MODELLING OF THE BIO-ECOLOGICAL DRAINAGE SYSTEM USING INFOWORKS SD

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ABSTRACT

Nowadays, Malaysia has been widely practiced rapid disposal, localized, reactive and mono-functional drainage concepts. With increasing in urbanization and population in urban areas the essentiality to new approach in drainage system is necessary. One of these approaches that launched in Malaysia is Bio-Ecological Drainage System (BIOECODS). The Bio-Ecological Drainage System (BIOECODS) is a Sustainable Urban Drainage System (SUDS) that was developed by the River Engineering and Urban Drainage Research Centre (REDAC) and Drainage and Irrigation Department (DID) to demonstrate the utilization of 'control at source' approaches for urban stormwater management. It is an environmentally friendly drainage system that was designed to increase infiltration, reduce peak flow at outlets, improve water quality, and increase the aesthetic value of the surrounding area through a number of SUDS components. Major components of BIOECODS systems are ecological grasses swale, and ecological ponds namely retention pond, dry detention pond and wet land. The BIOECODS combines three engineering techniques to manage stormwater based on control at source approach, namely infiltration, storage and conveyance system by swales, subsurface drainage modules, dry ponds and constructed wetland. The main objectives of this study are to develop a model with integrated surface and subsurface conveyance with high accuracy compare to real situations, increase understanding about rainfall-runoff respond in BIOECODS system and assessment of Best Management Practices (BMP) components in urban stormwater management, in peak discharge attenuation and surface and sub-surface flow relationship. A new technique has been adopted in the effort to fully integrate or couple both the surface and on-line subsurface conveyance (single node) to present overall interaction of this component in the BIOECODS system. The new technique has been used Storm Water Management Model (SWMM) model which uses the non-linear reservoir method and Kinematic wave approximations of the Saint-Venant equation to describe overland flow routing and Horton method in conjunction to Soil Conservation Service Method (SCS) used to model infiltration or subsurface flow. The observed data in terms of water level, and velocity in the constructed monitoring stations in the study area for different rainfall events is compared with that obtained from the model's simulation. The calibrated and validated model for the whole watershed area was then used to consider different scenarios to evaluate the effectiveness of BIOECODS and each BMP component in decreasing water level and respectively peak flow attenuation. Overall, the results indicate a peak water level reduction for the total study area of 28000m^2 of more than 100% during low intensity events, and in the range of ±60-85% for events of medium and high intensity. They also show that the lag time to peak for events of medium and high intensity were ±15 minutes. The results also show that ecological swale with on-line subsurface drainage system is very effective in terms of decreasing peak flow and improving the infiltration characteristic of an urban area. Also subsurface drainage module integrated with swale is able to cater a percentage of surface runoff volume approximately 60% to 76% for rainfall events. Through this study, the technique being utilized to define the surface and on-line subsurface conveyance system is proved to be successful to integrate the flow in both components and their interactions. Although the results doesn't only represent the findings for BIOECODS system, the modelling efforts for such a sustainable drainage system could be used for the entire world and all SUDS components. The effort of this modelling can illustrate new the idea to the designing, planning and strategies for preventing flash flood in urban areas and also to ensure that SUDS systems will work properly during the rainfall events.

