demanding material, hydrocarbon and heavy metals which have adverse impact towards water quality and environment (Lariyah et al., 2011). It is needed to reduce the gross pollutants from entering stormwater drainage system. Gross pollutants in urban waterways are defined as material that would be retained by 5 mm mesh screen of treatment devices (Allison et al., 1998). Amount of gross pollutants generated in the waterways depends on land use, rainfall patterns, population, physical catchment characteristics and drainage systems (Lariyah et al., 2011). The litter, sediments and debris are often referred to as gross pollutants and a threat to aquatic environment (Ball, 2002). The individual components of gross pollutants are described as:

Debris: It is an organic matter such as leaf litter, twigs and grass clippings transported by stormwater (DLWC, 1996). It may be derived from both natural and anthropogenic sources. They can block the drainage system. The Cooperative Research Centre (CRC) for Catchment Hydrology monitoring study indicated that nutrient loads from vegetative matter in stormwater are about two orders of magnitude lower than the loads measured in stormwater samples. However, because of its large volume the plant matter should be taken into account in the design of gross pollutant traps and in controlling pipe blockage (Chiew et al., 1997).

Litter: This includes plastic, paper, glass, metals, cigarette butts and cloths. It is derived from anthropogenic sources and can clog the urban drainage system.

Sediment: It is the larger particulates that are considered gross pollutants associated with stormwater runoff. Sediments are often attached to litter and debris (Allison et al., 1998).

The load of gross pollutants is dependent on the individual pollutant species and load. Typically the gross pollutants comprised approximately 70% debris, 25% litter and the remaining portion coarse sediment (Ball, 2002).

2.3.2 Nutrients

Nutrients are essential to living organisms and are compounds containing nitrogen, phosphorus, carbon, calcium, potassium, iron and manganese (Oladoye et al., 2008). Point sources (e.g. industry) and nonpoint sources (e.g. urban runoff) have been identified as nutrient sources (Hatt et al., 2004). Nitrogen and phosphorus are available from many nonpoint sources and their mobilisation can have detrimental effects on stormwater. In stormwater, total phosphorus (TP) exists as dissolved phosphorus (polyphosphate, organic phosphorus, orthophosphate) and particulate phosphorus while total nitrogen (TN) occurs as ammonium nitrogen (NH_4-N), organic nitrogen and nitrite nitrogen (NO_2-N) (Taylor et al., 2005). Major sources of P and N to stormwater are fertiliser effluent, fuel combustion, soil and vegetation (Wong et al., 2000). These two nutrients play an important role in water quality deterioration.

During runoff the water may entrain nutrients from the surface by dissolving them or eroding and suspending them (Henderson and Markland, 1987). Nutrients involved in eutrophication mainly are phosphorus in the form of phosphate and nitrogen in the form of nitrate or ammonia. Phosphorus has been identified as the limiting nutrient of eutrophication in freshwater systems (river and inland lakes) while nitrogen is limiting in marine ecosystems (Barabas, 1981; McCutcheon et al., 1993). There are several factors influencing the high nutrients concentration in urban runoff. The main factors are land use, duration and intensity of rainfall, inter-event dry periods, geology and topography of the catchment (Newman, 1995). For effective management of nutrients, it is essential to identify the sources and magnitude of the input of nutrients.

2.3.3 Nutrients (phosphorus and nitrogen) in leaf litter

Urban areas are planted with trees and can shed large quantities of leaves. The fallen leaves are referred to as leaf litter. The leaf litter produced from these urban plantings is a source of nutrients and organic matter (Li et al., 2011) in catchment and in urban waterways as they breakdown. Leaf litter from urban areas can contribute to nutrient load in the stormwater runoff (Cowen and Lee, 1973). The increased velocity of surface runoff (Paul and Meyer, 2001) due to urbanization increases the potential of leaf litter to be transported directly into water ways. This study focussed on leaf litter in urban stormwater that are captured by structural devices. Specifically this study investigates the leaf litter degradation in these devices and thereby developed model to quantify nutrient loads in urban receiving waters.

Among all the leaf litter nutrients, nitrogen and phosphorus are the most important urban stormwater pollutants (Hogan and Walbridge, 2007). Therefore, high leaf litter input enhancing the eutrophication. Nitrogen content with a typical value of 0.75% (Rubino et al., 2009) and phosphorus content with a typical value of 0.075% (Parsons et al., 1990) are a common measurement of leaf litter quality (Gallardo and Merino, 1992). Scowcroft et al. (2000) found that nitrogen and phosphorus concentration in Metrosideros leaf litter were varied from 0.27–1.02 % and 0.022–0.067% for N and P, respectively. Peter and Imre (2006) carried out experiments on apple leaves and found that the leaves content 0.15–0.45% and 2–3.9 % were phosphorus and nitrogen respectively. Lusk et al. (2003) found 0.44%–0.84% nitrogen and 0.04%–0.12% phosphorus concentrations for different leaf litters of four different species. Weerakkody and Parkinson (2006) carried out experiment for three leaf species and found N and P content were 1.4–3.3% and 0.05–0.18% respectively. Jones and Bromfield (1969) used phalaris leaves with N and P content ranges between 0.54%–1.91% and 0.052%–0.17% respectively in their experiments.

From the above studies it is concluded that the TP in leaf litter is about 0.022–0.45% of dry leaf weight while the TN is about 0.27–3.9% of dry leaf weight. Leaf litter contributed more nitrogen than phosphorus. Therefore, quantification of N and P associated with leaf litter is important to control water quality.

2.3.4 Leaf litter decomposition

The chemical composition of leaf litter is a mixture of organic and inorganic compounds (Coleman et al., 2004). The decomposition of leaf litter in water involves three different mechanism: leaching of soluble substances (Tukey, 1970), physical fragmentation of litter mass (Rubino et al., 2010) and biochemical oxidation of organic matter (Webstar and Benfield, 1986). At initial stage mass loss from leaf litter was rapid, followed by a slower decreasing stage (Berg et al., 2003). Other studies reported that, the initial rapid mass loss was responsible for carbon, nutrients and water soluble organic compounds (Davis et al., 2003). Depending on leaves species, it was also observed that among the nutrients of leaf litter N and P are lost rapidly whereas Mg and Ca lost more slowly (France et al., 1997). Later stages the structural compounds such as lignin, cellulose and hemicelluloses are lost very slowly from leaf litter (Chapin et al., 2002).

Leaf litter decomposition of five tree species was carried out by Upadhyaya et al. (2012). They found that the decomposition pattern and nutrient (P, N) release varies with individual leaf species. They also found that the variation of nitrogen concentration was higher whereas phosphorus concentration did not showed significant difference among the species. The decomposition rate constants depend on the substrate quality and aquatic environment (Satchell, 1974). The information about the large amount of vegetation loss in Australia is available (Lindenmayer and Burgman, 2005); however, the breakdown of vegetation and their decay's specially leaf litter are rarely been carried out. Therefore, this study collected samples from Centennial Park, Sydney, Australia and carried out leaching experiment into deionised water to observe the breakdown processes. It is assume that plant litter is homogeneous i.e. all constituent of the detritus have an equal probability of decomposing at any time leads first-order exponential decay model (Olson, 1963; Peterson and Cummins, 1974; Gasith and Lawacz, 1976; Singh and Gupta, 1977). Therefore, the overall nutrient release process can be best described by first-order decay model.

2.3.5 Leaf litter decay model

The negative exponential function is widely used to model the fraction of the litter mass remaining at different time intervals (Olson, 1963). This model is used to determine decay rate (k) which represents the decrease in mass loss rate over time (Olson, 1963). An example of generalized negative exponential curve of litter mass loss over time during decomposition is shown in Figure 2.2.

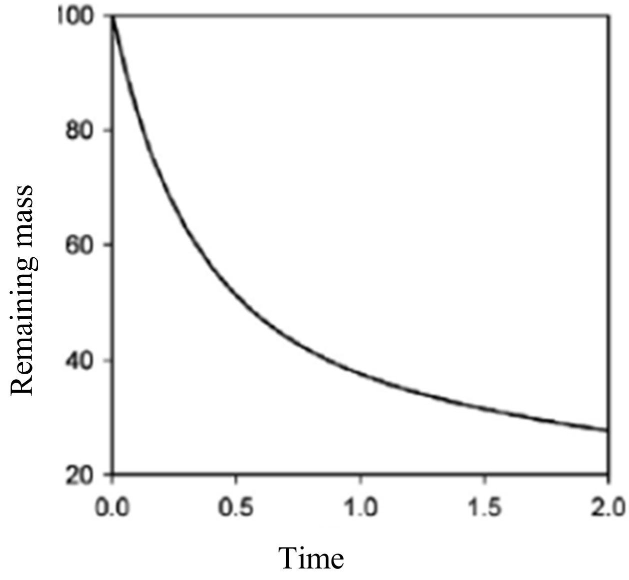

Figure 2.2 Typical decay curve of litter mass loss over time (Rovira and Rovira, 2010)

The decay constants for leaf litter were calculated using a single exponential decay model (Olson, 1963) expressed as equation 2.1:

$$X/X_o = \exp^{(-kt)} \qquad (2.1)$$

where, X is the mass of dry matter remaining at time t, X_o is the initial mass of dry matter, exp is the base of natural logarithm, k is the decomposition rate constant and t is the time.

2.3.6 Phosphorus and nitrogen release from leaf litter

Prasad et al. (1980) carried out leaching experiment for leaf species and found that 0.006–0.07% and 0.05–0.24% of TP and TN, respectively, was leached into de-ionised water. Their experiments also suggest that 48 hours is adequate to leached out most of the soluble substances. Dorney (1986), soaked leaves in distilled water for 2 hours and was observed that 0.004–0.026% of TP was leached out. Cowen and Lee (1973) collected oak and poplar tree leaves from Madison, USA and carried out leaching experiments for 1.5 hours in distilled water. They reported that TP released was 0.005–0.023%. Other studies, Qiu et al. (2002) found that 25–37 % phosphorus leached out at 24 hours. The above studies indicated that leaching experiments were carried out for a shorter period of time. It was also found that seasonal rains leached 25.7–84.1% of total P in leaf litter under field conditions (Qiu et al., 2005).

2.3.7 Partitioning

Phosphorus transportation occurs as either particulate or dissolved (soluble) phases by stormwater runoff. Phosphorus partitioning between these two phases is highly variable depending on site location and specific conditions with the particulate fraction ranging from 20% to > 90% of the total load. N and P loads as particulate matter are needed to evaluate source control, fate and treatment mechanisms (Ma et al., 2010). Previous studies indicated that the phosphorus load transported by stormwater is likely to be about 50% particulate and 50% soluble depending on location (NYSDEP, 2010). Weibel et al. (1964) observed that 62% of the total hydrolysable P in their runoff samples was soluble hydolyzable P. On the other hand, Kluesener and Lee (1974) reported that about 58% of the total P in their samples was dissolved reactive P as determined by the soluble ortho-phosphate using colorimetric procedure. Therefore, about 40% of the total P in urban runoff may occur as particulate P. The total P loadings from urban runoff can be expressed (Cowen and Lee, 1976) by equations 2.2 and 2.3:

$$TP = TSP + PP \tag{2.2}$$

$$\text{Available TP} = TSP * (\text{\% of TSP available}) + PP * (\text{\% of PP available}) \tag{2.3}$$

where, TP = total phosphorus, TSP = total soluble phosphorus, and PP = particulate phosphorus.

As the total P required for algae and the total P content in urban runoff were unknown. It is assumed that all of the total soluble P is converted to soluble orthophosphate which is fully consumed by algae content in the receiving water. Then the equation 2.3 can be used to determine the particulate P fraction of runoff allows estimation of the percentage of total P that should become available to algae (Cowen and Lee, 1976).

Phosphorus in urban waterways can be categorised into a number of divisions with the primary division being into organic and inorganic phosphorus. Therefore, in discussing the decomposition of leaf litter, it is important to consider the different forms of phosphorus which can occur within an urban stormwater system. The partitioning of phosphorus in stormwater and sewage effluent as presented by Waller and Hart (1986) and was reported in the literature are shown in Tables 2.1 and 2.2 :

Table 2.1 Phosphorus partitions (Waller and Hart, 1986)

	Soluble P (%)	Particulate P	
		Organic (%)	Inorganic (%)
Sewage	83	17	0
Stormwater	4.2	11.6	84.2

Table 2.2 Proportion of phosphorus transported in a particulate form

Particulate Percentage	Reference
up to 90	Camp Scott Furphy (1988)
99	Hvitved-Jacobsen et al. (1986)
84–96	Ball and Abustan (1995)

As shown in Table 2.2, the majority of phosphorus transported in urban stormwater runoff is particulate in nature. Decay of leaf litter trapped in a GPT, however, has the potential to result in a change in the relative importance of the soluble and particulate phases of phosphorus. This change in the relative importance of the particulate and soluble phases of phosphorus, in turn, will influence the effectiveness of downstream measures employed for treatment of stormwater borne phosphorus; most treatment measures employed involve sedimentation of particulates or filtering of the stormwater.

2.3.8 Conversion between forms

Phosphorus in aquatic systems usually exists as organic or inorganic species. It can be either dissolved in water or particulate form. Both organic and inorganic phosphorus can be soluble (dissolved) and insoluble (particulate) inorganic species and labile (easily decomposable) and non-labile organic species. Measurements of phosphorus in the environment are commonly made as TP which may include total soluble and particulate P. The bioavailable total phosphorus (TP) load can vary from different sources such as wastewater, runoff and tributary. Fractionation methods that rely on sequential extractions are typically used to identify receiving water or influent fractions of decreasing lability or bioavailability (Cowen and Lee, 1976; Young et al., 1985; Auer et al., 1998). Dissolved inorganic orthophosphates (DIP) whose species vary with system pH, are generally considered most immediately bioavailable, although some algae and microbes can also assimilate selected dissolved organic phosphorus compounds (DOP) (Reddy et al., 1999). A small quantity of particulate phosphorus may also bioavailable upon entering receiving water, depending upon selected physical, biological and chemical properties of the sediment layer, water column, and influent that influence phosphorus solubility.

Phosphorus Cycle

Aquatic plants need dissolved inorganic phosphorus and convert it to organic phosphorus. Animals take the organic phosphorus by eating either aquatic plants, other animals or decomposing plant and animal material. As plants and animals excrete wastes or die, the organic phosphorus they contain sinks to the bottom, where bacterial decomposition converts it back to inorganic phosphorus, both dissolved and particulate form. This inorganic phosphorus gets back into the water column when the bottom is stirred up by animals, human activity, chemical interactions, or water currents. Then this inorganic P is taken up by plants and the cycle begins again (USEPA, 2000) is shown in Figure 2.3**.**

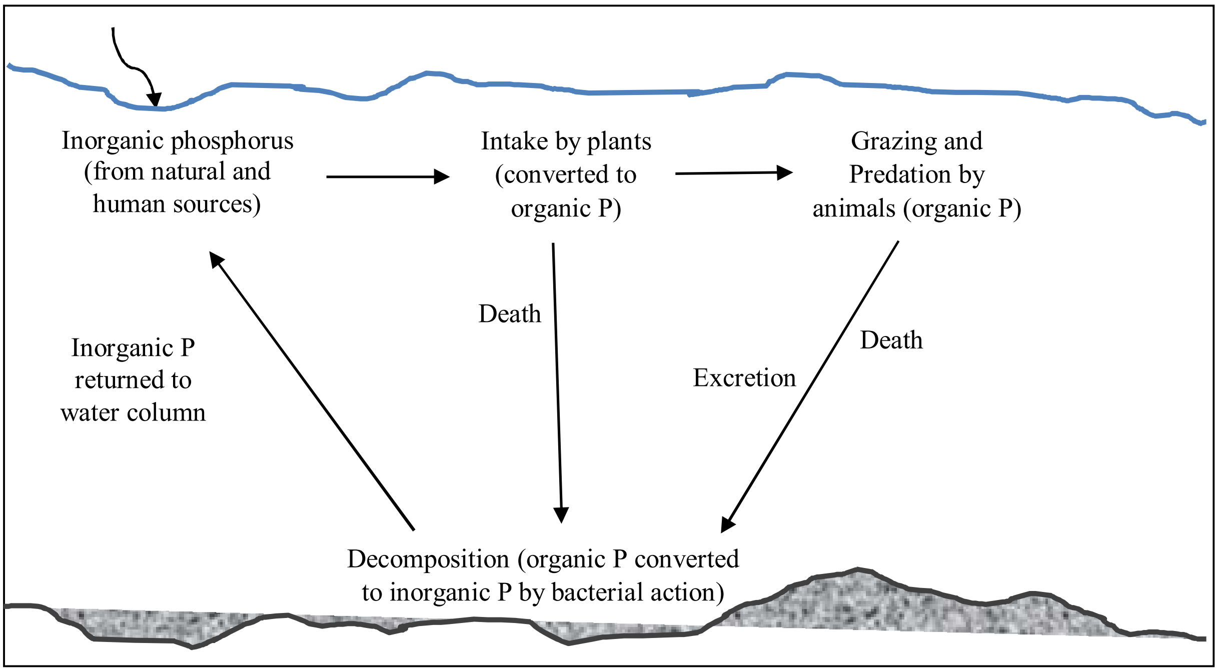

Figure 2.3 Phosphorus cycle (USEPA, 2000)

2.3.9 Stormwater pollutant load

The stormwater runoff load consists of pollutant. The quantity of nutrient load due to storm runoff can be estimated by dry and wet weather days. Any computation of annual total load must be done by the summation of two components: one is the load in dry weather days and the other is the load in wet days. In case of long term nutrient load estimation, it will often be less than that actual load if it is performed on the basis of field data observed in dry weather days. It is difficult to direct measure all storm runoff load from urban drainage system. However, it is better to measure the basic runoff patterns of nutrients by considering several different hydrological conditions.

Nutrient generation rates can be obtained from model applications (Letcher et al., 2002) or from detailed field studies monitoring pollutant concentrations and stream flows for specific catchment conditions and land use composition. A nutrient balance model predicts total loads produced in the catchment by calculating the nutrient loads generated from different land uses and summing these across all land uses within the catchment (Cuddy et al., 1994). These models can be useful for management decisions.

Stormwater pollutant runoff models are also useful tool to predict quality of urban storm-water (DeCoursey, 1985; Tsihrintzis and Hamid, 1997; Zoppou, 2001) which follows a combination of accumulation and washoff equations. Catchment and rainfall characteristics on urban runoff quality are strongly related with accumulation and washoff processes. The total amount of pollutant is a function of the initial mass on the surface area and the length of the antecedent storm dry period. Pollutants accumulation on impervious surfaces is an exponential increase (Alley and Smith, 1981). This exponential model was a function of the available mass and rainfall intensity. Other authors have proposed the usage of the total volume of runoff as opposed to rainfall rate (Haiping and Yamada, 1996).

2.4 Urban catchment modelling

Catchment modelling is an emerging tool currently being used for understanding the stormwater quantity and quality impacts on urban receiving water. It assists catchment manager to develop conceptual catchment management framework, evaluation of management quality system, prediction of pollutant concentration and remediation strategies, for sustainable catchment management practices. To represent catchment and their associated system such as geological, topographical and meteorological information, using appropriate modelling system is a complex task. Therefore, a review of catchment modelling is necessary for this study. In this section, the types of catchment modelling approaches are reviewed and modelling is used to investigate hydraulic variability (i.e. peak flow and infiltration loss) of the study catchment for different temporal pattern and quantify the runoff volume generated (see chapter 6). This data is used to develop conceptual phosphorus model for simulation of P in a GPT.

Impervious surface area is significantly higher in urban catchment than rural areas which influence different hydrological components in catchment modelling. Most of the previous work of hydrological model was developed using fundamental mathematical equation related to rural natural catchment rather than urban catchment. Considering this issues urban catchment modelling were developed by introducing some modification to accurately model urban catchment (Huber and Dickinson, 1988).

Models are constructed and designed to address the following purposes (Parker et al., 2002):

- a source of contemporary knowledge for storage and retrieval
- a collation tool for allowing different sets of data to be viewed or examined together
- to help develop an understanding of the system being managed and the types of interactions that exist between, for example, the social, economic and biophysical sub-systems
- an instrument of prediction in support of decision making or policy formulation
- a device for communicating scientific notions to and/or from a scientifically lay audience, and
- an exploratory vehicle for scenario building

The appropriate model for any given application is related to the following factors (Merritt et al., 2003):

- the data requirements of the model
- the components of the model
- the characteristics of the catchment
- the intended use of the model
- system (computer) requirements of the model
- the model accuracy, validity and underlying assumptions

Complex conceptual or physics based models are required large number of input data to predict pollutant loads and consequently difficult to use (Merritt et al., 2003). Therefore models are needed that can provide useful information using minimum data input as required. In addition, as the scale at which the catchment subdivision is carried out decreases, the required input data for the model increases (Moore and Gallant, 1991).

2.4.1 Model concept

Current developments in urban modelling system are implemented in an integrated computer model. Therefore, the individual modelling system can be arbitrarily subdivided into a number of conceptual components so that it is convenient to analyse the structured catchment model. Based on structured procedure of catchment models, the subdivision of catchment modelling system was proposed by Ball (1992) in order to create an integrated catchment modelling system. From the above concept, he suggested four conceptual components of a catchment modelling system as:

Generation: The module in the system concerned with modelling the spatial and temporal variation of rainfall, the availability of pollutant constituents, and any models associated with control parameters estimation.

Collection: The module in the system primarily concerned with the accurate prediction of the temporal variation of the stormwater quantity and quality flux at the entry points to the transport module of the system. This module generally is considered to be the hydrologic component of the system.

Transport: The module in the system where the quantity and quality of the stormwater runoff is routed through the physical links in the drainage system. This module generally is considered to be the hydraulic component of the system.

Disposal: The module of the system concerned with the manner by which the stormwater quantity and quality is discharged into the receiving waters.

The above mentioned four conceptual components are presented as an irreversible flow line diagram (Figure 2.4). The flow in this case represents the flow of information through the modelling system. It is irreversible as correct prediction of water characteristics in the last component does not imply the models in the individual components are correct.

GENERATION
Spatial and temporal variation of rainfall
Spatial variation of pollutant

↓

COLLECTION
Simulation of surface runoff
Simulation of constituent washoff

↓

TRANSPORT
Movement of water and constituents
through drainage network

↓

DISPOSAL
Discharge of runoff and constituents into
the receiving waters

Figure 2.4 Four conceptual components of a catchment modelling system (Ball, 1992)

It is important to note that a successful reproduction of discharge hydrograph in the outlet does not imply that all processes that influence the outflow discharge are simulated correctly or the selected values of control parameters are accurate. The satisfied simulation performance may be explained by the error compensation phenomenon occurring in the application of a catchment modelling system. For example, different spatial rainfall models generate different average depths of rainfall for a catchment, however, a similar value of catchment average depth of rainfall excess may be obtained because these differences can be compensated by differences in the parameters used in the loss model. As a result, there are a number of alternative parameter sets which generate similar values of the catchment response.

2.4.2 Model classification

The catchment modelling system is consists of a number of component depending on the level of detailed used in the model. Based on physical process simulated and the data dependence of the model, the catchment modelling systems can be classified as, Empirical model, conceptual model and physically based model (Letcher et al., 1999).

Empirical model

Empirical models are the simplest of all three types of model. The essential criteria of empirical models are that they are based primarily on the analysis of observations. The computational and data requirements for such models are usually less than for conceptual and physics based models, often being capable of being supported by coarse measurements (Merritt et al., 2003). The characteristics of this model are their high level of spatial and temporal aggregation and their incorporation of a small number of causal variables (Jakeman et al., 1999). Parameter values in empirical models may be obtained by calibration, but are more often transferred from calibration at experimental sites. They are particularly useful as a first step in identifying sources of sediment and nutrient generation. Also it can be used as a base for additional indepth studies (Hamlett et al., 1992). Empirical models are often criticised for employing unrealistic assumptions about the physics of the catchment system, ignoring the heterogeneity of catchment inputs and characteristics, such as rainfall and soil types, as well as ignoring the inherent non-linearities in the catchment system (Wheater et al., 1993). Usually this model is not event responsive, ignoring the processes of rainfall runoff in the catchment being modelled. However, Empirical models are frequently used in preference to more complex models as they can be implemented in situation with limited data and parameter inputs.

Conceptual model

Conceptual models are based on the representation of a catchment. They usually incorporate the underlying transfer mechanisms of sediment and runoff generation in their structure, representing flow paths in the catchment as a series of storages, each requiring some characterisation of its dynamic behaviour (Merritt et al., 2003). Conceptual models are lump representative processes over the scale at which outputs are simulated (Wheater et al., 1993). Conceptual models include a general description of catchment processes, without including the specific details of process interactions, which would require detailed catchment information (Sorooshian, 1991). This allows these models to provide an indication of the qualitative and quantitative effects of land use changes, without requiring large amounts of spatially and temporally distributed input data. Parameter values for conceptual models have typically been obtained through calibration against observed data, such as stream discharge and concentration measurements. In general, simpler conceptual models have fewer problems with model identification than more complex models. This models play an intermediary role between empirical and physics based models (Beck, 1987).

Physically based model

Physics-based models are based on the solution of fundamental physical equations describing stream flow and sediment and associated nutrient generation in a catchment (Merritt et al., 2003). In theory, the parameters used in physics-based models are measurable and so are 'known'. In practice, the large number of parameters involved and the heterogeneity of important characteristics, particularly in catchments, means that these parameters must often be calibrated against observed data (Beck et al., 1995; Wheater et al., 1993). This creates additional uncertainty in parameter values (Merritt et al., 2003).

Deterministic and Stochastic model

The two fundamental types of models are the Deterministic and Stochastic model. Deterministic models which have same output for a specific sets of input if run through the model under identical conditions. Stochastic models which involved the same input will produce different sets of output if run through the model under externally seen, identical conditions. The system considers the variability in hydrological processes and the output will have fairly consistent statistical properties. Most catchment modelling systems were developed based on the deterministic theory because urban runoff models are deterministic (Nix, 1994).

Lumped and distributed models

Catchment modelling system can further be classified as lumped models and distributed models depending on spatial data handled. A lumped model considers the catchment system as one unit, with state variables and parameters that represent average values for the entire catchment (Abbott and Refsgaard, 1996). A distributed model consider prediction that are distributed in space with state variables and parameters that represent average values for entire subcatchment, by discretising the catchment into a number of elements (or grid squares) and solving the equation for the state variables and parameters associated with every elements (Singh and Frevert, 2006). Distributed models are capable to some extent of taking into accounts special variability of processes, input, boundary conditions and catchment characteristics. On the other hand, lumped models taking no account of special variability of processes, input, boundary conditions and catchment characteristics. Distributed models are functions of time and space and lumped models are functions of time only. When catchments are discretised into many subcatchments, each of which considered having homogeneous characteristics within its areas, then the model can be used as a distributed model on a catchment scale but a lumped model on a subcatchment scale. Selection of lumped or distributed model depends on the desired output of the model and the nature of possible management interaction provenance (Merritt et al., 2003).

Event based and continuous models

Catchment models can be classified as event based and continuous model on the basis of their operational period. Continuous models simulate many storm events over a period of time. While event based model simulate only one event. The model parameters which are adjusted through calibration process for event based simulation may not be applicable for continuous simulation since the model parameters adjusted in the event based models are affected by the catchment antecedent wetness conditions assumed for each storm events (Nix, 1994). Therefore, runoff process and calibration parameters depend on whether a single or continuous event is used.

Other types of classification

Models may be implemented as a set of procedures or calculations performed by hand, or embodied in a computer program (or suit a programs), which may be termed a numerical model (Ball, 1992). Several numerical models are available for the simulation of runoff water quantity and quality from a catchment. There are few examples of numerical models are as follows:

SWMM (Storm Water Management Model)

It is a computer model used for simulation of urban runoff quality and quantity. SWMM subdivides the overall catchment into sub catchments and simulates the quantity and quality within each sub catchments. The model predicts runoff from the subcatchments on the basis of their physical properties and combining their outflows using a flow routing method. This research will mainly focus on the SWMM that is used to simulate the quality and quantity of runoff in the study catchment and to predict peak flow. Details of SWMM are discussed in chapter 4.

RAFTS (Runoff Analysis and Flow Training Simulation)

It simulates runoff hydrographs of both observed and design throughout the catchment for specific rainfall events. The model can be used for analysing pipes, water ways, retention and retarding basins and formalised channels, and combines any of these components within the catchment. RAFTS needs the catchment to be divided into several sub catchments. This model uses Philip's infiltration equation or initial loss – continuing loss model to simulate excess runoff. Like SWMM, it does not consider directly connected impervious area and supplementary area separately. However it can model pervious and impervious area separately.

RORB (Rainfall Runoff Routing using Burroughs)

It is a surface hydrologic and hydraulic routing program used to calculate flood hydrographs from rainfall and other input. This model is generally used to predict flood due to runoff in rural and urban areas. This model requires the subdivision of the catchment into several sub catchments. Each sub catchment is considered as a node and is connected with non-linear storages to model the flow from one sub catchment to another. It computes the rainfall excess for each sub catchments which is routed through the non-linear storage. This model computes the rainfall excess using initial loss-continuing loss or initial loss-proportional loss. This model allows the impact of urbanisation by weighting reach length by a factor. This factor is used to scale the reach length considered for the catchment and channel lag. The drawbacks of this model was, it consider always equal direction of flow and reject effect of reverse water flow. It does not model the pipe hydraulics. Other important drawbacks of using this model, it lumping total impervious area in a sub catchment rather than directly connected and supplementary areas separately, for urban catchment.

HSPF (Hydrological Simulation Program-Fortran)

It can be used as a continuous model or event model. It is an agricultural model, improved to handle the impervious surface. It computes rainfall excess based on the Stanford watershed model (Crawford and Linsley, 1966). This model is basically a planning model. It does not model detailed pipe networks and therefore is not suitable detailed drainage system.

WBNM (Watershed Bounded Network Model)

It is used for urban and rural catchment. It is an event based runoff routing model. It has different types of storages for each type of sub catchments. It takes into account separate rain losses to generate rainfall excess for pervious and impervious areas within each sub catchment. A number of loss models such as horton equation, Green-Ampt model, initial loss-continuing loss, initial loss-proportional loss or initial loss-constant loss are available to calculate rainfall loss in WBNM. For channel routing it used nonlinear routing, Muskingum routing or time-lag routing method.

STORM (Storage, Treatment, Overflow, Runoff Model)

It was developed to analyse quality and quantity of runoff from urban catchments. Runoff is routed first to treatment, then storage and then any excess is modelled as overflow proceeds in an hourly basis by simple runoff volume and pollutant mass balance within the catchment. This model is a continuous model, simulating a catchment using percent of land in each land use type. Usually, this model is used for planning and it is not suitable for detailed quantity and quality modelling.

2.4.3 Modelling methods

A catchment model is a spatially distributed hydrological process. It is a combination of mathematical procedures, an approximation of natural hydrological process. The basic principle of catchment modelling is a transformation of rainfall to runoff. In this process a portion of rainfall will contribute to runoff while the remaining portion is lost due to interception (by vegetation), infiltration (into the soil), storage on the surface and evaporation. A number of mathematical procedures are used to simulate different components in the hydrological process (Laurenson and Mein, 1985), such as Green-

Ampt model can be used to estimate infiltration loss while the Manning's equation can be used to simulate overland flow.

Stormwater models are widely used to study the urban catchment water quality and quantity modelling. These models are useful for different catchment management strategies such as planning, design and operation. Urban stormwater quality model is an integrated model where water quantity inputs are needed to estimate pollutant load. For this stormwater model consists of a combination of individual rain-fall model and pollutant transport model. Rainfall-runoff modelling simulates the generation of surface and sub-surface runoff from excess precipitation while pollutant transport model routing the flows and pollutants through the stormwater infrastructure, such as pipe networks, open channels and storages (Zoppou 1999). Stormwater quantity model consider hydrologic and hydraulic processes of urban stormwater systems. Computer models can contribute to a better understanding of hydrologic and hydraulic systems and their interactions in a quantitative way for catchment studies. Hydrologic and hydraulic computations such as loss modelling, overland flow routing and pipe routing are used for urban catchment modelling to simulate runoff processes.

2.4.3.1 Loss modelling

Rainfall loss is the amount of storm precipitation that does not appear as the immediate runoff after a storm (Hill et al., 1998). This loss includes intercepted by vegetation, infiltration into the soil and retained on the surface (depression storage). These losses can be modelled by different loss components: initial loss from both impervious and pervious area depression storages, pervious area infiltration loss and evaporation loss from both impervious and pervious surfaces.

Impervious and pervious area depression storages: Depression storage is the volume that must be filled in the beginning of the storm, prior to the commencement of surface runoff on both pervious and impervious areas is referred as an initial loss. It is a loss by interception, surface wetting and surface ponding.

The initial loss is subtracted from rainfall hyetograph to estimate the effective rainfall excess i.e. runoff occurs when the rainfall intensity exceeds the initial loss. Depression storage in the impervious area is depleted only by evaporation. On the other hand, the pervious depression storage is reduced by infiltration and evaporation and therefore it is continuously and rapidly replenished. However, in rainfall event modelling, the evaporation loss is significantly less compared to other losses and therefore the impervious area and pervious depression storage are assumed to be a constant in most urban drainage models. Typical values would be 0 to 2 mm and 2 to 10 mm for impervious area and pervious area depression storage, respectively (O'Loughlin, 1993). In addition, for long-term water balance analysis, evaporation is an important parameter (Bedient and Huber, 1992).

Pervious area infiltration loss: There are various equations developed for modelling the infiltration process**.** The Horton equation, Green-Ampt model and Phillip equation are generally used to determine infiltration loss. Spatially lumped model is a class of infiltration loss model. These models are widely used which have been conceptualised in simple forms. These types of models are proportional loss, constant loss rate, initial loss-continuing loss, SCS curve procedure and antecedent precipitation index (IEAust., 1998).

Horton equation

According to Horton (1940), infiltration capacity decreased with time until it reached a constant value. This process is expressed as equation 2.4:

$$f_p = f_c + (f_o - f_c)^{-kt} \qquad (2.4)$$

where, f_p is the infiltration capacity (mm h^{-1}), f_c is the final infiltration capacity (mm h^{-1}), f_o is the initial infiltration capacity (mm h^{-1}) at time t=0, t is the time (h) and k is the decay constant (h^{-1}). The parameters f_o, f_c and k can be obtained from catchment calibration. The parameters depend on soil type, vegetation, and soil moisture content. SWMM and MOUSE are used the Horton equation in infiltration loss modelling. It is only applicable for shallow ponded conditions. The Horton equation is generally suitable for small catchment as in the larger catchments the soil type, vegetation, and soil moisture content varies throughout the catchment.

Green-Ampt model

The Green and Ampt (1911) infiltration model is based on Darcy's Law assuming ponded conditions, a constant matric potential at the wetting front and uniform moisture content and conductivity to model infiltration. Mein and Larson (1971) showed that the Green-Ampt model could be presented for a constant intensity rainfall at the surface. The Green-Ampt model is expressed by equation 2.5:

$$fp = ks\left(1 + \frac{M\psi}{F}\right) \qquad (2.5)$$

where fp is the infiltration capacity (mm h^{-1}), ks is the standard hydraulic conductivity (mm h^{-1}), M is the initial loss moisture deficit (vol vol^{-1}), ψ is the capillary suction at wetting front (mm of water) and F is the cumulative infiltration volume from beginning of the event (mm). ks, and ψ and M can be obtained from catchment calibration using rainfall/runoff data. In the SWMM model Horton or Green-Ampt equation can be used to estimate infiltration loss from pervious areas within the catchment.

