RAINFALL-RUNOFF MODELLING IN GAUGED AND UNGAUGED URBAN CATCHMENTS USING URBAN STORMWATER MODEL (USwM)

by

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LIST OF ABBREVIATIONS

CSPA	Cumulative score point average
DID	Department of Irrigation and Drainage, Malaysia
DOA	Department of Agriculture, Malaysia
GUI	Graphical user interface
JUPEM	Department of Survey and Mapping, Malaysia
MAS	Model Assessment System
MASMA	Urban Stormwater Management Manual for Malaysia
mm/hour	Millimetre per hour
MMS	Malaysia Meteorological Services
SPA	Score point average
SWMM	Stormwater Management Model
SWMM4	Stormwater Management Model version 4
SWMM5	Stormwater Management Model version 5
USwM	Object-oriented Urban Stormwater Model

PERMODELAN HUJAN-AIR LARIAN DI TADAHAN BANDAR YANG BERTOLOK DAN TANPA TOLOK MENGGUNAKAN “URBAN STORMWATER MODEL (USwM)”

ABSTRAK

Kajian ini dijalankan bagi meningkatkan efisiensi permodelan air larian ribut dari segi kebolehsenggaraan model dan kemampuan dalam ramalan air larian di tadahan bandar. Kajian yang dijalankan termasuklah analisa hujan-air larian, ujikaji penyusupan, pembangunan semula Urban Stormwater Model (USwM) dan permodelan air larian ribut menggunakan USwM. Dua tadahan bandaran digunakan, tadahan Sg. Kayu Ara digunakan dalam penentukuran dan pengesahan dan, tadahan Sg. Kerayong digunakan dalam ramalan air larian. Hubungan hujan-air larian tadahan Sg. Kayu Ara diterbitkan dalam bentuk persamaan linear (Air larian=0.60xHujan–2.83) dengan menggunakan 104 peristiwa hujan. Nilai 60% kawasan perbandaran dan purata storan lekukan tadahan sebanyak 2.83mm daripada persamaan ini didapati selaras dengan maklumat peta gunatanah. Hasil ujikaji penyusupan di tapak mendapati terdapatnya perbezaan ketara dalam kadar susupan bagi tanah berpasir. Nilai purata padanan parameter Horton mendapati 210 mm/jam bagi kadar susupan awalan dan 18mm/jam bagi kadar susupan akhir dengan pemalar susut bernilai 0.196/minit. Keputusan analisa varians pula menunjukkan tiada perbezaan ketara di antara nilai purata padanan parameter Horton bagi tanah pasir basah dan kering serta, bagi tanah pasir lom dan tanah pasir. Urban Stormwater Model (USwM) berorientasikan objek telah dibangunkan semula menggunakan Visual C++ dengan menyingkirkan komponen salji, kualiti air, dua pilihan input sejatan dan satu input pilihan Horton. Penentukuran dan pengesahan USwM dijalankan secara model teragih berdasarkan kaedah permodelan air larian ribut menggunakan nilai cerapan sebagai matalmat simulasi. Pekali penentuan (R^2) bersamaan 0.83 dan 0.90 didapati bagi aliran puncak dan isipadu air larian. Bagi ramalan air larian tadahan Sg. Kerayong, R^2 bersamaan 0.72 didapati berdasarkan aras air maxima. Matalmat kajian dicapai dengan peningkatan kebolehsenggaraan model melalui pembangunan semula USwM menggunakan teknologi berorientasikan objek dan kemampuan dalam ramalan air larian melalui kaedah permodelan air larian ribut.

RAINFALL-RUNOFF MODELLING IN GAUGED AND UNGAUGED URBAN CATCHMENTS USING URBAN STORMWATER MODEL (USwM)

ABSTRACT

This research was carried out to enhance the stormwater modelling efficiency in terms of model maintainability and improvement in ability for runoff prediction in urban catchments. The work included rainfall-runoff analysis, site infiltration tests, redevelopment of Urban Stormwater Model (USwM) and, finally model simulation using USwM. Two urban catchments were used, the Sg. Kayu Ara for model calibration and validation and, Sg. Kerayong catchment for runoff prediction. The rainfall-runoff relationship for the Sg. Kayu Ara catchment was established as a linear equation, Runoff = 0.60 x Rainfall – 2.83, based on 104 rainfall events. The 60% urban area and average catchment depression storage of 2.83mm indicated by the established equation was found consistent with the information extracted from land use map. The results of infiltration tests showed that infiltration rates vary greatly on sandy soil. The fitted Horton parameter values were 210 and 18mm/hr for initial and final infiltration rate and 0.1955/minute for decay constant. Analysis of variance indicated no significant difference between mean of fitted Horton parameters for dry and wet sandy soil and, for the soil types of loamy sand and sand. Object-oriented Urban Stormwater Model (USwM) was redeveloped using Visual C++ as the programming language. The work removed snow and water quality components, two evaporation input options and one optional input in Horton method. USwM was calibrated and validated in Sg. Kayu Ara catchment using the formulated generic stormwater modelling procedures with the observed records used as simulation target. The coefficients of determination (R^2) from distributed modelling were 0.83 and 0.90 for peak discharge and runoff volume. For runoff prediction at Sg. Kerayong catchment, the R^2 of 0.72 for peak water level was obtained. The research goal has been achieved with enhanced model maintainability using object-oriented technology and improved ability for runoff prediction through the formulated generic stormwater modelling procedure.

CHAPTER 1 INTRODUCTION

1.1 BACKGROUND

Knowledge of catchment rainfall-runoff relationship is fundamental to various urban stormwater management decisions. Among these are flood forecasting (Blöschl et al., 2008), formulation of stormwater management strategy (Chen and Adams, 2007; Leow et al., 2007), drainage design and evaluation (Crobeddu et al., 2007), urban drainage networks operation, maintenance and management (Previdi et al., 1999; Boukhris et al., 2001).