ABSTRAK

Sehingga hari ini, sistem peparitan di Malaysia masih kebanyakan bersifat pelupusan pesat, tempatan, reaktif, dan hanya mempunyai fungsi tunggal. Namun, dengan proses pembandaran and populasi yang semakin menigkat, keperluan konsep baru dalam mempertingkatkan sistem peparitan yang sedia ada semkain mendesak. Salah satu pendekatan yang telah dilancarkan di Malaysia ialah pengunaan sistem peparitan 'Bio-Ecological' (BIOECODS). Sistem pepraritan tersebut menggunakan konsep 'Sustainable Urban Drainage System' (SUDS) , iaitu sistem peparitan mampan yang dapat menyokong keperluan pembandaran dan dalam masa yang sama mesra alam. Kegunaan sistem peparitan mampan dilancarkan oleh River Engineering and Urban Drainage Research Centre (REDAC) and Drainage and Irrigation Department (DID) Malaysia memperlihatkan aplikasi konsep 'kawalan di sumber' untuk air ribut bandar. Konsep tersebut yang mesra alam menggalakkan peningkatan penyusupan air ribut, pengurangan aliran puncak, menigkatkan kualiti air dan nilai estetika di kawasan sekitar. Komponen-komponen utama BIOECODS ialah parit rumput dan kolam ekologi yang terdiri daripada kolam pengekalan, kolam kering dan tanah basah. Sistem BIOECODS menggunakan tiga teknik kejuruteraan yang mengutarakan konsep 'kawalan di sumber' untuk mengurus air ribut bandar. Ketiga-tiga teknik tersebut ialah penyusupan, penyimpanan dan penghantaran melalui sistem peparitan permukaan, sistem peparitan bawah tanah, kolam kering dan tanah basah. Objektif utama kajian ini adalah untuk mencipta satu model yang dapat mengintegrasikan sistem peparitan permukaan tanah and sistem peparitan bawah tanah yang tepat supaya pengetahuan mengenai hubungan air-ribut dan air-larian, pengurangan aliran puncak dan hubungan aliran permukaan dan bawah tanah dengan penggunaan sistem BIOECODS dapat dikaji. Satu teknik baru telah digunakan untuk mengintegrasikan kedua-dua sistem penghantaran permukaan dan bawah tanah supaya interaksi kesulurahan komponen-

konponen BIOECODS dapat dicapai. Teknik baru tersebut telah digunakan oleh model 'Storm Water Management Model (SWMM)' yang menggunakan non-linear reservoir method dan Kinematic wave approximations of the Saint-Venant equation untuk mengintepretasi aliran permukaan dan Horton method untuk mengintepretasi penyusupan dan aliran bawah tanah. Data –data yang dapat dikesan seperti tahap air dan kelajuan (velocity) air di stesen-stesen pemantauan di tempat kajian untuk beberapa acara air ribut dibandingkan dengan data-data daripada model tersebut. Model yang telah ditentukur dan disahkan untuk keseluruhan kawasan tadahan air kemudian digunakan untuk menilai beberapa senario air ribut di mana keberkesanan sistem BIOECOD secara keselurhan dan keberkesanan setiap komponen SUDS dalam pengurangan tahap air dan aliran puncak. Secara keseluruhan, keputusan menunjukkan pengurangan aliran puncak sebanyak 100 peratus di tempat kajian yang seluas 28000 m2 semasa hujan intensiti rendah dan sekitar 60 – 85 peratus untuk hujan yang intensiti sederhana dan tinggi. Di samping itu, masa untuk aliran puncak telah ditundarkan dalam acara hujan intensiti sederhanda dan tinggi untuk sekitar 15 minit. Keputusan yang didapati turut menunjukkan sistem peparitan ekologi dan sistem peparitan bawah tanah adalah sangat berkesan dalam mengurangkan aliran puncak dan meningkatkan penyusupan air ke dalam tanah di kawasan Bandar. Di samping itu, sistem peparitan bawah tanah yang diintegrasikan dengan parit permukaan dapat mengurus air aliran permukaan sebanyak 60 hingga 76 peratus dalam acara hujan. Kajian ini telah menunjukkan bahawa teknik yang digunakan untuk mengintegrasikan sistem peparitan permukaan dan bawah tanah adalah berkesan dalam mengesan aliran air permukaan dan bawah tanah dan juga interaksi dalam kedua-dua komponen tersebut. Walaupun keputusan dalam kajian ini didapati daripada sistem BIOECODS, teknik-teknik pemodelan yang dipamerkan dalam kajian ini dapat digunakan untuk kesemua komponen-komponen SUDS. Usaha-usaha pemodelan ini boleh digunakan untuk melahirkan idea baru dalam reka bentuk, perancangan dan strategi dalam usaha menghalang kejadian banjir kilat di kawasan bandar dan pada masa yang sama memastikan sistem SUDS dapat berfungsi dengan betul semasa kejadian hujan.