2.4.3.2 Overland flow modelling

Runoff hydrographs can be obtained using overland flow modelling simulation for an urban drainage system (ASCE, 1996). Common overland flow methods are applied for both pervious and impervious areas are:

- Nonlinear reservoir representation
- Time-area routing with linear time-area diagram, and
- Muskingum routing approach

Linear and Nonlinear reservoir representation of a catchment

The overland flow over catchment surface can be represented by linear or nonlinear reservoirs. Nonlinear reservoir model is based on successive storage routing without translation among storages. The model uses both storage and continuity equation (ASCE, 1996) as equations 2.6 and 2.7:

$$\text{Storage equation, } S = K\, q^{n} \qquad (2.6)$$

$$\text{Continuity equation, } dS/dt = I - Q \qquad (2.7)$$

From equations 2.6 and 2.7, the overland flow routing equation can be obtained (Nix, 1994) as equation 2.8:

$$I - Q - n\,K\,Q^{n-1}\,(dQ/dt) = 0 \qquad (2.8)$$

where S is the storage , I is the inflow , Q is the outflow , n is the number of reservoirs, K is the storage coefficient, and t is time from starts of runoff. In case of single linear reservoir, the value of n = 1 and K equals to the time lag between hyetograph and hydrograph. Nonlinear routing is used in SWMM model for modelling overland flow routing.

2.4.3.3 Pipe and channel flow modelling

Different methods used to model the pipe and channel flow are as follows:

- unsteady flow models
- steady flow models
- time-lag method
- linear and nonlinear reservoir routing, and
- Muskingum routing

Unsteady flow models

The simplified complete dynamic equation (i.e. Saint-Venant equation) of flow used in this method can be expressed (Nix, 1994) as following equation 2.9:

$$gA\frac{\partial Y}{\partial x} + \frac{\partial}{\partial x}\left(\frac{Q^2}{A}\right) + \frac{\partial Q}{\partial t} + gAS_f - gAS_o = 0 \qquad (2.9)$$

where t is the time, x is the longitudinal direction measured horizontally, A is the flow cross-sectional area normal to x, Q is the discharge through A, Y is the depth of flow, S_o is the channel slope, S_f is the friction slope, and g is the gravitational acceleration.

In the above equation 2.9, the first term indicates the pressure force, the second term is known as the convective acceleration and the third term is the local acceleration. The fourth term is the resistance due to bed friction. The last term represents the gravity force due to bed slope. The last two terms of the equation 2.9 is used for the Kinematic wave equation.

Previous studies have used the finite difference technique to solve the full dynamic Saint-Venant equation in urban runoff models (Roesner et al., 1983). This modelling approach is useful to accurate simulation but it requires large number of data input and computer time consuming to produce the results. Kinematic or full dynamic equation can be used with SWMM.

2.4.3.4 Influence of rainfall characteristics in catchment modelling system prediction

Rainfall pattern play an important role in many hydrological models. Primarily temporal and spatial input data is strongly effects on runoff calculations and modelling system (Umakhanthan and Ball, 2005). The lack of available spatial and temporal data input due to high variability of rainfall intensity with time, the quality data input is difficult with relation to the model output (Terranova and Iaquinta, 2011). Rainfall intensity varies significantly over distances of less than 1 km and a time of less than a few minutes and large data set is required to obtain regional profiles. Therefore, the research is necessary to better understanding of the spatial and temporal variability of rainfall in determining the characteristics of predicted hydrographs. Several studies investigated the effect of spatial variability on predictive performance, but only a few studies have examined the temporal variability on model predictive performance (Wang et al., 2009). In this study the effect of temporal variability of rainfall on runoff prediction was investigated.

Effect of temporal variability of rainfall

The temporal distribution of rainfall between storm events leads to change the urban hydrology. Studies have shown that the impacts of temporal variability of rainfall (Lambourne and Stephenson, 1987; Ball, 1994) approached the problem by comparing the catchment responses to alternate temporal rainfall patterns. Ball (1994) simulated overland flows for different rainfall excess patterns having rectangular, triangular, etc. patterns of rainfall excess and found that the peak flow and time of occurrence depended on the temporal pattern of rainfall excess. Also, he reported that estimation of the time of concentration for a catchment is dependent on the temporal pattern of the rainfall excess, and may be up to 22% longer or 19% shorter than that predicted using a constant rate of rainfall excess.

The effect of temporal distribution for a small urban catchment (1.42 ha in area) was studied by Lambourne and Stephenson (1987). They used catchment runoff to simulated runoff peaks and volumes for a series of synthetic 5 year return period storms having rectangular, triangular and bimodal temporal distributions compiled from depth-duration-frequency (D-D-F) relationships. The storm with a triangular temporal pattern generate 14% higher total runoff and a 44% greater peak flow than a storm with the same volume of rainfall and a uniform intensity. The variations between temporal patterns could cause variations of up to a factor of 3 in peak flow on a small urban catchment (49 ha area) while for a rural catchment (120 ha) that changes in temporal patterns of rainfall events could result in changes of up to an order of magnitude in peak flow at the catchment outlet (Ward et al., 1980; Burke et al., 1980).

Typical triangular shaped rainfall hyetograph with the time of peak 't_p' varying between the start of the time (T_p=0) and the end (T_p=1) was investigated by Lambourne and Stephenson (1987). They observed that if the storm intensity peaked in the first part of its duration ($T_p < 0.5$) the peak runoff was less than that for a uniform storm of the same average intensity. This was valid for peaks up to 80% of the duration, after the commencement of rain**.** Only for the peak at the end of the storm (T_p=1) did the peak runoff exceed that for a uniform intensity storm. In this case, the peak runoff was approximately 10% greater than for a uniform storm of the same duration. When the storm duration was not equal to the time of concentration for a uniform storm, the peak could be higher. It was found that when a storm peaked near the end, and the watershed was saturated, the peaks could be up to 30% greater than for uniform storms (USEPA, 1985).

2.5 Stormwater management

There are many socio-economical and technical factors related to successfully managing nutrients within the urban catchment. Specially, from non-point source which pollutant to control, identifying and prioritizing natural and anthropogenic sources, allocating loads, and developing, implementing, and measuring the success of comprehensive catchment management plans. Currently, to control non-point and diffuse pollutant sources, implementation of Best Management Practices (BMPs) is an important component of catchment management plans which is protecting and enhancing the values of receiving waters. The NSW EPA, local government councils and Sydney Water have all in recent policy emphasized the necessity for stormwater treatment units in stormwater management. However, large uncertainties associated with the control of non-point source, and will continue to, hinder the successful implementation of management measures (Griffin, 1995).

Both non-structural and structural method is effective to control gross pollutant (Allison et al., 1997). Structural methods are traps placed in a drainage system to separate and contain gross pollutants, and non-structural methods involve motivate the community through education, and waste management programme. The structural measure of urban stormwater management is based on the concept of "control-at-source" with the objective to control stormwater quantity and quality (Lariyah et al., 2006). Structural stormwater treatment methods control pollutants in urban water ways through physical, chemical and biological processes to improve water quality. Treatment methods are selected based on local site condition, types of pollutants and catchment characteristics. The commonly used pollutant treatment methods with varying treatment mechanisms are gross pollutant traps, sedimentation basins, grass swales, filter strips, wetlands and infiltration systems. Figure 2.5 showed the relationship between the particle size range of pollutants and treatment processes.

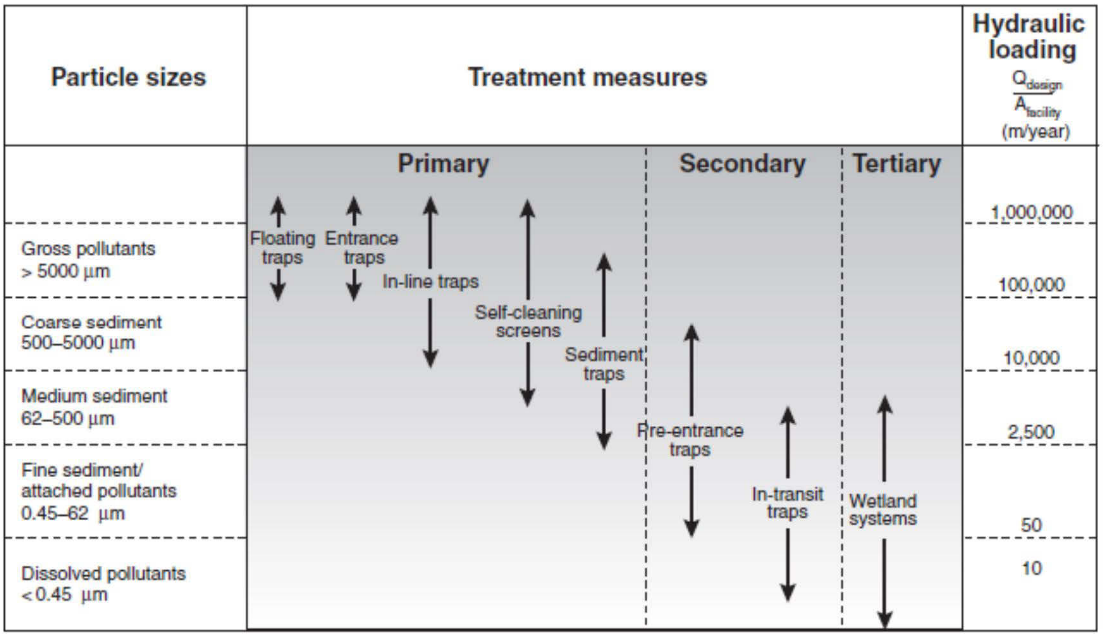

Figure 2.5 Desirable design ranges for treatment measures and pollutant sizes (Adapted from CSIRO, 1999)

According to particle size, a GPT can be classified as a primary treatment device with particle capture of those particle larger than 5000 micro meter (5 mm) in size. This section describes the structural methods commonly used for reducing gross pollutants in Australian context known as Gross Pollutant Traps (GPTs).

2.5.1 Gross Pollutant Traps (GPTs)

Gross pollutant traps (GPTs) are one of the structural devices used in a stormwater drainage networks as a component of the treatment train (Mouritz, 2006) to improve storm water quality before discharge into receiving waters. These GPT operate by filtering gross pollutants from storm water through the use of coarse screens (>5 mm). The main objective of a GPT is to trap pollutants from stormwater and protecting the downstream receiving waters from the trapped pollutants. Traps can be small, such as a screen over an inlet pit, or very large when it straddles a channel. GPT are designed using one or a combination of the following techniques:

- Screening
- Stilling or stopping the flow of water
- Flow separation
- Sedimentation
- Flotation

Shown in Figure 2.6 is an example of a GPT of the type considered herein. GPT which store trapped items in a dry state are generally cheaper to operate, because the collected material can be delivered to local landfill facilities without issue (Hunter, 1999). GPT that are collect pollutants in wet sump are more expensive to operate as it requires vacuum cleaning and the wet wastes are classified as toxic liquids (Hunter, 1999). There is also the risk of further pollution occurring if the trap is cleaned infrequently; biochemical reactions take place between pollutants in the store area and the by-products can be washed into the waterway, especially in overflow conditions. Based on the path way of operating systems, five types of GPT are commonly used in Australia such as side entry pit trap (SEPT), litter control device (LCD), continuous deflective separation (CDS), floating debris trap (FDT) and trash rack (Allison et al., 1997). This study is concerned with the GPT in continuous defective separation system.

2.5.2 Continuous Deflective Separation (CDS)

The CDS GPT is a cylindrical underground structure that retains gross pollutant (i.e. sediments, floatable and settleable trash and debris over a wide range of flow conditions) from stormwater with a non-mechanical and non-blocking screening technique. A CDS device can also provide the essential pre-treatment as the initial step in a treatment train by using ultra-fine filtration and/or adsorption/absorption for removal of very small particulates, dissolved pollutants and oil/water separators. It uses a combination of a balanced hydraulic design, the deflective characteristics of fine perforated screens and the natural energy in the flowing water for separation of solid particles. Storm water from the storm drainage system is diverted to a separation chamber adjacent to the drain. Storm water passes through this chamber and gross pollutants are retained into the sump. A CDS device can be designed to treat flow ranges from 0.0283 m^3 s^{-1} to 8.5 m^3 s^{-1} and higher (Payton, 2002). CDS capacity flow passes through the unit and the excess flow spills over the diversion weir to downstream. CDS unit is effective to remove 100% of the trash, debris and particulates in storm water larger than the minimum screen aperture size (USEPA, 1999). A typical example of CDS is shown in Figure 2.6.

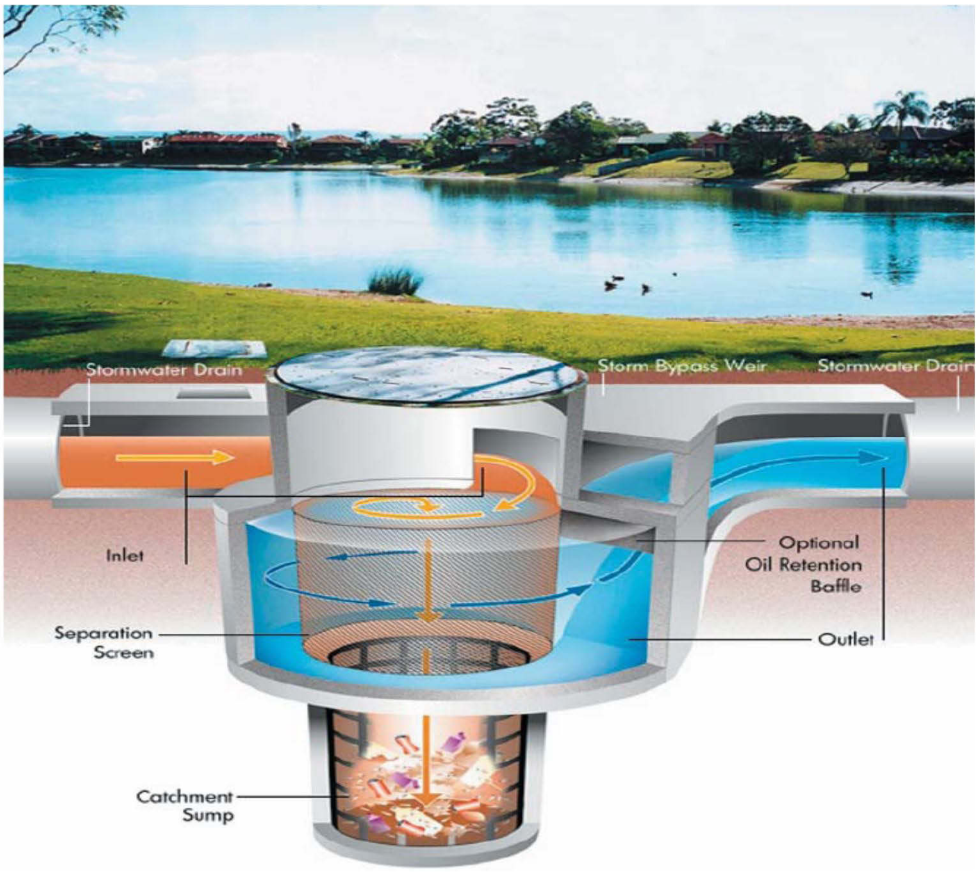

Figure 2.6 Continuous deflective separation technologies (CDS Technologies, 2007)

2.5.3 Impacts of GPT on receiving water quality

It has been suggested that GPTs using a wet sump to store gross pollutants have an adverse effect on downstream water quality. In many GPTs the trapped pollutants are held within a wet sump until their removal. The trapped pollutants may be classified as litter, debris and sediments of which 80% is organic in nature and primarily leaf litter (Ball, 2002). Before removal, this leaf litter may decay and hence has the potential to release both phosphorus and nitrogen into the water column; this phosphorus and nitrogen may then be flushed downstream by subsequent storm events. Also it was reported that leaching of contaminants such as heavy metals, petroleum hydrocarbons, nutrients and herbicides is taking place within GPT's (Ball et al., 2000). Other studies found that the pollutant load accumulated under a body of water (as occurs within a GPT) and in conditions of no light, little or no flow, reduced oxygen, and low pH a toxic pollutant load will leach toxicants into the surrounding waters (Abel, 1989). Qiu et al. (2002) reported that litter fall in areas fringing wetlands leached an average of 30% total P in 24 h. This suggests that significant amount of phosphorus may release from leaf litter when stored in wet sump. Therefore it is required frequent cleaning of wet sump GPT to reduce pollution and it is involved high costs.

There are field monitoring procedures for GPT cleaning in Australia that are well documented (IEAust., 2006). However, there is a lack of data about the pollutant release that might escape to receiving water, during interval of cleaning procedures. These processes are also influenced by frequency and intensity of storm events, land use within the catchment (Hall and Anderson, 1986) and design and maintenance of the GPT (Allison et al., 1998). Laboratory modelling data considered to be effective to quantify escaped pollutants and will help to make proper maintenance schedule which reduce costs as well as control the pollution.

Previous studies have found that when leaf litter was incubated at 20^{o}C under anaerobic condition the breakdown of organic material will occur, the organic acid was the predominant organic product formed together with other organic (alcohols, phenolic compounds) and inorganic (H_2, and CO_2) (Kusel and Drake, 1996). As a result of the depletion of dissolved oxygen and the formation of acidic conditions the pH decreases.

The reduction of dissolved oxygen increases the bioavailability of the phosphorus and nitrogen (Ball and Powell, 2006). In a storm event leached pollutants (i.e. total phosphorus) are likely to be flushed into receiving waters in unstable and bioavailable forms. This bioavailable phosphorus is easier for algae to take up and hence has the potential to lead to blooms. A significant increase in the productivity of blooms in a number of Australian rivers, estuaries and lakes has been the result of excessive inputs of nitrogen and phosphorus in the water bodies (Congdon, 1986; Schofield and Birch, 1986; Anon, 1987; Lukatelich et al., 1987; Bergman et al., 1988). Thus, attempts to limit algal bloom productivity have focussed on controlling nutrients and particularly phosphorus (Hartley et al., 1984).

Rate of leaching is rapid when leaves are flooded in water (Day, 1983). There is little information in the literature on the nutrient release rate of leaf litter leaching from GPT into water. To control water quality pollution, this study focuses on leaf litter as a source of stormwater pollutants and their release in a GPT environment.

2.5.4 GPT modelling

In order to control receiving water quality, structural measures is provided in the waterways. Information relevant to the response of this measure is needed to manage the quantity and quality of stormwater. This information may be obtained by, a) through monitoring of the system for stormwater quantity and quality; and b) by mathematical simulation of the system, or systems through catchment modelling systems (Ball and Luk, 1998). But high cost is associated with the collection, and analysis of stormwater quality sampling data. Also, it is time consuming and laborious. Using models capable of predicting nutrients may solve these difficulties. To design stormwater pollutant control system and take management decision to meet national legislative requirements, predictive stormwater model can be very useful to quantify the behaviour of environmental systems.

The importance of nutrient transport models is increased over recent years. Gerard-Marchant et al. (2005) studied P loss from manure during rainfall. They used two kinetic models (first-order and second-order kinetic) model to predict P release from manure. They also used Elovich and power function model to predict P loss from soils.

Several studies have attempted to quantify catchment nutrient export from different sources. Most of the research concerned about removal of pollutant in GPT, but few data is available of GPT as the source of pollutant release particularly phosphorus from leaf litter. Therefore it is required to quantify phosphorus release from leaf litter stored in GPT and flushed downstream during storm events. In this study, SWMM model is used to simulate water quality such as total phosphorus, since it is required to develop the basic conceptual model of phosphorus release from GPT before evaluating simulation output.

2.6 Summary

The discussion included the previous works on hydrologic and water quality impacts due to urbanisation and approaches of stormwater quality and quantity modelling. Increase of impervious surfaces reduces the infiltration and that leads to increase in runoff volume, runoff peak flow and a reduced time to peak flow. The major pollutants found in stormwater runoff are solids, oil and grease, heavy metals, organic micro pollutants, nutrients and pathogens. This pollutant is transported from urban catchment areas and plays an important role for the degradation of receiving water. Various sources specially, leaf litter resulting from urbanisation introduces pollutants such as phosphorus and nitrogen by urban runoff into the receiving waters and degraded the receiving water qualities. Literature review indicated that the transportation of pollutant influenced by the rainfall intensity and duration of rainfall and runoff volume and rate. Understanding of pollutant characteristics and their transportation are important in order to relate to the target pollutants and the approaches required for water quality improvement. Many researchers evaluated the stormwater treatment devices for the removal of pollutants from stormwater runoff and modelling. This study uses mathematical and catchment model to investigate the outlet phosphorus concentration of GPT with respect to catchment runoff. Review of literature showed that GPT is used to control of pollutant larger than 5 mm before discharge into the receiving water. Leaf litter trapped in GPT during stormwater runoff. If these devices are not managed properly, degradation occurs and falls into the water environment during storm event. In this context, developing a model on the basis of urban storm water quality and quantity is required to control stormwater pollutant. This information is necessary for cost effective water quality management.

CHAPTER 3

Description of the Study Area

3 Description of the Study Area

3.1 Introduction

A number of ponds exist within the Centennial Park. The need for management of water quality issues (e.g. eutrophication within the Centennial Park ponds) is becoming increasingly important as the population grows within the catchment. The Gross Pollutant Trap (GPT) was installed in the drainage system before its discharge into these ponds for the restoration of water quality. To evaluate the impact of GPT, the Centennial Park catchment was chosen as the test catchment for this research. The area of the Centennial Park Catchment is 1.27 km^2 which would be considered a small catchment but is a typical size of many urban catchments.

This chapter also describes the important physical characteristics of the catchment including location, topography, geology, vegetation, ponds, land uses, drainage system and meteorological information.

3.2 Location

The Centennial Park catchment is located at the eastern suburbs of Sydney, Australia, less than 5 km from Sydney's Central Business District (CBD) (Figure 3.1). It covers the western side of Randwick City Council and the eastern side of Waverly City Council.

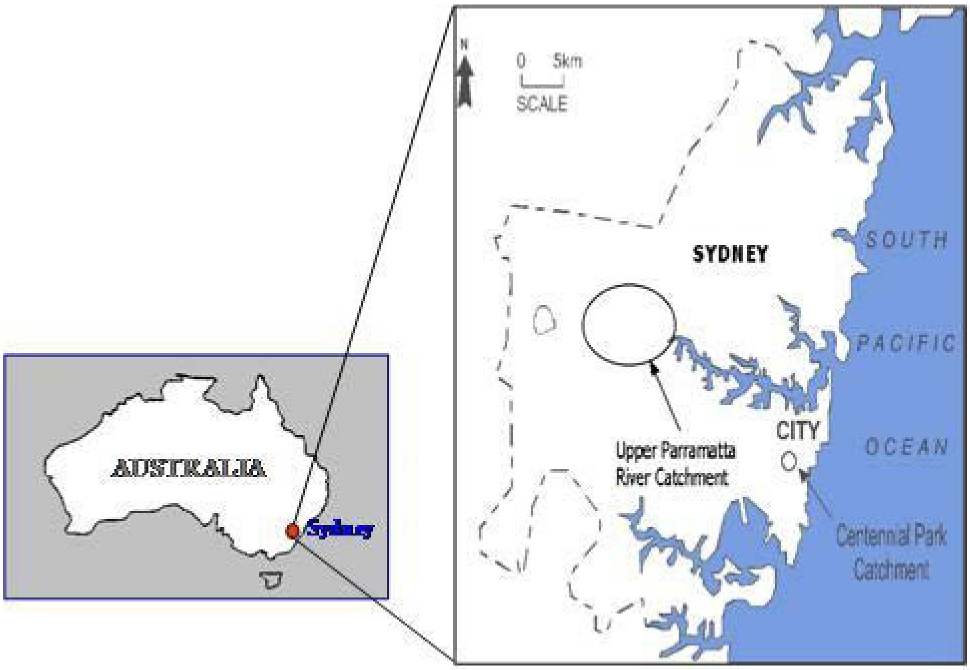

Figure 3.1 Location of Centennial Park catchment

3.3 Catchment details

3.3.1 Introduction

A description of the physical and hydrological environment of the Centennial Park catchment is presented herein. This description includes details about the topography, geology, land use, drainage systems and vegetation within the catchment. Additionally, the hydrometeorological information available is presented.

3.3.2 Topography

The topography of the Centennial Park catchment has a non-uniform gradient. The elevation of the north eastern and eastern side is higher than the north-west and west side of the catchment. The average slope of the catchment is about 5% with elevation ranging from 98 m to 43.2 m Australian Height Datum (AHD) at the catchment outlet located at the gauging station. The maximum slope is 12.4% and the minimum slope is 0.49% with the steepest slope is adjacent to Carrington Road and Queen’s Park. Figure 3.2 shows the topographic map of the catchment.

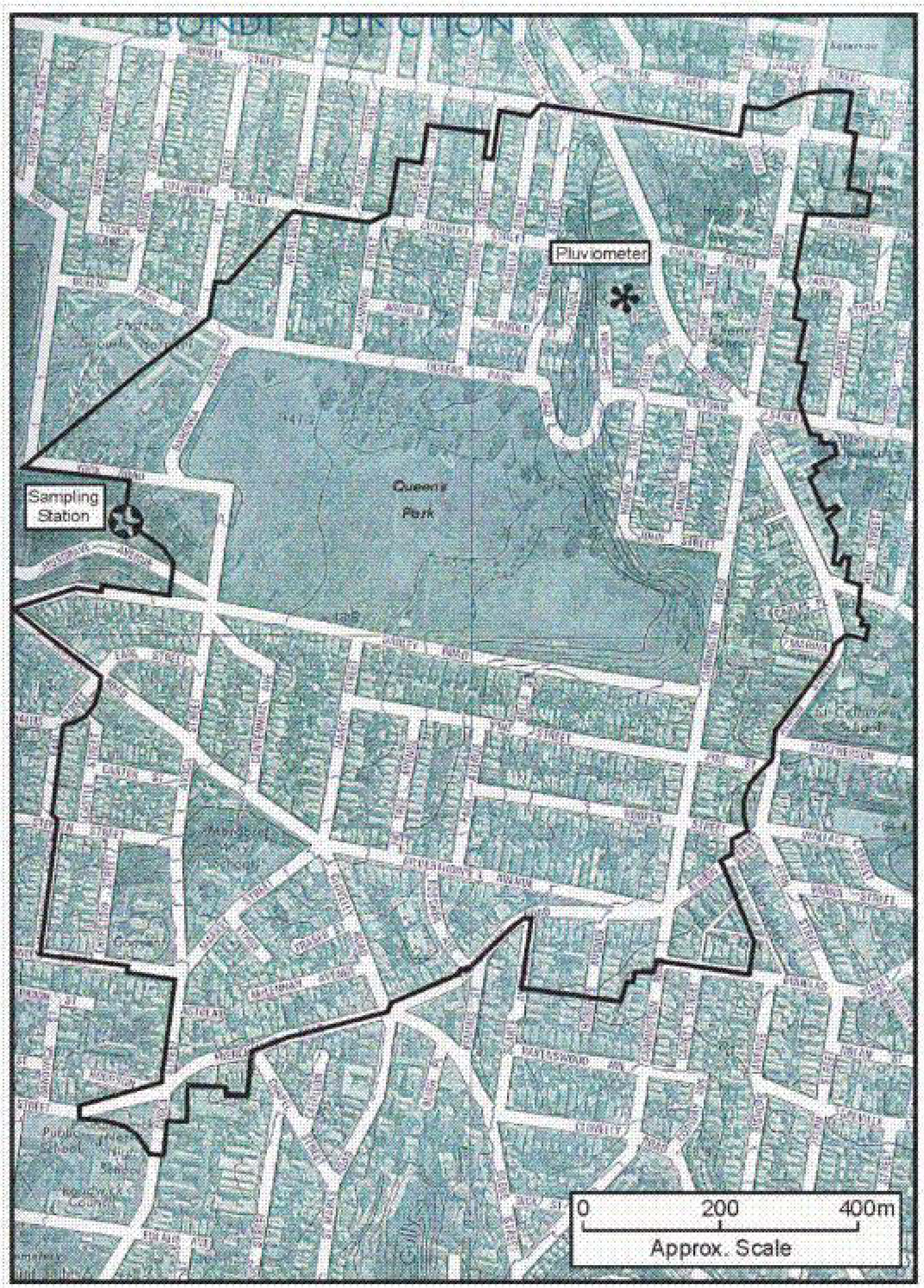

Figure 3.2 Topographic map of the Centennial Park catchment

3.3.3 Geology

The study site is located along the northern region of Botany Basin (Figure 3.3) which was formed as a sequence of sedimentary deposits in the Triassic period. The geology of this area mainly represented by Botany sands overlying the old Triassic sedimentary bedrock (Hawkesbury Sandstone and the Wianamatta Group) (Abustan, 1997). Hawkesbury Sandstone group is composed of highly lenticular beds of quartz rich sandstone while Wianamatta group is a sequence of interbedded grey shales and lithic sandstones. The type of the soil was mostly found to be Hammondville soil (85 %) and Moore soil (15 %) in the botany sand (Fang and Ball, 2007). Other studies were reported that sandy soil has large field capacities and slow drainage (Liden and Harlin, 2000).

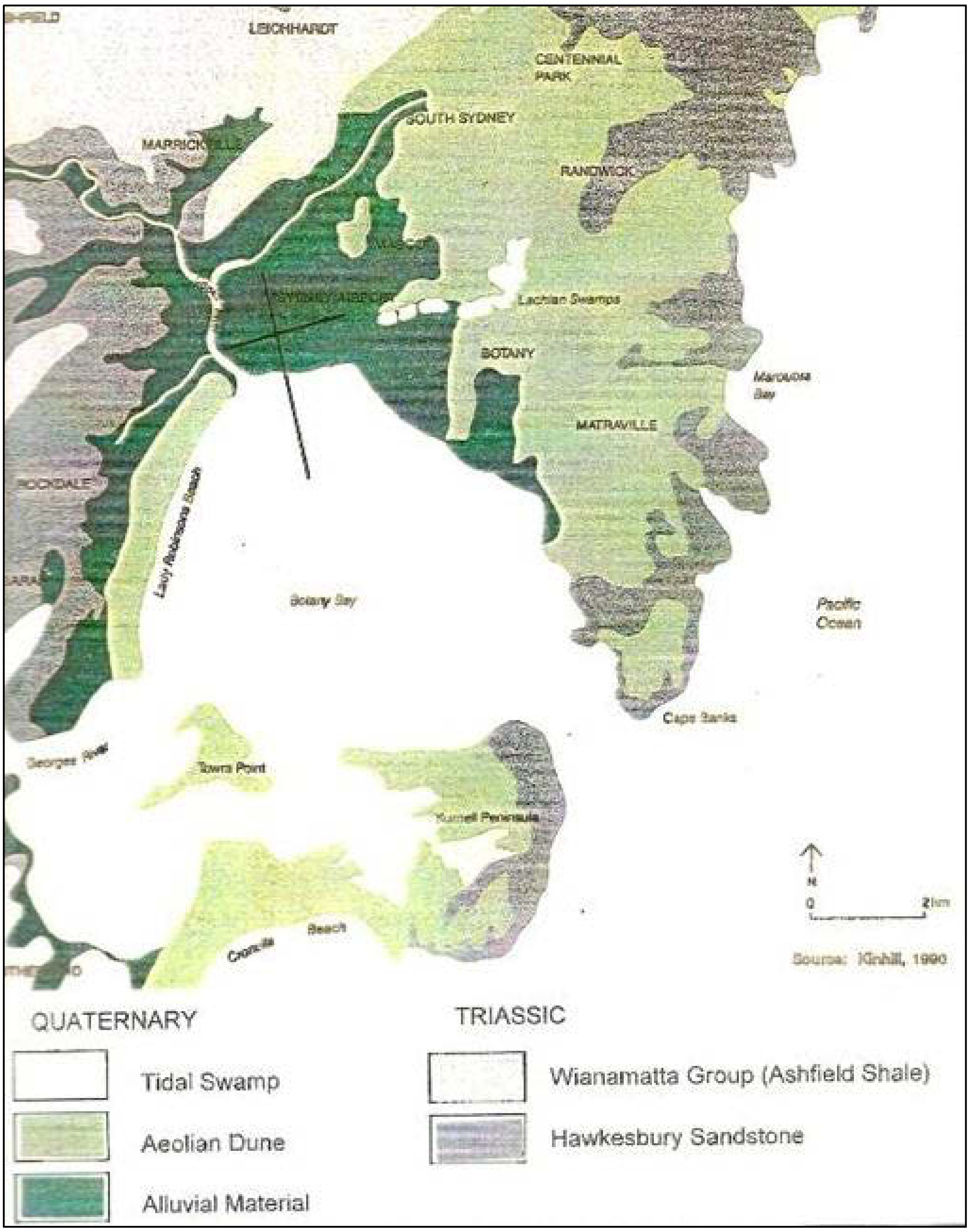

Figure 3.3 Geological map of Botany Basin, Sydney

3.3.4 Vegetation

The vegetation within the catchment is a part of a larger ecological system of plant communities belonging to the Botany sands topography and that of the Hawkesbury sandstone ridges and slopes (PWD, 1990). The natural landscape of the catchment has been changed with a cultural one since 19th century. The latter half of the 19th century, the common lands transform into three public parks such as Centennial Park, Moore Park and Queen's Park. In late 19th century landscape provide useful shade, ornamental gardens and minimal use of shrubs to maintain more space. Currently, the catchment park lands have more than 15000 individual trees including 115 different species e.g. Australian Figs, evergreen oaks, exotic pines, eucalypts and paperbarks. There are 13 species of Fig with the Port Jackson Fig is dominate in the Parklands. Other dominant plant species are Australian Teak, Blueberry Ash, Broad-leaved Paperbark, Dragons Blood tree, Algerian Oak and Sweet Wattle. Port Jackson Fig can be found at Grand Drive and Randwick Gates near Gross Pollutant Trap. These plant species are found throughout the catchment area and therefore were considered to be representative. Hence Port Jackson Fig, Broad-leaved Paperbark and Algerian Oak leaves were used for this study.

3.3.5 Ponds

A number of ponds exists within the catchment and provide a vital role in the management of stormwater runoff. The ponds have a significant ecological value in an urban environment and a flood mitigation resource, receiving and treating stormwater and runoff from the surrounding catchment area. For example, Musgrave pond is located on the eastern side of Centennial Park catchment, Sydney near York road gates (Figure 3.4). Wet period stormwater flows directly to the Centennial Park Ponds system. It enters into the Musgrave pond.