Rainfall-runoff modelling is normally carried out to establish the rainfall and runoff relationship in an urban catchment. The ultimate objective of rainfall-runoff modelling is to enhance the ability to predict catchment runoff from the rainfall data used as input. A properly performed modelling will lead to the establishment of effective and efficient decisions for urban stormwater management. The use of new technology has been proposed to support stormwater modelling (DID, 2000; Chen and Adams, 2007).

In carrying out rainfall-runoff modelling, some researchers utilised the physical hydrological data (Fauzi, 2007; Leong, 2007) and catchment physiographic information to establish the rainfall-runoff characteristics for the catchment of interest (Rodriguez et al., 2003; Hayes and Young, 2006). The data include rainfall, streamflow, river cross section, topographic and land use. There are advantages of using this approach.

First, the rainfall-runoff relationship is established from the physical catchment data and hence, is representative of physical catchment runoff characteristics (Chen and Adams, 2007). Then, the established rainfall-runoff relationship can be used for extraction of useful catchment information (Terstriep and Stall, 1974; Doyle and Miller, 1980; Huber and Dickinson, 1992; DID, 2000; Fauzi, 2007; Leong, 2007). Along the way, numerous computer software such as the geographical information system (GIS), database, spreadsheets and word processing applications can be utilised. Innovative tools can be developed using these software to automate various repetitive and routine tasks (DID, 2000; Chen and Adams, 2007). These tools can improve the efficiency of data storage, retrieval, processing and presentation besides reducing human errors that lead to the issues of standardisations and subjectivities.

However, this rainfall-runoff modelling approach is dampened by the need to use large amount of data to obtain a representative outcomes. Besides that, the information extracted may be on lumped basis since only one discharge information is available at one catchment outlet. In addition, the modelled outcomes may be "site specific" which means that it is non-transferable among catchments and difficult for generalisation. These disadvantages limit the applicability of this approach for rainfall-runoff modelling in ungauged catchments.

To overcome the issues related to data availability, outcomes transferability and generalisation, some researchers utilised computer stormwater models to represent the rainfall-runoff mechanism for urban runoff prediction (Whigham and Crapper, 2001; Waggener et al., 2004; Jakeman et al., 2006; Mayhun, 2006; Boughton and Chiew, 2007). This rainfall-runoff modelling approach using stormwater model has been the centre of research since its inception in the 1960s (Zoppou, 2001; Ajami et al., 2004; Boughton, 2005). In this approach, rainfall data (Blöschl et al., 2008) and percentage of impervious area (Elliott and Trowsdale, 2007) are among the most important input for catchment runoff simulation. The recorded streamflow discharge data on the other hand are used as simulation target for model calibration and verification.

These stormwater models are utilised as the simplified representation of the rainfall-runoff characteristics (System) with theoretical descriptions, to assist in appreciating the System and its responses under some test scenarios and conditions (Nix, 1994; Chapa, 1997). Mathematics is used in these models to represent the System. The operations of the Systems are described by various equations used to represent the reality and the effects of external stimuli to the physical Systems (Chow, et al., 1988; Chapra, 1997). For example, physically based stormwater models use mathematics to represent the physical processes such as the loss functions, the surface runoff mechanism and channel hydraulics (Chow et al., 1988; Singh, 1996).

The advantage of stormwater model is the ability to extend data (Post and Jakeman, 1999; Seibert, 1999; Boughton and Chiew, 2007). For instance, the stormwater model can be used for urban runoff prediction based on various hypothetical input conditions such as rainfall intensity, amount of infiltration and percentage of impervious area, etc. Besides, stormwater model is able to describe the variability and magnitude of water movement, distribution and storage in terms of time, space and frequency of occurrence (Singh, 1996). The greatest challenge however, is the know-how in using the model. This includes the selection of suitable model, in-depth understanding of model structure and operating the model.

In summary, rainfall-runoff modelling needs careful handling to obtain a representative outcome. There are strengths and weaknesses in both the physical data and stormwater model approach. Hence, it would be advantageous to incorporate both approaches to obtain a representative outcome.

1.2 PROBLEM ANALYSIS

Understanding of catchment rainfall-runoff is essential for urban stormwater management. However, due to the non-homogeneity of catchment characteristics, it is difficult to establish a representative, generalised catchment rainfall-runoff relationship (Rajurkar et al., 2004; Chen and Adams, 2007). The matter is further complicated in an urban catchment due to the complex nature of the catchment (Sullivan et al., 2004; Chen and Adams, 2007; Farahmand et al., 2007). This poses great challenges to urban rainfall-runoff modelling that attempts to model the mechanism to translate rainfall into runoff and to establish representative catchment rainfall-runoff relationship. Besides, there are other limitations that hamper the effort.

First, there is lack of data. Lacking in data is identified as the most serious constraint to rainfall-runoff modelling (Linsley, et al., 1988). That includes both the hydrological and physiographic data that represent the factors affecting catchment runoff (Chow, 1964). The lack of hydrological data is in terms of quantity of data available, quality of available data and length of records available (DID, 2000). Lack of physiographic data refers to the failure to incorporate the most recent catchment information such as land use, river condition, gradient and cross section. To complicate the issue further, establishment of catchment rainfall-runoff relationship needs large amount of data in both spatial and temporal respects (Seibert 1999). In this case, the quality of data is the most important factor influencing the modelling outcomes (Boughton, 2006). This shortfall results in difficulty to derive meaningful generalisation and, reduces the reliability of the derived generalisation.

The effects of lack of data are more obvious for river discharges (Seibert, 1999). As a result, only a few catchments are gauged with others left ungauged. This increases the demand for runoff prediction capability especially the event-based estimation needed for urban stormwater management.