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TABLE OF CONTENET

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS AND ABBREVIATION

SUDS	Sustainable Urban Drainage System
BMPs	Best Management Practices
BIOECODS	Bio-ecological Drainage System
REDAC	River Engineering and Urban Drainage Research Centre
DID	Department of Irrigation and Drainage
WIA	Water Impact Assessments
LID	Low Impact Development
WSUD	Water Sensitive Urban Design
MSMA	Stormwater management manual for Malaysia
TSS	Total Suspended Solids
MRM	Modified version of Rational Method
TRRL	UK Transport and Road Research Laboratory
BOD	Biochemical Oxygen Demand
CBOD	Concentration of Biochemical Oxygen Demand
DO	Dissolved Oxygen
ARI	Average Recurrence Interval

CHAPTER 1: INTRODUCTION

1.1 Introduction

Urbanization has been recognized as the major reason responsible for the increase in peak flow and surface runoff volume, as the infiltration capacity in urban areas decreased compared to pre-developed conditions (Barber et al., 2003; Seilheimer et al., 2007; Ouyang et al., 2006; Newcomer et al.; 2014, Chen and Adams, 2006). Within the last 5 decades urbanization has grown remarkably as a major regional, national, and international environmental and human health and safety concern. Physical and biological effects of humans on the Earth's system is something that is not recent instead, it is tight with our history.

As human population has grown, so has their influence, which between 30%-50% of undeveloped area transferred to pre-developed or developed areas (Vitousek et al., 1997; Grübler, 1994; Lambin et al., 2001). Conventional development of undeveloped or pre-developed sites are often causes land to be covered with large areas of impermeable material (Goonetilleke et al., 2005) which cause, increasing stormwater runoff volumes and peak flows (Barbosa et al., 2012; Oraei et al., 2012) that may wash out to water body and ground-water and create flash flood during rainfall events (Vrebos et al., 2014; Huong and Pathirana, 2013; Jumadar et al., 2008).

Stormwater is the flow of water, which results from precipitation and occurs immediately after rainfall. Stormwater runoff can accumulates pollutants such as oil and grease, chemicals, nutrients, metals, and bacteria as it travels across land. Heavy precipitation can also cause sewer overflows that may contaminate water sources with untreated human and industrial waste, toxic materials, and other debris (Butler and Davies, 2011).

Stormwater runoff has been identified as one of the leading causes of degradation in the quality of receiving waters, especially during the first flush, responsible for the discharge of an enormous quantity of pollutants (Lee and Bang, 2000). Adverse impacts include downstream flooding, channel scour, sediment and pollutant transport. Therefore, intense storms in an urban area can cause disastrous flooding and enormous human and economic losses (Smith, 2006; Perrin et al., 2001; Di Baldassarre et al., 2013).

A popular approach to control flash flood and pollutant is Sustainable Urban Drainage System (SUDS). Sustainable Urban Drainage System (SUDS) is a concept that concern about the environmental and social factor of the human activity in the long terms in designing and planning for drainage system. The function is to manage the stormwater in developments that replicate the natural drainage. The objectives of this approach are to prevent pollution, to control flooding which may occurred in the downstream and to use the stormwater to recharge into groundwater. It also provides other environmental benefits such as aquatic life ecosystems, improved aesthetics or community resources.

Runoff is collected and stored to allow natural cleaning to occur prior infiltration or controlled released to watercourse. Generally, four general design options are filter strips and swales; filter drains and permeable surfaces, infiltration devices, basins and ponds. In order to control the possibility of pollution and flooding, one or combine of these designs might be proposed at selected urban locations. Sustainable drainage systems will generally discharge water in one of three ways. The Building Regulations Approved Document H (DTLR, 2002) lists the discharge options in order or priority which are:

1. Infiltration to the ground via soakways or other system which will ultimately reach groundwater.
2. Discharge to a watercourse or other surface water.
3. Discharge to a sewer.