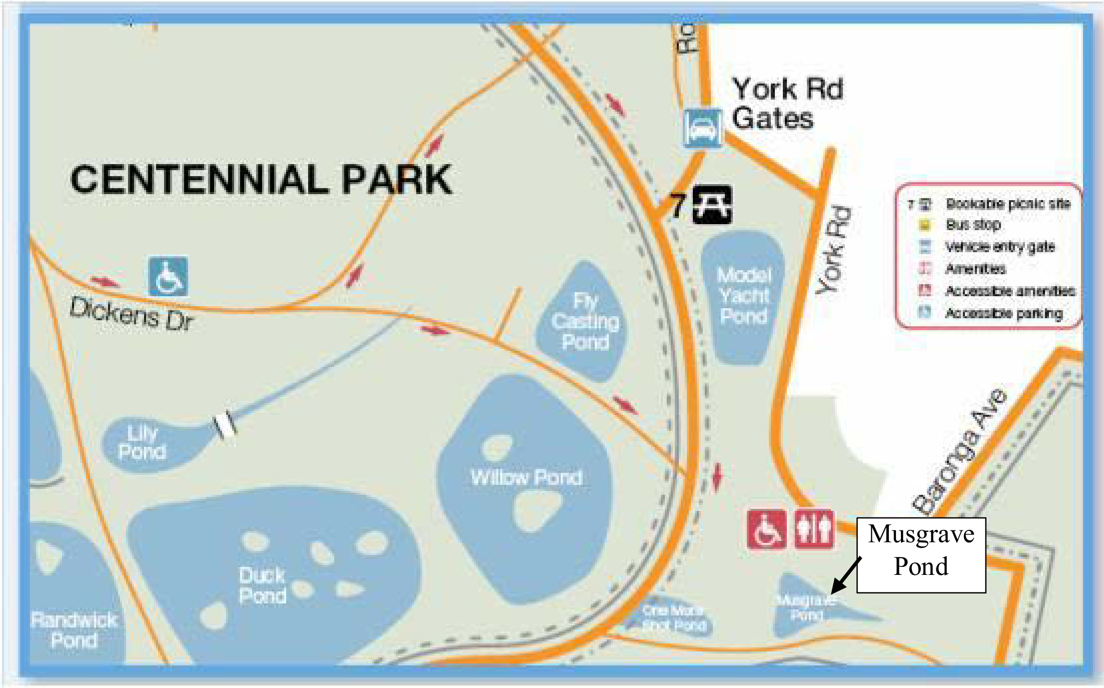

Figure 3.4 Centennial Park pond systems

3.3.6 Land uses

The catchment is occupied by variety of uses, dominated by highly urbanised residential areas include road surfaces, light commercial outlets, public buildings, residential buildings and open spaces. The total catchment area is about 1.27 km^2 and the breakdown of the catchment land use as a percentage of total catchment is shown in Table 3.1.

Table 3.1 Land use within the Centennial Park catchment (Modified from Choi and Ball, 2002)

Land use types	Percentage of catchment area	Area covered (ha)
Residential Buildings	40.1	50.93
Public Buildings (school, hospital and church)	12.4	15.75
Commercial/Industrial Buildings	2.7	3.43
Open Spaces (park and natural catchment)	21.6	27.43
Roads and streets	23.2	29.46

A total 40.1% (50.93 ha) of the catchment area is occupied by residential buildings including 30% (38.1 ha) of semi-detached houses and single houses while 12.4% (15.75 ha) of catchment area is covered by public buildings (i.e. school, hospital, church etc.) and 2.7 % (3.43 ha) commercial/industrial buildings. The road and streets occupies 23.2% (29.46 ha) area of the catchment with 14.9 km arterial road and 3.6 km small lanes and footpath. The open spaces consists of 21.6% (27.43 ha) area located at the downstream outlet of the catchment (e.g. Centennial Park, Queen's Park) is used for picnics, sports and recreational purpose.

The study catchment area in details of existing zoning plan is shown in Figure 3.5.

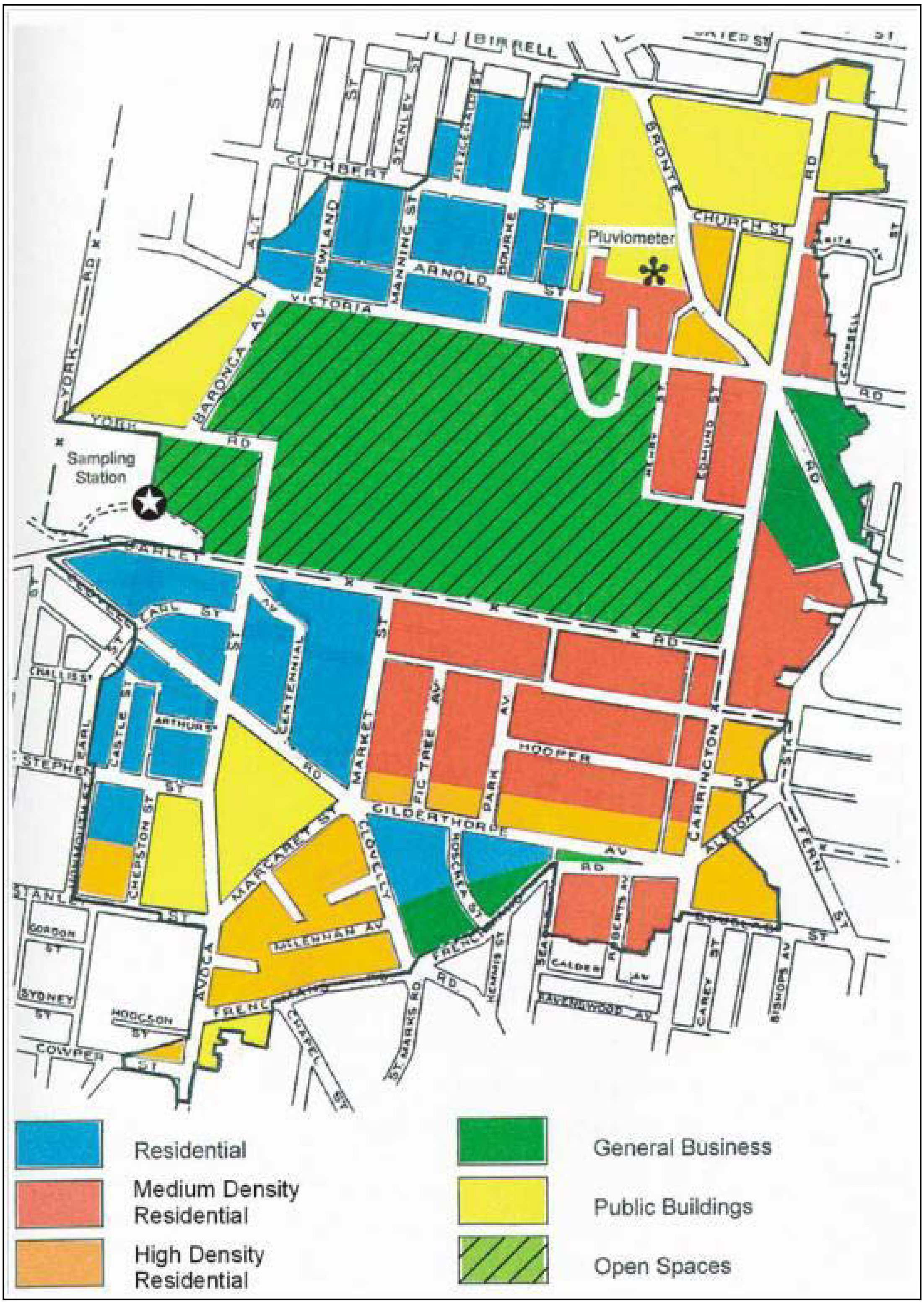

Figure 3.5 Land use zoning in Centennial Park catchment

As shown in Figure 3.5, the most common land use in the catchment is low density residential buildings. Within the last decades there has been an increase of medium to high density residential buildings. General business activities are centred at the corner of Bronte Rd and Carrington Rd and along the French Rd. Public buildings are mainly located along the Bronte Rd and York Rd. The middle portion of the catchment is occupied by open space.

3.3.7 Drainage system

The catchment is drained by separate sanitary sewer and stormwater drainage systems. The stormwater drainage system from the upstream of the catchment to the location of the gauging station at the Musgrave Avenue pond consists of series of pipes, box culverts and 5.2 km open channels. A Gross pollutant trap (e.g. continuous defective separation, CDS) was installed at stormwater outlet close to Musgrave pond which acts as a filter to catch and remove the stormwater debris (such as leaves) greater than 5 mm in diameter to prevent it polluting the pond. The diameter of the circular pipe system is 914 mm and the maximum dimension of the box system is 1.52 m×1.17 m. Smaller diameter (<900 mm) pipes are operated by Randwick city Council and Waverely Council while larger diameter (>900 mm) pipes are operated by Sydney Water. Catchment drainage system has a trapezoidal section with a "V notch" to maintain minimum flow with open channel at the outlet of the catchment before connecting to the Musgrave pond. The stormwater from the Centennial Park pond system transports through a surface drainage system into Lachlan Swamp and then discharge to the Botany Bay. Table 3.2 shows details of the main drainage system (Abustan, 1997).

Table 3.2 Main drainage system in Centennial Park catchment (Abustan, 1997)

Section	Length (m)	Dimension (m)	Description	Slope
A – B	158.3	4.31×1.41	Trapezoidal Channel	1 in 287
B – C	25.1	1.45×1.22	Box Culvert	1 in 113
C – D	192.7	1.52×1.17	Box	1 in 110
D – E	234.6	1.22×1.14	Box	1 in 72
E – F	70.2	1.22×0.914	Box	1 in 72
F – G	88.7	0.914×0.914	Box	1 in 43
G – H	144.1	0.914 Ø	Circular Pipe	1 in 35
D – D_1	237.7	0.914 Ø	Circular Pipe	1 in 125
E – E_2	61.0	1.37×1.07	Box	1 in 120
E_2 – E_3	91.4	1.22×0.914	Box	1 in 55
E_3 – E_4	61.0	0.991×0.914	Box	1 in 30

The main drainage system map of the Centennial Park catchment is shown in Figure 3.6.

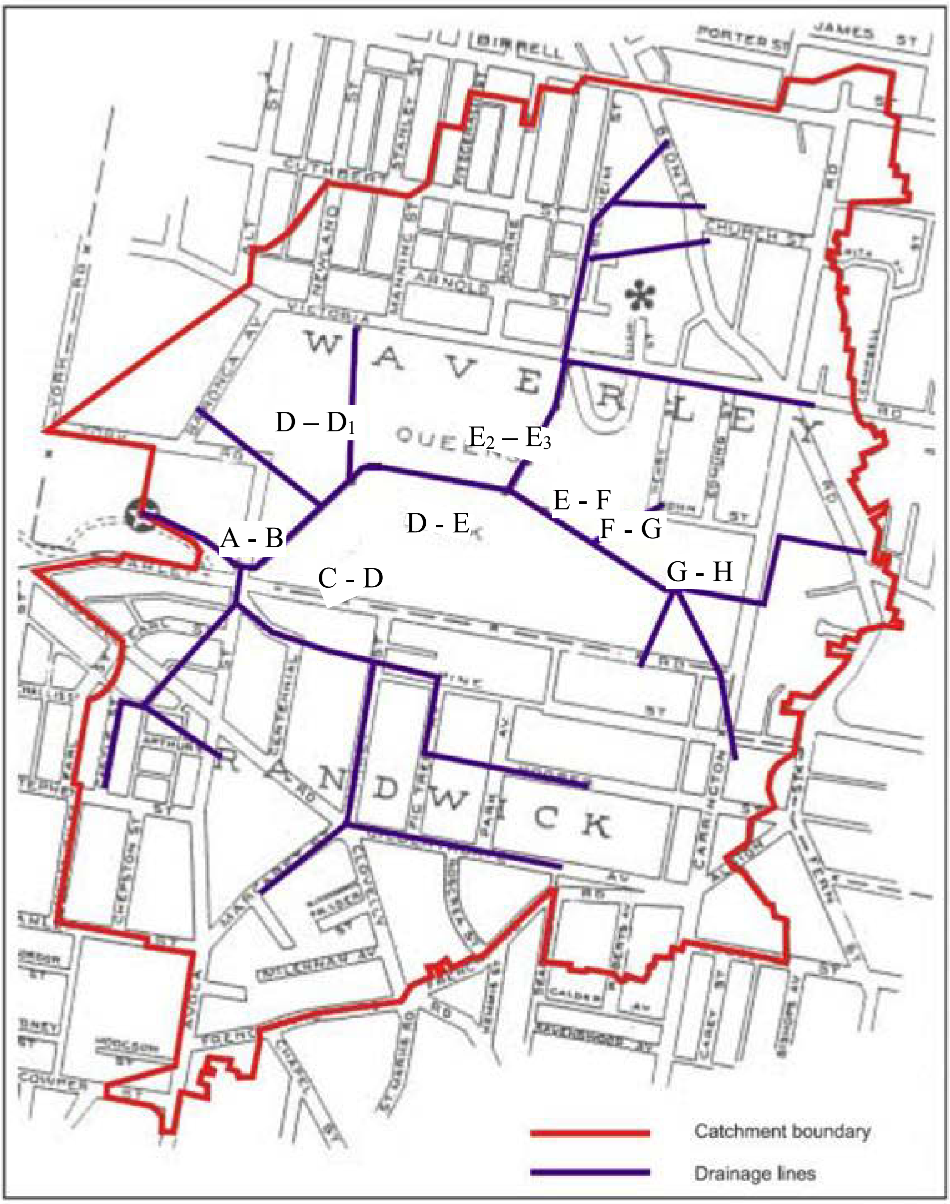

Figure 3.6 Stormwater drainage systems in Centennial Park catchment

Three authorities are responsible for the management of stormwater drainage system within the Centennial Park catchment are:

1. Sydney Water Corporation: responsible for the management of open channels and pipe larger than 900 mm diameter.
2. Randwick City Council: responsible for the management for the pipe less than 900 mm diameter within Randwick City Council.

3. Waverly City Council: responsible for the management for the pipe less than 900 mm diameter within Waverly City Council.

3.3.8 GPT

The Centennial Park Pond system is located downstream of the study catchment. Stormwater flowing from the study catchment enters the Musgrave Avenue Pond by a large stormwater channel. To restore water quality in the ponds system, a CDS Gross Pollutant Trap was installed upstream of Musgrave Pond. Shown in Figure 3.7 is a cross-sectional view of the device. It operates like a giant sieve and remove any solid rubbish greaer than 5 mm in diameter. This rubbish is stored in the sump until it is removed by cleaning. Furthermore, this rubbish is inundated as the sump is below the water surface in the connected channel and pond.

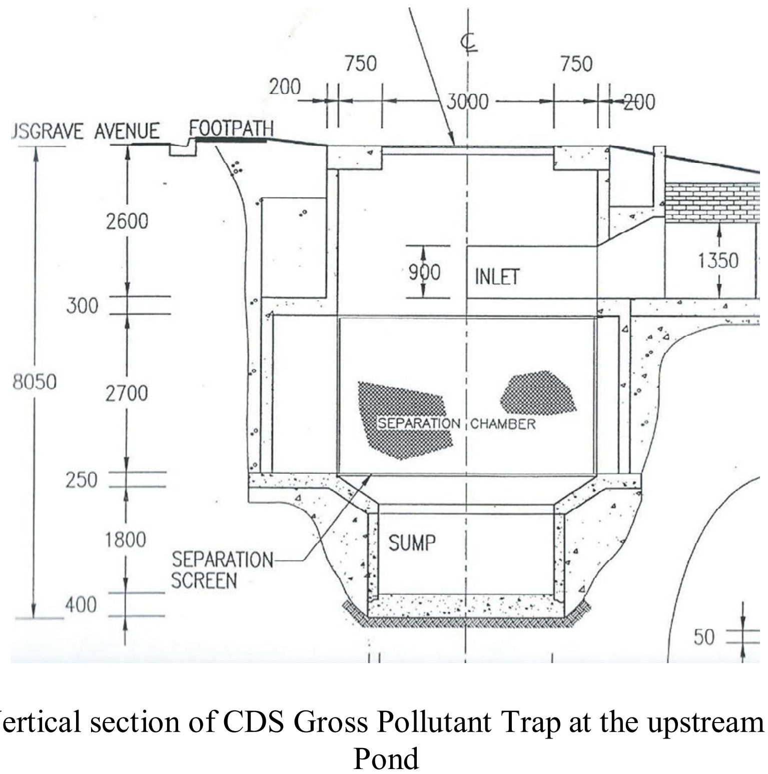

Figure 3.7 Vertical section of CDS Gross Pollutant Trap at the upstream of Musgrave Pond

3.4 Meteorological information

The catchment is under temperate climate with four seasonal variations in rainfall such as Spring (September to November), Summer (December to February), Autumn (March to May) and wet mild Winter (June to August). The distribution of rainfall comprises 24, 31, 26 and 19% for Summer, Autumn, Winter and Spring, respectively, of the annual mean rainfall (1858 to 2013 data). From 154 year (1859 to 2013) data, it was observed that the minimum mean monthly temperature (7.7^{o}C) occurs in July while the maximum mean monthly temperature (25.9^{o}C) found in January.

3.4.1 Precipitation data

A hyetograph (a plot of rainfall depth/intensity versus time) data is required for catchment simulation. Hyetograph data from single or multiple gauges available in the catchment can be used for the simulation. For the study catchment long term rainfall records around the catchment and a few years flow data at the catchment outlet are available.

Initially, precipitation data of this catchment is recorded by six rain gauge station located within a 10 km radius from study site operated by different authorities (Table 3.3, Figure 3.8). The oldest gauge at Paddington has been operated by Sydney Water since 1956 to date and Bureau of Meteorology operates Kingsford-Smith Airport gauge from 1960 to date. University of New South Wales has been maintained the gauge at Avoca Street and Storey Street, from 1977 to 2004. It is desirable to have pluviometer for small catchment located close to the centroid and a network of pluviometer station over the catchment larger than 5 km^2 (Weeks, 1982). Also, during storm events, spatial variation of rainfall is common within larger catchment (Ball and Luk, 1998). Considering these issues

University of New South Wales installed and operated two more gauge at Waverly Public School and Musgrave Avenue Stormwater Channel from 1994 to 2002 within the catchment boundaries (Figure 3.8) to get better spatial rainfall pattern. A HydroMace 2000 data logger, Ultrasonic Level Sensor and Gamet Automatic grab sampler was also installed at Musgrave Avenue stormwater channel to collect rainfall data. More details about the installation, operation and data collection system of these two gauging stations are discussed elsewhere (Abustan, 1997). Figure 3.9 shows the mean monthly rainfall of the catchment based on data collected at Waverly Public School gauging station from January 1995 to January 2001. During this period, maximum daily rainfall and mean annual rainfall of the catchment were 211 mm d^{-1} and 1265 mm respectively.

Table 3.3 Rain gauging stations and the operation authorities in Centennial Park catchment

Station No.	Station Name	Operation Authority	Operation Time
566032	Paddington	Sydney Water	1956 to date
566002	Avoca Street	UNSW	Feb, 1977 to 2004
566006	Storey Street	UNSW	Feb, 1977 to 2004
66037	Kingsford-Smith Airport	Bureau of Meteorology	1960 to date
566010	Waverley Public School	UNSW	Oct, 1994 to May, 2002
2132238	Musgrave Avenue	UNSW	Dec,1996 to May, 2002

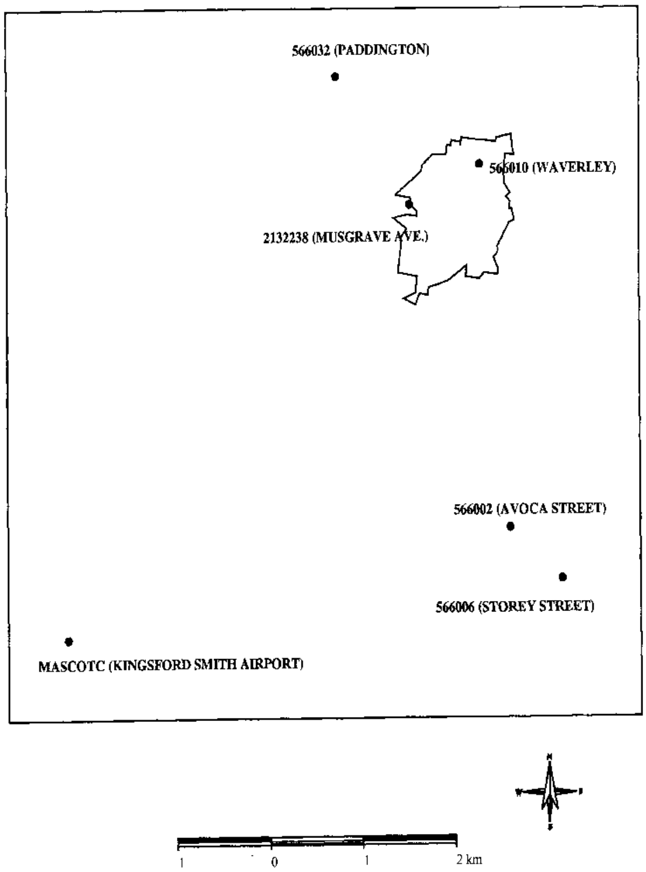

Figure 3.8 Location of rain gauges in Centennial Park catchment (Umakhanthan and Ball, 2005)

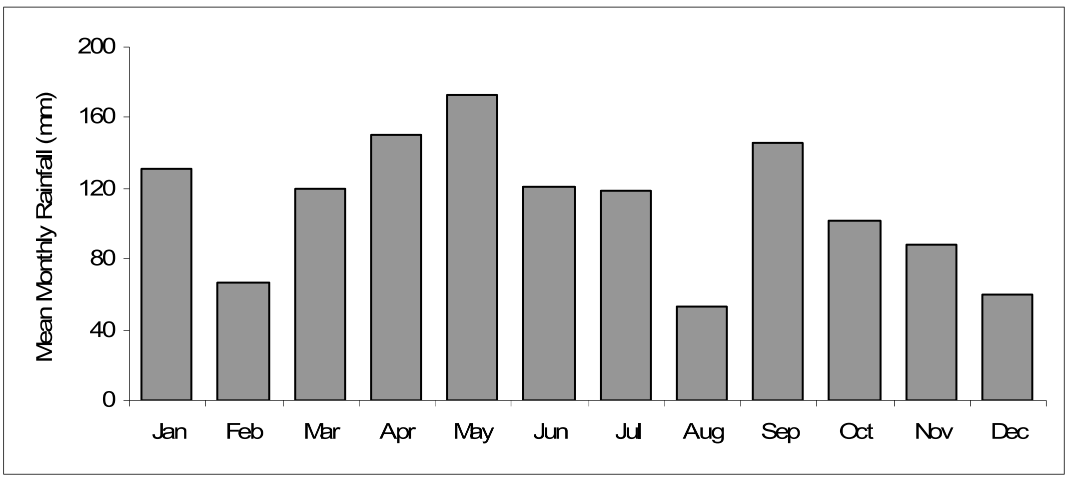

Figure 3.9 Mean monthly rainfalls in Centennial Park catchment (Jan 1995 to Jan 2001)

3.4.2 Inter-Event dry period

The rainfall or runoff can be represent as a uniform, rectangular hydrograph, characterised by its duration, volume, average flow rate or intensity and the time elapsed since the last event (inter-event time) (USEPA, 1989). Rainfall parameters for a specific site can be calculated from historical records. A minimum inter-event time is the duration that are separated by storm events. The rainfall values separated by less than this duration are considered part of the same storm event. The rainfall values separated by times greater than or equal to this duration are considered to be independent. Several methods are used to determine this duration (Heaney et al., 1977). In general it is assumed that the inter-event times are exponentially distributed (Restrepo-Posada and Eagleson, 1982). An exponential distribution is a special case of the gamma distribution (USEPA, 1989).

Rainfall data of Sydney Observatory Hills from 1859 to 2002 was collected and investigated for frequency of inter- event dry periods which is presented in Figure 3.10. The range of dry day duration found from one day to hundred and one day in which one day dry period has the largest frequency. The dry day duration of 50 days and over has very less frequency (1–5). Frequency is decreased as the duration of dry days increase.

In this studies, Gamma distribution is used to represent inter-event dry periods. The probability function of the gamma distribution is given by equation 3.1

$$f(x) = \frac{\left(\frac{x}{\beta}\right)^{\alpha-1} \exp\left[-\frac{x}{\beta}\right]}{\beta\Gamma(\alpha)}, \quad x, \alpha, \beta > 0 \qquad (3.1)$$

where α and β are called shape parameter and scale parameter respectively

Method of moments was used to estimate the parameters α and β. Parameters α, β and the Gamma probability density function (PDF) (Figure 3.11) were calculated using the statistical software known as S–Plus/R.

Chi-square goodness of fit test were used to compare the observed data with expected data. It was found that the observed frequency was a poor fit to the corresponding expected frequencies, which leads to a high value of chi-square (23.65). Hence it was concluded that a gamma distribution does not adequately describe the likelihood of inter-event dry periods.

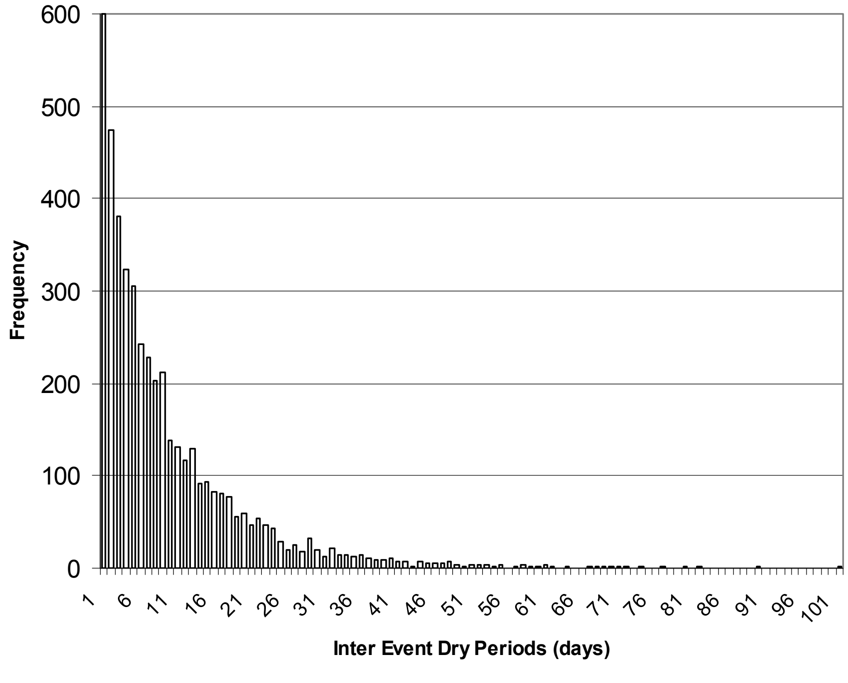

Figure 3.10 Frequency of inter-event dry periods observed in 1859–2002 rainfall data

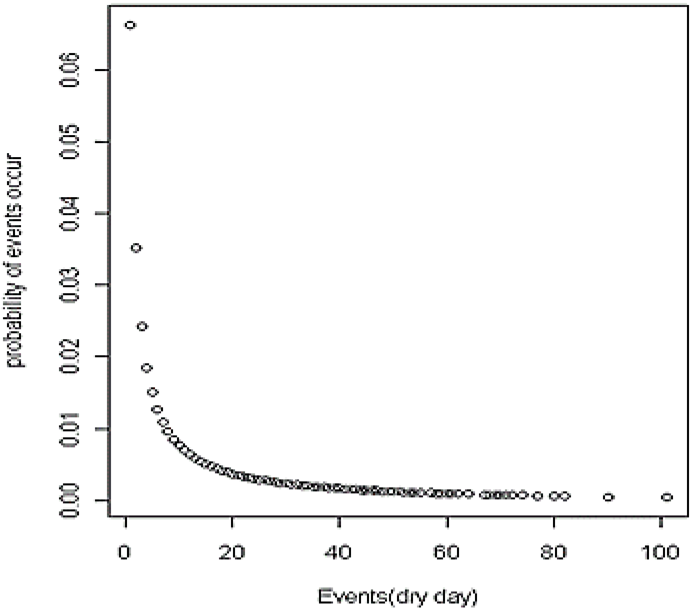

Figure 3.11 Probability density function of inter-event dry period

3.4.3 Evaporation data

No evaporation data was available within the study catchment. Hence, the required data was based on long term weather records in Sydney sourced from the Bureau of Meteorology. However, it should be noted that the evaporation rate is not sensitive data for single event simulation by SWMM (Huber and Dickinson, 1988).

3.5 Flow data

An ultrasonic probe was used to monitor the water levels of the Musgrave Avenue Stormwater channel. The water level was then converted to flow by using a rating curve.

Rating curve

For conversion of the recorded depth to a flow, a rating curve is needed. For this catchment, rating curves have been developed by the Water Board and Tilly et al. (1999) were available. A third rating curve based on Manning's equation was also available. From a comparison of these three rating curves, the rating curve developed by Tilly et al. (1999) was considered to be most reliable. Therefore, the Tilly et al. (1999) rating curve used for this study. Shown in Figure 3.12 is the adapted rating curve. For clarity purposes, the other two rating curves are not shown in this Figure.

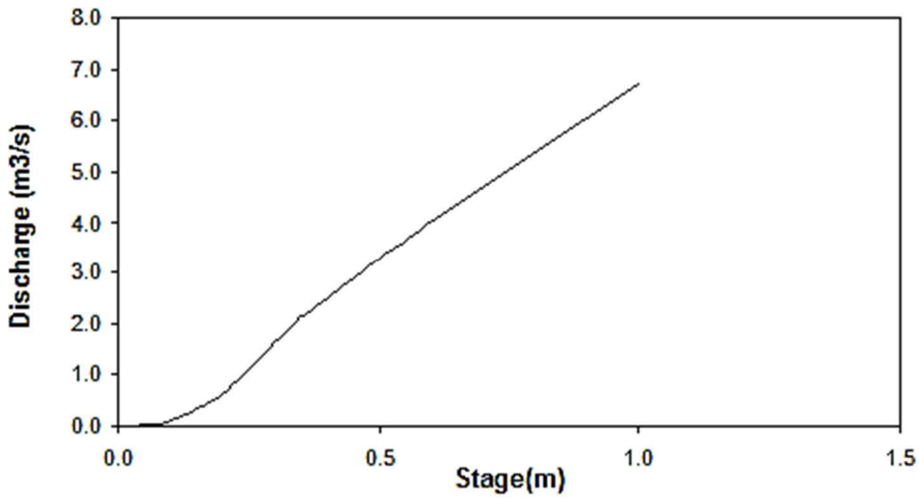

Figure 3.12 Musgrave Avenue stormwater channel rating curve

3.6 Summary

This chapter has described the physical characteristics of the study catchment, since these characteristics influence the water quality within the catchment. By presenting these characteristics subsequent researchers can assess the similarities of their catchments to that used in this study. Key points regarding the catchment characteristics follow a total 78.4% of the catchment area was impervious area with 21.6% pervious area. Impervious area mainly consisted of various types of buildings and roads while pervious area mainly open space. There are many trees found in this site and fallen leaves were collected for laboratory analysis. A number of ponds are exists within the catchment including the Musgrave pond. A GPT is installed in the upstream of Musgrave pond and was selected for detailed investigations as the part of this study. Catchment area, topography, precipitation data and inter-event dry period were used to simulate catchment runoff.

CHAPTER 4

Storm Water Management Model

4 Storm Water Management Model

4.1 Introduction

The Storm Water Management Model (SWMM) is a comprehensive hydrological and water quality computer model used for single or continuous event of rainfall in urban areas. It was developed by US Environmental Protection Agency (USEPA). It comprises various blocks such as Runoff, Transport, Extran and Storage/Treatment. The Component of SWMM operates by discretized the area to be modeled into a collection of subcatchments that receive precipitation and generate runoff and pollutant loads (Huber and Dickinson, 1988). In SWMM, a flexible set of hydraulic model used to route runoff and external inflows through a drainage network of pipes, channels, storage and treatment units which can be used to simulate hydrology through natural areas (Huber and Dickinson, 1988).

SWMM is used for urban catchment because of its ability to effectively simulate urban runoff. The SWMM was applied for modelling quantity and loading of TP in Centennial Park catchment. In this study runoff and transportation block was used to predict catchment runoff. Horton equation was used to estimate pervious area infiltration loss.

4.2 SWMM blocks

SWMM is structured in the form of four computational and six service blocks. These blocks are as follows:

Computational blocks: Runoff, Transport, Extran and Storage/Treatment.

Services blocks : Executive, Rain, Temp, Graph, Statistics and Combine

Each block has a specific function. The primary functional characteristics of these blocks are explained in the user's manual by Huber and Dickinson (1988). The model structure of computational blocks and their interrelations is shown in Figure 4.1. In simplest terms the program is constructed in the form of "blocks" are given below:

1. The input sources:

The Runoff Block generates surface and subsurface runoff based on rainfall hyetographs, antecedent conditions, land use and topography.

2. The central cores:

The Runoff, Transport and Extended Transport (Extran) Blocks route flows and pollutants through the drainage system. Very sophisticated hydraulic routing may be performed with Extran.

3. The correctional devices:

The Storage/Treatment Block characterizes the effects of control devices upon flow and quality. Elementary cost computations are also made.

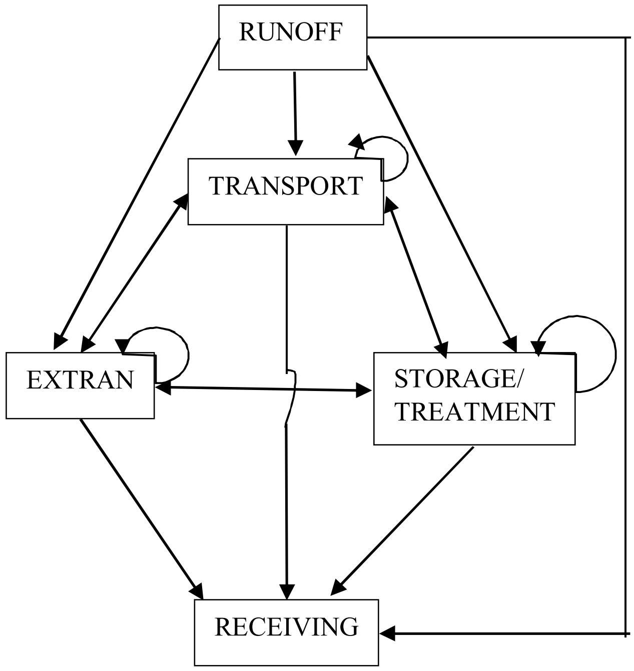

Figure 4.1 Model structure of computational blocks (Huber and Dickinson, 1988)

The six service blocks of SWMM program are as follows:

1. The EXECUTIVE block, which assigns logical unit numbers to off-line files (disk/tape/drum) and determines the block or sequence of blocks to be executed.
2. GRAPH block, which plots hydrographs, pollutographs and other time series output.
3. COMBINE block manipulates multiple interface files in order to aggregate results of multiple previous runs for input subsequent blocks.
4. RAIN block processes long term precipitation data into the Runoff Block for continuous simulation.
5. TEMP block processes long term temperature data input into the Runoff block for snowmelt calculations.
6. STATISTICS block perform statistical analysis of the long term series of hydrographs and pollutographs and identify specific hydrological events.

Figure 4.2 showed an overview of the model structure of the different blocks and their interactions.