Furthermore, the lack of data has led to difficulty in studying the hydrological characteristics in urban catchment. Locally, this shortage limits the understanding of rainfall-runoff relationship in urban catchments. Thus, this has compounded to the lack of local developed urban computer stormwater models and the relevant modelling procedure. As a result, local engineers settle for the stormwater models developed for temperate regions (DID, 2000). Verification works are needed to confirm the applicability of the temperate regions based stormwater model in local humid tropical climatic conditions. This includes in-depth studies of model source code and comprehensive model calibration and verification to ensure that the model’s concept, structure, program flow, parameters used and data requirements all conform to local conditions. Modifications of model source codes may be required in the events of non-conformity. In this case, thorough understanding of program algorithm including its parameters is vital to the success of the works (Linsley et al., 1988).

However, there are complications that hamper the modification works. First, there is complication due to unavailability of model source code. The source code is only available for public domain stormwater model but not all public domain models are released with source code. For example, the HEC series models from U.S. Army Corp of Engineers (USACE) are public domain but the USACE does not release the source code. This indicates that modification works can only be carried out for public domain stormwater models that are released together with the source code.

Secondly, there is complication due to increased model complexity. From the available stormwater models, there is tendency of developing more complex model with additional components especially with increased computational power (Blöschl et al., 2008). This results in difficulty to understand the whole stormwater model source code that has broad coverage including both the hydrological and hydraulic components.

Thirdly, object-oriented technology has not been fully utilised in stormwater model development. Development of stormwater model focuses on rainfall-runoff components without any considerations from software engineering point of view. This has resulted in difficulty in maintenance, expansion and modification of the developed stormwater model. As a result, it is time consuming for the modeller to read and comprehend the whole program code before finding the “entry point” to start the modification.

In addition, lacking in established modelling procedures brings about the elements of subjectivity in urban stormwater modelling. This has an impact on the modelling outcomes where the modelled results are highly dependent on the judgement made by the modeller. With availability of diverse approaches, this affects the decisions on selection of method used in stormwater modelling. Among these are the highly sensitive percentage of impervious area in urban runoff simulation and the objective functions used in assessing the modelled outcomes. The wide divergence of opinions among the modellers results in variations in stormwater modelling outcomes. This leads to difficulty in generalisation of modelling outcomes and the transferability of the calibrated model for flow forecasting in ungauged catchments.

In summary, the issues in urban rainfall-runoff modelling are interrelated. These issues have an impact on stormwater modelling in terms of the reliability of the modelling outcomes and its applicability for runoff prediction in ungauged catchments. The outcomes of problem analysis are summarised as follows:

- Knowledge of urban rainfall-runoff relationship is important for catchment stormwater management. However, there are difficulties due to the lack of essential data.
- Stormwater model is useful for urban stormwater management i.e. to establish catchment rainfall-runoff relationship, extend data and fill the gaps resulted from lack of data. However, there is difficulty due to lacking in utilisation of object-oriented technology for the development of easy to maintain stormwater model.
- Preparation of input data and selection of objective functions for stormwater model application are important. However, the works are bound to be subjective due to the lack of established standard procedure.

The outcome of this research is targeted at fulfilling the needs for urban rainfall-runoff modelling from local perspective. The outcome can then be used for runoff prediction at ungauged urban catchments.

1.3 OBJECTIVES

The objective of this research is to establish a package of measures to enhance the stormwater modelling efficiency in terms of model maintainability and improvement in ability for runoff prediction in urban catchments. The specific objectives of this research are:

- To establish the rainfall-runoff relationships in a local urban catchment using the available physical data to form as baseline study for the research;

- To evaluate various approaches used to establish the catchment rainfall-runoff relationships;
- To compile the infiltration data of disturbed urban soil and to fit the data to Horton infiltration model for stormwater modelling;
- To redevelop a stormwater model based on available public domain model engine using object-oriented paradigm to form as generic stormwater model framework that is easy to maintain, expand and modify;
- To formulate a standard procedure for stormwater modelling that includes GIS pre-processing, estimation of parameter values, approach for quantification of directly connected impervious area and to establish a metric for quantitative assessment of stormwater model performance;

To evaluate the redeveloped stormwater model and the formulated procedure by calibration and validation at gauged urban catchment and, perform runoff prediction in ungauged urban catchment based on the established stormwater model assessment metric.

1.4 STRUCTURE OF THE THESIS AND WORK COMPONENTS

This research focuses on rainfall-runoff modelling in local urban catchments. The works carried out are documented in eight chapters. Chapter 1 covers the introductory materials related to urban rainfall-runoff modelling with focus on the approaches used in the context of this research. The chapter follows on to describe the issues identified and scope the objective of the research.

Chapter 2 reports the outcomes of review of previous works in relation to rainfall-runoff modelling with focus on rainfall-runoff modelling in urban catchments together with the approaches adopted.

Chapter 3 describes the study areas selected for this research. The write-up starts with criteria for the selection and proceeds to the descriptions of the two urban catchments selected. Then, the descriptions on data requirements, sources and methods adopted for data processing are presented.

The four main component of works carried out are then documented in sequence in Chapter 4, 5, 6 and 7.

Chapter 4 presents the first component of works that involve establishment of urban rainfall-runoff relationship. The work starts from rainfall analysis that include evaluation of methods for infilling of missing rainfall data and analysis of rainfall spatial distribution. Then, work for the establishment of urban rainfall-runoff relationship is presented.

Chapter 5 presents the works in relation to infiltration test on urban soil. The works comprise experimental design, fieldwork for infiltration test, laboratory works, fitting of infiltration data to Horton infiltration model and statistical analysis.

Chapter 6 reports the third component of works i.e. to redevelop an easy to maintain stormwater model based on established public domain stormwater model. The development works is carried out based on a series of supporting tasks including requirements gathering, system analysis and design. After that, programming for implementation of stormwater model is performed. Initial quality assurance test is then carried out to test the developed model.