In almost all cases, the strategy being used in most of the latest designs are to increase infiltration, peak flow attenuation at outlet, and to expand water quality through various Best Management Practices (BMPs). An example of such project in Malaysia is the Bio-Ecological Drainage System (BIOECODS) constructed by the River Engineering and Urban Drainage Research Centre (REDAC) in collaboration with Department of Irrigation and Drainage (DID) Malaysia. The BIOECODS project has taken a series of measures to reduce runoff rates, runoff volumes and pollutant loads by implementing a source control approach for stormwater management as suggested in the Stormwater Management Manual (DID, 2000; DID, 2012) for Malaysia.

1.2 Problem Statement

Surface water drainage from urban developed area is increasingly affecting the river catchments. As development intensifies, so more water runs rapidly into rivers and less filters through the soil. This sealing of the ground can and does lead to localized flooding and water pollution, and will only get worse as our climate changes. We need a new approach to drainage that keeps water on site long, prevents pollution and allows storage and use of the water at the same time also support aquatic life that promote balance of eco-system.

Previously in Malaysia, urban drainage practice has been based on the 1975, Urban Drainage Design Manual that covers essentially the planning, basis of design, storm drainage for urban streets, detention storage, erosion, sediment control and information to be submitted with design by Department of Irrigation and Drainage (DID) (DID, 2000; DID 2012).

As a result, Malaysia has been widely practicing rapid localized, disposal, mono-functional and reactive drainage system. The traditional approached widely practiced in Malaysia is to allow developers to put in drains where the location is appropriate.

Furthermore, the architect has more or less to put alignment for drainage after packing in the most number of housing units allowable in the area. The engineer's job is only to determine drain size to comply with drainage capacity and final discharge outlet requirements. So to further maximize housing density, developers normally channel all drainage to one large trunk drains. All drains connected to trunk drains are normally concrete-lined and of the open channel type to minimize the land area required. (Embi, A.F & Kassim, A. H., 1998). Consequently, stormwater management issues have drawn increased attention in recent years.

Over the period of 2006 to 2009, state of Johor Bahru in Malaysia, has suffered from the impact of floods which cost over USD 500 million and claimed 46 lives (Ngai, 2012). And in 2014 a big disaster happened in state of Kelantan which takes almost 2 months to recover the flooded areas and unfortunately no official reports evaluate the cost of this flood. As the urbanization increase, these problems are expected to become more severe and thus, viable and cost-effective solutions are highly sought after to reduce the impacts. In line with this issue, one of the efforts under the Government of Malaysia is the publication of the "Urban Stormwater Management Manual for Malaysia (MSMA)" by the Department of Irrigation and Drainage Malaysia (DID, 2000; DID, 2012). The new manual promotes new concept of control at source (i.e. within the catchment) and adopts Best Management Practices (BMP's) where all new development in Malaysia must fully comply with the new guideline to control stormwater from the aspect of quantity and quality runoff. Among the BMP's facilities being recommended in the manual for flood control and stormwater management are dry detention, ecological ditch/swale, wet ponds or retention pond, wet land, etc. Different studies conducted to assess and simulate the BMP's facilities such as swales, detention ponds, etc. However, none of previous modelling efforts have been very successful, due to the difficulty in integrating/coupling both surface and subsurface drainage in a single system. Without a reliable computer model to assess the BIOECODS components and their interactions in single system the effectiveness of this innovative drainage system in peak flow attenuation and flood control is still remain unknown.

1.3 Significance of study

The design of Sustainable Urban Drainage Systems (SUDS) is based on principles of ecological engineering, which aims to preserve natural drainage patterns and emulate the natural hydrological cycle. Some approaches such as swales and constructed wetlands incorporate the use of vegetation technique, which improves the quality of storm water runoff by trapping suspended solids and related pollutants.