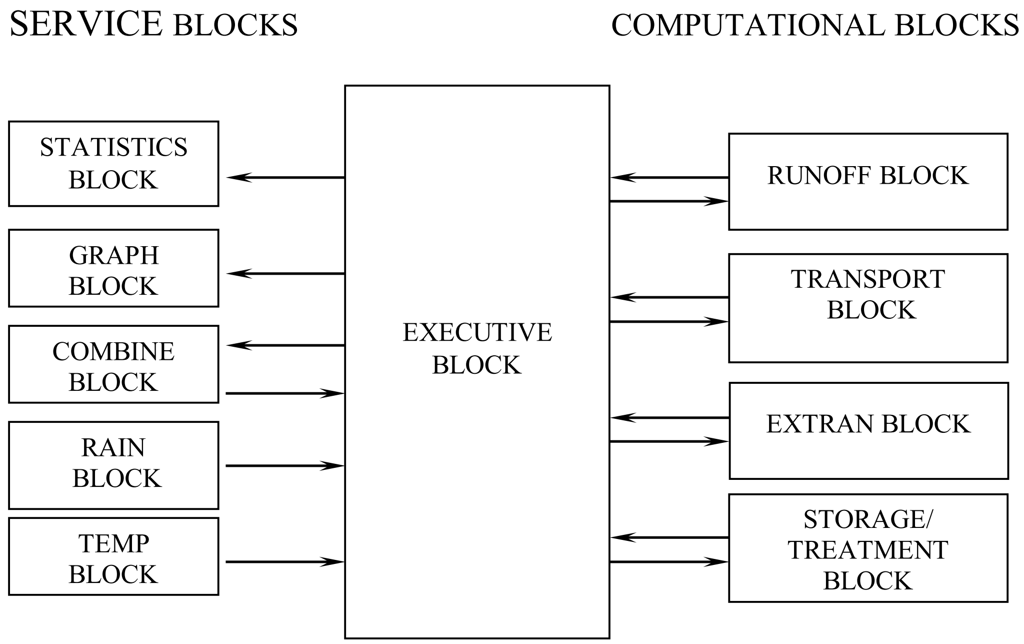

Figure 4.2 Overview of SWMM program structure (Huber and Dickinson, 1988)

The Executive block is the main block of the program and responsible for transferring the data, in the form of interface files between the blocks and external programs. The Runoff block uses input files directly but does not receive input from other computational blocks. For continuous simulation, it may receive meteorological input from Rain and Temp blocks whereas the Transport, Extran and Storage/Treatment blocks receives input from Runoff computational block. In this study, Runoff and Transport blocks are used to simulate quantity of catchment runoff for single event as the input to GPT.

4.3 Water quantity modelling

SWMM are used for runoff quantity modelling. This requires the following main information: Physical catchment characteristics-total catchment area, percentage of impervious area, catchment width, average slope, surface depression storage and surface roughness; rainfall; and infiltration-maximum infiltration rate, ultimate infiltration rate and decay constant. This study focused on water quantity modelling using SWMM to predict catchment runoff and hence simulating the pollutant transport and predicting the stormwater loads. For modelling, the catchment is discretised into subcatchments. Subcatchments are further subdivided into three sub areas to simulate impervious areas with and without depression storage and pervious area with depression storage. Each subcatchment is treated as a nonlinear reservoir with a single inflow (precipitation) (Figure 4.3).

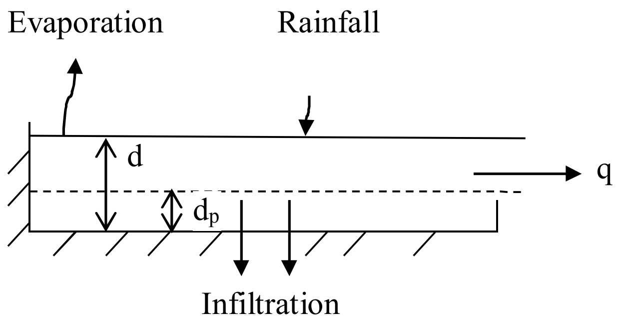

Figure 4.3 Nonlinear reservoir model of a subcatchment (Huber and Dickinson, 1988)

The nonlinear reservoir expression is derived by coupling the continuity equation and Manning's equation. These two equations combine into one non-linear differential equation that produces the non-linear reservoir equation as:

$$\frac{d_2-d_1}{\Delta t} = (i-f) - \frac{W}{A\times n}\left(d-d_p\right)^{\frac{5}{3}} S^{\frac{1}{2}} \tag{4.1}$$

where, d = water depth, d_1 = water depth at the beginning of time step, d_2 = water depth at the end of time step, Δt = time step = $t_2 - t_1$, W = subcatchment width, n = Manning's roughness coefficient, d_p = depth of depression storage, S = subcatchment slope, A = surface area of subcatchment, and i = rainfall intensity, f = evaporation rate/infiltration rate.

The required parameter can be determined from the equation 4.1 at different time interval by means of a finite difference technique. The equation 4.1 can be written as:

$$\frac{d_2-d_1}{\Delta t} = (i-f) - \frac{W\times S^{\frac{1}{2}}}{A\times n}\left[d_1 + \frac{1}{2}(d_2-d_1) - d_p\right]^{\frac{5}{3}} \tag{4.2}$$

Equation 4.2 is then solved for d_2 using a Newton-Raphson iteration. Given d_2, the instantaneous outflow at the end of each time step is computed using the following form of Manning's equation:

$$Q = W \times \frac{1}{n}\left(d-d_p\right)^{\frac{5}{3}} S^{\frac{1}{2}} \tag{4.3}$$

where, Q = outflow rate and W, n, d, d_p and S are previously defined.

4.4 Water quality modelling

In urban catchment, population increases with the increase of building and other facilities and thus changes land use. The quality of catchment runoff and pollutant discharge is increasing concern. To minimise the impact of land use change on the receiving water quality, catchment management strategies are in practised in Australia. A range of best management practices (BMPs) are implemented to mitigate the adverse effects of land use change and achieve required water quality standards in receiving waters. The process to simulate water quality can be described using the following runoff blocks:

Runoff block

The runoff block within the SWMM model can be used to simulate water quality in urban catchment through several mechanisms such as buildup and washoff and rating curve approach. The brief review of these mechanisms are as follows:

Buildup and washoff: In an urban impervious area of a catchment, it is assumed that a supply of pollutants is buildup on the land surface during dry weather period preceding a storm event. Such a buildup may or may not be a function of time and other factors such as street sweeping, land use, traffic flow and dry fall out. After the storm takes place, this material is washed off from the catchment area and accumulated into the drainage system.

Typically pollutant buildup can be computed as a fraction of dust and dirt accumulation. SWMM program provides four options for individual pollutant buildup: (1) Linear (2) Power-Linear (3) exponential and (4) Michaelis-Menton (Figure 4.4).

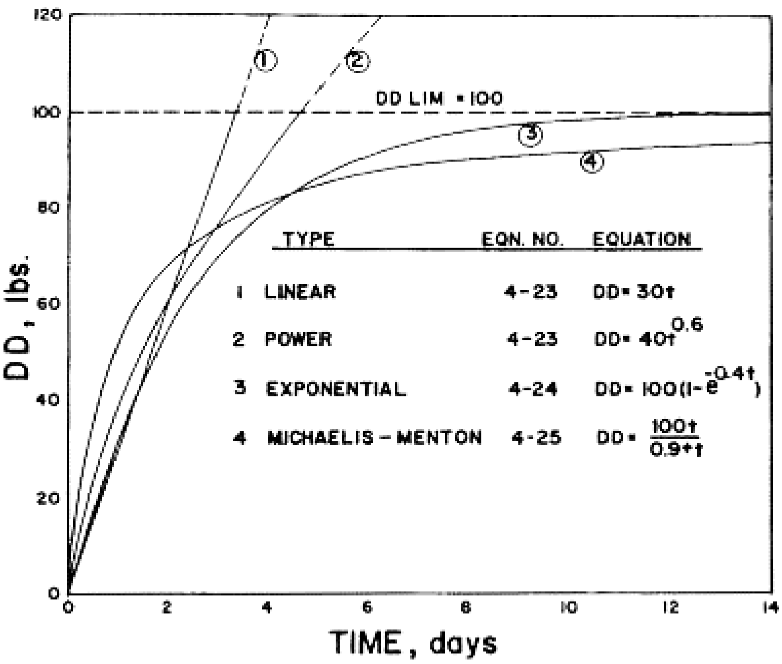

Figure 4.4 Buildup equations of dust and dirt (Huber and Dickinson, 1988)

Buildup equation use in runoff block of SWMM can be expressed by following equations:

Linear, $q = a \times t$ (4.4)

Power-Linear, $q = a \times t^b$ (4.5)

Exponential, $q = q_m (1-e^{-kt})$ (4.6)

Michaelis-Menton, $q = q_m \times t / (t_{1/2} + t)$ (4.7)

where, q = Mass of pollutant on the catchment surface, a = coefficient of the linear deposition rate (weight d^{-1}), t = number of dry days preceding storm runoff or street cleaning, b = exponential coefficient, q_m = maximum amount of pollutant that can be deposited on the catchment, k = removal rate of pollutant, $t_{1/2}$ = number of days when half of the maximum load has been deposited.

Washoff is the process of erosion or solution of pollutants from a catchment surface during a period of runoff. The concentration of pollutant decreases with time during runoff and the quantity remaining on the surface also continue to decrease. In SWMM, the accumulated pollutant washoff can be modelled as:

$$q_{off} = \frac{dq_p}{dt} = R_c \times r \times q_p \tag{4.8}$$

or, the exponential form of the mass of pollutant washoff from the catchment surface is obtained by integrating equation 4.8 is:

$$q_i - q_p = q_i(1 - e^{R_c r \Delta t}) \tag{4.9}$$

where, q_{off} = rate at which pollutant is washed off on the land surface at time t, q_p = amount of pollutant on the land surface at time t, R_c = washoff coefficient and r = runoff rate over the land surface at time t, q_i = amount of pollutant present on the land surface at the beginning of time step and Δt = time step.

The equation 4.8 is subsequently evaluated and the results combined with other possible inflow loads to a gutter/pipe or inlets, before dividing by the total flow rate to obtain pollutant concentration. Equation 4.9 indicates decreasing concentration of pollutants with time from the beginning of the runoff. Therefore, it can only simulate advanced type load characteristic curve (Figure 4.5). However, four types of load characteristics curves are used by many researchers (Ellis and Sutherland, 1979; Jewel et al., 1980).

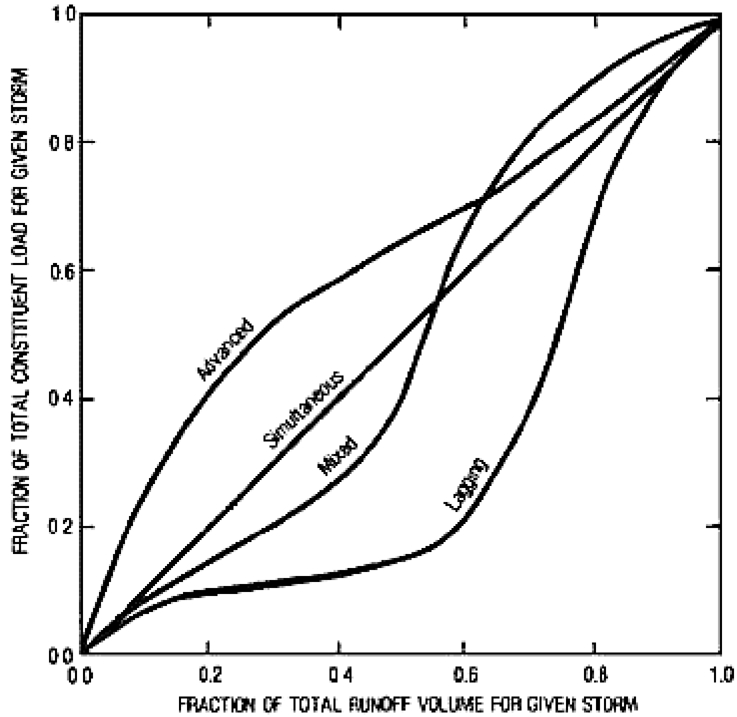

Figure 4.5 Runoff pollutant load characteristics curve (Alley, 1981)

The relationship used in SWMM by making washoff at each time step proportional to a power of the runoff rate and the amount of pollutant left on the catchment (Huber and Dickinson, 1988). Hence the basic washoff equation can be expressed as:

$$q_{off} = R_c \times r^n \times q_p \tag{4.10}$$

where n is the power of runoff rate and q_{off}, R_c, r, q_p are previously defined

Rating Curve: An alternative use of a buildup-washoff calculation, quality loads can be computed for each subcatchment at each time step by a rating curve method. In this approach, quality load are generated proportional to flow raised to some power and expressed as following equation 4.11:

$$q_{off} = R_c \times r^b \tag{4.11}$$

where, q_{off} is pollutant load washed off at time t, R_c is the washoff coefficient, r is the runoff rate over the land surface at time t and b is the exponential coefficient.

4.5 Calibration and validation

The application of SWMM to simulate surface runoff quantity and quality requires proper calibration and validation of the different parameters involved in the operational process models and their influences on the routed hydrograph and pollutograph. In addition calibration and validation processes acts as a working useful tool to minimise the errors associated with model parameters or input data (e.g., impervious area factor, Manning's roughness coefficient, subcatchment length/ width ratio, pervious area detention storage) in model implementation system.

Calibration is the process of selecting model parameter values of a specific model where the observed data events are reproduced. So that catchment can be simulated adequately using this parameter. The process of calibration can be either manual or automatic. Manual calibration involves adjustment of parameter values by hand, until the output of the model closely matches the observed data. The process of adjusting the parameter is carried out by the modeller by trial and error process. In reality it is difficult to determine the best fit or to determine a clear point indicating the end of the calibration process, and hence different results can be obtained by different modellers (Wheater, 2002). The process is time consuming in nature and related to the modellers expertise on the model structure as well as understanding of the catchment characteristics. Automatic calibration involves adjustment of parameter values automatically by using a specific algorithm for optimisation of certain fitness criteria. The automatic process can provide more objectivity, less time consuming and reduce the need for human expertise with the particular model (Sorooshian and Gupta, 1995). The development of computer based method for automatic calibration is still in progress. The full use of automatic calibration instead of manual method is not yet practised due to the difficulty of constructing objective functions and optimisation algorithms. However, automatic calibration can be successfully used in conjunction with manual calibration.

Nix (1994) suggested the following techniques which can be applied to calibrate SWMM:

- Adjust the runoff "volume" parameters. It is probably better to first adjust those parameters that have the most effect on runoff volume. Without a fairly accurate representation of the runoff volumes, the process of adjusting parameters that effect peak flows and hydrograph shapes will be much more difficult.
- Adjust the hydrograph "peak and shape" parameters (assuming that hydrograph simulation is desired). The peak and shape of the runoff event or events should be adjusted after the simulated runoff volumes are reasonably fit with the observed data. However, the effect of changing the value of one of these parameters may alter the runoff volume results to some degree and readjustment of other parameters is required.
- Adjust the water quality parameters. A model that is not calibrated for quantity cannot produce reliable quality results. Therefore, parameters reasonable for

generating pollutant loads and their transport through the catchment should be adjusted after calibrating the quantity parameters.

Calibration is an iterative process. For example while calibrating a model to one event, the adjustment of “peak and shape” parameters will likely require readjustment of the volume parameters. “Calibrated” parameters for a second event will probably not agree with those of the first event. All of this inevitably leads to a compromise final parameter values that produce model results that probably fit no one event extremely well but most of the measured data reasonably well.

Model results that probably best fit in the calibration process are difficult. However, Nix (1994) stated that a model is considered to have a ‘reasonable” fit or be ‘reasonably well calibrated” when it reproduces the system or catchment behaviour well enough to meet the modelling objectives. In other way, how closely the hydrological behaviour of the catchment can be simulated that is the main concern.

Models are required for catchment manager to improve focusing of land management and remediation activities. Parameters may be adjusted within a certain range during calibration until obtained good agreement between observed and predicted values and the average calibrated parameter values can be used for validating the model. Models have been developed to provide information of runoff quantity and quality based on catchment scale.

Validation is the investigating of the performance of calibrated model parameters on some portion of data which was not used in model calibration. This process requires the calibrated model without changing the parameters values, to simulate the runoff for a period other than the calibration period. The model is considered validated against the calibrated parameters within the validation period if its accuracy and predictive capability lies within acceptable limits or to provide acceptable errors as specified in the performance criteria. According to Nix (1994), validation is the process of collecting data to describe the behaviour and characteristics of the urban catchment (i.e. precipitation, runoff quantity, runoff quality, etc.) for a wide range of conditions and for adjusting the model to ensure that it adequately replicates the catchment as depicted by these data. Validation is probably the most important process in establishing the model credibility which includes the important tasks of calibration and data collection.

A systematic model validation process described by Nix (1994) as:

- Step 1: Prioritise the model factors - the determination of which parts of the model are relevant to the application. The sensitivity analysis can be useful to determine the model factor (parameters, variables etc.) that has significant impact on the model output.
- Step 2: Classify the important model factors - it is important to classify the model factor on the basis of their measurability. Some model factors can be measured directly and have a clear physical meaning such as topographic, meteorological, land use and drainage system data. Those factors that do not meet the above criteria will most likely be those used to calibrate the model.
- Step 3: Design and implement the data collection program - to validate the model parameters, a data collection program is needed that meets the overall study objectives. It is required that the data collection and modelling efforts must be

complement each other. Also, the data used for calibration should cover the range of conditions under which the model will be used to make predictions.

- Step 4: Calibrate the model - it includes the adjustment of the parameters that were identified in Step 2 so that the model output agrees with the actual measurements made during several independent events. Since, the calibration process is iterative with adjustments made between several independent events, the end result will probably be a compromise with no one event calibrated perfectly but many satisfactorily.

The use of relative error (RE) in the assessment criteria, it is expected that the positive and negative differences cancel each other and give a false appearance of agreement. The absolute relative error (ARE) ensures the true values. Many researchers (Baffaut and Delleur, 1989; Srinanthakumar and Codner, 1992) suggested that, a model calibration can be considered good if the average RE is within ± 10 % and the average ARE is less than 15 % for quantity assessment tests while for quality assessment test an average ARE must be less than 20 % (Baffaut and Delleur, 1989). On the other hand, Sivakumar et al. (1995) recommended that, a model calibration can be considered good or satisfactory when the average ARE is less than 30% and 60 % respectively for quality assessment tests.

Goodness of fit

The reliability of calibration and validation results can be assessed using the following goodness of fit criteria (Nix, 1994):

- Relative Error (RE)

$$\mathrm{RE}(\%) = \frac{O-Q}{O} \times 100 \qquad (4.12)$$

- Absolute Relative Error (ARE)

$$\mathrm{ARE}\ (\%) = \left|\frac{O-Q}{O}\right| \times 100 \qquad (4.13)$$

where, O is the measured value and Q is the predicted output.

The following normalized objective functions are expressed as follows:

- Mean Square Error (MSE)

$$\mathrm{MSE} = \frac{1}{n}\sum_{i=1}^{n}(O_i - Q_i)^2 \qquad (4.14)$$

- Root Mean Square Error (RMSE)

$$\mathrm{RMSE} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(O_i - Q_i)^2} \qquad (4.15)$$

- Bias (B)

$$B = \frac{1}{n}\sum_{i=1}^{n} O_i - \frac{1}{n}\sum_{i=1}^{n} Q_i \qquad (4.16)$$

where, O_i is the measured value , Q_i is the predicted value and n is number of observations in the time series.

- Variance (S)

$$S = \mathrm{MSE} - B^2 \qquad (4.17)$$

where, MSE is the Mean square error, B is bias.

- Efficiency (E)

$$E = 1 - \frac{MSE}{S} \tag{4.18}$$

where, MSE is the Mean square error, S is variance

4.6 Implementation of SWMM

4.6.1 Subcatchments

The catchment is discretised into subcatchments depends on the generation and transportation process of surface runoff and their simulation. Also, the number of subcatchments depends on the available information and the objective of simulation (Zaghloul, 1981).

For modelling purposes, the study catchment was subdivided into 42 subcatchments with varying in size from ~0.5 to ~ 27 ha. In an urban catchment, surface runoff transported through the overland flow path. Therefore, the catchment was divided primarily based on topography, land uses and drainage system. The length of the stormwater channel in each subcatchment was between 24.1 and 258.2 m. The average subcatchment slope is about 5.3 %. The percentage of impervious area is 35.2. Smaller subcatchments were predominantly in the residential areas while the larger subcatchments mainly located at open spaces, which have homogeneous land uses. The detailed of subcatchments are listed in Table 4.1. The identification number and subcatchment boundaries used in the modelling is shown in Figure. 4.6.

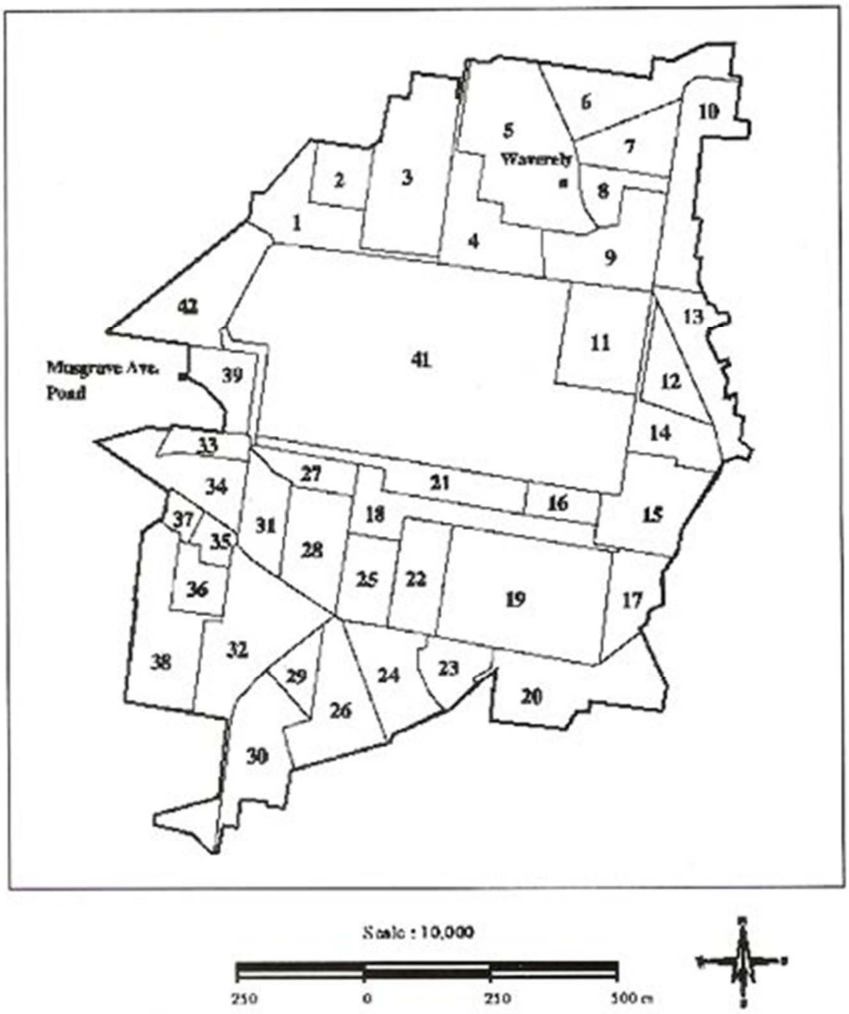

Figure 4.6 Subcatchment boundaries in Centennial Park catchment

Table 4.1 Subcatchment ID and area of Centennial Park catchment

Subcatchment ID	Area (ha)	Subcatchment ID	Area (ha)	Subcatchment ID	Area (ha)
1	2.76	15	3.21	29	1.01
2	1.37	16	0.96	30	3.17
3	5.14	17	1.79	31	1.76
4	3.13	18	2.91	32	5.38
5	6.27	19	7.38	33	0.88
6	3.39	20	4.23	34	2.58
7	1.97	21	2.45	35	0.64
8	1.17	22	2.17	36	1.21
9	3.17	23	1.46	37	0.50
10	3.35	24	2.60	38	3.89
11	3.32	25	1.80	39	1.50
12	1.56	26	3.05	40	0.53
13	2.42	27	1.15	41	27.26
14	1.96	28	2.60	42	3.63

4.6.2 Selected storm events

The rainfall data used for this catchment was collected at Musgrave Avenue gauging station from HYDSYS database which was installed by the School of Civil and Environmental Engineering, UNSW. HYDSYS is computer software used to store, process, analyse and report hydrometric time series. Temporal hydrologic data (i.e. rainfall, flow depth) can be extracted with different time steps using HYDSYS. In this study, rainfall data for selected storm events were collected at 5 minutes time step for the whole period. Other studies also found that with 5 minutes or shorter intervals rainfall time series data is appropriate for simulating urban storm events (Bedient and Huber, 1988). Considering these criteria, five storm events were extracted for analysis in the year 1984 to 1997 and are shown in Table 4.2. The events were selected with a reasonable correlation existed between rainfall and runoff and considered to be suitable for validation.

Table 4.2 Characteristics of the selected storm events

Events	Rainfall (mm)	Duration (min)
Nov. 01, 1994	7.8	190
Jan. 28, 1997	131.8	600
Feb. 11, 1997	9.8	110
Feb. 18, 1984	10.41	210
Oct. 23, 1985	12.26	90

Antecedent wetness of the catchment

Storm events are used to calibrate and verify the stormwater model. It can be classified as: storm event that produce runoff from impervious area and storm event that produce runoff from pervious and impervious areas (Dayaratne and Perera, 1999). The storm events likely to produce runoff from impervious area are considered for this study. The catchment antecedent wetness classified as dry, rather dry and wet according to the amount of rainfall 0–2.5, 2.2–5.0 and >5.0 mm respectively within 24 hours used in this study.

4.6.3 Calibration of SWMM

Calibration and validation was carried out at Centennial Park catchment between 1994 and 1995 to develop SWMM input parameter for water quantity and quality modelling (Abustan, 1997). The statistics of calibration data for peak flow and runoff depth are shown in Tables 4.3 and 4.4.

Table 4.3 Statistical fit between observed and simulated runoff depth for calibrated events (Abustan, 1997)

Events for analysis	Root Mean Square Error (RMSE)	Relative Error (RE) (%)	Absolute Relative Error (ARE) (%)
Nov 23, 1975	0.03	-1.6	1.6
Dec 04, 1975	0.03	-14	14
Oct 21, 1994	0.03	1.6	1.6
Oct 31, 1994	0.23	-16	16
Jan 02, 1995	0.02	-3.8	3.8
Feb 28, 1995	0.08	2.8	2.8
Average	0.07	-5.2	6.7

Table 4.4 Statistical fit between observed and simulated peak flow for calibrated events (Abustan, 1997)

Events for analysis	Root Mean Square Error (RMSE)	Relative Error (RE) (%)	Absolute Relative Error (ARE) (%)
Nov 23, 1975	0.39	12	12
Dec 04, 1975	0.04	-29	29
Oct 21, 1994	0.05	-6.6	6.6
Oct 31, 1994	0.01	-1.8	1.8
Jan 02, 1995	0.06	12	12
Feb 28, 1995	0.04	1.5	1.5
Average	0.10	-2.0	10

4.7 Summary

SWMM consists of several modules or blocks namely RUNOFF, TRANSPORT, STORAGE/TREATMENT and generally is used for hydrologic and hydraulic analysis of urban catchments. Calibration of a SWMM model is needed to select parameter values that represent the generic catchment response. In this study, the SWMM RUNOFF and TRANSPORT blocks were used to generate runoff quantity and quality for the catchment.

CHAPTER 5

Nutrient Release from Leaf Litter in Gross Pollutant Trap

5 Nutrient Release from Leaf Litter in Gross Pollutant Trap

5.1 Introduction

Nutrients release from leaf litter decomposition is complex and involves chemical, physical and biological processes (Berg et al., 2003). There are several factors related to the decomposition of leaf litter such as leaf litter chemical composition, diversity of leaf litter and environmental condition (Swift et al., 1979). Leaf litter decomposition experiment was studied by Prasad et al. (1980). They found 48 hours period was adequate to release most of the soluble substances, such as phosphorus, from single leaf species. McCann and Michael (1995) investigated the release rate of nutrients and observed that P release was occurred after 28 days in water. Davis et al. (2003) was found that almost complete leaching occurred between 3 to 25 days. The leaching data from leaf litter is contradictory and further studies are needed. There is a lack of data about the time frame necessary for leaching of leaf litter and the release of nutrients. In addition, the relevance of the period relates to the duration of the inter-event dry period. Previous studies have not considered this factor and hence research into the relationship between the release of nutrients from leaf litter and the duration of the inter-event dry period need to be considered. Another aspect of this research was to determine the nutrient release rate from leaf litter in a condition to represents GPT environment.

Most of the previous work concentrated decomposition studies on leaching experiment using individual leaf species, but this study used mixed leaf species collected from Centennial Park, Sydney, for the estimation of nutrients release from leaf litter. A leaf litter decomposition experiment was carried out using litter bag technique to determine the release of TP and TN. Water quality such as pH, electrical conductivity and dissolved oxygen were examined during decomposition of leaf litter.

5.2 Methodology

The prediction of nutrient (P and N) release from leaf litter stored in a GPT was conducted in laboratory scale experiments using leaf species typically found in the Centennial Park. The major species tested were the Port Jackson Fig, Algerian Oak and broad-leaved paper bark. The leaching of leaf litter were studied with a litter bag techniques (Graca et al., 2005) using 25 cm × 25 cm nylon net litter bags with 5 mm mesh.

5.2.1 Leaf litter collection

The time of leaf litter collection is important to restore nutrients quality and quantity. Wet litter can begin to decompose and lose mass during rainy season (Berg and Laskowski, 2006). Therefore, the sample leaf litter was collected during dry weather conditions. Freshly fallen and undamaged leaves were collected from the study catchment area and used in this experiment.

5.2.2 Leaf sample preparation

The leaf litter samples were cleaned and air dried at approximately 21–23ºC up to 3 days for dry weight measurement.

Leaf sample: Three bags air dried leaves (10 g each bag) sample were kept in the oven at 50ºC for 48 hours. Then the oven dried sample was grind, passed through 0.5 mm mesh and was taken in a crucible and put in the muffle furnace at 550ºC for 2 hours. After combustion the samples was cooled in room temperature and determined the ash free dry mass of the leaf samples. Approximately 5 mg of ash free dry mass was taken for TP and TN analysis (Graca et al., 2005).

Water sample (Leachate): Water samples were collected in acid-washed bottles from buckets at selected interval of time for chemical analyses.

5.2.3 Leaf litter leaching experiment

Approximately 10 g of leaf species were placed in 5 mm mesh nylon litter bag in replicates of three with a total of 93 bags being prepared. For the experiment, 3 (three) 20 L clean opaque buckets were filled with distilled water and 30 bags of samples were placed in each bucket. Three bags were kept for initial total nutrient determination. The buckets were allowed to remain undisturbed in the ambient laboratory environment. Three parallel samples were collected from each bucket after 1, 5, 10, 15, 22, 37, 56, 70, 90 and 180 days. These samples were analysed for nutrients and water quality measurements. A control was set up using the same buckets filled with the same distilled water but without the bags of leaves. The control samples did not exhibit the remarkable physical changes in the distilled water. The difference between replicates in all samples was less than 5% of the mean.

To represent leaf litter in GPT, mixed leaf species was used which is common in surrounding area of the Centennial Park catchment. Also the wet sump conditions of GPT i.e. no light, little or no flow, no air (anaerobic) is considered in the laboratory experiment. All experiments are carried out at the room temperature 21–23°C.

5.2.4 Instrument, equipment and chemicals

Conductivity meter, pH meter, dissolved oxygen (DO) meter and HACH 2000 spectrophotometer were used to measure the water quality parameter. Drying oven, analytical balance, mortar pestle, muffle furnace, hot plate, syringes, acid washed pipettes and Erlenmeyer flasks were used for laboratory experiments. Analytical Reagent Grade chemicals such as Potassium Persulfate Powder Pillows, Sodium Hydroxide Solution, H_2SO_4, HCL, PhosVer3 and Phosphate Reagent Powder Pillows were used for chemical analysis.

5.2.5 Analytical method

For each sample, the pH, electrical conductivity and dissolved oxygen in the water were determined. The total nitrogen and total phosphorus concentration in both the water and the leaves were analysed. TP was measured using persulphate digestion followed by PhosVer3 blue colour method with a spectrophotometer (APHA/AWWA/WEF, 1998) in the Environmental Engineering R&D Laboratory, UTS. Using the level of total phosphorus in the water and calibration curves, the amount of leachable phosphorus per gram of air-dried leaf was determined. Total nitrogen (TN) was measured by National Measurement, Govt. Laboratory, Sydney, NSW.

Phosphorus in natural waters consists of three parts, such as soluble reactive phosphorus (SRP), soluble unreactive or soluble organic phosphorus (SUP or SOP) and particulate phosphorus (PP) (Rigler, 1973). The sum of SRP, SUP and PP components is termed as total phosphorus (TP). Results of the TP test include all filterable forms of SRP (both organic and inorganic that are converted to ortho phosphate by the digestion method), plus all filterable forms of SOP (soluble organic phosphorus that are converted to organic phosphate by the digestion) and PP (the acid-hydrolysable (condensed) phosphate) i.e. the determination of the organic phosphate plus the ortho phosphate and the acid-hydrolysable phosphate.

5.2.6 Data Analysis

Exponential decay model

The decay constants for leaf litter were calculated using a single exponential decay model (Olson, 1963) can be expressed equation 5.1:

$$X/X_o = \exp^{(-kt)} \qquad (5.1)$$

The integrated form can be expressed as equation 5.2:

$$Ln(X) = \ln(X_o) - kt \qquad (5.2)$$

where, X is the mass at time t, X_o is the initial mass, exp is the base of natural logarithm, k is the decomposition rate constant and t is the time in days.

Statistical analysis

Standard deviation was used to measure the variability between the data set and the mean values (Fowler et al., 1999) were reported. It is calculated as equation 5.3:

$$S = \sqrt{\frac{\Sigma(O - O^{-})^2}{n-1}} \qquad (5.3)$$

where,

S = standard deviation,

O = the value of observation

O^{-}= mean of the observations

n = number of observations

5.3 Results and discussion

Batch leaf litter leaching experiments were conducted in water. The results indicated that decomposition of leaf litter followed a biphasic pattern. The initial mass loss of leaf litter decreased rapidly followed by slower phase with the increase of incubation time. The main reason of initial higher mass loss is due to rapid leaching from the leaf litter. It was reported that soluble substances usually occur rapidly during leaching when fresh litter submerged in water (Xiong and Nilsson, 1997). Other studies found that leaf litter has a readily soluble materials which may leached during early decomposition while long term physical losses may be less significant (Berg and McClaugherty, 2003; Cleveland et al., 2006).

Berg (1986) and Takeda (1995) were proposed that the decomposition of leaf litter was divided into two stages. They mentioned that the first stage of leaf litter decomposition was responsible for the soluble substances and non-lignified carbohydrates e.g. cellulose and hemicelluloses while the second decomposition stage was responsible for lignin and lignified cellulose. Also the decomposition of leaf litter is affected by the environmental factors under which decomposition takes place (Gillon et al., 1994). The TP and TN concentrations in leaves were 0.095 % (0.381 mg g^{-1}) and 1.28 % (5.1 mg g^{-1}) dry mass of leaves respectively, found in this study. These concentrations are within the range of values reported in the literature (Weerakkody and Parkinson, 2006). Other studies also reported that TP and TN compositions of up to 0.1% and 1.2%, respectively in leaf litter in Australian forests (Attiwill and Leeper, 1990).

5.3.1 Phosphorus release from leaf litter

The total phosphorus (TP) released from leaf litter during experiment was evaluated. It appears that in the first stage (i.e. 90 days), a significant decrease in phosphorus in the leaf litter occurred. At the second stage of leaching, phosphorus release was lower than the previous stage of leaching (Figure 5.1).