Chapter 7 presents the final component of works i.e. stormwater modelling in local urban catchments. A set of generic procedures for stormwater modelling is formulated to supplement the modelling works using the redeveloped stormwater model. The stormwater modelling procedure covers: (i) GIS pre-processing; (ii) preparation of input data; (iii) development of approach for quantification of impervious area and, (iv) establishment of stormwater model performance assessment system. With these procedures and other information extracted from the established rainfall-runoff relationship (Chapter 4) and infiltration test (Chapter 5), the redeveloped stormwater model (Chapter 6) is then calibrated and validated. Then, the formulated procedure and the redeveloped stormwater model are used for prediction of runoff in an ungauged urban catchment and, evaluation of the effect of storm direction and infiltration characteristic on catchment runoff.

Chapter 8 concludes the work based on the outcomes of the works carried out as reported in earlier chapters. Recommendation for future research is also presented.

CHAPTER 2 LITERATURE REVIEW

2.1 INTRODUCTION

This chapter compiles the outcomes of review of literature in the context of this research. The coverage begins with urban catchment rainfall-runoff relationship and its significance to stormwater management. Then, the work related to urban soil infiltration test is presented. Subsequent sections cover several topics related to the field of stormwater modelling. These sections focus on reviews of available stormwater models, redevelopment works on stormwater model, Stormwater Management Model (SWMM) and stormwater modelling applications in gauged and ungauged catchments. The review that follows covers the numerical schemes for stormwater model assessment. The final section summaries and concludes the findings from the literature review.

2.2 URBAN CATCHMENT RAINFALL–RUNOFF RELATIONSHIP

2.2.1 General

Catchment rainfall-runoff relationship has long attracted the interest of hydrological research due to its importance to stormwater management decisions (Previdi et al., 1999; Merritt et al., 2003; Chen and Adams, 2007; Leow et al., 2007). Among various usage of the established rainfall-runoff relationship, its most valuable contribution is facilitation of catchment flow forecasting. This includes data extension in gauged catchment or flow estimation in ungauged catchments (Linsley et al., 1988).

However, the rainfall-runoff relationship is non-linear, non-uniform, time-varying (Boukhris et al., 2001; Whigham and Crapper, 2001), dynamic and, highly variable due to the heterogeneity of catchment characteristics. In urban catchment, the development works complicate the establishment of rainfall-runoff relationship (Sullivan et al., 2004; Chen and Adams, 2007; Farahmand et al., 2007; Rodriguez et al., 2007). Locally, the issue is further complicated by lack of data and representative baseline study, shortage of established computer models and modelling procedures (DID, 2000).

Rainfall-runoff modelling is normally performed to establish the rainfall-runoff relationship. Among the available rainfall-runoff modelling approaches, two frequently used methods involve: (i) modelling using physical catchment data with analysis and interpretation of rainfall, runoff and topographic information; (ii) rainfall-runoff modelling using computer stormwater models.

The section that follows discusses rainfall-runoff modelling using physical catchment data. Subsequently, rainfall-runoff modelling using stormwater model is presented.

2.2.2 Establishment of Urban Catchment Rainfall-runoff Relationship

Rainfall-runoff relationship is influenced by the complex rainfall-runoff processes involving numerous above ground and underground processes that are difficult to quantify. For instance, the loss functions such as interception, depression storage, evaporation and infiltration reduce the net rainfall amount while the infiltrated water increases the baseflow that eventually adds to increase the streamflow. Various factors contribute to affect the rainfall-runoff process and hence, the catchment rainfall-runoff relationship. Chow (1964) broadly classified the factors into two groups namely, climatic and physiographic factors. The climatic factors include rainfall and its various loss functions while the physiographic factors refer to catchment and channel related characteristics. Among the processes, only those related to the context of this research are incorporated. Generally, the rainfall-runoff relationship can be represented as:

$$\text{Runoff} = F \times \text{Rainfall} \qquad \textbf{Equation 2.1}$$

In Equation 2.1, F is a fraction lesser than one that represents the factors affecting runoff. Various deviations of the relationship can be developed from Equation 2.1. For example, the Rational Method (e.g. $Q = C\ I\ A$) that incorporates runoff coefficient (C) as reduction factor , rainfall intensity (I) and catchment area (A) to derive discharge (Q). In this case, the runoff coefficient is taken as the combination of both the climatic and physiographic factors that comprise the loss functions, land use, soil type and surface roughness.

The relationship can also be represented as a linear equation (Terstriep and Stall, 1974; Doyle and Miller, 1980; Huber and Dickinson, 1992; Boughton and Chiew, 2007; Fauzi, 2007; Leong, 2007) as shown in Equation 2.2. In this format, the linear relationship is established by plotting a graph with runoff at vertical axis versus rainfall at horizontal axis of selected rainfall-runoff events. This relationship can be easily established with the aid of computer spreadsheets applications with built-in least squares method for data fittings. The output comprises a graph with scattered data points, a well fitted straight line with coefficient of determination and a linear equation representing the catchment rainfall-runoff relationship.

$$\text{Runoff} = m \cdot \text{Rainfall} + D \qquad \textbf{Equation 2.2}$$

The computational steps to establish the best fitted linear rainfall-runoff relationship is iterative. The use of computer that is most suited for repetitive works provides great advantages especially when dealing with large amount of data. In addition, computer eliminates errors due to human judgement and subjectivity.

The linear rainfall-runoff relationship can be modified according to the researchers' application domain. For instance, some researchers establish the rainfall-runoff relationship in annual scale (Post et al., 1998; Boughton and Chiew, 2007) while others establish on event basis (Fauzi, 2007; Leong, 2007). In this context, the annual scale relationship is more suitable for water resources planning such as resource allocation based on forecast of water demand. The event based rainfall-runoff relationship on the other hand fits better for stormwater management decisions such as mitigation of flash flood and design of drainage structures. In terms of data requirements, the annual scale rainfall-runoff relationship emphasises on the availability of long duration data but not the interval of data while the event based rainfall-runoff relationship requires that the data are available in short intervals.