In recent years, a number innovative concepts such as control at source (Zakaria et al., 2003; DID, 2000, DID, 2012), zero impact development (Zakaria et al., 2003; DID, 2000, DID, 2012), low impact development (Wulkan, 2007; Fisher et al., 2007; Shaver and Puddephatt, 2007; Clar et al., 2007), sustainable urban drainage system (Zakaria et al., 2003) have been suggested by various researchers for urban stormwater management. Based on these concepts, many award winning drainage systems or urban stormwater management projects have been designed/developed in various countries including Malaysia to solve various water related difficulties such as flood, flash flood, water contamination and at the same time, to increase the aesthetic value of the surrounding area.

The concept of the BIOECODS is to integrate the drainage component with ecological pond components for the further treatment of stormwater runoff. The design component is include ecological swales, in-line sub-surface conveyance system, detentions and ponds while ecological pond components is wet pond, a detention pond, a constructed wetland, a wading stream and recreational pond. In combination, these increase runoff lag time, increase opportunities for pollutant removal through settling and bio filtration, and reduce the rate and volume of runoff through enhanced infiltration opportunities.

The ecological swale as mentioned above is a dual drainage system which consists of a surface swale with vegetated surface and on-line subsurface modular conveyance system aligned in parallel arrangement. It enabled the water from surface runoff that flow into a swale to further infiltrate into the subsurface conveyance system to reduce peak flow and to filter the water that will be discharged into the downstream water body.

Since the completion of the pilot BIOECODS project in year 2002, there are more and more BIOECODS projects completed in Malaysia in recent years. A number of study (Lai et al., 2009; Li et al., 2010; Lai et al., 2012) have also been carried to evaluate the effectiveness of BIOECODS in urban stormwater management. In view of the potential of implementations of BIOECODS or other similar sustainable urban drainage system in future to overcome surface runoff problems, it is crucial to have a model, which is capable of simulating the rainfall-runoff interaction, besides, simulate SUDS components and their interactions effectively. Such a model will be a useful point of reference for further analysis, assessment, strategies and design of similar projects in future.

1.4 Objectives

The main objectives of this study are to create a model that is capable to simulate BIOECODS system with high accuracy compare to real situation and increase understanding about rainfall-runoff respond in drainage system. The specific objectives are:

- To develop a new integrated/coupling technique for flow in surface and on-line subsurface conveyance system for modelling purposes,
- To develop a computer simulation model for BIOECODS project

- To simulate the rainfall-runoff response of various BMP components in BIOECODS such as ecological swale with on-line subsurface modular conveyance system, dry ponds, detention ponds, etc.
- To analyze the performance evaluation of various BMP components and the overall effectiveness of BIOECODS in peak flow attenuation.

1.5 Scope of the study

This study consists of the research about Sustainable Urban Drainage System (SUDS) and Best Management Practices (BMP's) in stormwater management. The focus of this research is to develop a computer model for BIOECODS project based on the environmental aspects of stormwater quantity control, which needs to be balanced and controlled against the urbanization effects of flooding. This study attempted to develop a model that solve the coupling issue for surface and subsurface drainage system and evaluate the performance of different components of BMP and in overall effectiveness of BIOECODS drainage system in flow attenuation.

In view of the potential of Bio-ecological Drainage System (BIOECODS) and existing BMP components in flow attenuation or other similar projects for future implementation to overcome surface runoff problems, it is important to have a model that is capable of simulating the rainfall-runoff respond in an effective manner. Such a model and technique will be useful for further analysis, assessment, and the design of such projects in the future.

During the first stage, the main objective is to collect and gather as much relevant information from previous studies, research and at the same time try to understand the concepts of SUDS, BMP's in BIOECODS systems. For the time being the objective is to explore and investigate the study area and gathering require data for modelling such as precipitation, water level, flow velocity and survey data to develop a ground model for the study area.

The next stage is to evaluate the collected field data to create a versatile model and simulate the existing BIOECODS system. The next step is to calibration and validation the results to ensure the developed model, capable to model the actual situation, after this step, effectiveness of the current system and each SUDS components evaluated in different scenarios.