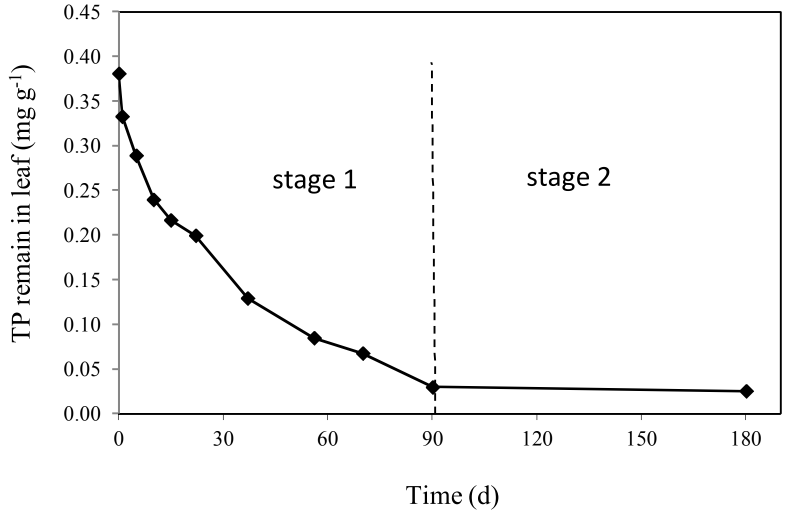

Figure 5.1 Total phosphorus remains in mixed leaves as dry mass

The decrease in TP for first 90 days is primarily due to higher rate of leaching where TP loss from the leaves about ~88% of the available P. The data analysis shows that approximately 54% of the phosphorus in the leaf litter was released to the water during the first 22 days with the majority of the remainder being released over the next 68 days

(Table 5.1). The rapid loss of TP was observed in the initial stage of decomposition were reported for several leaf litters (Lousier and Parkinson, 1978). It was mentioned that the high water soluble TP in leaves may lead to higher rates of TP loss during initial leaching (Martin and Cunningham, 1973; Berg and Tamm, 1991; Polglase et al., 1992). This could be the plausible explanation for the higher TP release from leaf litter at initial stage. This result was confirmed in this study. In the later 90 days, the P in the leaves leached at a slower rate than the previous stage. The decrease in the removal of P from the leaves in the second stage of the process suggests that the leaching of P is slower due to refractory components of leaves (Schlesinger, 1985). This study showed lower TP released after 90 days of decomposition. The results from leachate sample collected at selected time intervals are given in Table 5.1.

Table 5.1 Phosphorus release from leaf litter with time

Decomposition (days)	TP in water mg L^{-1} (mean ± SD)	TP remained in leaf litter mg g^{-1} dry mass	TP released (%)
1	0.7667 ± 0.038	0.3341	11.4
5	1.6833 ± 0.057	0.2851	26.2
10	2.3000 ± 0.100	0.2433	37.0
15	2.6000 ± 0.100	0.2208	42.6
22	3.1333 ± 0.251	0.1821	54.4
37	3.7333 ± 0.305	0.1210	70.1
56	4.0667 ± 0.251	0.0808	80.0
70	4.1667 ± 0.252	0.0671	82.1
90	4.2667 ± 0.321	0.0325	87.5
180	4.4000 ± 0.361	0.0259	93.3

initial TP in mixed leaves = 0.381 ± 0.03 mg g^{-1} of dry mass. Each data point is the mean of three replicates ± SD (standard deviation). Standard deviation indicates the variability between data sets. TP - total phosphorus

The decay constants for leaf litter were calculated using a single exponential decay model (Olson, 1963). Considering first-order kinetics in P degradation which is a good approximation for the first 90 days of the degradation. The plot ln (P/P_o) versus decay time for phosphorus degradation is well fitted for the first 90 days with the r^2 value 0.98 (Figure 5.2 and Table 5.2).

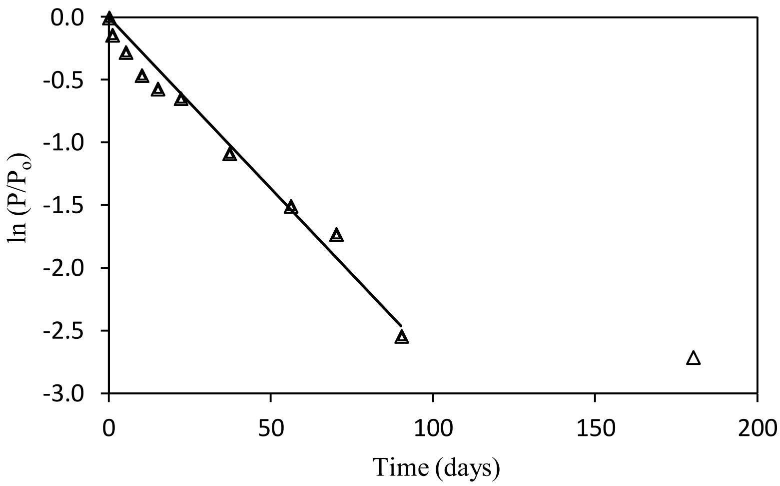

Figure 5.2 Degradation of phosphorus during leaf litter decomposition

Table 5.2 Decay constant of TP leached from leaf litter

Time (d)	Decay constant (k) (d^{-1})	r^2
90	0.0274±0.0007	0.977
180	0.0195±0.0001	0.783

TP-total phosphorus

The results indicated that the rate of phosphorus release was 0.0274 d^{-1} for the first 90 days and the overall release rate was 0.0195 d^{-1} for 180 days are comparable and within the range (0.01–0.067 d^{-1}) of leaf litter decomposition as reported by other studies (Kwabiah et al., 2001; Li et al., 2011; Pettit et al., 2012). The variation of decay constant may be attributed to the litter quality. It was also reported that, the rate of decomposition of Nauclea leaves was faster when they were mixed with Melaleuca leaves than when incubated separately (Pettit et al., 2012).

5.3.2 Nitrogen release from leaf litter

The nitrogen concentration fluctuated during the decomposition from leaf litter throughout the experiments. TN change showed three different stages. At initial stage, it was decreased up to 22 days (Table 5.3) and after a further increase (90 days) it then decreased for the remaining period of incubation. Previous studies reported that nitrogen decomposition in leaf litter showed different stages (Berg et al., 1987; Cameron and Spencer, 1989). The decrease in nitrogen in the initial stage may be due to the leaching of soluble compounds during decomposition of leaf litter (Berg and McClaugherty, 2003). Further increase in nitrogen in the following 68 days may be due to the progressive reduction in the amount of organic carbon present (Ausmus et al., 1976) and a demand for nitrogen by heterotrophic organisms during litter decomposition (Gilbert and Boccok, 1960; Lousier and Parkinson, 1978). The decrease in nitrogen at the end of experiment can be defined by the NH_3 volatilization and leaching (Laishram and Yadava, 1988). The initial decrease portion (22 days) of the curve was used to calculate the decay constant of nitrogen (Figure 5.3). The results from leachate sample collected at selected time intervals are given in Table 5.3. The data after 22 days are shown in appendix A.

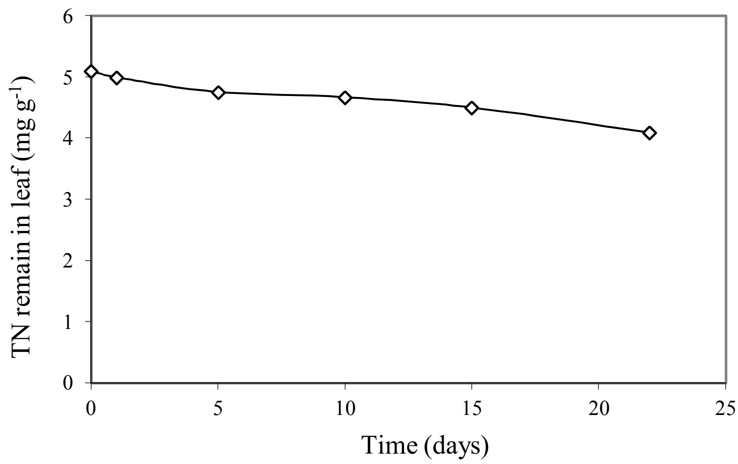

Figure 5.3 Total nitrogen remains in mixed leaves as dry mass

The plot $\ln(N/N_o)$ versus decay time for nitrogen degradation are well fit for the experimental data (22 days) with the r^2 value 0.964 and the decay constant was 0.009 d^{-1} (Figure 5.4).

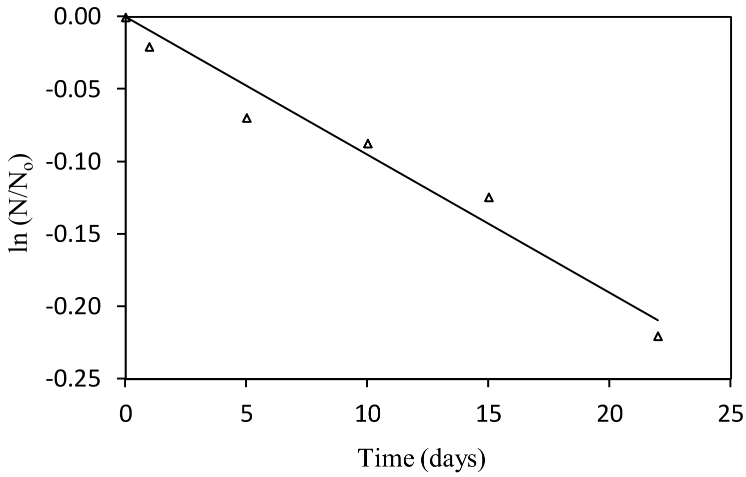

Figure 5.4 Degradation of nitrogen during leaf litter decomposition

Table 5.3 Nitrogen release from leaf litter with time

Decomposition (days)	TN in water mg L^{-1} (mean ± SD)	TN remained in leaf litter mg g^{-1} dry mass	TN released (%)
1	1.73 ± 0.681	4.998	2.01
5	5.50 ± 0.985	4.757	6.73
10	6.77 ± 1.124	4.674	8.36
15	9.00 ± 0.557	4.505	11.68
22	13.67 ± 2.517	4.092	19.77

initial TN in mixed leaves = 5.1 ± 0.17 mg g^{-1} of dry mass. Each data point is the mean of three replicates ± SD (standard deviation). Standard deviation indicates the variability between data sets. TN - total nitrogen

The quantity of TP and TN released from leaf litter in 22 days of incubation did not follow the same percentages (Table 5.1 and 5.3). The initial loss of TP was higher than the TN loss. This suggests that initial loss of TN is lower than the loss of TP (Berg et al., 1987; Berg and Cortina, 1995; Berg and McClaugherty, 2003) and phosphorus in the leaf litter was release faster. Also, it was found that the decay constant of TP (0.034 d^{-1}) was higher than the decay constant of TN (0.009 d^{-1}) within 22 days. This indicated higher rate of leaching of phosphorus from the leaf litter (Swift et al., 1981).

Initially, TP decreased more rapidly than nitrogen in the leaf litter decomposition (Howard-Williams and Davies, 1979). In this study about 54% of the total phosphorus leached out in 22 days while 20% of the total nitrogen leached out within the same time frame. Therefore considerable amount of TP were leached out in initial stage. Other studies also reported that about 25% nitrogen and 50% phosphorus were released during leaching of leaf litter (Parsons et al., 1990; Taylor and Parkinson, 1998) which is consistent with this study.

5.3.3 Change of pH, conductivity and dissolved oxygen

The conductivity, dissolved oxygen and pH were monitored during leaf litter leaching experimental tests. The initial pH, EC and DO of water were approximately 5.7, 4.6 µS cm^{-1} and 4.4 mg L^{-1} respectively. The pH, electrical conductivity (EC) and dissolved oxygen (DO) of water containing submerged leaves varied with time.

pH

The initial pH value showed decrease up to 5 days due to leaching and was followed by increase in all collected samples for 37 days where after the pH change remained approximately constant throughout the experiment (Table 5.4).

Table 5.4 Electrical conductivity (EC), pH and dissolved oxygen (DO) values in leachate samples during leaching experiment, 23°C

Time (days)	pH (mean ± SD)	Electrical Conductivity (µS cm^{-1}, mean ± SD)	Dissolved Oxygen (mg L^{-1}, mean ± SD)
0	5.65 ± 0.055	4.63 ± 1.021	4.37 ± 0.115
1	5.37 ± 0.131	115 ± 5.100	0.90 ± 0.036
5	5.04 ± 0.093	278 ± 9.640	0.77 ± 0.038
10	5.50 ± 0.023	419 ± 18.50	0.37 ± 0.021
15	5.83 ± 0.069	532 ± 11.50	0.23 ± 0.015
22	6.29 ± 0.160	618 ± 17.60	0.13 ± 0.012
37	6.80 ± 0.332	721 ± 32.50	0.06 ± 0.010
56	6.91 ± 0.233	775 ± 28.90	0.03 ± 0.006
70	6.89 ± 0.180	791 ± 22.6	0.03 ± 0.015
90	7.04 ± 0.197	803 ± 23.8	0.02 ± 0.006
180	7.11 ± 0.242	817 ± 18.8	0.001 ± 0.00

Each data point is the mean of three replicates ± SD (standard deviation). Standard deviation indicates the variability between data sets.

The maximum deviation from the mean on any sample was less than 5%. The correlation coefficient of pH with total phosphorus was 0.8683. The initial decrease in pH (Figure 5.5) suggests a leaching of leaf components. The subsequent increase after 5 days was observed may be due to microbial activity (Godshalk and Wetzel, 1978).

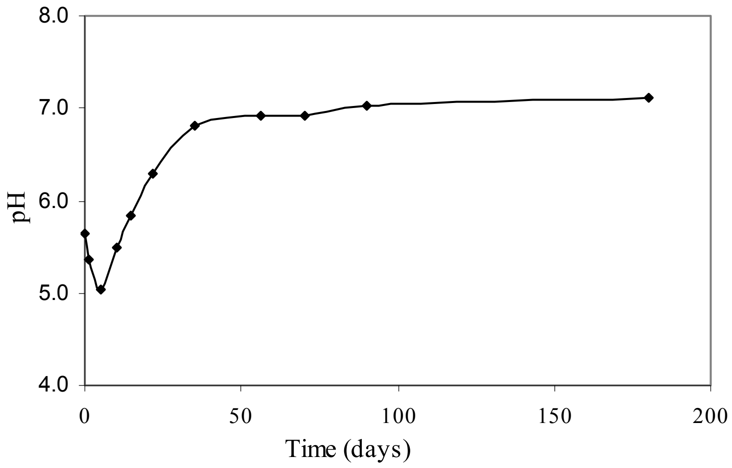

Figure 5.5 pH values of the water during the decomposition of leaf litter

Conductivity

It was found that the conductivity increased with time (Table 5.4) and that it was strongly correlated with concentration of total phosphorus in the water. Therefore, conductivity was strongly correlated with the release of phosphorus. The correlation coefficient of EC with total phosphorus was 0.99. The increase in conductivity (Figure 5.6) is indicated the increase of dissolved solids in water. This may cause by the increase of inorganic ions such as chloride, nitrate, sulphate and phosphate rather than dissolved organic compounds as fresh leaves did not show a change in conductivity (Gessner and Schwoerbel, 1989).

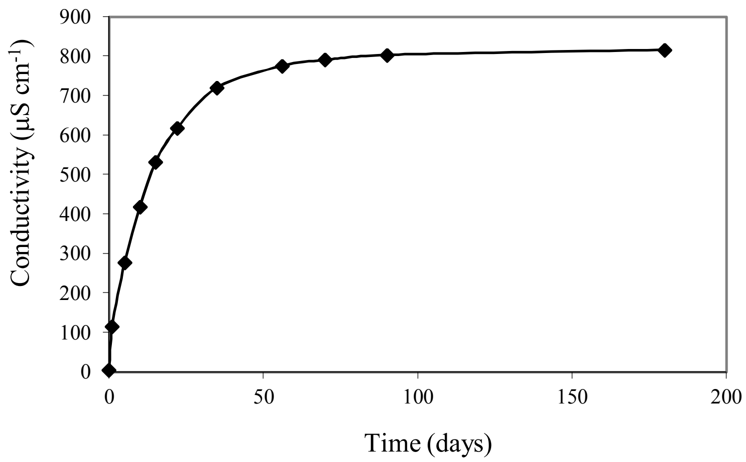

Figure 5.6 Conductivity of the water during the decomposition of leaf litter

Dissolved oxygen

It was found that the DO decreased with time (Table 5.4). Due to microbial activity, dissolved oxygen concentration of the water decreased (Figure 5.7) throughout the experiment (Godshalk and Wetzel, 1978) and was negatively correlated with the phosphorus concentration. The correlation coefficient of DO with total phosphorus was -0.7855.

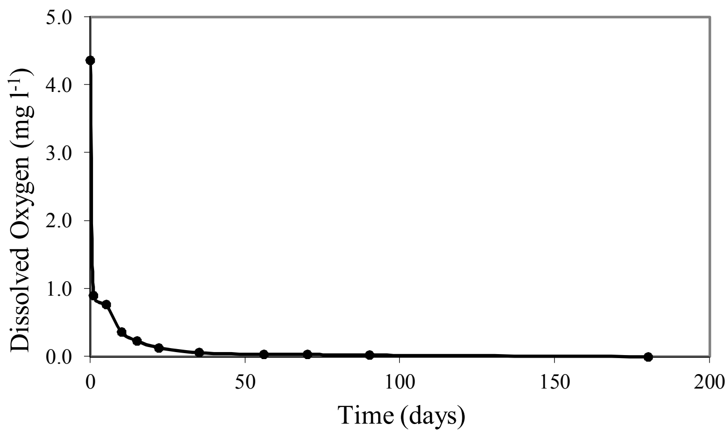

Figure 5.7 Dissolved oxygen of the water during the decomposition of leaf litter

The EC continued to increase and DO decrease in water for all samples. The pH value initially decrease followed by increase. This change in pH, EC and DO could be attributed to the leaching of leaf matrix. It was found that the conductivity and pH increased with time as the concentration of total phosphorus increased in the water, whereas dissolved oxygen decreased with time. Therefore, conductivity and pH were positively correlated with the release of phosphorus from the leaf litter.

Leaves may decompose at different rates in the summer and winter. Leaf species quality may also have influenced decomposers activity (Goncalves et al., 2006). The dissolved oxygen concentration decreased throughout the experiment was probably due to microbial activity. The increased in microbial activity, which increased oxygen consumption in water, hence affecting the pH and the rate of nutrient (TP, TN) released in water. This suggests that water quality changed rapidly during decomposition. Initial pH decrease can be associated with rapid leaching of acids during the initial phase and rapid dissolved oxygen depletion through microbial respiration (Godshalk and Wetzel, 1978).

5.4 Conclusions

The laboratory experiments to determine the rate of nutrient leaching were undertaken in a manner designed to replicate the GPT environment. The results showed that initial leaching rate was higher compared to later stages. The initial leaching data indicated that the TP leached at a more rapid rate than TN. The analysis of leaching samples demonstrated that pH, conductivity and dissolved oxygen changed rapidly during leaching. The results also revealed that initial phosphorus leaching is rapid in the first 90 days while general GPT cleaning period is every 180 to 360 days. In order to avoid significant leaching of leaf litter nutrients it is desirable to remove leaf litter more frequently from GPTs. If these devices are not cleaned regularly a large percentage of the nutrients from leaf litter collected in the GPT will be released and flushed downstream. Based on the results reported herein more frequent cleaning of GPT is needed to minimise nutrient transport to receiving water from urban runoff.

CHAPTER 6

Runoff Variability

6 Runoff Variability

6.1 Introduction

A common problem encountered in urban water management is the prediction of runoff. This problem conceptually consists of estimating the depth and temporal pattern of rainfall, the depth and pattern of losses, and the routing of surface flows through the available catchment storage. Rainfall has a significant variation in space and time which influence the magnitude of runoff. Temporal distribution of rainfall significantly effect the formation of hydrograph shape, flood volume and peak flow. According to the approach of Cordery (1987), continuing losses are assumed usually to be independent of the storm duration and the temporal pattern of rainfall. The robustness of this assumption was investigated in this study based on the application of a calibrated catchment modelling system with different design rainfall intensities, durations, and patterns. Predictions obtained were analysed to consider the influence of different storm durations and temporal patterns on the magnitudes of the predicted losses, and the effect of these losses on the predicted design peak flow.

The spatial and temporal pattern of rainfall has significant influence on runoff volume within and from a catchment. The infiltration parameters have also influence on the catchment runoff. In order to predict accurate flow, variability of peak flow and infiltration loss was investigated for alternative rainfall pattern. Runoff volume generated in the catchment is used as GPT inflow which can be obtained from catchment modelling. To compare the catchment runoff volume and GPT volume, catchment runoff volume was estimated from daily Sydney rainfall data and the GPT volume was calculated from the structural design drawings.

Previous studies (Walsh et al., 1991; Hill et al., 1998) have shown that the loss model and its associated parameters have a significant impact on the transformation of rainfall to runoff. Hill and Mein (1996) showed that inconsistencies in the different design parameters can result in over-estimation of design peak discharges for a given flood quantile. Rigby and Bannigan (1996) reviewed Australian Rainfall and Runoff (ARR' 87) design flood estimation procedure and found that this procedure was unsuccessful to allow antecedent condition prior to a design burst due to limited dataset which may lead upto 40% underestimation of peak discharge. Ilahee et al. (2001) found that the initial losses from 882 rainfall events in eastern Queensland were much higher than the recommended values in ARR'87 for the same region. Ilahee and Imteaz (2009) also observed in their studies with 270 rainfall events, that the continuing loss decays with storm duration. These studies and ARR'87 have focussed on larger rural catchments rather than the smaller catchments typically found in urban environments. Thus there is limited information available regarding appropriate parameter values for design flood quantiles within urban environments. Presented herein is an analysis of the influence of one of the parameters that are assumed to be probability neutral; this parameter is the temporal pattern of rainfall on the predictions from a catchment modelling system and on design flood quantile estimation.

6.2 Catchment modelling system

The prediction of design flood quantiles may be estimated from a frequency analysis of the recorded data**.** In most cases, however, suitable data are not available and simulation techniques therefore are employed to generate the necessary data for estimation of the desired flood quantile. Use of simulation techniques for prediction of the response of a catchment to a storm event or a sequence of storm events typically involves evaluation of many forms and types of parameters necessary for implementation of catchment modelling systems. These catchment modelling systems are used to estimate the depth and temporal pattern of rainfall, the depth and temporal pattern of losses, and the routing of surface runoff through the available catchment storage. In this context, the losses are the precipitation which does not appear at the catchment outlet as surface runoff. Hence the parameters and process models associated with the conceptual loss model are an important component of the catchment modelling system. Previous authors concluded that time and space varying rainfall inputs that influence the simulated catchment response time and hence the magnitude of the peak (Dawdy and Bergman, 1969; Krajewski et al., 1991; Seliga et al., 1992). Temporal variability is considered as a major source of variation in the resulting catchment hydrograph, there is no direct experimental evidence is available. This concept is verified through a catchment modelling system using the available data.

6.2.1 Alternative Loss model

Rainfall loss is the initial portion of rainfall that is not included in the runoff of a storm event. Losses can be occurring due to various reasons, such as: interception by vegetation, infiltration into the soil, retention on the surface (i.e. depression storage) and transmission loss through stream bed and banks. All these losses are depends on the characteristics of topography, soils, vegetation and climate of the catchment (Laurenson and Pilgrim, 1963). However, many loss models treated the losses as infiltration into the soil. As the losses differ with event to event, design loss can be considered as probabilistic or statistical estimates of the most likely values (Nandakumar et al., 1994).

In a catchment modelling system, a loss model is used to convert the rainfall to rainfall excess. Ball (1992) described a catchment modelling system as the summation of the numerous hydrologic, hydraulic and other process models necessary to simulate catchment response to a storm event. One of the important hydrologic processes is the loss model. There are numerous alternative models for estimation of the losses occurring during storm events. Cordery (1987) categorised loss models as:

- Proportional loss rate (PLR) - Loss is a constant fraction of the rainfall depth in each time period.
- Constant loss rate (CLR) - The rainfall excess is the residual remaining after a constant rate of infiltration is satisfied. With this loss model, it is assumed that the loss continues at a constant rate regardless of the rainfall intensity.
- Initial loss–continuing loss (IL-CL) model - In this loss model, it is assumed that the loss continues at a constant rate once the initial loss capacity is satisfied regardless of the rainfall intensity.
- Initial loss and an infiltration curve or equation- It is representing capacity rates of loss decreasing with time.
- US Soil Conservation Service (SCS) curve number relationship.

These alternative loss models are illustrated in Figure 6.1. In case of South Western Australia, the proportional loss rate (PLR) model with an initial loss model showed well prediction (Harvey, 1981). Dyer et al. (1994) found better result by applying PLR on 24 catchments when compared with IL-CL. However, ARR recommend this model like Harvey (1981) for some portion of Western Australia only.

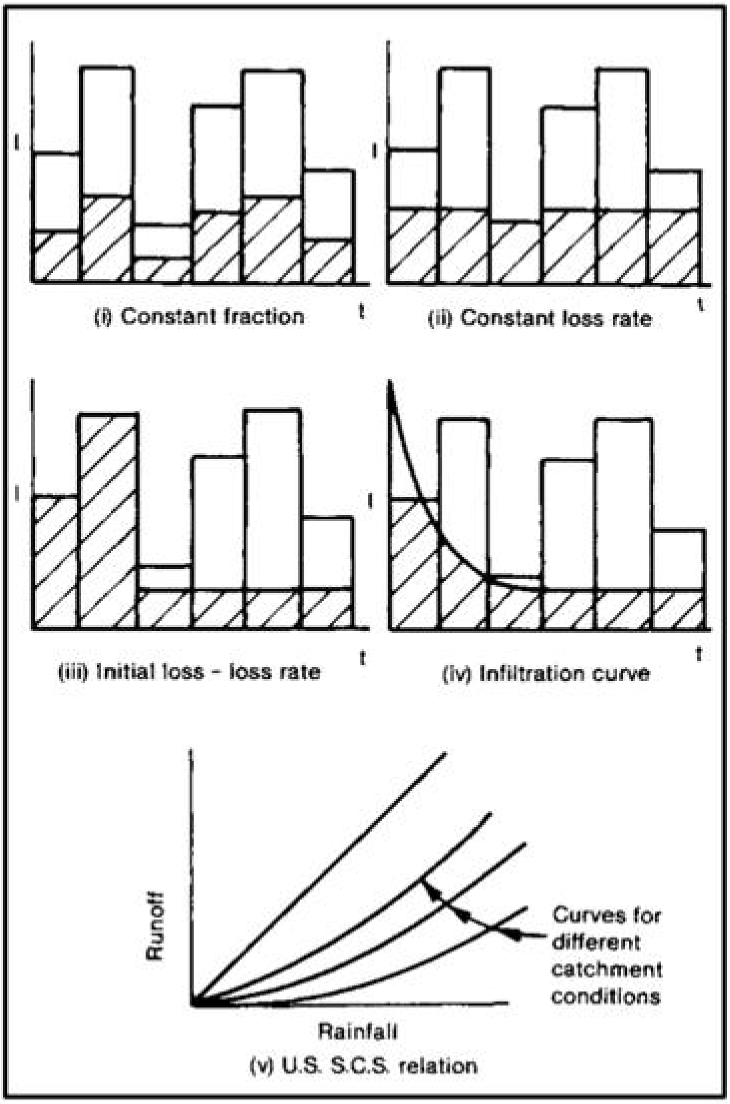

Figure 6.1 Alternative loss model (Cordery, 1987)

Nandakumar et al. (1994) mentioned that conceptualisation of constant loss rate model does not match with many Australian catchment, it can only be used for catchment have high storm runoff. IEAust. (1998) also suggested that this model is more appropriate for large storms which produce significant runoff. For flood estimation IL-CL model is widely used in Australia due to its simplicity and better approximation of temporal pattern. For this model, the initial loss is considered to be the losses that occur prior to the commencement of surface runoff. Cordery and Pilgrim (1983) reported that it was difficult to find relationship between the catchment characteristics and the parameter of the loss model due to the inadequacy of conceptualisation of the loss model with temporal and spatial process of real catchment. On the other hand, continuing losses are those losses that occur during the supply period of the storm event, or storm burst event. Commonly, the continuing loss rate occurs at a constant rate which is independent of the storm duration or the temporal pattern of rainfall; this is the approach adopted by Cordery (1987) in recommending parameter values for continuing loss models that are currently used for flood estimation in Australia.

6.2.2 Alternative rainfall model

A second important model in a catchment modelling system is the rainfall model. The importance of this model has been recognised in the literature. Umakhanthan and Ball (2005) was discussed the importance of the rainfall model in reproduction of historical events. There are three components to a rainfall model as:

- Depth or average intensity of rainfall
- Temporal pattern of rainfall and
- Spatial pattern of rainfall.

The first and second components are of interest herein. Determination of the average intensities of rainfall during the storm event was obtained from the Intensity-Frequency-Duration (IFD) diagram for the catchment area; the IFD was determined in accordance with the procedures outlined in ARR by Pilgrim (1987). Temporal patterns of rainfall during the storm event were obtained from:

- Constant pattern – this pattern assumes no temporal pattern and the rainfall intensity is constant over the duration of the event;
- ARR'87 – these patterns are based on the concept of average variability as outlined by Pilgrim and Cordery (1975). While these patterns as presented in ARR'87 have temporal dimensions, these patterns can be made non-dimensional in a temporal dimension. It was the non-dimensional form of these patterns that were considered herein; and
- Varga et al. (2009) – these patterns are based on stochastic generation of patterns with the same statistical characteristics as the historical storms. As described by Varga et al. (2009), the generated non-dimensional temporal patterns of rainfall are subdivided into Frontal and Convective events with these categories subdivided further into front, middle, and back-loaded patterns. For each category of storm, a total of ten alternative patterns were developed giving a total of 60 different patterns. Furthermore, each pattern is non-dimensional so that the pattern could be scaled to the desired burst duration.

For any selected duration, therefore, a total of 62 alternative temporal patterns of rainfall were available. The response time of the Centennial Park catchment is expected to be approximately 15 min. Hence the limit of the storm burst durations considered during this study was 120 minutes. Durations considered were 5, 10, 20, 30, 60, and 120 min. Additionally, a range of Average Recurrence Intervals (ARIs) were considered; the ARIs considered were 1, 5, 10, 20, 50 and 100 years.

6.3 Results and discussion

The catchment modelling system such as SWMM was employed herein for prediction of design flood flows. The SWMM was used to simulate the rainfall consisting of the set of the generated hyetographs with different temporal distribution of rainfall. Within SWMM, losses are predicted using either the Horton or the Green-Ampt infiltration equations. In this study, Hortonian infiltration was assumed to occur. While Abustan (1997) previously calibrated SWMM for the study catchment, these calibrated parameter values were reviewed using new data. an example of the performance is shown in Figure 6.2. Based on this review, parameter values (Appendix B1) derived by Abustan (1997) were assumed to be valid.

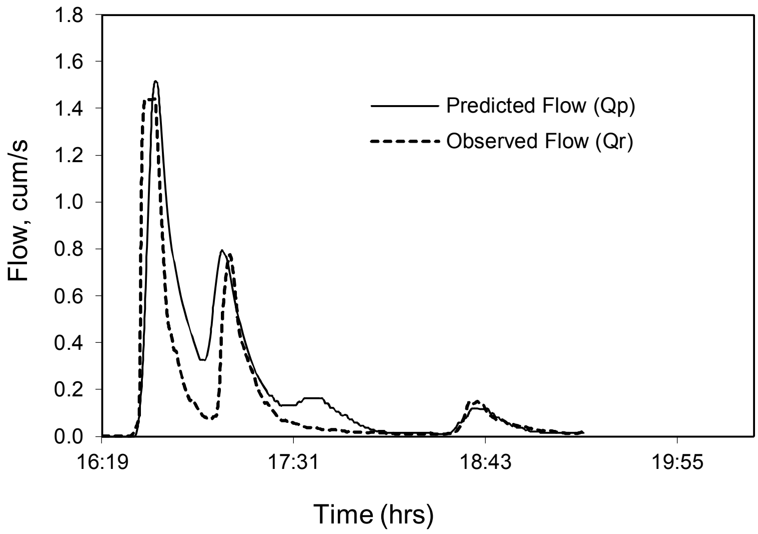

Figure 6.2 Predicted and monitored flows for Nov. 1, 1994

To assess the variability in the runoff prediction arising from the temporal pattern of rainfall, each of the 62 alternative temporal patterns of rainfall were applied with the design rainfall intensity for a given Average Recurrence Intervals (ARI). The calibrated SWMM model is used to obtain 62 alternative design flow predictions for 6 different storm burst durations.

6.3.1 Variability of rainfall losses

To estimate design flood flows from rainfall, several input is required, of which loss is an important input. The rainfall loss is depends on catchment characteristics and thus exhibits a high degree of temporal and spatial variability in a rainfall events. Therefore it is necessary to investigate the variation of losses for prediction of surface runoff. Estimation of the design flood flows were obtained using SWMM to predict the catchment response to storm bursts with the following characteristics:

- Rainfall intensities –1, 5, 10, 20, 50, 100 year ARI;
- Burst durations –5, 10, 20, 30, 60, 120 minutes; and
- Temporal patterns – constant, ARR patterns, and Varga et al. (2009) patterns.

Design rainfall intensities for the different durations and for the alternative ARI were estimated using information available in ARR'87 (Pilgrim, 1987). However, while analyses were undertaken on alternative storm burst ARIs, the following discussion will focus on the results obtained for estimation of the 100 year ARI storm bursts. Other ARIs are discussed in Appendix B. Furthermore, the discussion will focus on the loss model and the appropriateness of the assumption of consistent continuing loss model parameters as currently recommended in ARR.

From the simulations obtained from SWMM, the total infiltration depth (equivalent to the total continuing loss) can be extracted for the alternative storm bursts. These infiltration losses were then converted into equivalent constant continuing loss rates, in other words, continuing loss rates were computed from the infiltration losses simulated using a Hortonian model. These results are shown in Table 6.1 for the total infiltration depth and Table 6.2 for the equivalent continuing loss rate for 100 year ARI. Similarly, for 50, 20, 10, 5 and 1 year ARI total infiltration depth and loss rate are shown in Tables B2–B11 in Appendix B.

Table 6.1 Total precipitation loss for 100 year ARI

Duration (min)	Total Loss (mm)							
	I_{const}	I_{ARR}	I_{CFL}	I_{CML}	I_{CBL}	I_{FFL}	I_{FML}	I_{FBL}
5	13.27	13.27	12.50	12.59	12.50	12.76	13.16	13.13
10	20.86	20.88	18.82	18.87	18.82	19.57	20.36	19.93
20	30.84	29.29	27.67	27.09	27.67	29.23	30.09	28.46
30	36.59	35.86	33.62	32.25	33.62	35.55	35.66	33.49
60	44.57	43.39	43.17	40.31	43.17	44.79	43.27	40.83
120	48.75	52.79	52.90	48.34	44.96	55.12	50.83	46.38

I_{const} =infiltration for constant intensity, I_{ARR}= infiltration for ARR pattern, I_{CFL} = infiltration for Convective Front loaded pattern, I_{CML} = infiltration for Convective Middle loaded pattern, I_{CBL} = infiltration for Convective Back loaded pattern, I_{FFL} = infiltration for Frontal Front loaded pattern, I_{FML} = infiltration for Frontal Middle loaded pattern, I_{FBL}= infiltration for Frontal Back loaded pattern.