Furthermore, some researchers incorporate different factors such as catchment trees stocking rate (Post et al., 1998) and potential evapotranspiration rate (Boughton and Chiew, 2007) in the linear equation. Then, the established rainfall-runoff relationship is used for estimation of runoff in ungauged catchments with the aid of stormwater model based on daily time step.

The work from Fauzi (2007) and Leong (2007) is found to be relevant for stormwater management in urban catchments. For instance, the D value in Equation 2.2 indicates the average depth of depression storage in the catchment (Huber and Dickinson, 1992; Fauzi, 2007; Leong, 2007). This information on catchment depression storage can be used in the Stormwater Management Model (SWMM) for runoff estimation.

From the literature, it can be found that the works by Post et al. (1998) and Boughton and Chiew (2007) need extra information that adds complication to the establishment of catchment rainfall-runoff relationship. For instance, both the trees stocking rate (Post et al., 1998) and potential evapotranspiration rate (Boughton and Chiew, 2007) are difficult to quantify. This leads to uncertainty in the simulated runoff. Besides, the trees stocking rate and potential evapotranspiration rate may not be available in ungauged catchment.

2.2.3 Factors Affecting the Establishment of Rainfall-runoff Relationship

Rainfall and streamflow data are used to establish the catchment rainfall-runoff relationship. The method adopted in the computation will have an impact on the established relationship. This subheading discusses the methods in the context of this research.

There are a number of available methods for baseflow separation. For instance, the constant-discharge, constant-slope, concave baseflow separation and master depletion curve method (McCuen, 2005). However, the discussion on baseflow separation is not incorporated despite its involvement in the establishment. The omission has been made based on the comments by Linsley et al. (1988). They noted that currently available baseflow separation methods have no physical basis to differentiate surface runoff from baseflow with insignificant difference between the computed outcomes.

2.2.3 (a) Rainfall Analysis

Rainfall is the main driving force to rainfall-runoff modelling and important to the establishment of rainfall-runoff relationship (Segond et al., 2007). Hence, in-depth analysis of the rainfall data is pre-requisite and vital to the validity of the rainfall-runoff modelling outcomes. In the context of this research, evaluation of methods for infilling of missing rainfall data is among the first task carried out. Then, analysis is carried out on rainfall spatial distribution and estimation of mean areal rainfall.

Methods for Infilling of Missing Rainfall Data

There are over 10 methods available for use in infilling of missing rainfall data (Singh, 1989; Coulibaly and Evora, 2007). Singh (1989) comments that among the methods, there is no significant advantage of any one over the others. Despite the comment, there are variants in the opinions on the best methods for infilling of missing data. For instance, the normal ratio method with three to four index stations has been identified as able to provide the best estimate (Linsley et al., 1988; Tang et al., 1996). The disagreement may be due to the existence of other influencing factors such as elevation, geographic location and wind (Linsley et al., 1988, Singh, 1989).

Locally, Tang et al. (1996) found that the modified normal ratio, normal ratio and inverse distance are among the best methods to estimate missing monthly, annual and annual maximum rainfall data. They (Tang et al., 1996) recommended application of these methods to daily and hourly duration rainfall events. This suggestion poses great challenge as Linsley et al. (1989) has commented on the reliability issue in relation to estimation of short interval missing data such as the daily data.

Review of literature also reveals the wide acceptability of conventional methods (e.g. simple arithmetic mean, modified normal ratio, normal ratio and inverse distance method) despite the availability of more advanced regression methods (Makhuvha et al., 1997a; Makhuvha et al., 1997b; Pegram, 1997) and the artificial intelligence techniques (Trafalis et al., 2002;

Chang et al., 2005; Coulibaly and Evora, 2007). This is supported by the National Weather Services (NWS) which recommends the simple arithmetic mean method and normal ratio method (Gilman, 1964; Singh, 1989). In the recommendation, the simple arithmetic mean method is proposed for cases when the variations between the neighbourhood index stations are small. The normal ratio method on the other hand is recommended if the variations between the neighbourhood index stations are greater than 10%.

Spatial Distribution of Rainfall

Effects of rainfall spatial distribution on rainfall-runoff modelling have attracted attention of researches. Numerous studies have been conducted on different sizes of catchments such as 4.4 ha (Faurès et al., 1995); 6.73 km^2 (Lopes, 1996); 71, 1120 and 10700 km^2 (Andrassian et al., 2001) and; 1400 km^2 (Segond et al., 2007). Although the catchment scale varies in large quantum, all studies recognise the impacts of rainfall spatial distribution to rainfall-runoff modelling for runoff prediction. Furthermore, Andrassian et al. (2001) highlights that smaller catchment needs higher raingauge density to obtain good modelling outcomes. This coincides with Faurès et al. (1995) who finds significant improvement in simulated peak flow and runoff volume when more raingauge are installed for a 4.4ha catchment. These findings indicate that the effect of rainfall spatial variability on runoff is scale dependent (Andrassian et al., 2001) with increasing effect in urban catchment (Segond et al., 2007).

In terms of method for analysis of rainfall spatial distribution, spatial interpolation (Jeffrey et al., 2001; Desa and Rakhecha, 2007) and correlation analysis (Desa and Niemczynowicz, 1996; Tang et al., 1996) are among the frequently used. Both methods can be performed using computer. For spatial interpolation, the use of computer makes the outcome more presentable (Jeffrey et al., 2001) and reliable with reduced human subjectivity. However, the graphical nature limits its applicability as it is more suitable for qualitative analysis.

Study of rainfall spatial distribution using correlation analysis on the other hand provides a quantitative outcome i.e. the correlation coefficient. The value of correlation coefficient is within the range of zero to one with zero indicating no correlation between the two variables. The correlation between the variables increases as the value of the computed coefficient approaches one with the value of one indicating perfect correlation. A negative coefficient value may be generated. However, the interpretation for negative value remains the same except it indicates the negative relationship between the variables. The primary advantage of correlation analysis is its quantifiable outcome that is easy to understand and interpret.