1.6 Outline of the thesis

This thesis prepared based on conventional format, which include six chapters. Chapter 1 is a general introduction about research topic and the background of the study include the recent research and the important of study. Chapter 2 contains a comprehensive literature review which includes the latest advances in urban drainage systems, their components and their advantages and disadvantages and modelling software in stormwater management. Chapter 3 gives a brief description of the case study areas, methods, calibration and validation procedures and tools used in the research, while the results and discussion presented in Chapter 4 according to the objectives of thesis. The conclusions and recommendation for future studies of the research are presented in Chapter 5.

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

Rainfall and corresponding runoff generated are most important scheme in hydrological processes, which depends on different parameters, such as local physiographic, climatic, and topography factors. Runoff from a catchment area in any specific period means the total quantity of water, which drains into a drain or basin, which can be expressed as millimeters of water over a basin or total water volume in cubic meter. Rainfall and corresponding runoff is one of the important topics in urban stormwater management due to increasing population and fast development in urban areas.

Undeveloped land in rural areas has very little surface runoff whereby most of the rainfall soaks into the top soil and evapotranspirates or migrate slowly through the soil mantle as interflow to the streams, lakes or estuaries but the hydrological process in urban areas is similar to those in rural areas, but they occur at smaller temporal and spatial scales in urban areas than in rural regions (Delleur, 2003). This concept involves the development and execution of a new combination of structural and non-structural approaches to merge the conveyance and storage function of stormwater systems to improve the quality and quantity of urban stormwater runoff prior to receiving waters.

The optimum design, operation, maintenance, and use of existing or proposed urban stormwater management projects in a particular urban area requires detailed knowledge of the rainfall and the corresponding runoff generated in a particular time interval/period.

2.2 Stormwater Management

Stormwater management defines as a knowledge used to understand, control, and utilize water in their different forms within the hydrologic cycle. It is applied in developing areas with very high level of human interference with natural processes. Urban stormwater management also can be defined as everything done within the catchment to remedy existing stormwater problems and to prevent the occurrence of new problems (Walesh, 1989; DID, 2000; DID, 2012).

Problems with management of urban stormwater are closely related to the concentration of population growth in a relatively area. These developments had initiated many concern about water quality in the urban areas (Black and Aitken, 1997) and the environmental impacts on the outlying areas that support urban life (Butler and Parkinson, 1997). In order to enhance the living standard and better transportation system, large impervious areas are constructed. Most paved surfaces and rooftops allow no water to infiltrate, but instead divert them directly to stream channels and drains. This cause a dramatic effect on the hydrology of receiving water especially for the rivers and streams. A normal rainfall events now produce more runoff volume compare to the given rainfall events in the past (Roesner et. al., 1974). The increased amount of water that flows into drains or streams causing the flash flood.

Martin et al. (2006) and Hatt et al. (2004) mentioned in their research due to an extensive increase in urbanization, there has been an increase in surface runoff, while Badr et al. (2004) proved that Water Impact Assessments (WIA) and their mitigation, or improvement, and observing procedures are not sufficient and effective, by this means, creating potential problems for urban stormwater management in aspect of water quality and quantity.

Braune & Wood, 1999; D'Arcy et al., 1998; and Miltner et al., 2004, indicated that the surface runoff is the main transporter for contaminants, such as hydrocarbons (oils and petrol), pathogens and debris, metals and nutrients and sediment, which can cause significant pollution of lakes, rivers, and groundwater. Steedman (1988) states that the quality of surface runoff has direct correlation with the urbanization in its surrounding watershed area. Dasch (2003) has highlighted another impact of urbanization on runoff, which as a result of impervious area development, most precipitation has no chance to percolate downward to groundwater. Therefore, the supply of groundwater to wells is reduced.

The impacts of urbanization to stormwater management, the traditional conveyance approach in stormwater management has been shifted during the 1970's to storage approach with a focus on detention, retention and recharge in the world (Zakaria, et al., 2003). Later on, during 1990's stormwater came to be considered as a significant source of pollution. Although, the main objectives of stormwater management is to protect the natural water cycle and ecological systems with the introduction of control at source, flow attenuation and treatment in natural or constructed systems such as ponds, wetlands, and root-zone treatment facilities (Niemczynowicz, 1999).