Table 6.2 Precipitation loss rate for 100 year ARI

Duration (min)	Continuing Loss Rate (mm hr^{-1})							
	I_{const}	I_{ARR}	I_{CFL}	I_{CML}	I_{CBL}	I_{FFL}	I_{FML}	I_{FBL}
5	159.24	159.23	150.06	151.10	150.06	153.16	157.97	157.55
10	125.13	125.30	112.95	113.24	112.95	117.41	122.13	119.57
20	92.52	87.86	83.01	81.28	83.01	87.70	90.26	85.37
30	73.17	71.73	67.23	64.51	67.23	71.11	71.32	66.98
60	44.57	43.39	43.17	40.31	43.17	44.79	43.27	40.83
120	24.37	26.39	26.45	24.17	22.48	27.56	25.41	23.19

I_{const} =infiltration for constant intensity, I_{ARR}= infiltration for ARR pattern, I_{CFL} = infiltration for Convective Front loaded pattern, I_{CML} = infiltration for Convective Middle loaded pattern, I_{CBL} = infiltration for Convective Back loaded pattern, I_{FFL} = infiltration for Frontal Front loaded pattern, I_{FML} = infiltration for Frontal Middle loaded pattern, I_{FBL}= infiltration for Frontal Back loaded pattern.

As part of flood management it is worthwhile to consider the proportion of the storm event, or storm burst, which is converted into surface runoff. The inverse of this is the proportion of the precipitation that is needed to satisfy the continuing losses that occur during development of the surface runoff.

Consideration of these results indicates that the continuing loss varies with duration and temporal pattern of rainfall. As expected, the total loss increases with the duration of rainfall. Conversely, the loss rate decreases with the rainfall duration. The importance of losses that occur after the cessation of rainfall is illustrated through consideration of these results.

Shown in Figures 6.3–6.10 is the portion of the rainfall that is needed for satisfaction of the continuing losses as a function of the burst duration and the ARI of the average intensity of the rainfall. As shown in these Figures, the portion of the rainfall lost changes with the rainfall intensity. It was found that the expected result of the higher rainfall intensities resulted in a lower portion of the rainfall forming losses. Also, it was observed that the portion of the storm rainfall forming losses for the higher intensity events was more variable with duration. This can be interpreted as highlighting the importance of the higher infiltration capacity at the commencement of storms.

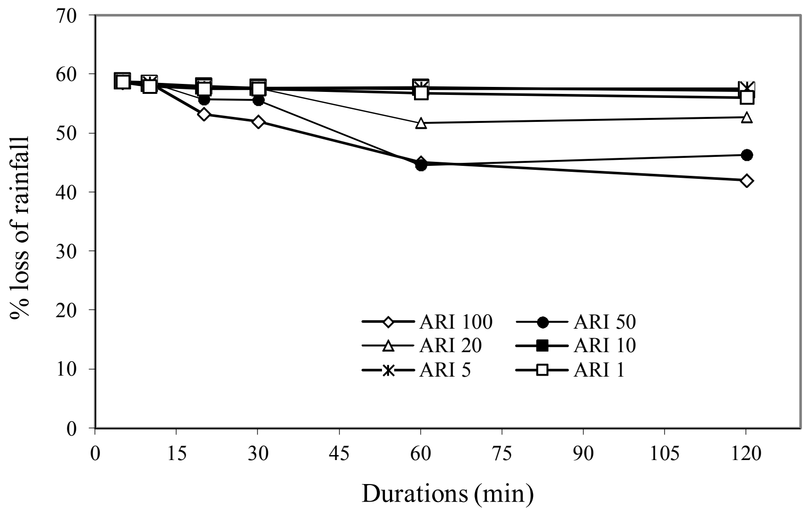

Figure 6.3 Percentage rainfall loss for ARR pattern

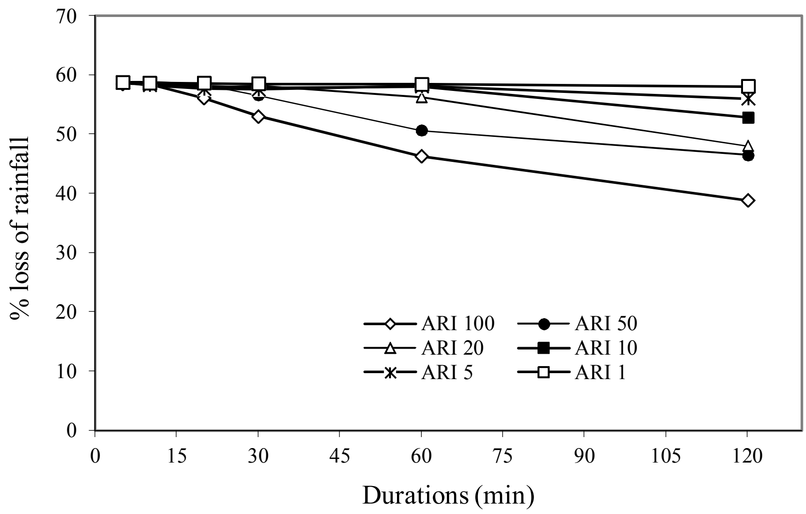

Figure 6.4 Percentage rainfall loss for constant intensity of rainfall

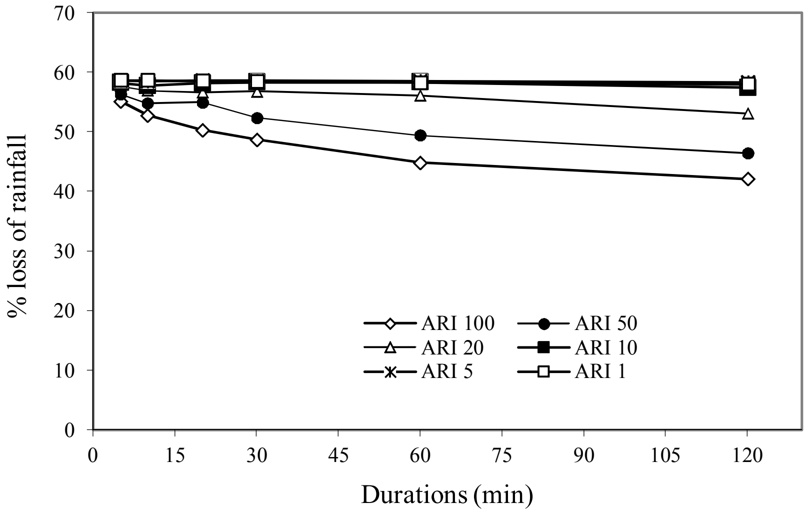

Figure 6.5 Percentage rainfall loss for Convective Front loaded (CFL) pattern

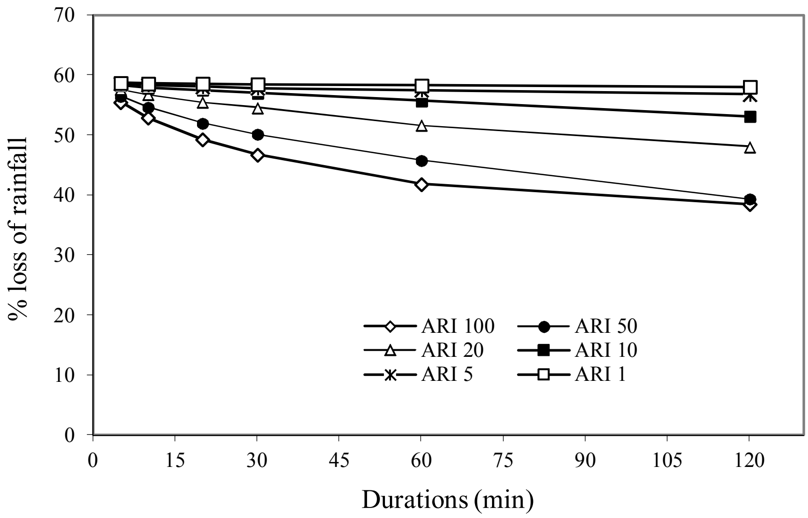

Figure 6.6 Percentage rainfall loss for Convective Middle loaded (CML) pattern

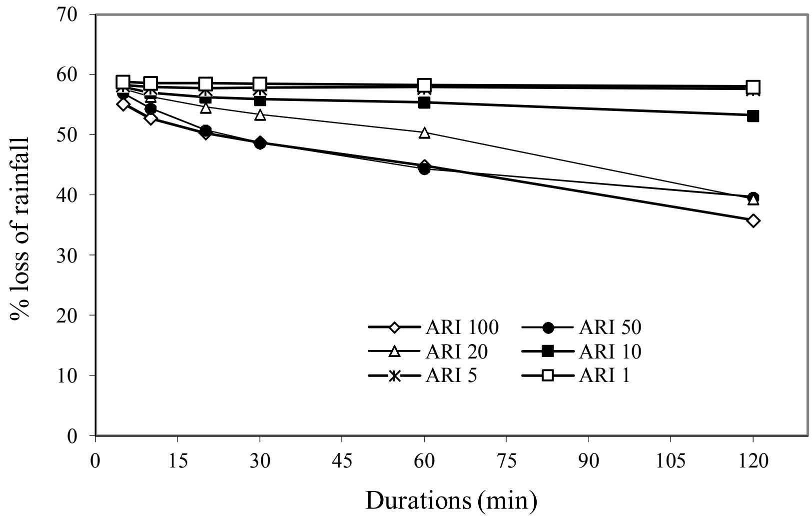

Figure 6.7 Percentage rainfall loss for Convective Back loaded (CBL) pattern

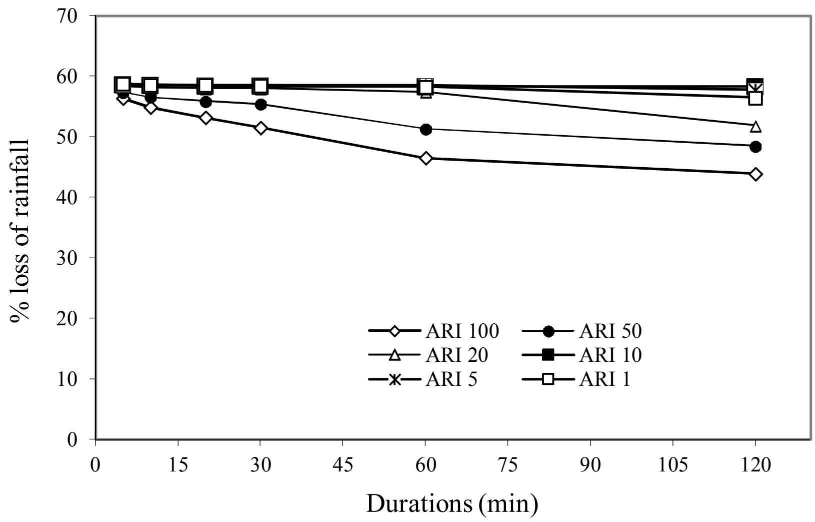

Figure 6.8 Percentage rainfall loss for Frontal Front loaded (FFL) pattern

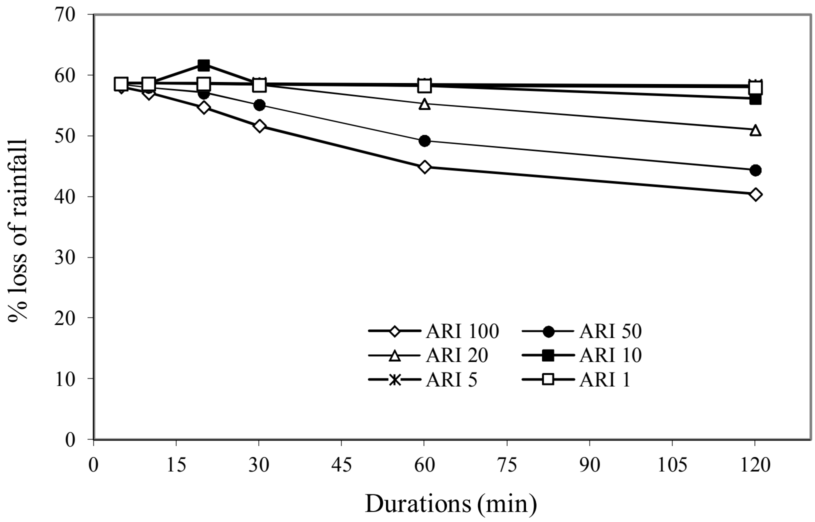

Figure 6.9 Percentage rainfall loss for Frontal Middle loaded (FML) pattern

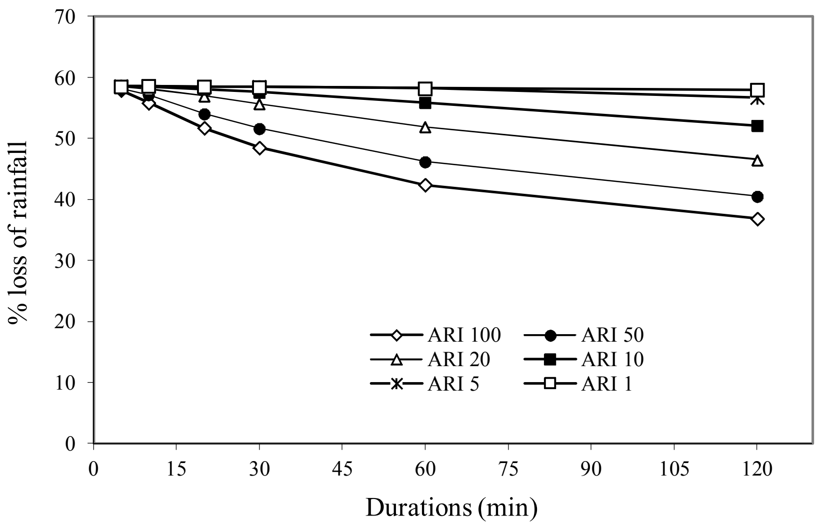

Figure 6.10 Percentage rainfall loss for Frontal Back loaded (FBL) pattern

The variability of infiltration loss for the temporal patters proposed by Varga et al. (2009) is shown in Figures 6.11 to 6.16. It was found that, even though all the parameters are same, the infiltration loss varied with the temporal patterns of the storm and that this variability increased with the storm duration. Based on the results of analysis done for both considering and non-considering rainfall patterns, variation of loss for 10 minutes duration is less than those for 120 minutes duration. It indicates that infiltration loss is more sensitive to rainfall temporal pattern for 120 minutes storm duration.

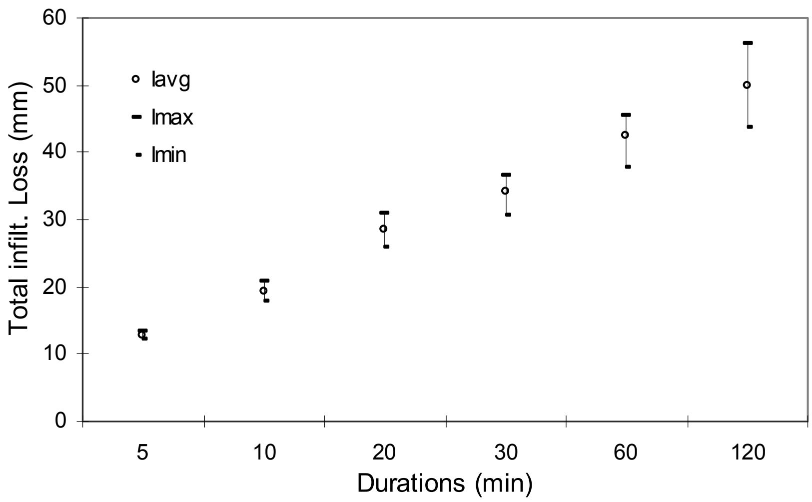

Figure 6.11 Variation of loss with temporal pattern for ARI 100 year

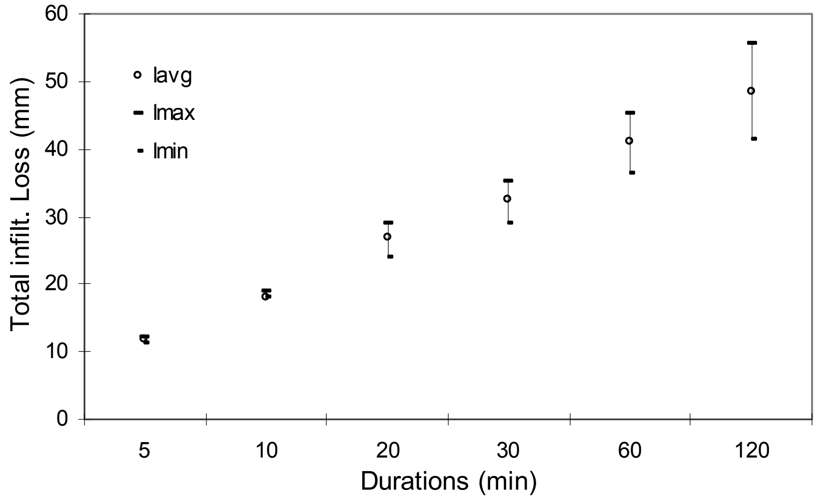

Figure 6.12 Variation of loss with temporal pattern for ARI 50 year

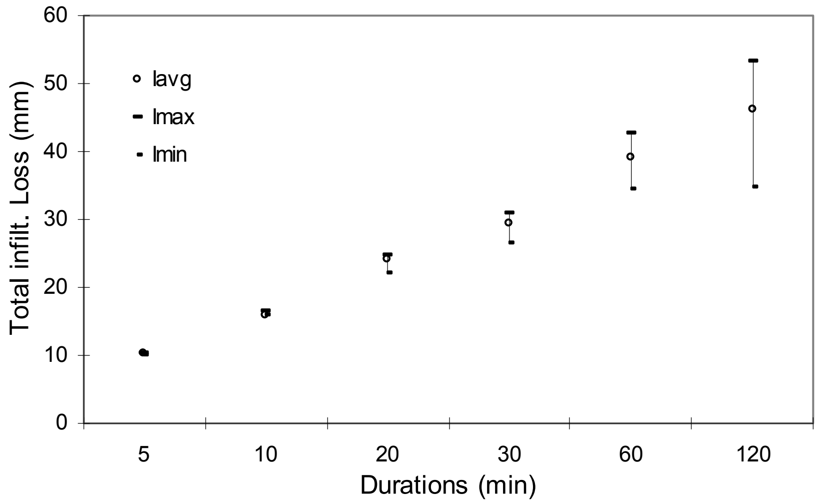

Figure 6.13 Variation of loss with temporal pattern ARI 20 year

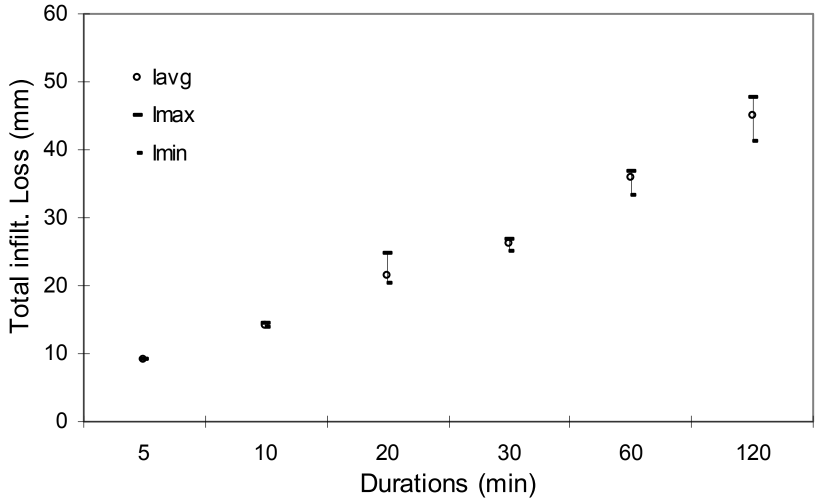

Figure 6.14 Variation of loss with temporal pattern ARI 10 year

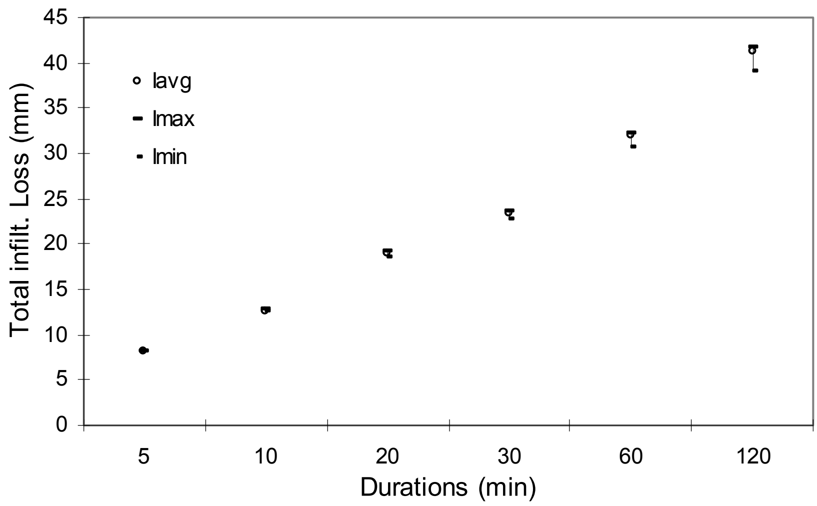

Figure 6.15 Variation of loss with temporal pattern for ARI 5 year

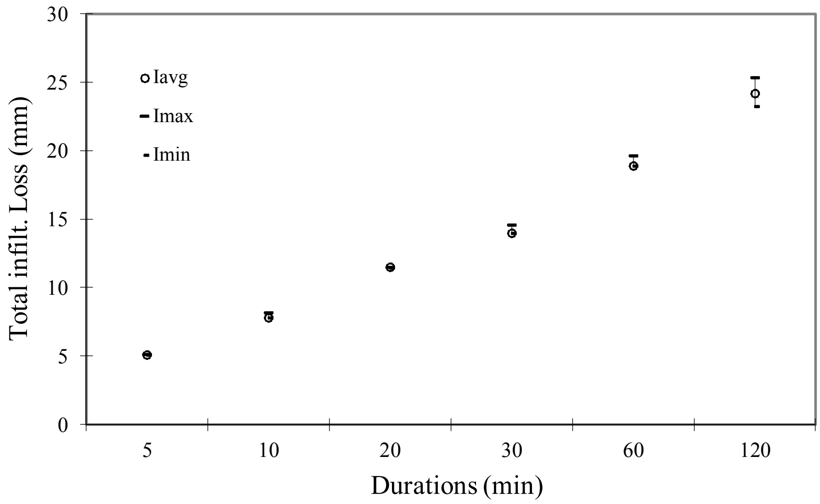

Figure 6.16 Variation of loss with temporal pattern for ARI 1 year

6.3.2 Variability in peak flows

The catchment was simulated with different temporal pattern of rainfall while other variables were same to examine the effect of temporal pattern of rainfall on peak flow. Shown in Figure 6.17 are the ranges of predicted 100 year ARI peak flows for the different storm burst durations; shown are the average of the predicted flows for that duration and the maximum and minimum design flows. Normalising the flows is shown in Figure 6.17 by the predicted design flow for constant rainfall intensity over the duration of the storm burst. The normalised values are shown in Table 6.3. While the results shown in this Table and Figure were derived from consideration of the 100 year ARI design storm bursts, similar results were obtained from the other storm bursts. Range of predicted design flows and normalised range of predicted peak flows for 50, 20, 10, 5 and 1 year ARI are shown in Figures C1–C5 and Tables C1–C5 in Appendix C.

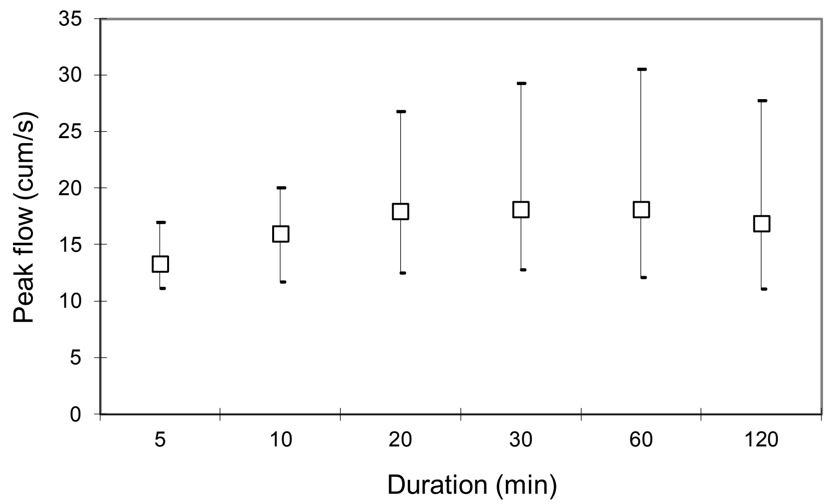

Figure 6.17 Range of predicted design flows for 100 year ARI

Table 6.3 Normalised range of predicted peak flows for 100 year ARI

Duration (min)	Predicted peak flows				
	Maximum	Minimum	Average	Constant	ARR
5	1.32	0.87	1.03	1.00	1.00
10	1.66	1.03	1.32	1.00	0.97
20	2.21	1.03	1.48	1.00	1.10
30	2.3	1.01	1.42	1.00	1.09
60	2.25	0.90	1.34	1.00	1.13
120	2.40	0.96	1.42	1.00	1.34

While knowledge of the average predicted peak flow is useful, it is the variation in the predicted peak flows that is the major concern herein. Figure 6.17 indicates, the effect of temporal pattern on peak flow is significant. Analysis of standard deviation was used to test the statistical significance. An assessment of the variability can be obtained from consideration of the standard deviation of the predicted peak flows. Shown in Figure 6.18 are the standard deviations in the predicted flows for all ARIs considered where the magnitude of the standard deviation increases with ARI; in other words, the standard deviation is largest for the more rare design events.

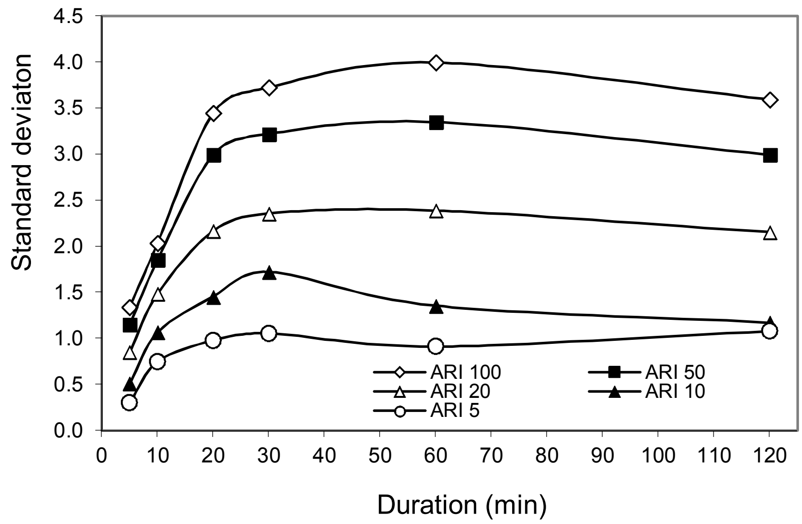

Figure 6.18 Standard deviation of the predicted peak flow for different ARI

However, consideration of the Coefficient of Variance (CV) (Table 6.4) suggests that this increase in the magnitude of the standard deviation of the predicted peak design flow is the result of increases in the predicted design peak flows rather than a change in the variability of the predicted peak flow. Nonetheless, as shown in Table 6.4, the CV does increase with burst duration before stabilising at approximately 0.22 for the 60 minute burst duration.

Table 6.4 Characteristics of predicted design flows for 100 year ARI

Duration	Predicted peak flow			Standard	CV	Confidence
	Const. Intensity	ARR	Average	Dev.		Limits
(min)	($m^3 s^{-1}$)	($m^3 s^{-1}$)	($m^3 s^{-1}$)	($m^3 s^{-1}$)		(%)
5	12.95	12.95	13.32	1.34	0.101	±16.6
10	12.13	11.78	15.96	2.03	0.128	±21.0
20	12.14	13.31	17.96	3.45	0.192	±31.5
30	12.77	13.98	18.13	3.73	0.206	±33.8
60	13.57	15.35	18.14	4.00	0.220	±36.2
120	11.60	15.56	16.48	3.60	0.218	±35.9

CV-Coefficient of Variance

In presentation of predicted design discharges obtained from statistical analysis of recorded flow sequences, it is common practice to show the 90% confidence limits to illustrate the prediction variability. Shown in Table 6.4 are the 90% confidence limits determined from the alternative rainfall patterns for the 100 year ARI storm bursts. Similar to the CV, these confidence limits increase with storm burst duration before stabilising at ±36% for storm bursts longer than 60 minutes.

It is worth noting that the predicted peak design discharge obtained from use of a constant intensity storm burst rainfall pattern will generally be lower than the average obtained from use of alternative rainfall patterns. Similar comments are valid for the design rainfall patterns recommended for use in Australian by ARR (Pilgrim, 1987). However, both predictions are within the 90% confidence limits.

6.3.3 Estimation of GPT and catchment runoff volume

Runoff volume generated in the Centennial Park Catchment was estimated. Design rainfall with 5 min duration and 1, 2, 5, 10, 20, 50 and 100 year ARI was used for catchment simulation using SWMM and runoff volume was extracted while GPT volume was calculated from the structural design drawings (Figure 6.19).

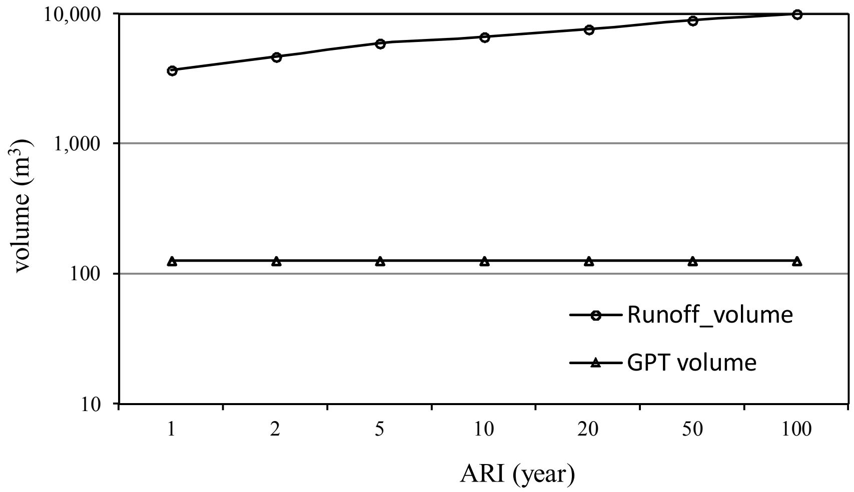

Figure 6.19 Catchment runoff volume for different ARI

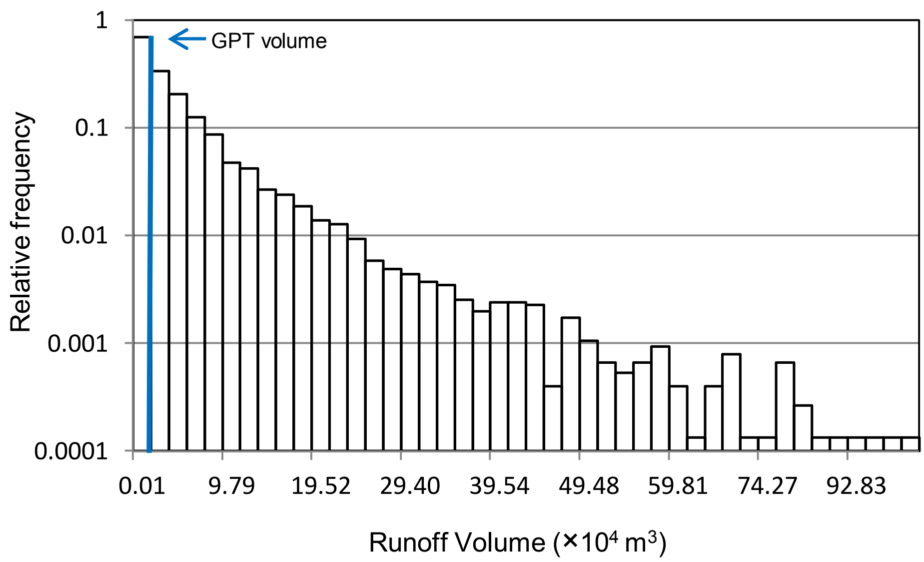

Figure 6.20 Frequency of catchment runoff volume

The daily rainfall data in Sydney observatory (1859–2002) was also investigated to determine the frequency of rainfall event and their corresponding runoff (Figure 6.20). In both cases (Figures 6.19 and 6.20), the runoff volume is much higher than the GPT volume.

6.4 Conclusions

It was found that the rainfall loss varied significantly with the variation of storm patterns, ARIs and durations. Furthermore, it was found that the rainfall loss increased and the rainfall loss rate decreased with storm duration. Hence a single loss rate independent of storm duration is unlikely to be appropriate for design flood estimation. From the analysis it was found that variation in the predicted design peak flows occurred. It was found that a constant intensity storm tended to predict a design peak flow which was less than the average predicted design peak flow but within the 90% confidence limits of the predictions. Confidence limits around the average predicted peak design flow were determined. The extent of these confidence limits increased with storm burst duration from 5 minutes to 60 minutes and reached ±36% of the average predicted peak flow. These non-dimensional confidence limits were found to be independent of the storm burst frequency (i.e. storm burst ARI). Finally, given the variability in the predicted design peak flow arising from the temporal pattern of the design rainfall, it is suggested that the common assumption used in prediction of design flows, namely that the storm burst frequency can be transferred to the flow frequency, is suspect. Estimated runoff volume and the GPT volume implies that the rainfall runoff volume from the catchment have minimal influence on the outlet nutrient release from GPT.

CHAPTER 7

Phosphorus Modelling in GPT

7 Phosphorus Modelling in GPT

7.1 Introduction

The deterioration of water quality is the major environmental issues in urban catchments (Zoppou, 1999). A number of CDS Gross Pollutant Trap have been installed in urban catchment drainage systems to restore water quality (Ball, 2004). Nutrients (N, P) release from trapped leaf litter in a GPT that enters downstream water bodies during storm events and causing degradation in water quality (Hogan and Walbridge, 2007). Many researchers carried out hydraulic modelling studies to evaluate the efficiency of removal of pollutant from storm water in GPT (Phillips et al., 1989; Quinn et al., 2005). This study was carried out phosphorus release from leaf litter and a novel conceptual model was developed for the prediction of phosphorus at the outlet of GPT. SWMM was applied to determine the catchment runoff which is used as GPT inflow and mathematical model used to create an integrated model able to predict the phosphorus response from GPT. The influence of inter-event dry period was also examined to determine the P release from leaf litter in GPT.