Estimation of Mean Areal Rainfall

There are numerous methods that can be used for estimation of mean areal rainfall. Among these methods, Singh (1989) comments that the performance of the simpler arithmetic mean and Thiessen Polygon methods are on par with the other more complex methods. For instance, the arithmetic mean and Thiessen Polygon methods provide comparable outcomes for daily, monthly and annual rainfall values. In these cases, the deviations between the methods reduce as the time frame increases e.g. from day to month to year. Despite the deviations, the differences are kept within 10% for monthly and yearly rainfall data and this quantum can be considered small and deemed acceptable. This finding provides a good support for utilising the Thiessen Polygon method in the estimation of mean areal rainfall.

Lopes (1996) however comments that the Thiessen Polygon method is unable to produce accurate result in distributed catchment modelling despite its ability in providing good estimation of areal rainfall at catchment scale. This disadvantage however may not be the problem of Thiessen Polygon method but due to the problem of wrongly placed raingauge network. This is because the Thiessen Polygons are generated based on the distribution and location of rainfall stations without the involvement of other variables. Furthermore, the outcome of the same study has revealed that the catchment response and estimated runoff are largely affected by rainfall spatial distribution. Inability to represent rainfall spatial distribution implies that there is flaw in the setting up of rainfall station network in the study area. Hence, a new network design is needed to redistribute the rainfall stations or increase the station density for proper representation of the rainfall events in the study area.

2.3 INFILTRATION TEST ON URBAN SOIL

Information on rainfall abstractions is important to catchment rainfall-runoff investigations. Among the rainfall abstractions, infiltration is the most important abstraction process (Chin, 2000) amounting to about 70% of rainfall in the United States (Chow, 1964; Singh, 1989).

However, infiltration is largely reduced as a result of urbanisation (Singh, 1989; Pitt et al., 1999). The reduction is due to increased impervious area; removal of vegetation cover, surface and top soil; soil structure alterations with imported materials and; soil compaction during construction (Pitt et al., 2002; Bochis-Micu and Pitt, 2005). In the same context, Burton and Pitt (2001) address that the soil type, profile, texture and structure are altered during the process of urbanisation. They also highlighted the importance to evaluate the impacts of earthwork, compaction and landscaping on infiltration and urban runoff.

Numerous tests have been carried out to measure infiltration rates and to fit the data to infiltration models (Berndtsson, 1987; Pitt et al., 1999; Telis, 2001; Ramos, 2004). In terms of urban soil infiltration, more comprehensive elaborations are provided by Pitt et al. (1999), Pitt et al. (2000) and Burton and Pitt (2001). In the literature, they report on the method adopted to carry out 153 infiltration tests on urban soil at 10 sites with multiple tests at each location. Based on their study, they find that school playing fields have the lowest infiltration rates among urban soil due to substantial disturbance during construction (Pitt, 1999; Pitt et al., 1999; Pitt et al., 2001).

Among over 20 available infiltration models, the Horton infiltration model (Equation 2.3) is preferred when measured data is available (Berndtsson, 1987; Singh, 1989; Pitt et al., 1999; Burton and Pitt, 2001; Ramos, 2004). Horton infiltration model is an empirical model (Singh, 1989). It is chosen in preference to other models because of its simplicity and it fits better for measured data when compared with other infiltration models (Berndtsson, 1987; Singh, 1989; Ramos, 2004). The major drawback however, is the difficulty for estimating its parameters namely initial infiltration rate (f_0), asymptotic or final infiltration rate (f_c) and decay constant (k) (Singh, 1989; Ramos, 2004). This is because the Horton model is nonlinear and thus, requires a nonlinear technique for fitting its parameters (Ramos, 2004).

$$f_p = f_c + \left(f_o + f_c\right)\, e^{-kt}$$ **Equation 2.3**

Where

f_p	Potential infiltration rate (mm/hour)
f_0	Initial infiltration rate (mm/hour)
f_c	Asymptotic /final infiltration rate (mm/hour)
k	Decay constant (1/minute)
t	Elapsed time (minute)

2.3.1 Values of Horton Infiltration Parameters

Numerous literature reports on the range of infiltration rates and the values of Horton infiltration parameters for various types of soils (Berndtsson, 1987; Pitt et al., 1999; Rossman, 2008). Among these published values, some literature specifically refers to infiltration rates on disturbed urban soil (Pitt et al., 1999; Pitt et al., 2000; Burton and Pitt, 2001). Table 2.1 shows the published values of Horton infiltration parameters.

From Table 2.1, it can be seen that the published values of Horton infiltration parameters vary largely in terms of both initial and final infiltration rates for all types of soils (Akan, 1999; Pitt et al., 1999; Telis, 2001; Rossman, 2008). However, these values need to be interpreted with caution especially the USGS values. This is because Telis (2001) does not classify the infiltration according to engineering soil texture (e.g. sand, loam and clay) and does not provide any explanation on the large initial infiltration rate (f_0) of 212,256mm/hr. Besides, there are diverse opinions in the values of decay constant (k) published. Some authors provide a constant value, e.g. Akan (1999) and Rossman (2008) while Pitt et al. (1999) publish high values of 37 and 46 for sandy soils and clayey soils, respectively.

The reasons for the differences may be due to the methods adopted and assumptions made in fitting the measured infiltration data to the Horton infiltration model. Furthermore, there is insufficient information on how the data has been fitted. For instance, only Pitt et al. (1999)

and Telis (2001) provide information on fitting data to the Horton model while Akan (1999) and Rossman (2008) do not indicate methods used for data fitting.