Urban drainage is a very old field in stormwater management, dating back to at least 3000 BC (Burian and Edwards, 2002) with a primary focus on conveyance of water away from urban areas. In the recent decades start from 1970's, different approaches presented to manage stormwater runoff in an urban drainage system in aspect of water quality and quantity. Besides, there has been rapid growth in the use of these approaches such as Low Impact Development, LID (Department of Environmental Resources, 1999), Sustainable Urban Drainage Systems, SUDS (CIRIA, 2000), Water Sensitive Urban Design, WSUD (Whelans et al., 1994; Wong, 2007), Best Management Practices, BMPs (Schueler, 1987) and alternative techniques (Azzout et al., 1994).

2.2.1 Essentiality of new concept in Stormwater Management

Urban drainage practice, has been based on the philosophy of overcoming the floods either with transferring the flow into the drains by increasing the size and volume in drainage system or by constructing storm overflows to prevent flash flood.

Andoh, (1994) identified that removing the surface runoff from the land so fast cause to increase in volume and flow rates in downstream, and thereby, overloading the natural drainage system which are not designed for that flow rate. This causes severe damage not only to drainage system but also damage to urban areas environment. Therefore, new approach in dealing with stormwater is essential not only for urban areas but also for environment itself. He also suggested a new approach of urban drainage which is environment friendly, which inspired by the concept of natural distributed system. This alternative approach can minimize the peak flow before they arrive at the downstream areas.

Andoh (1994) described a number of different case studies and identified that the new approach of control at source is more cost effective than the traditional solutions that has involved relief sewers and large storage tanks.

Allison. et al., (2006) identified that runoff problem in developed and pre-developed areas can be solved using either with an integrated management systems, such as large conveyance system and water treatment, or regionalized systems, such as porous pavement, detention/retention ponds, soakways, grass swale. Although one of the benefits of integrated approach is reducing the fluctuation in stream flows and flash flood risk in urban areas.

Stormwater drainage system considered to provide the fastest proper way to transport surface runoff out of the watershed area into the main drains. However, proposed approaches by previous researcher combined different aspects of stormwater management such as distributed storage, treatment and infiltration as well as delayed transport. According to this for sustainable development, ecological criteria are taken into account in the new drainage system design that is much more closer to nature than the traditional approaches.

2.2.2 Urban Stormwater Management in developing countries

Germany is one of the developed countries that different approaches for stormwater management are very popular topics of development for urban drainage system. For example, the pilot projects (Sieker and Harms, 1987; Grotehusmann et al., 1994) which include the investigation of the effects on the groundwater quality (Grotenhusmann, 1995). According to Geiger and Dreiseitl, (1995) stormwater best management principles are widely used in drainage planning and designing in developed and developing countries nowadays. This approach is also used more widely in other European countries such as United Kingdom (Bettess, 1996), France (Chocat et al., 1997) as well as in the rest of the world such as US (Urbonas, 1979) and Australia (Argue and Pezzati, 1998).

Malaysia is moving towards achieving a developed nation status by the year 2020 (DID, 2000; DID, 2012). In the last decades, this shown by its quick socio-economic development. Industrials and urban areas have developed in different parts of the country, particularly in the West Coast of the peninsular. This development and urbanization in the entire Malaysia caused significant concerns to the environment, such as ecological and hydrological changes. Malaysia, like many other developing tropical countries, is striding to upgrade the social well-being of its urban citizens by alleviating ever increasing water, pollution and flash flood problems. The specific problems focused on the stormwater management approaches in this country.