7.2 GPT modelling

GPT modelling involves hydrological and constituents inputs such as water flows and pollutant loading to describe the water quality process. To quantify phosphorus concentration it is needed to consider the hydraulic conditions related to GPT. Therefore, inflow and out flow relationship was established using level pool routing. Conceptual model was developed using hydraulic parameter based on continuity equation of flow and conservation of mass. The model was used to observe the variation of phosphorus concentration with hydraulic factors in the simulated system in response to the input data from catchment runoff hydrograph. Mass balance is the basic principle used to develop the model. The water system is divided in small segment for mass balance. The important components of the mass balance for water systems are as follows (Loucks et al., 2005):

- Changes of flow and concentration of pollutants into and out in a water system by transportation
- Changes by physical or chemical processes occurred within the segment such as biological degradation
- Changes by sources/ discharges to or from the water system. It means the addition of mass by trapped leaf litter and the mass from storm water by intakes. These are considered the overall source of the model boundary. The water flowing into or flowing out of the model is derived from a water quantity model

The mass balance components of a substance in a water system can be expressed by equation 7.1:

$$M_i^{t+\Delta t} = M_i^t + \Delta t\left(\frac{\Delta M_i}{\Delta t}\right)_{Tr} + \Delta t\left(\frac{\Delta M_i}{\Delta t}\right)_P + \Delta t\left(\frac{\Delta M_i}{\Delta t}\right)_S \qquad (7.1)$$

Where

- Δt is the time step
- M_i^t is the mass in the system at the beginning of the time step t
- $M_i^{t+\Delta t}$ is the mass in the system at the beginning of the time step $t+\Delta t$
- $(\Delta M_i/\Delta t)_{Tr}$ is the changes of mass in the system by transportation
- $(\Delta M_i/\Delta t)_p$ is the changes of mass in the system by physical, chemical or biological processes
- $(\Delta M_i/\Delta t)_S$ is the changes of mass in the system by sources

7.2.1 Conceptual model of GPT

As a part of treatment structure, GPT is installed in line in the drainage channel to remove gross pollutants from runoff. It is designed to retain gross pollutants including leaf litter from the incoming storm water. It was found that retaining leaf litter in GPT are decayed (Ball and Powell, 2006) with time. Runoff from upstream enters into the GPT, mixed with the sump water containing phosphorus which was released from stored leaf litter and flushes out to the downstream. A conceptual model was developed for transportation of phosphorus within the GPT. Catchment runoff enters the GPT through the inlet structure. The water then flows to wet sump through a concrete channel and controlled by diversion weir. During high inflow a part of inflow bypass through a bypass channel. The water from wet sump flows into outlet structure and then fall into the pond through outlet channel. The overview and basic understanding of the conceptual model of GPT system is shown in Figure 7.1.

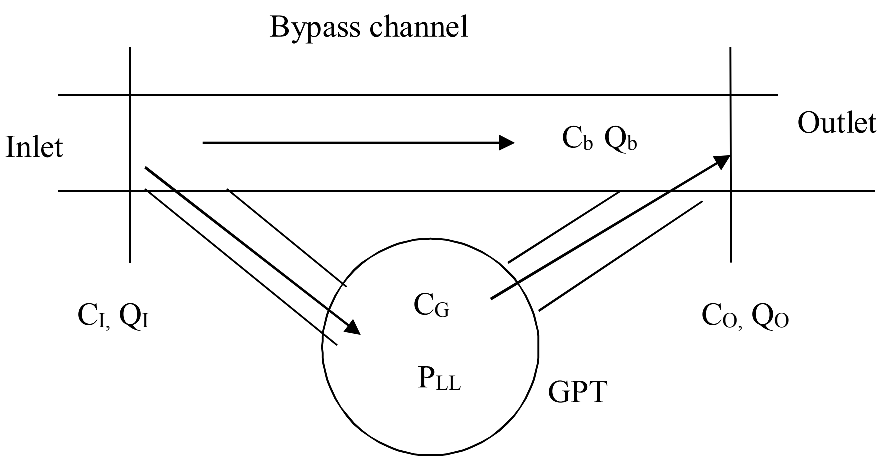

Figure 7.1 Conceptual model of phosphorus transportation through GPT

Where,

C_I = concentration of phosphorus at the inlet of GPT

C_O = concentration of phosphorus at the outlet of GPT

Q_I = flow of water at the inlet of GPT

Q_O = flow of water at the outlet of GPT

C_b = concentration of phosphorus in the bypass of GPT

Q_b = flow of water in the bypass of GPT

P_{LL} = mass of phosphorus released from leaf litter in GPT

C_G = concentration of phosphorus in GPT

Figure 7.1 shows the flow path of phosphorus in GPT system. In the diagram, arrows represent P transport with the flows. An Excel spread sheet was used for model simulation, based on the principle of conservation of mass (Jørgensen, 1994). The rate of change of volume of water in GPT can be expressed by mass balance equation. The conceptual model using the mass balance equations are outlined below in equation 7.2:

Rate of change of volume of water = Inflow – Outflow

$$\frac{\Delta V}{\Delta t} = Q_{GI} - Q_{GO} \qquad (7.2)$$

or, $$\frac{V_2 - V_1}{\Delta t} = \left(\frac{Q_1^I + Q_2^I}{2}\right) - \left(\frac{Q_1^O + Q_2^O}{2}\right)$$

or, $$\frac{Q_1^O + Q_2^O}{2} = \left(\frac{Q_1^I + Q_2^I}{2}\right) - \left(\frac{V_2 - V_1}{\Delta t}\right)$$

where,

Q_{GI} = inflow in GPT, $m^3\ s^{-1}$

Q_{GO}= outflow in GPT, $m^3\ s^{-1}$

Δt = time step, s

V = volume of water in GPT, m^3

Q_1^I = inflow in GPT at the beginning of time step Δt, $m^3\ s^{-1}$

Q_2^I = inflow in GPT at the end of time step Δt, $m^3\ s^{-1}$

Q_1^O = outflow in GPT at the beginning of time step Δt, $m^3\ s^{-1}$

Q_2^O = outflow in GPT at the end of time step Δt, $m^3\ s^{-1}$

V_1= volume of water in GPT at the beginning of time step Δt, m^3

V_2= volume of water in GPT at the end of time step Δt, m^3

7.2.2 Phosphorus model for GPT

Phosphorus released in GPT depends on the quantity of trapped leaf litter and length of storage. Thus, release of phosphorus increased with the amount of leaf litter, inter-event dry periods and cleaning interval. In each time interval it is assumed that the inflow is completely mixed with the water content in GPT. This means, the concentration of P in the outflow is equal to the concentration of P in GPT. The rate of change of mass of phosphorus in GPT is expressed in equation 7.3:

$$\frac{\Delta P}{\Delta t} = P_{GI} - P_{GO} + P_{LL} \qquad (7.3)$$

where,

ΔP = Change in mass of P in GPT mg

Δt = time step, s

P_{GI} = Mass of P entering in GPT at Δt, mg

P_{GO}= Mass of P leaving from GPT at Δt, mg

P_{LL}= Mass of P release from leaf litter in GPT at Δt, mg

Mass of phosphorus can be calculated from volume of water (V) and concentration of phosphorus (C) can be expressed as equation 7.4:

$$P = V \times C \tag{7.4}$$

Equation 7.3 can be expressed as equation 7.5 due to change in mass at the time interval Δt:

change in mass of P	=	mass of P entering at Δt	–	mass of P leaving at Δt	+	mass of P release at Δt

$$C_2^G V_2 - C_1^G V_1 = \frac{C_1^I Q_1^I + C_2^I Q_2^I}{2}\Delta t - \frac{C_1^O Q_1^O + C_2^O Q_2^O}{2}\Delta t + P_{LL}\Delta t \tag{7.5}$$

where,

C_1^G = Concentration of P in GPT at the beginning of time step Δt, mg L^{-1}

C_2^G = Concentration of P in GPT at the end of time step Δt, mg L^{-1}

C_1^I = Concentration of P at inlet of GPT at the beginning of time step Δt, mg L^{-1}

C_2^I = Concentration of P at inlet of GPT at the end of time step Δt, mg L^{-1}

C_1^O = Concentration of P at outlet of GPT at the beginning of time step Δt, mg L^{-1}

C_2^O = Concentration of P at outlet of GPT at the end of time step Δt, mg L^{-1}

P_{LL}= Mass of P release from leaf litter at time step Δt

P_{LL1}= Mass of P release from leaf litter at the beginning of time step Δt

P_{LL2}= Mass of P release from leaf litter at the end of time step Δt

V_1, V_2, Q_1^I, Q_2^I, Q_1^O and Q_2^O are previously defined.

Equation 7.5 can be rearranged to equation 7.6:

$$C_2^G V_2 = C_1^G V_1 + \frac{C_1^I Q_1^I + C_2^I Q_2^I}{2}\Delta t - \frac{C_1^O Q_1^O + C_2^O Q_2^O}{2}\Delta t + (P_{LL2} - P_{LL1})\Delta t \qquad (7.6)$$

It assumed that concentration of P in GPT is same as the concentration of P at the outlet of GPT, i.e. $C_1^G = C_1^O$ and $C_2^G = C_2^O$

$$C_2^G V_2 = C_1^G V_1 + \frac{C_1^I Q_1^I + C_2^I Q_2^I}{2}\Delta t - \frac{C_1^G Q_1^O + C_2^G Q_2^O}{2}\Delta t + (P_{LL2} - P_{LL1})\Delta t$$

or,

$$C_2^G V_2 + \frac{C_2^G Q_2^O}{2}\Delta t = C_1^G V_1 + \frac{C_1^I Q_1^I + C_2^I Q_2^I}{2}\Delta t - \frac{C_1^G Q_1^O}{2}\Delta t + (P_{LL2} - P_{LL1})\Delta t$$

or,

$$C_2^G \left(V_2 + \frac{Q_2^O}{2}\Delta t\right) = C_1^G V_1 + \frac{C_1^I Q_1^I + C_2^I Q_2^I}{2}\Delta t - \frac{C_1^G Q_1^O}{2}\Delta t + (P_{LL2} - P_{LL1})\Delta t$$

or,

$$C_2^G = \frac{C_1^G V_1 + \frac{C_1^I Q_1^I + C_2^I Q_2^I}{2}\Delta t - \frac{C_1^G Q_1^O}{2}\Delta t + (P_{LL2} - P_{LL1})\Delta t}{(V_2 + \frac{Q_2^O}{2}\Delta t)} \qquad (7.7)$$

Now, leaching of phosphorus during the time step is negligible (0.002%). Therefore it is considered that the amount of phosphorus present in GPT is constant, $P_{LL2} - P_{LL1} \sim 0$. Equation 7.7 can be written as equation 7.8:

$$C_2^G = \frac{C_1^G V_1 + \frac{C_1^I Q_1^I + C_2^I Q_2^I}{2}\Delta t - \frac{C_1^G Q_1^O}{2}\Delta t}{(V_2 + \frac{Q_2^O}{2}\Delta t)} \tag{7.8}$$

Now, C_1^G, V_1, Q_1^I, C_1^I, Q_2^I, Δt are known and discussed earlier. Q_1^O and Q_2^O are also known from application of continuity. Thus the only unknown, C_2^G can be estimated from equation 7.8.

The inflow hydrograph, stage discharge relationship, initial volume of water in GPT and time step were used in modelling. The inflow hydrograph for each event was obtained from catchment simulation. Initial volume of water was calculated from GPT size and initial outflow was taken as zero. One minute time step was used for routing. The initial mass of TP in GPT was used with respect to different inter-event dry period. TP concentration at inflow was considered as 0 for model simulation. Rainfall event for 1 year ARI and the duration 5, 10, 20, 30, 45, 60 and 120 min were considered for catchment simulation and the simulated hydrograph was used as the inlet flow. The selected model parameter were inlet flow, volume of water in GPT, maximum inflow, phosphorus release rate from leaf litter and mass of leaf is shown in Table 7.1.

Table 7.1 Selected model parameters for GPT

Name	unit	Source
Q_I (inflow)	$m^3\ s^{-1}$	Catchment simulation
Q_{Imax}(maximum inflow)	$m^3\ s^{-1}$	CDS authority
Q_O (outflow)	$m^3\ s^{-1}$	Stage-discharge relationship
V (volume of water)	m^3	Calculated from CDS (GPT) size
k (TP release rate)	d^{-1}	Determined from leaching experiment
M_{LL} (mass of leaf litter)	kg	Assumed

7.3 Application of model

The model is applied to simulate GPT installed at the study site. The hydrograph obtained from catchment simulation using SWMM (Huber and Dickinson, 1988) was used as the inlet hydrograph and the outflow was determined by level pool routing. Initial mass of TP in GPT was calculated based on the experimental result in chapter 5. It was assumed that the sump of GPT is full with leaf litter only.

7.3.1 Flow scenarios

An inflow hydrograph was generated by catchment simulation at GPT inlet. Using the inflow and storage volume in GPT, outflow was determined. A mass balance was used to obtained outflow. Mass balance can be expressed by the continuity equation (Viessman and Lewis, 2002) which states that the change in storage is equal to the inflow minus the outflow as equation 7.9:

$$\frac{\Delta S}{\Delta T} = I - Q \qquad (7.9)$$

where I = inflow rate, $m^3\ s^{-1}$

Q = outflow rate, $m^3\ s^{-1}$

S = storage, m^3

T = time

The required stage-discharge relationship and the hydrologic form of continuity equation were established which is used to obtain the outflow hydrograph.

Stage-discharge relationship

The flow Q at the outlet of GPT can be estimated by Manning's equation 7.10:

$$Q = \frac{1}{n} A R^{\frac{2}{3}} S_g^{\frac{1}{2}} \tag{7.10}$$

where,

A = wetted cross-sectional area, m^2

R = Hydraulic radius of A, $R = \frac{A}{W_P}$

W_P = Wetted perimeter of A

n = Manning's roughness coefficient, 0.012 for concrete surface (Huber and Dickinson, 1988)

S_g = gradient of water surface = $\frac{H_1 - H_2}{L}$

H_1 = Elevation of reach head of GPT

H_2 = Elevation of reach foot of GPT

H = Elevation difference = $H_1 - H_2$

L = Distance between diversion weir and outlet = 15.026 m

Cross-sectional area (A) and hydraulic radius (R) can be obtained from the following calculations (Figure 7.2).

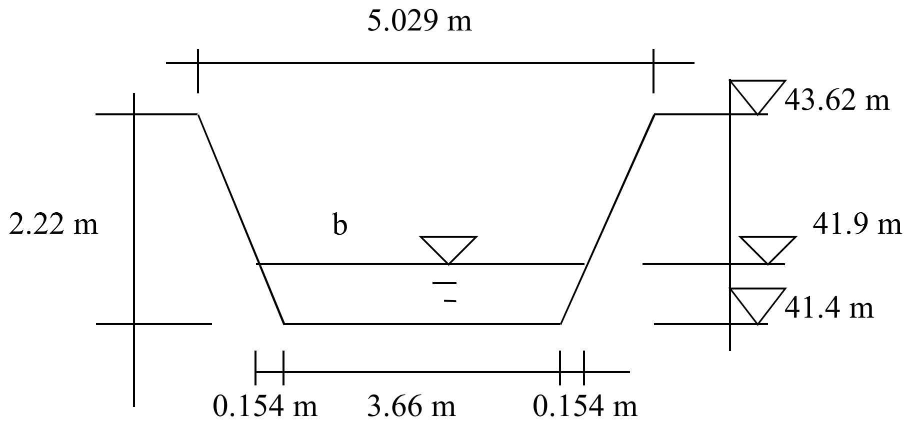

Figure 7.2 Cross-section of the GPT outlet

Now, b = 3.66 + 2 × 0.154 = 3.97 m, A = (3.66 + 3.97)/2 × 0.5 = 1.91 m^2

$W_P = 3.66 + 2 \times \sqrt{((0.5)^2 + (0.154)^2)} = 4.71$ m

R = 1.91/4.71 = 0.41

Stage and corresponding discharge is given in Table 7.2

Table 7.2 Stage and discharge of GPT at Centennial Park: cross-sectional area of flow = 1.91 m^2, hydraulic radius, R = 0.41m

Elevation of reach head, H_1 (m)	Elevation of reach foot, H_2 (m)	Manning's roughness coefficient, n	H_1-H_2 (m)	Gradient of water surface, S_g	Outflow Q (m^3 s^{-1})
41.90	41.9	0.012	0.00	0.000	0.000
41.95	41.9	0.012	0.05	0.003	5.069
42.00	41.9	0.012	0.10	0.007	7.169
42.05	41.9	0.012	0.15	0.010	8.780
42.10	41.9	0.012	0.20	0.013	10.138
42.15	41.9	0.012	0.25	0.017	11.335
42.20	41.9	0.012	0.30	0.020	12.417
42.30	41.9	0.012	0.40	0.027	14.338
42.40	41.9	0.012	0.50	0.034	16.030
42.50	41.9	0.012	0.60	0.040	17.560
42.60	41.9	0.012	0.70	0.047	18.967
42.70	41.9	0.012	0.80	0.054	20.277
42.80	41.9	0.012	0.90	0.060	21.507
42.90	41.9	0.012	1.00	0.067	22.670
43.00	41.9	0.012	1.10	0.074	23.777
43.10	41.9	0.012	1.20	0.080	24.834
43.20	41.9	0.012	1.30	0.087	25.848
43.30	41.9	0.012	1.40	0.094	26.824
43.40	41.9	0.012	1.50	0.101	27.765
43.50	41.9	0.012	1.60	0.107	28.676
43.60	41.9	0.012	1.70	0.114	29.558

Storage-discharge relationship

It is required to develop relationship with storage and outflow of GPT. The storage-discharge relationship was developed to route an inflow hydrograph through GPT using the hydrologic form of continuity equation, the continuity equation 7.9 can be rewritten as equation 7.11:

$$S_2 - S_1 = \frac{I_1 + I_2}{2}\Delta t - \frac{Q_1 + Q_2}{2}\Delta t \qquad (7.11)$$

where

S_1 = storage at the start of time step, m^3

S_2 = storage at the end of time step, m^3

I_1 = inflow at the start of time step, $m^3\ s^{-1}$

I_2 = inflow at the end of time step, $m^3\ s^{-1}$

Q_1 = outflow at the start of time step, $m^3\ s^{-1}$

Q_2 = outflow at the end of time step, $m^3\ s^{-1}$

Δt = time step, s

The equation 7.11 can be rewritten as equation 7.12:

$$(I_1 + I_2) + \left(\frac{2S_1}{\Delta t} - Q_1\right) = \left(\frac{2S_2}{\Delta t} + Q_2\right) \qquad (7.12)$$

To determine the unknown values S_2 and Q_2 in equation 7.11, the relationship between stage (H) and discharge (Q) is essential. The stage-discharge relationship was developed and used to derive storage discharge data, hence a relationship established between Q and

($2S_2/\Delta T + Q_2$). From stage-discharge relationship, the storage discharge data was obtained is shown in Table 7.3. The value of Q was calculated from a given stage (H) and the corresponding value of storage (S). The values of S and Q are then used to determine ($2S_2/\Delta T + Q_2$). The outflow of the next time step is obtained from the calculated value of ($2S_2/\Delta T + Q_2$) and Q and the steps were repeated for the duration of each event to get the outflow hydrograph.

Table 7.3 Storage-discharge relationship

Elevation of reach head, H_1 (m)	Elevation of reach foot, H_2 (m)	Discharge, Q ($m^3\ s^{-1}$)	Storage, S (m^3)	$2S/\Delta T + Q$ ($m^3\ s^{-1}$)
41.90	41.90	0.00	127.00	4.23
41.95	41.90	5.07	130.1	9.41
42.00	41.90	7.17	133.2	11.61
42.05	41.90	8.78	136.3	13.32
42.10	41.90	10.14	139.4	14.79
42.15	41.90	11.34	142.5	16.09
42.20	41.90	12.42	145.6	17.27
42.30	41.90	14.34	151.8	19.40
42.40	41.90	16.03	158	21.30
42.50	41.90	17.56	164.2	23.03
42.60	41.90	18.97	170.4	24.65
42.70	41.90	20.28	176.6	26.16
42.80	41.90	21.51	182.8	27.60
42.90	41.90	22.67	189	28.97
43.00	41.90	23.78	195.2	30.28

Volume of water in GPT (V)

Volume of sump = $\pi r_s^2 h_s$

where,

r_s = the radius of the sump, 1.5 m

h_s = the height of the sump, 2.05 m

Volume of sump = $\pi \times (1.5)^2 \times 2.05 = 14.49$ m^3

Volume of separation chamber = $\pi r_{sc}^2 h_{sc}$

where,

r_{sc} = the radius of the separation chamber, 3.192 m

h_{sc} = the height of the separation chamber, 3 m

Volume of separation chamber = $\pi \times (3.192)^2 \times 3.5 = 112.03$ m^3

Total initial volume of water in GPT = 126.52~127 m^3

Maximum inflow = 3 m^3 s^{-1}

To ensure the mass balance, the relative errors between the total inflow volumes and outflow volumes of each event were calculated using equation 7.13:

Relative error = (Total inflow–Total outflow)/ Total inflow*100% (7.13)

The relative errors were in the range 0.001% to 0.004% is shown in Table 7.4

Table 7.4 Relative error of inflow and outflow volume

Event (min)	Inflow ($m^3 s^{-1}$)	Outflow ($m^3 s^{-1}$)	Relative Error (%)
5	49.483	49.481	0.003
10	63.963	63.962	0.002
20	81.022	81.020	0.002
30	103.344	103.342	0.002
45	128.768	128.767	0.001
60	146.397	146.395	0.001
120	201.032	201.024	0.004

7.3.2 Phosphorus scenarios

The model predicted the concentration of phosphorus at the outlet of GPT. The model was simulated for storm events with 5, 10, 20, 30, 45, 60 and 120 minutes duration and 1 year ARI. For each storm event, 3, 5, 7, 10, 15, 20, 30, 60 and 90 days inter-event dry periods were used to estimate the mass of TP released from 1000 kg leaf litter (Table 7.5) considering the sump of GPT is full with leaf litter only. It is expected that 8 to 90% of the TP content in leaf litter can be released with respect to selected inter-event dry period. The amount of TP released at different mass of leaf litter was also determined and is shown in Table 7.6.

The mass of phosphorus release was determined using the first-order kinetic model is expressed as equation 7.14:

$$P_m = P_o (1-e^{-kT}) \qquad (7.14)$$

Where,

P_m= mass of P release at time t, mg

P_o= Initial P content in leaf litter, mg g^{-1}

k = decay constant, d^{-1}

T = Inter-event dry period, d

The mass of total P load in GPT was calculated as follows:

$P_{LL} = P_m \times M_{LL}$

Where, M_{LL} is the mass of leaf litter, P_{LL} and P_m are previously defined

Table 7.5 Phosphorus released from leaf litter in GPT at different inter-event dry periods

Mass of leaf litter in GPT (M_{LL}) (kg)	Initial P content in leaf litter (P_o) (gm kg^{-1})	Decay constant (k) (d^{-1})	Inter-event dry periods (T) (d)	e^{-kT}	Mass of P release P_{LL} (gm)
1000	0.381	0.0274	3	0.921	30.066
1000	0.381	0.0274	5	0.872	48.779
1000	0.381	0.0274	7	0.825	66.495
1000	0.381	0.0274	10	0.760	91.313
1000	0.381	0.0274	15	0.663	128.402
1000	0.381	0.0274	20	0.578	160.742
1000	0.381	0.0274	30	0.440	213.531
1000	0.381	0.0274	60	0.193	307.389
1000	0.381	0.0274	90	0.085	348.644

Table 7.6 Phosphorus released from different mass of leaf litter in GPT

Mass of leaf litter in GPT (M_{LL}) (kg)	Initial P content in leaf litter (P_o) (gm kg^{-1})	Decay constant (k) (d^{-1})	Inter-event dry periods (T) (d)	e^{-kT}	Mass of P release P_{LL} (gm)
100	0.381	0.0274	30	0.440	21.533
200	0.381	0.0274	30	0.440	42.706
300	0.381	0.0274	30	0.440	64.059
400	0.381	0.0274	30	0.440	85.412
500	0.381	0.0274	30	0.440	106.765
600	0.381	0.0274	30	0.440	128.118
700	0.381	0.0274	30	0.440	149.472
800	0.381	0.0274	30	0.440	170.825
900	0.381	0.0274	30	0.440	192.178
1000	0.381	0.0274	30	0.440	213.531

7.4 Results and discussion

The model predicted the concentration of phosphorus in outflow at different time steps. The decay constant determined experimentally (see chapter 5), was used to obtained mass of TP released from trapped leaf litter in GPT with respect to different inter-event dry period and the results are used in model simulation. The simulation results are shown in Figures 7.3–7.9:

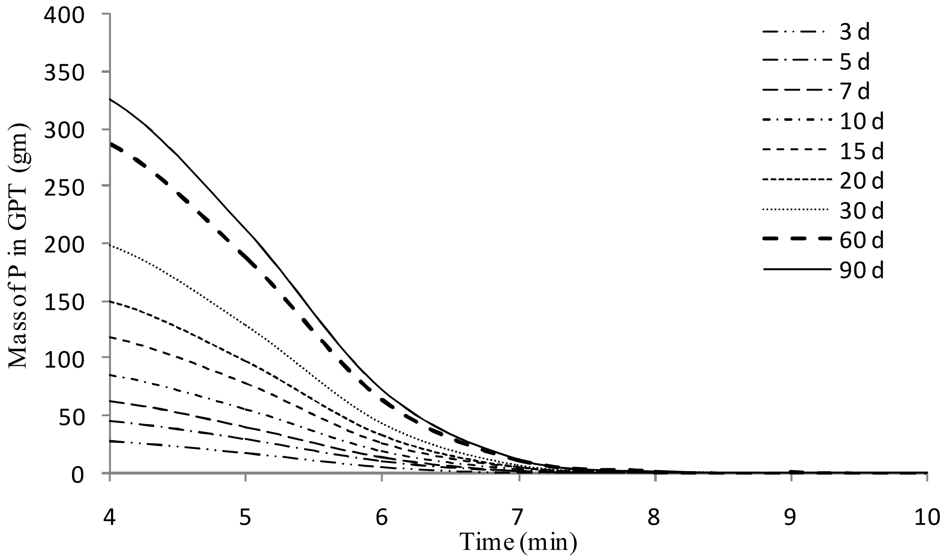

Figure 7.3 Mass of TP load in GPT with time for ARI 1 year, duration 5 min event

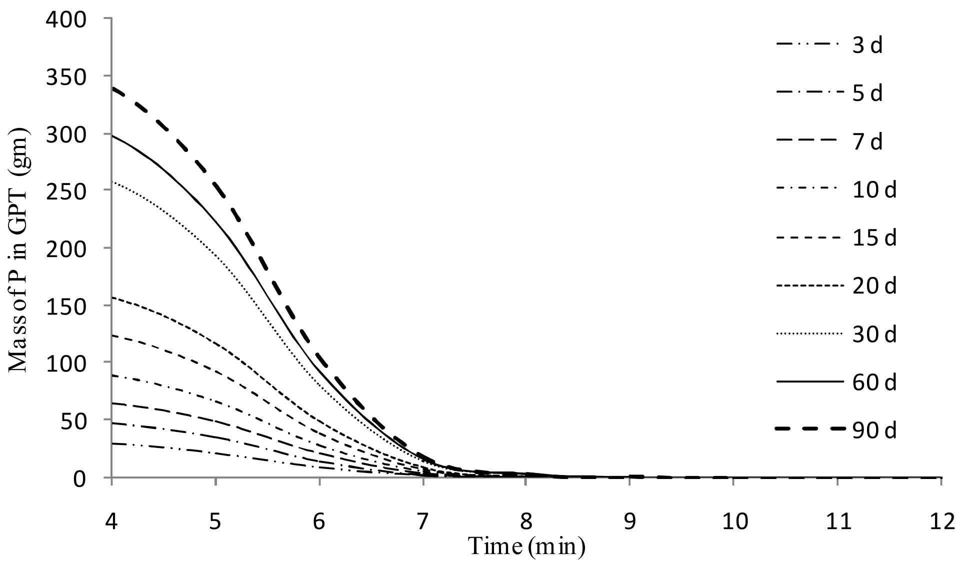

Figure 7.4 Mass of TP load in GPT with time for ARI 1 year, duration 10 min event

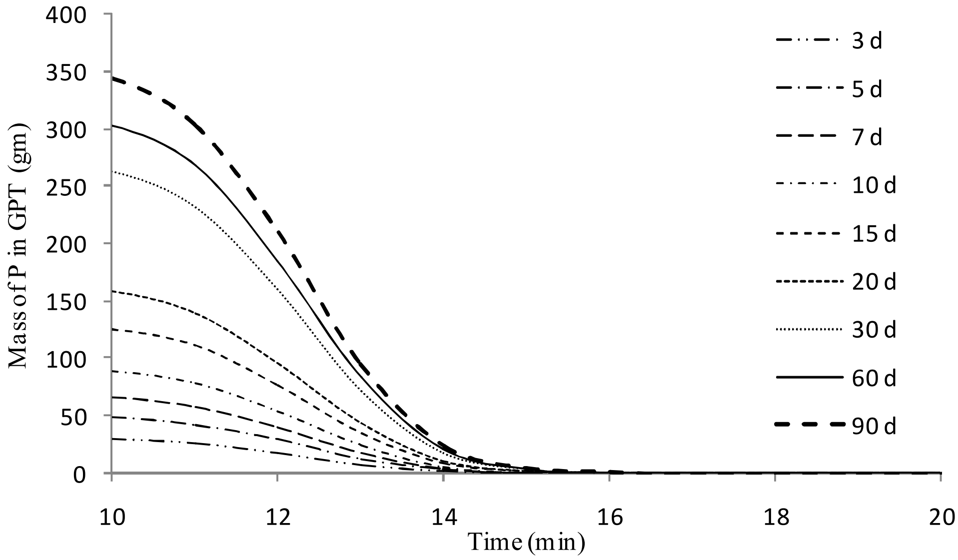

Figure 7.5 Mass of TP load in GPT with time for ARI 1 year, duration 20 min event

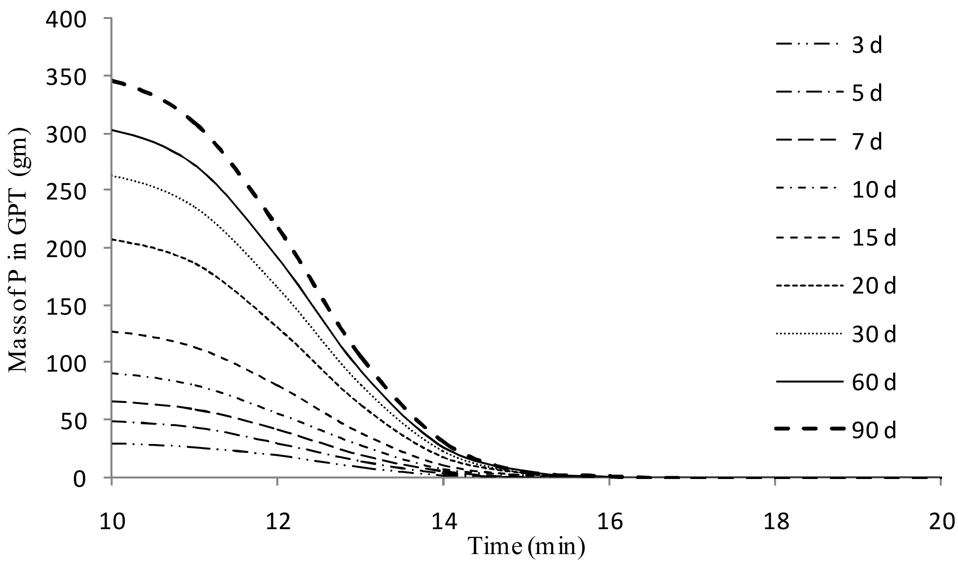

Figure 7.6 Mass of TP load in GPT with time for ARI 1 year, duration 30 min event

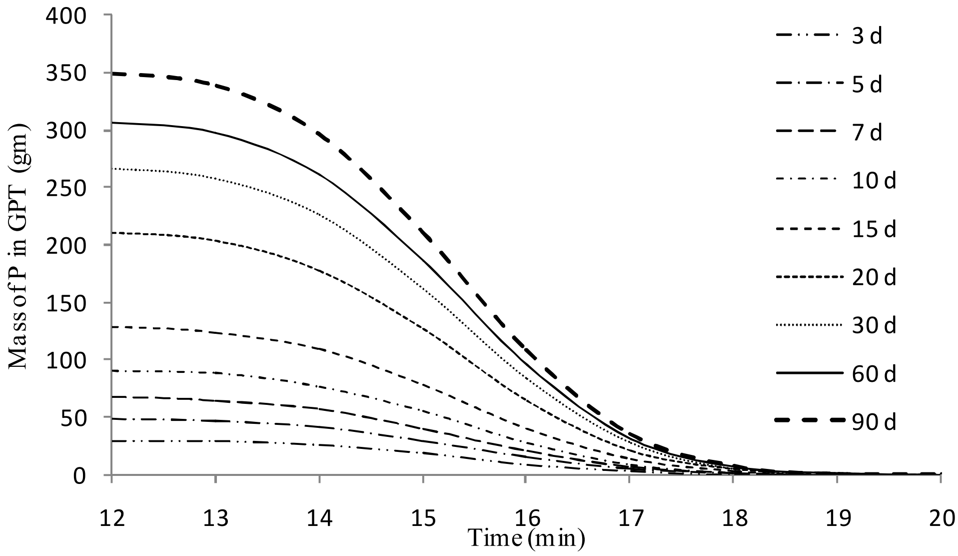

Figure 7.7 Mass of TP load in GPT with time for ARI 1 year, duration 45 min event

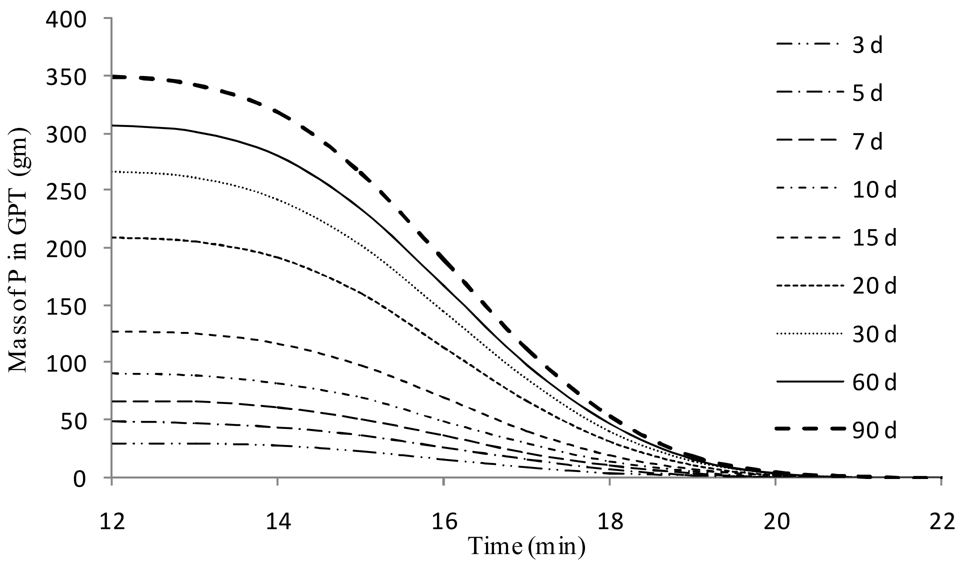

Figure 7.8 Mass of TP load in GPT with time for ARI 1 year, duration 60 min event

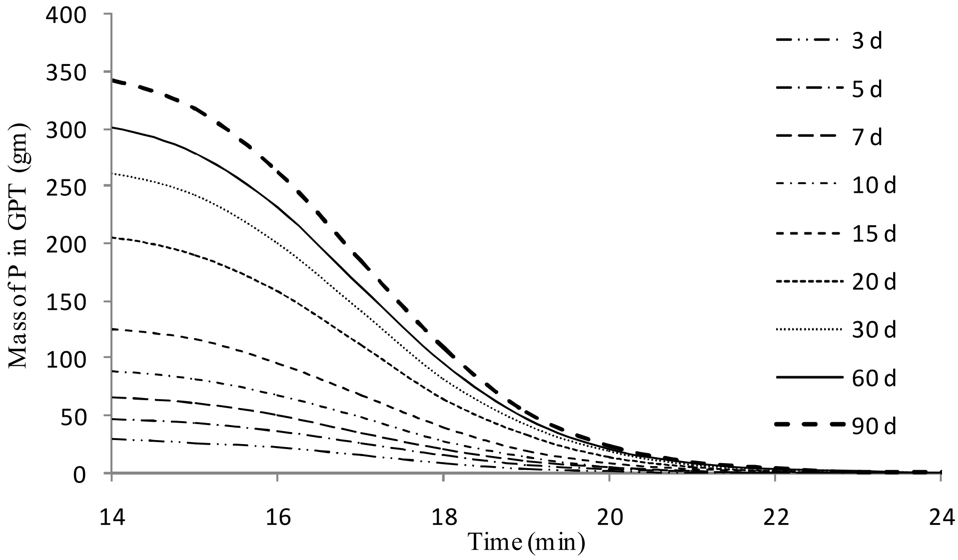

Figure 7.9 Mass of TP load in GPT with time for ARI 1 year, duration 120 min event

From model simulation, it was found that the amount of total phosphorus contain in GPT was flushed downstream within 15–30 minutes at the beginning of runoff. The total phosphorus (TP) released from leaf litter in GPT is increased over a longer period of time (Table 7.5) and consequently concentration of TP increased at the outlet. Simulation results revealed that all the TP flushed out at each event. This could be the reason of large volume of inflow to GPT from catchment which is enough to replace the water in GPT. This is a plausible explanation of complete flushed out of TP contain in GPT. The TP load in GPT found in this study at different inter-event dry period was also compared with TP load in the catchment runoff determined by other study (Abustan, 1997) and is shown in Table 7.7.