Table 2.1: Published Values of Horton Infiltration Parameters

Soil Group	f_0 (mm/hr)	f_c (mm/hr)	k (1/min)
	Range	Range	Range
Clay soil (Akan, 1999)	8–25	0–1.3	0.069
Loam soil (Akan, 1999)	25–75	3.8–7.6	0.069
Sandy clay loam (Akan, 1999)	43–250	1.3–3.8	0.069
Sand, loamy sand, sandy loams (Akan, 1999)	43–250	7.6–11.4	0.069
Clayey soils (USEPA) (Pitt et al., 1999)	0–1,500	0–610	-0.62–46
Sandy soils (USEPA) (Pitt et al., 1999)	3–3,710	3–640	1.0–37
Sandy soils (Wisconsin Department of Natural Resources) (Pitt et al., 1999)	Less than 3 to 640	Less than 3 to 380	Not available
Values from USGS (Telis, 2001)	23–212,256	2.5–115	0.015–1.73
Clay soils (SWMM5) (Rossman, 2008)	8.5–51	0.3	0.0333–0.1167
Loam soils (SWMM5) (Rossman, 2008)	25–152	3.3	0.0333–0.1167
Sand (SWMM5) – Rossman, 2008	42–254	120	0.0333–0.1167
Loamy sand (SWMM5) – Rossman, 2008	42–254	30	0.0333–0.1167
Sandy loam (SWMM5) – Rossman, 2008	42–254	11	0.0333–0.1167

Source: Akan, 1999; Pitt et al., 1999; Burton and Pitt, 2001; Telis, 2001; Rossman, 2008.

In carrying out data fitting, Pitt et al. (1999) uses the recorded average amount of water level dropped over the first 5-minute period as f_0 but does not indicate the method used for fitting f_c and k. Telis (2001) uses the multiple nonlinear regression analysis to estimate f_c but does not indicate method for fitting f_0 and k. Furthermore, the published report by Telis (2001) shows that the graph of infiltration rate versus time starts at the 5-minute point instead of the vertical axis as per the definition for f_0 as initial infiltration rate. This raises question of how the model is fitted as the infiltration rate between the 5-minute point and earlier initial may differ largely due to the exponential nature of Horton model.

The other issue raised is the classification of soil groups and the associated parameter values. For instance, Akan (1999) lumps the three soil types of sand, loamy sand and sandy loam and uses a single parameter set for these soil types. Rossman (2008) on the other hand, differentiates the three soil types but uses only different parameter values for f_c while the other two parameters are kept constant. The values of f_c for sand and loamy sand by

Rossman (2008) are also much higher than those published by Akan (1999). This indicates the uncertainty in infiltration rates as commented by Burton and Pitt (2001).

2.3.2 Experimental Design for Infiltration Test on Urban Soil

As noted, there are several publications reporting on the values of Horton infiltration parameters for various soil types and ground covers. There are however, limited provisions on the experimental design for infiltration test.

Among the available information, Pitt et al. (1999), Pitt et al. (2000) and Burton and Pitt (2001) conduct the infiltration test based on 2^3 factorial designs. They incorporate soil moisture, soil texture and level of soil compaction as the main factors affecting infiltration on urban soil. Berndtsson (1987) on the other hand mentions random sampling but does not incorporate detailed description of the method. Based on the available information, the method adopted by Berndtsson (1987) however can be interpreted as stratified random sampling as the test sites are chosen randomly based on known geomorphological zones.

2.4 STORMWATER MODELS

Stormwater models are considered the most reliable method to assist in the calculation of the mechanism for transforming rainfall to runoff (Linsley et al., 1988). The advantage is more profound in the computation that involves small time steps.

2.4.1 Available Stormwater Models

There are varieties of stormwater models available today in public domain or sold as commercial software. For the public domains, the examples include SWMM from USEPA, the HEC series models by the USACE, Full Equation Model (FEQ) (Franz and Melching, 1997) and FourPt (DeLong, 1997) from United States Geological Survey (USGS). The commercial counterparts include the MIKE series from the Danish Hydraulic Institute (DHI), Infoworks and, XP-SWMM from XP-Software, etc.

Among stormwater models, there are two distinct scopes i.e. the hydrologic and hydraulic component. The hydrologic component receives rainfall as input and incorporates various rainfall abstraction functions such as depression storage, infiltration and evaporation (Chin, 2000; Wurbs and James, 2002; Rossman, 2008). The outputs are presented as surface runoff in the form of hydrograph. The hydraulic component on the other hand, takes the generated runoff from the hydrologic component and performs flow routing in the drainage networks.

Numerous reviews have been carried out on the available stormwater models (Ball, 1992; Viessman and Lewis, 1996; Zoppou, 2001; Singh and Woolhiser, 2002; Merritt et al., 2003; Elliott and Trowsdale, 2007). The outcomes of these reviews indicate the wide scopes of urban stormwater models (Mitchell and Diaper, 2006). In this case, different model serve their own specific audience from specific user group with specific objectives function.

For example, some models are used for fairly simple application such as sizing hydraulic channel based on Manning's equation (Haestad Methods, 1998). Among the HEC series models, HEC-HMS is used for hydrologic modelling; HEC-RAS (previously HEC2) focuses on water surface profiles, elevations (Brunner, 2002) and floodplain modelling (Dyhouse et al., 2003). HEC-5 is used for regulation of water resources. The FEQ and FourPt from USGS solve the full, dynamic equations of motion for one-dimensional unsteady flow in open channels (DeLong et al., 1997; Franz and Melching, 1997). DAMBRK and FLDWAV from NWS are generalised hydraulic routing models for flood forecasting due to dam breaches or natural flooding (Fread and Lewis, 1998). SWMM on the other hand includes the hydrologic modelling, hydraulic flow routing and water quality modelling (Huber and Dickinson, 1992; Rossman, 2008) to offer a complete solution for urban stormwater simulation.

2.4.2 Model Architecture and the Mathematics in Stormwater Model

There are other deviations between stormwater models. This includes model architecture to incorporate spatial variations and mathematical schemes adopted to represent the hydrologic and hydraulic components. There are impacts on simulated hydrograph with these deviations.

2.4.2 (a) Spatial Variations in Stormwater Model

In terms of spatial variation, stormwater models are classified as lumped or distributed models depending on whether spatial variations are incorporated (Chow et al., 1988; Viessman and Lewis, 1996; Chin 2000). For instance, rainfall spatial distribution, infiltration characteristic, depression storage and overland surface roughness. Rainfall spatial distribution affects the average rainfall depth and arrival time of the discharge. Infiltration characteristic and depression storage affect the net rainfall contributed from a sub-catchment while the overland surface roughness has an influence on the surface runoff velocity. These spatial variations have impacts on the shape of the simulated runoff hydrograph.

2.4.2 (b) Mathematical Schemes in Hydrologic Component

Hydrologic component in stormwater model comprises the rainfall-runoff processes that occur on the ground surface i.e. before entering the hydraulic channel. In this research, the processes include infiltration, depression storage and overland flow.

Infiltration

Infiltration occurs on pervious ground surfaces and its rate is influenced by soil texture, initial soil moisture content, soil permeability, vegetation cover, intensity and amount of rainfall (Kirkby, 1979; Singh, 1986; Varshney, 1986; Wanielista et. al., 1997).

In the context of stormwater model, different approaches are adopted to calculate infiltration with some models incorporating more methods. Table 2.2 compiles the list of infiltration functions incorporated in some common stormwater models. From the table, one can observe the popularity of the NRCS curve-number method (CN method). The reasons for the popularity include its simplicity, predictability, stability and responsiveness to catchment properties such as soil type, land use, surface and antecedent conditions (Ponce and Hawkins, 1996). However, Smith (1997) and Willeke (1997) comment that the popularity of CN method instead is due to the support from the United States Department of Agriculture (USDA). This support protects the users in litigation i.e. the use of the CN method implies that the hydrological analysis has been carried out following an acceptable standard and thus, makes the CN method defensible in legal proceedings (Smith, 1997; Willeke, 1997). In the context of urban stormwater modelling, the use of the CN method needs careful handling due to its relatively poor performance in event simulation (Willeke, 1997).

Table 2.2: Infiltration Functions Used in Stormwater Models

Storm Water Model	**Infiltration Methods**						
	ELR	**Green-Ampt**	**Holtan**	**Horton**	**LCDF**	**Philip**	**CN Method**
HEC-1	X	X	X				X
TR-20							X
USGS						X	
HYMO							X
SWMM5		X		X			X
UCURM				X			
ILLUDAS			X				X
DR3M		X					
GWBRafler						X	
GISRafler						X	
SWM-IV					X		
USDAHL			X				

Notes:

ELR (Exponential Loss Rate); LCDF (Linear Cumulative Distribution Function); HEC-1 (HEC-1 Flood Hydrograph Package); TR20 (Computer Program for Project Hydrology); USGS (USGS Rainfall-Runoff Model); HYMO (Hydrologic Model Computer Language); SWMM5 (Stormwater Management Model version 5); UCURM (University of Cincinnati Urban Runoff Model); ILLUDAS (Illinois Urban Drainage Area Simulator); DR3M (Distributed Routing Rainfall-Runoff Model); GWBRafler (GW Basic Wits Rainfall-Runoff Erosion Model); GISRafler (GIS Wits Rainfall-Runoff Erosion Model); SWM-IV (Stanford Watershed Model IV); USDAHL (ARS Revised Model of Watershed Hydrology).

Source: Viessman and Lewis, 1996; Nyabeze, 2003; Jain et al, 2004; Rossman, 2008

Chin (2000) on the other hand comments that there is no single infiltration model that can fit all cases. The usage of infiltration model is linked to field data i.e. fitting the field data to the appropriate model to obtain the site-specific parameters (Chin, 2000). This comment is found to be in favour of Horton model as it is known for fitting well to field data (Singh, 1989; Ramos, 2004).

Depression Storage

Depression storage occurs on the ground surface of both pervious and impervious areas. The use of depression storage in stormwater model is more straightforward as it is normally fixed at constant value without involving any mathematical scheme. The depression storage together with other abstractions is deducted from initial rainfall to calculate the net rainfall. The amount of depression storage is dependant on the properties of ground surface such as the land use, surface type and slope (Chin, 2000). Table 2.3 presents some typical values of depression storage.

Table 2.3: Typical Values of Depression Storage

Surface Type	Depression Storage (mm)
Impervious surfaces	1.3 – 2.5
Lawns	2.5 – 5.1
Pasture	5.1
Forest litter	7.6
Pavement – steep	0.5
Pavement – Flat	1.5 – 3.5

Source: Chin (2000); Rossman (2008)

Overland Flow

Overland flow refers to surface runoff generated by excess rainfall. The overland flow can be computed with hydrodynamic or empirical methods. The hydrodynamic methods include non-linear reservoir routing (Huber and Dickinson, 1992; Rossman, 2008), kinematic wave (Ferguson and Ball, 1994; Singh, 1996), diffusion wave and dynamic wave methods (Singh, 1996). The empirical methods comprise the SCS, Tennessee Valley Authority (TVA), unit hydrograph and Rational Method (Singh, 1996). All these methods however are used as simplified representation of overland flow which may differ from the actual flow condition.

For instance, Chow et al. (1988) find from field studies that the laminar flow of catchment overland flow faces a resistance of 10 times greater than those in the laboratory test. The differences between the field study and laboratory test may be due to the effects of catchment heterogeneity such as topographical and vegetation factors. The findings imply the uncertainty in the representation of overland flow using the mathematical schemes. This condition however is considered acceptable in stormwater modelling as long as the uncertainty is properly addressed in the interpretation of the simulated outcome.