Table 7.7 Mass of total phosphorus (TP) in catchment runoff (Abustan, 1997)

Events	TP (mg L^{-1})	Runoff depth (mm)	Catchment area (km^2)	Runoff volume (m^3)	Mass of TP (g)
Nov.04, 1994	0.210	1.30	1.27	1651	347
Nov.20, 1994	0.836	2.27	1.27	2883	2410
Nov.29, 1994	0.517	0.75	1.27	953	493
Dec.08, 1994	0.300	0.95	1.27	1207	362
Dec.22, 1994	0.555	1.3	1.27	1651	916

Table 7.7 showed that the mass of total phosphorus associated with catchment runoff transported to the downstream were in the ranges 347–2410 g. The maximum amount of phosphorus released from leaf litter in GPT is 349 g found in this study (Table 7.5). This amount is 14% of the maximum (2410 g), 30% of the average (1163 g) and more than 100% of lowest (347 g) value of total phosphorus in the catchment runoff (Table 7.7). This suggests that the degradation of leaf litter play an important role to increase total phosphorus in GPT. Therefore, the phosphorus in catchment runoff may be accumulated with GPT phosphorus and transported to the downstream and TP concentration increased in the receiving water.

7.5 Conclusions

The predicted amount of phosphorus at the outlet of GPT suggests that total mass of TP released in GPT was flushed to the downstream. It is expected that the increase values of TP in GPT should result in an increase of outlet values. It was observed that, while increase the values of TP in GPT for different inter-event dry periods, the concentration of TP at the outlet was also increased. For all simulation, no negative concentration was found. This assured that the model developed in this study is suitable for predicting pollutant concentration at the outlet of GPT. Flow from different catchment and different species of leaf litter might differ the amount of TP flushed in relation to actual situation. However, it is difficult to predict accurately the future storm events. Also, it is not possible to know what extent of initial biological degradation would occur in an ecosystem because some decay processes assumed to occur instantaneously. This type of uncertainty strongly correlated with the P release consequently the P transportation system.

CHAPTER 8

Conclusions

8 Conclusions

8.1 Introduction

In this study, total phosphorus (TP) and total nitrogen (TN) release were evaluated from leaf litter in a GPT environment. Hence phosphorus transportation from the GPT was investigated by using the relationship between runoff volume and leaf litter decay in the GPT. This was carried out using modelling approach based on mass continuity for flow and for phosphorus. SWMM was applied to assess the variability of predicted catchment runoff and the influence of this variability on the phosphorus transported from a GPT. To achieve this, rainfall data for different ARI and duration were generated and used for modelling of nutrients at a GPT. Consideration of the results indicated that the runoff volume generated by 1 year ARI storm burst was sufficient to replace the water in GPT. Therefore, the biodegraded substances developed in a GPT during inter-event period will be flushed out with the runoff. The resulting work of this study will permit better guidelines for stormwater management.

Nutrients release from leaf litter

Nutrients were estimated from leaf litter in Chapter 5. It was found that TP and TN concentrations in leaves collected from Centennial Park were 0.095 % (0.381 mg g^{-1}) and 1.28 % (5.1 mg g^{-1}) dry wt of leaves respectively. The TP and TN release experiments were conducted from leaf litter in GPT environment. The results showed that the quantity of TP loss from leaf litter was higher for the first 90 days than that for the later 90 days. The phosphorus release from the leaf litter stored in a GPT process can be described by first-order decay model. It was also observed that the initial phosphorus release from leaf litter was faster than the nitrogen within the same time frame (22 d). The basic water quality parameters such as pH, conductivity and dissolved oxygen were also considered to determine the influence of this parameters during leaf litter decomposition.

Runoff variability

Hydraulic variability was investigated in Chapter 6 for the prediction of catchment runoff. The SWMM model was used to simulate the runoff resulting from rainfall consisting of the set of the generated hyetographs with different temporal patterns. Continuing losses were predicted using Hortonian infiltration. Rainfall temporal patterns such as constant intensity, ARR and Varga's (60) patterns were used with 6 different storm durations and 6 different ARIs to obtain 62 alternative design flow predictions. The storm durations considered were 5, 10, 20, 30, 60 and 120 minutes durations while the storm burst frequencies considered were 1, 5, 10, 20, 50 and 100 year ARIs. These alternative rainfalls were determined using information available in Australian Rainfall Runoff (ARR'87). The effect of temporal pattern on peak flow is significant. Assessments of the variability were undertaken using standard deviation of predicted peak flows and found it was increased with the increase of ARI. On the other hand, consideration of the Coefficient of Variance (CV) indicated that this increase in the magnitude of the standard deviation of the predicted peak design flow is the result of increases in the predicted design peak flows rather than a change in the variability of the predicted peak flow. The predicted peak design discharge obtained using constant intensity storm event was lower than the average obtained from use of alternative rainfall patterns. In both cases predictions are within the 90% confidence limits. The continuing loss was found to vary with the duration and temporal pattern of rainfall. The results showed that the higher the rainfall intensities were, the lower the storm rainfall losses were. Rainfall loss for the higher intensity events is also depends on the duration. This is related to the higher infiltration capacity at the commencement of storms. The results showed that infiltration loss is more sensitive to the rainfall temporal pattern for longer storm durations.

Modelling phosphorus

The conceptual model for the transportation of phosphorus from the GPT was developed in Chapter 7. The main objective of the model was to simulate the hydraulic conditions within the GPT based on inflow and outflow data measurement and to quantify TP and TN which influence on receiving water. The modelling is established the relationship among the mass of leaf litter captured by the GPT, nutrient release rate, catchment runoff, size of inlet and outlet and initial volume of water in GPT. The TP load from leaf litter in GPT was estimated using first-order rate constant which was determined experimentally for different inter-event dry period and this result were used in model simulation. GPT wet sump was considered filled with leaf litter only and model simulation was carried out for different retention time. From model simulation, it was found that total phosphorus load in GPT was flushed out to the downstream within the commencement of storm events (15–30 minutes). GPT phosphorus loading is also associated with the variation of phosphorus in catchment runoff.

8.2 Conclusions

Nutrients release from leaf litter

Leaf litter collected from Centennial Park is a significant source of nitrogen and phosphorus. TP released from leaf litter was found to be higher for the first 90 days due to higher leaching of phosphorus. The initial leaching data also showed that the TP released more rapid rate than TN. The TP released from leaf litter in a stagnant GPT provides a considerable contribution to TP load in a catchment. This implies that timely cleaning of GPT is required. The analysis of leaching data from leaf litter in terms of rate constant provided useful information for leaf litter decay. The release of TP from GPT was correlated to the mass of stored leaf litter and the inter-event dry period. The water quality parameters are influenced by the nutrient release from leaf litter.

Runoff variability

The predicted peak flow and loss were significantly varied with rainfall temporal patterns. The continuing loss does not remaining constant for the entire storm event but decrease with time. This suggests that a single loss rate independent of storm duration is unlikely to be appropriate for runoff prediction.

It was also observed that the runoff volume is significantly varied with temporal pattern of rainfall. However, runoff volume is much higher than the GPT volume. Since the outflow volume is strongly related by the inflow volume, this indicates that the rainfall runoff volume from the catchment have minimal influence on the outlet TP release from GPT.

Modelling phosphorus

The phosphorus at the outlet of GPT was quantified using this model. In a GPT, a longer inter-event dry period increases the concentrations of TP due to the degradation of leaf litter occurring within the GPT. This suggests that inter-event dry period play an important role in leaf litter decay processes within GPT. This information will help catchment managers to implement integrated catchment management system through timely cleaning GPT and control the receiving water quality.

8.3 Research contribution

This study has provided a fundamental knowledge for understanding the TP and TN released from leaf litter in a GPT and their control performance on water quality system through GPT modelling. To mitigate stormwater quality effective stormwater management is needed. This required considering the factors related to the stormwater quality. This work was contributed to improved understanding the impact of GPT which is one of the important factors in relation to urban stormwater quality as well as receiving water quality. Because the nutrient generates due to degradation during stagnant condition in GPT and fall into receiving water and deteriorated the water quality. However, most of the previous work was carried out for the removal of nutrients from GPT. There are different pollutants associated in stormwater. This study is confined on biological degradation of leaf litter to release nutrients (phosphorus, nitrogen) whereas the other type (chemical, biological and physical) of treatment, removal and separation are commonly researched. This research indicated that the impact of GPT in relation to phosphorus release from trapped leaf litter is an additional factor on urban stormwater quality and management should be taken into consideration these issues to mitigate the water quality problem. The quantification of phosphorus release from leaf litter in GPT is novel. Fundamental knowledge of this work including GPT modelling for phosphorus quantification as well as their transportation will provide the basis for field level studies. This work is the guidelines for effective operation and maintenance of GPT. This information is important for stormwater pollutants management in the urban environment.

8.4 Future research needs

The research study has provided an understanding the relationship between the inter-event dry period and leaf litter decay in a GPT system. However, there are a number of further works are needed which will enhance the knowledge gap.

The rate of nitrogen release from leaf litter in GPT is a complex and the initial decrease portion of the curve was used to determine the rate constant. However, further work is needed to better understand this mechanism. There is also need to investigate the TP and TN release rate for other leaf litter with different nutrient composition and location.

The initial biological degradation in an ecosystem which is associated with catchment runoff are needed to be considered with the TP release consequently the TP transportation system.

This study was carried out to investigate the phosphorus transportation in a GPT systems using a model based on conceptual approaches and decay analysis with respect to hydrologic conditions. Detailed further investigations should be carried out using laboratory scale model to validate this work.

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List of Publications

- Ball, J. E. and Ara, J. (2012). Variability in design flood flows from alternative rainfall temporal patterns. 10th International Conference on Hydroinformatics (HIC), July 14-16, Hamburg, Germany.
- Ball, J. E. and Ara, J. (2011). Variability of rainfall losses in urban flood prediction. 4th International Perspective on Water Resources and the Environment (IPWE), Singapore.
- Ball, J. E. and Ara, J. (2010). Phosphorus release from gross pollutant traps in urban environments. 6th International Symposium on Environmental Hydraulics, Athens, Greece.

Appendices

Appendix A

Table A1 Initial concentration of phosphorus and nitrogen in dry mass of leaf litter

Sample	Nitrogen ($mg\ g^{-1}$)	Phosphorus
Sample 1	5.1	0.408
Sample 2	4.9	0.388
Sample 3	5.1	0.349

Table A2 Concentration of phosphorus in water

Time	Concentration of phosphorus		
(days)	Bucket 1 ($mg\ L^{-1}$)	Bucket 2 ($mg\ L^{-1}$)	Bucket 3 ($mg\ L^{-1}$)
1	0.78	0.80	0.73
5	1.65	1.75	1.65
10	2.20	2.30	2.40
15	2.50	2.70	2.60
22	2.90	3.40	3.10
37	4.00	3.80	3.40
56	3.80	4.30	4.10
70	3.90	4.40	4.20
90	3.90	4.50	4.40
180	4.00	4.70	4.50

Table A3 Concentration of nitrogen in water

Time	Concentration of nitrogen		
(days)	Bucket 1 ($mg\ L^{-1}$)	Bucket 2 ($mg\ L^{-1}$)	Bucket 3 ($mg\ L^{-1}$)
1	1.5	2.5	1.2
5	5.2	4.7	6.6
10	8.0	6.5	5.8
15	9.6	8.5	8.9
22	11.0	14.0	16.0
37	11.0	12.0	19.0
56	6.1	8.2	8.1
70	5.7	4.9	5.6
90	6.3	4.0	5.0
180	12.0	11.0	13.0

Table A4 Nitrogen release from leaf litter with times

Decomposition (days)	TN in water mg L^{-1} (mean ± SD)	TN remained in leaf litter mg g^{-1} dry mass (mean ± SD)	TN released (%)
37	14.0 ± 4.36	4.083	19.94
56	7.47 ± 1.18	4.984	2.28
70	5.40 ± 0.44	5.271	-
90	5.10 ± 1.15	5.323	-
180	12.0 ± 1.00	4.443	12.88

initial TN in mixed leaves = 5.1 ± 0.17 mg g^{-1} of dry mass. Each data point is the mean of nine replicates ± SD (standard deviation). Standard deviation indicates the variability between data sets. TN - total nitrogen

Appendix B

Table B1 Default parameters for calibration (Abustan, 1997)

Parameters	Default values
Percentage of impervious areas	30%
Total width of the catchment	6280 m
Impervious depression storage	0.2 mm (dry), 1.0 mm (wet)
Pervious depression storage	2.5 mm
Impervious Manning's n	0.012
Pervious Manning's n	0.03
Hortons maximum infiltration rate	250 mm hr^{-1}
Hortons maximum infiltration rate	25 mm hr^{-1}
Hortons maximum infiltration rate	0.00115

Table B2 Total precipitation loss for 50 year ARI

Duration (min)	Total loss (mm)							
	I_{const}	I_{ARR}	I_{CFL}	I_{CML}	I_{CBL}	I_{FFL}	I_{FML}	I_{FBL}
5	12.09	12.09	11.59	11.63	11.71	11.80	12.04	11.98
10	18.99	18.96	17.71	17.68	17.60	18.28	18.74	18.50
20	28.99	27.69	27.29	25.83	25.22	27.74	28.36	26.88
30	35.04	34.48	32.47	31.08	30.18	34.33	34.20	32.03
60	43.56	38.37	42.56	39.45	38.22	44.19	42.39	39.82
120	52.08	51.93	52.08	44.13	44.50	54.35	49.84	45.55

I_{const} =infiltration for constant intensity, I_{ARR}= infiltration for ARR pattern, I_{CFL} = infiltration for Convective Front loaded pattern, I_{CML} = infiltration for Convective Middle loaded pattern, I_{CBL} = infiltration for Convective Back loaded pattern, I_{FFL} = infiltration for Frontal Front loaded pattern, I_{FML} = infiltration for Frontal Middle loaded pattern, I_{FBL}= infiltration for Frontal Back loaded pattern.

Table B3 Total precipitation loss for 20 year ARI

Duration (min)	Total loss (mm)							
	I_{const}	I_{ARR}	I_{CFL}	I_{CML}	I_{CBL}	I_{FFL}	I_{FML}	I_{FBL}
5	10.42	10.42	10.24	10.23	10.23	10.35	10.42	10.39
10	16.24	16.27	15.84	15.80	15.70	16.16	16.30	16.17
20	24.45	24.43	23.96	23.49	23.13	24.55	24.79	24.13
30	30.49	30.28	29.80	28.64	28.04	30.43	30.63	29.26
60	40.99	37.71	40.89	37.64	36.77	41.84	40.36	37.87
120	45.49	49.96	50.33	45.53	37.35	51.49	48.37	44.14

I_{const} =infiltration for constant intensity, I_{ARR}= infiltration for ARR pattern, I_{CFL} = infiltration for Convective Front loaded pattern, I_{CML} = infiltration for Convective Middle loaded pattern, I_{CBL} = infiltration for Convective Back loaded pattern, I_{FFL} = infiltration for Frontal Front loaded pattern, I_{FML} = infiltration for Frontal Middle loaded pattern, I_{FBL}= infiltration for Frontal Back loaded pattern.

Table B4 Total precipitation loss for 10 year ARI

Duration (min)	Total loss (mm)							
	I_{const}	I_{ARR}	I_{CFL}	I_{CML}	I_{CBL}	I_{FFL}	I_{FML}	I_{FBL}
5	9.16	9.16	9.07	9.09	9.02	9.14	9.15	9.14
10	14.19	14.21	14.05	14.09	13.88	14.24	14.28	14.24
20	21.32	21.24	21.32	21.08	20.63	21.42	22.63	21.32
30	26.38	26.32	26.63	26.02	25.52	26.63	26.77	26.32
60	36.87	36.25	36.64	35.00	34.81	36.62	36.60	35.13
120	43.10	46.72	46.85	43.33	43.46	47.57	45.87	42.54

I_{const} =infiltration for constant intensity, I_{ARR}= infiltration for ARR pattern, I_{CFL} = infiltration for Convective Front loaded pattern, I_{CML} = infiltration for Convective Middle loaded pattern, I_{CBL} = infiltration for Convective Back loaded pattern, I_{FFL} = infiltration for Frontal Front loaded pattern, I_{FML} = infiltration for Frontal Middle loaded pattern, I_{FBL}= infiltration for Frontal Back loaded pattern.

Table B5 Total precipitation loss for 5 year ARI

Duration	Total loss (mm)							
(min)	I_{const}	I_{ARR}	I_{CFL}	I_{CML}	I_{CBL}	I_{FFL}	I_{FML}	I_{FBL}
5	8.22	8.22	8.20	8.20	8.17	8.22	8.22	8.21
10	12.62	12.66	12.67	12.64	12.56	12.70	12.72	12.71
20	18.77	18.80	19.10	18.92	18.80	19.06	19.11	19.07
30	23.16	23.19	23.58	23.28	23.26	23.55	23.59	23.56
60	32.18	31.72	32.25	31.69	31.91	32.22	32.25	32.10
120	40.08	41.22	41.77	40.66	41.28	41.35	41.74	40.64

I_{const} =infiltration for constant intensity, I_{ARR}= infiltration for ARR pattern, I_{CFL} = infiltration for Convective Front loaded pattern, I_{CML} = infiltration for Convective Middle loaded pattern, I_{CBL} = infiltration for Convective Back loaded pattern, I_{FFL} = infiltration for Frontal Front loaded pattern, I_{FML} = infiltration for Frontal Middle loaded pattern, I_{FBL}= infiltration for Frontal Back loaded pattern.

Table B6 Total precipitation loss for 1 year ARI

Duration	Total loss (mm)							
(min)	I_{const}	I_{ARR}	I_{CFL}	I_{CML}	I_{CBL}	I_{FFL}	I_{FML}	I_{FBL}
5	9.16	9.16	9.07	9.09	9.02	9.14	9.15	9.14
10	14.19	14.21	14.05	14.09	13.88	14.24	14.28	14.24
20	21.32	21.24	21.32	21.08	20.63	21.42	22.63	21.32
30	26.38	26.32	26.63	26.02	25.52	26.63	26.77	26.32
60	36.87	36.25	36.64	35.00	34.81	36.62	36.60	35.13
120	43.10	46.72	46.85	43.33	43.46	47.57	45.87	42.54

I_{const} =infiltration for constant intensity, I_{ARR}= infiltration for ARR pattern, I_{CFL} = infiltration for Convective Front loaded pattern, I_{CML} = infiltration for Convective Middle loaded pattern, I_{CBL} = infiltration for Convective Back loaded pattern, I_{FFL} = infiltration for Frontal Front loaded pattern, I_{FML} = infiltration for Frontal Middle loaded pattern, I_{FBL}= infiltration for Frontal Back loaded pattern.

Table B7 Precipitation loss rate for 50 year ARI

Duration	Continuing loss rate (mm/hr)							
(min)	I_{const}	I_{ARR}	I_{CFL}	I_{CML}	I_{CBL}	I_{FFL}	I_{FML}	I_{FBL}
5	145.04	145.04	139.13	139.50	140.57	141.63	144.49	143.74
10	113.92	113.74	106.25	106.06	105.57	109.68	112.44	110.97
20	86.96	83.07	81.88	77.49	75.67	83.21	85.07	80.63
30	70.08	68.96	64.94	62.16	60.36	68.67	68.40	64.06
60	43.56	38.37	42.56	39.45	38.22	44.19	42.39	39.82
120	26.04	25.97	26.04	22.07	22.25	27.17	24.92	22.77

I_{const} =infiltration for constant intensity, I_{ARR}= infiltration for ARR pattern, I_{CFL} = infiltration for Convective Front loaded pattern, I_{CML} = infiltration for Convective Middle loaded pattern, I_{CBL} = infiltration for Convective Back loaded pattern, I_{FFL} = infiltration for Frontal Front loaded pattern, I_{FML} = infiltration for Frontal Middle loaded pattern, I_{FBL}= infiltration for Frontal Back loaded pattern.

Table B8 Precipitation loss rate for 20 year ARI

Duration	Continuing loss rate (mm/hr)							
(min)	I_{const}	I_{ARR}	I_{CFL}	I_{CML}	I_{CBL}	I_{FFL}	I_{FML}	I_{FBL}
5	125.06	125.05	122.86	122.74	122.80	124.15	125.02	124.63
10	97.45	97.63	95.06	94.79	94.19	96.96	97.79	97.01
20	73.36	73.28	71.89	70.47	69.38	73.66	74.38	72.40
30	60.98	60.55	59.60	57.28	56.08	60.86	61.25	58.53
60	40.99	37.71	40.89	37.64	36.77	41.84	40.36	37.87
120	22.74	24.98	25.16	22.76	18.68	25.74	24.18	22.07

I_{const} =infiltration for constant intensity, I_{ARR}= infiltration for ARR pattern, I_{CFL} = infiltration for Convective Front loaded pattern, I_{CML} = infiltration for Convective Middle loaded pattern, I_{CBL} = infiltration for Convective Back loaded pattern, I_{FFL} = infiltration for Frontal Front loaded pattern, I_{FML} = infiltration for Frontal Middle loaded pattern, I_{FBL}= infiltration for Frontal Back loaded pattern.

Table B9 Precipitation loss rate for 10 year ARI

Duration	Continuing loss rate (mm/hr)							
(min)	I_{const}	I_{ARR}	I_{CFL}	I_{CML}	I_{CBL}	I_{FFL}	I_{FML}	I_{FBL}
5	109.86	109.86	108.82	109.08	108.28	109.64	109.80	109.69
10	85.15	85.23	84.28	84.53	83.26	85.43	85.70	85.45
20	63.97	63.73	63.96	63.25	61.90	64.25	67.88	63.96
30	52.77	52.64	53.26	52.04	51.05	53.27	53.54	52.65
60	36.87	36.25	36.64	35.00	34.81	36.62	36.60	35.13
120	21.55	23.36	23.43	21.67	21.73	23.79	22.94	21.27

I_{const} =infiltration for constant intensity, I_{ARR}= infiltration for ARR pattern, I_{CFL} = infiltration for Convective Front loaded pattern, I_{CML} = infiltration for Convective Middle loaded pattern, I_{CBL} = infiltration for Convective Back loaded pattern, I_{FFL} = infiltration for Frontal Front loaded pattern, I_{FML} = infiltration for Frontal Middle loaded pattern, I_{FBL}= infiltration for Frontal Back loaded pattern.

Table B10 Precipitation loss rate for 5 year ARI

Duration	Continuing loss rate (mm/hr)							
(min)	I_{const}	I_{ARR}	I_{CFL}	I_{CML}	I_{CBL}	I_{FFL}	I_{FML}	I_{FBL}
5	98.69	98.69	98.41	98.45	97.98	98.62	98.60	98.54
10	75.73	75.95	76.02	75.83	75.33	76.18	76.30	76.23
20	56.32	56.39	57.31	56.76	56.40	57.18	57.32	57.22
30	46.31	46.38	47.15	46.57	46.52	47.10	47.19	47.13
60	32.18	31.72	32.25	31.69	31.91	32.22	32.25	32.10
120	20.04	20.61	20.89	20.33	20.64	20.68	20.87	20.32

I_{const} =infiltration for constant intensity, I_{ARR}= infiltration for ARR pattern, I_{CFL} = infiltration for Convective Front loaded pattern, I_{CML} = infiltration for Convective Middle loaded pattern, I_{CBL} = infiltration for Convective Back loaded pattern, I_{FFL} = infiltration for Frontal Front loaded pattern, I_{FML} = infiltration for Frontal Middle loaded pattern, I_{FBL}= infiltration for Frontal Back loaded pattern.

Table B11 Precipitation loss rate for 1 year ARI

Duration	Continuing loss rate (mm/hr)							
(min)	I_{const}	I_{ARR}	I_{CFL}	I_{CML}	I_{CBL}	I_{FFL}	I_{FML}	I_{FBL}
5	98.688	61.608	61.584	61.592	61.716	61.632	61.656	61.624
10	75.732	46.512	47.104	47.052	47.073	47.034	47.088	47.066
20	56.316	33.927	34.545	34.555	34.533	34.533	34.557	34.545
30	46.314	27.594	28.076	28.074	28.087	28.076	28.072	28.072
60	32.183	18.458	18.946	18.95767	18.955	18.95	18.952	18.952
120	20.0385	19.939	12.185	12.19083	12.19775	11.809	12.185	12.186

I_{const} =infiltration for constant intensity, I_{ARR}= infiltration for ARR pattern, I_{CFL} = infiltration for Convective Front loaded pattern, I_{CML} = infiltration for Convective Middle loaded pattern, I_{CBL} = infiltration for Convective Back loaded pattern, I_{FFL} = infiltration for Frontal Front loaded pattern, I_{FML} = infiltration for Frontal Middle loaded pattern, I_{FBL}= infiltration for Frontal Back loaded pattern.

From Table B2 to B11, it was shown that the continuing loss varies with duration and temporal pattern of rainfall. The total loss increases while the loss rate decreases with the duration of rainfall.

Appendix C

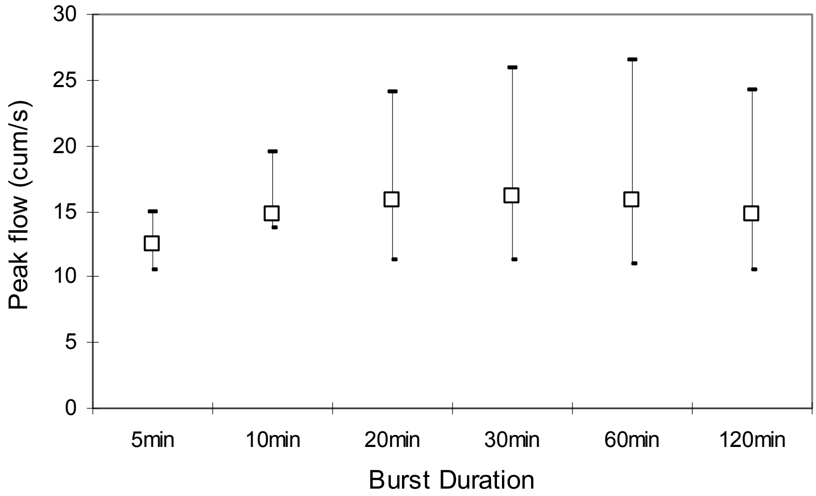

Figure C1 Range of predicted design flows for 50 year ARI

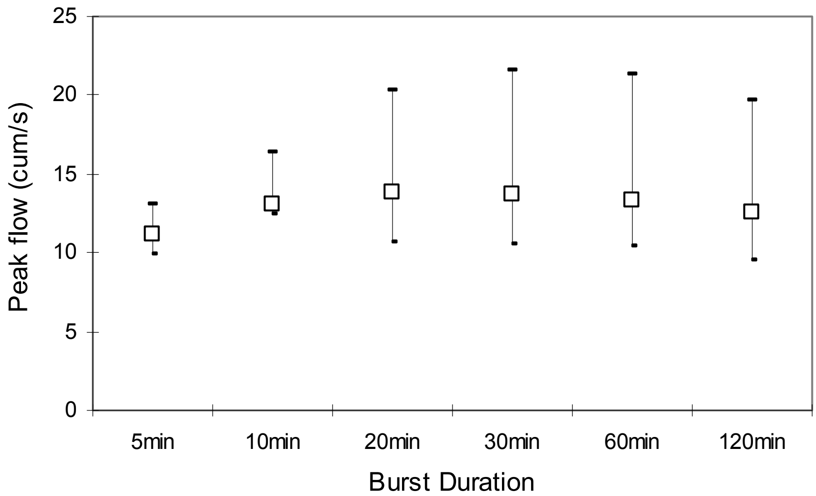

Figure C2 Range of predicted design flows for 20 year ARI

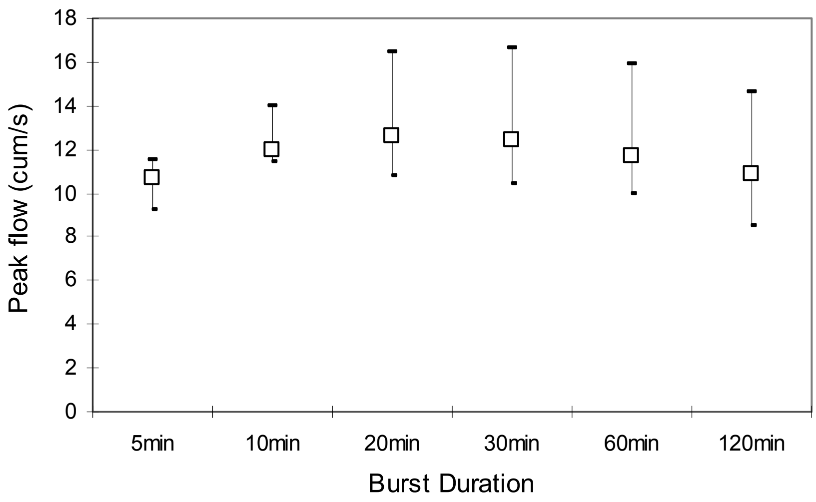

Figure C3 Range of predicted design flows for 10 year ARI

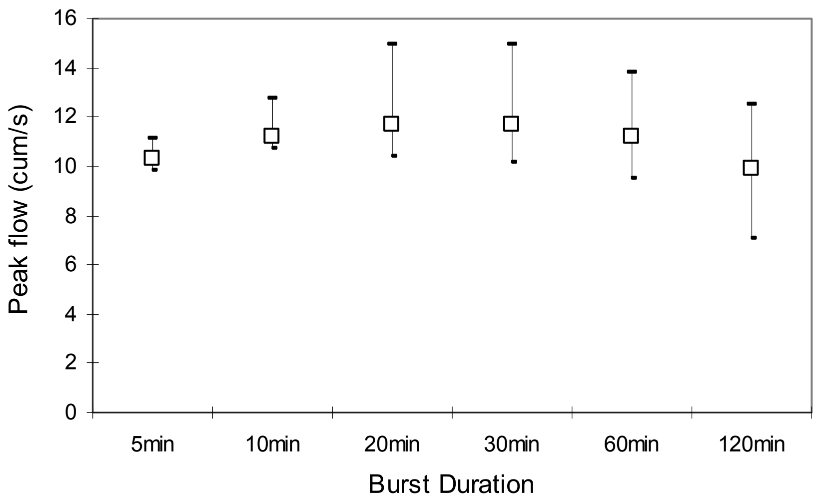

Figure C4 Range of predicted design flows for 5 year ARI

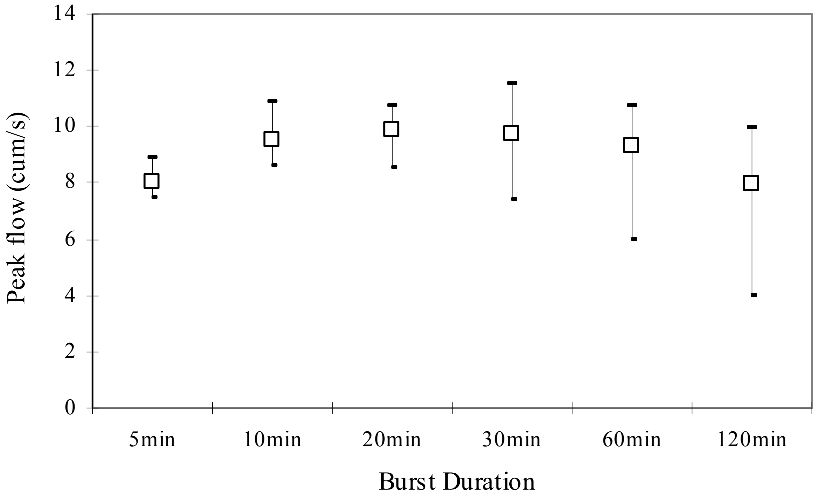

Figure C5 Range of predicted design flows for 1 year ARI

Table C1 Normalised range of predicted Peak Flows for 50 year ARI

Duration	Predicted peak flows				
(min)	Maximum	Minimum	Average	Constant	ARR
5	1.30	0.92	1.08	1.00	1.06
10	1.71	1.20	1.29	1.00	0.99
20	2.11	0.98	1.39	1.00	1.06
50	2.32	1.01	1.44	1.00	1.12
100	2.15	0.89	1.29	1.00	1.08

Table C2 Normalised range of predicted Peak Flows for 20 year ARI

Duration	Predicted peak flows				
(min)	Maximum	Minimum	Average	Constant	ARR
5	1.14	0.86	0.98	1.00	1.00
10	1.38	1.04	1.09	1.00	0.89
20	1.87	0.98	1.27	1.00	1.07
50	2.09	1.03	1.33	1.00	1.14
100	2.02	0.98	1.25	1.00	1.14

Table C3 Normalised range of predicted Peak Flows for 10 year ARI

Duration	Predicted peak flows				
(min)	Maximum	Minimum	Average	Constant	ARR
5	1.07	0.86	1.00	1.00	1.00
10	1.23	1.00	1.05	1.00	0.94
20	1.58	1.03	1.21	1.00	1.07
50	1.71	1.07	1.27	1.00	1.13
100	1.87	1.17	1.38	1.00	1.30

Table C4 Normalised range of predicted Peak Flows for 5 year ARI

Duration	Predicted peak flows				
(min)	Maximum	Minimum	Average	Constant	ARR
5	1.01	0.90	0.94	1.00	1.00
10	1.18	1.00	1.04	1.00	0.99
20	1.50	1.05	1.18	1.00	1.07
50	1.62	1.10	1.27	1.00	1.17
100	1.80	1.24	1.46	1.00	1.37

Table C5 Normalised range of predicted Peak Flows for 1 year ARI

Duration	Predicted peak flows				
(min)	Maximum	Minimum	Average	Constant	ARR
5	1.08	0.91	0.98	1.00	1.00
10	1.23	0.97	1.08	1.00	0.94
20	1.33	1.06	1.22	1.00	1.14
50	1.70	1.08	1.43	1.00	1.38
100	2.29	1.27	1.98	1.00	1.94