Rapid urbanizations change pervious surfaces to impervious surfaces that generally resulted in problem of flash flood and heavy pollution of urban drainage system and other receiving waters (DID, 2000; DID, 2012). Past experience shown that mono functional, rapid disposal, reactive and localized drainage concepts had been widely used in Malaysia. This standard design have been used since early 1970s. (DID, 2000; DID, 2012) The different approaches in terms of design, planning, techniques and methods have not been upgraded and reviewed. Although these approaches in urban stormwater management and urban drainage technology are continuing changing as the water quality and frequency of flash flood increasing dramatically in many urbanizing area in entire Malaysia. Since 2000, stormwater management manual for Malaysia known as MSMA, introduced by Department of Irrigation and Drainage (DID), and approved in Malaysia and replaced as a reference for earlier manual in stormwater management in Malaysia.

2.3 Sustainable Urban Drainage System (SUDS)

As the urbanization and respectively, population increased during the last decades. Increasing in urbanization follows with increasing the paved surfaces where the water can't penetrate and infiltrate into the soil. The consequences are, high peak flows, which happens quickly after storms initiates. The traditional pipe systems in the cities normally are not designed to carry these high peak flows, due to this flooding is often results in this case. In response to these problems, new approaching in sustainability have been reviewed and studied, with various names in different countries:; Sustainable Urban Drainage Systems (SUDS), in the United Kingdom; Low Impact Development (LID), in the USA and Canada; Low Impact Urban Design and Development (LIUDD), in New Zealand and Water Sensitive Urban Design (WSUD), in Australia (Butler and Davies, 2004). Nevertheless of the name and the countries, the concepts and ideas of these sustainable drainage system are very similar to each other, and all mainly focus on the hydrologic cycle variables and their interactions on the watersheds (EA, 2003i; Scholz, 2006; Poleto and Tassi, 2012).

Sustainable Urban Drainage Systems (SUDS) are a concept that embraces varying types of stormwater management solutions (DEFRA, 2007). SUDS could be defined as an approach to manage stormwater rainfall events practically, which replicates natural drainage. SUDS also mimics natural catchment processes and it is a more sustainable approach when compared to the traditional urban drainage system. The idea behind SUDS is to utilize the watershed areas in the best possible scenarios with a combination of different drainage techniques which has a tight relationship of land use and watershed characterization (CIRIA, 2007). With this introduction of SUDS, stream flow toward downstream will be delayed (EA, 2003ii). The difference in peak-flows discharge and lag time for pre- developed and developed urban conditions can be seen in Figure 2.1.

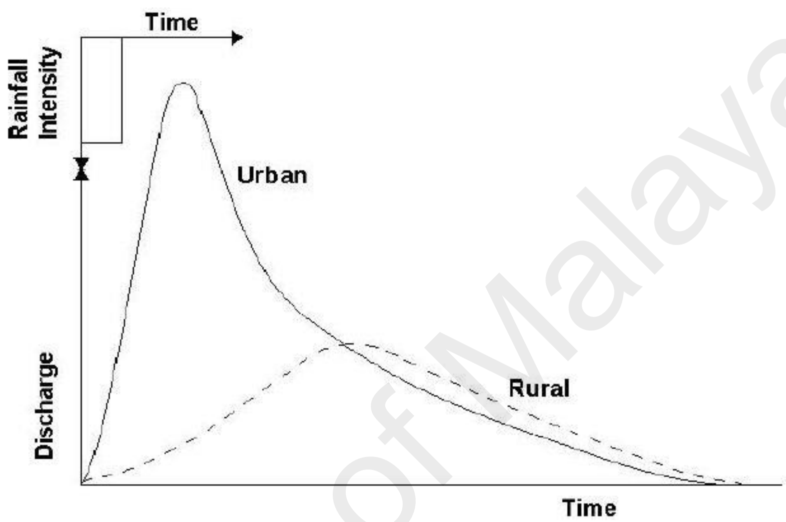


Figure 2.1: Impact of urbanization on runoff quantity (Ramachandra and Mujumdar, 2009)

As seen in Figure 2.1, there is significantly increased in the peak flow, and reducing in the time to peak in the urban areas compared to rural areas. This issue increase dramatically, and needs to have a Sustainable Drainage System for urban areas to decrease the runoff and delay the time to peak for the runoff when the storm started.

The concept of Sustainable Urban Drainage System approach is shown in Figure 2.2.

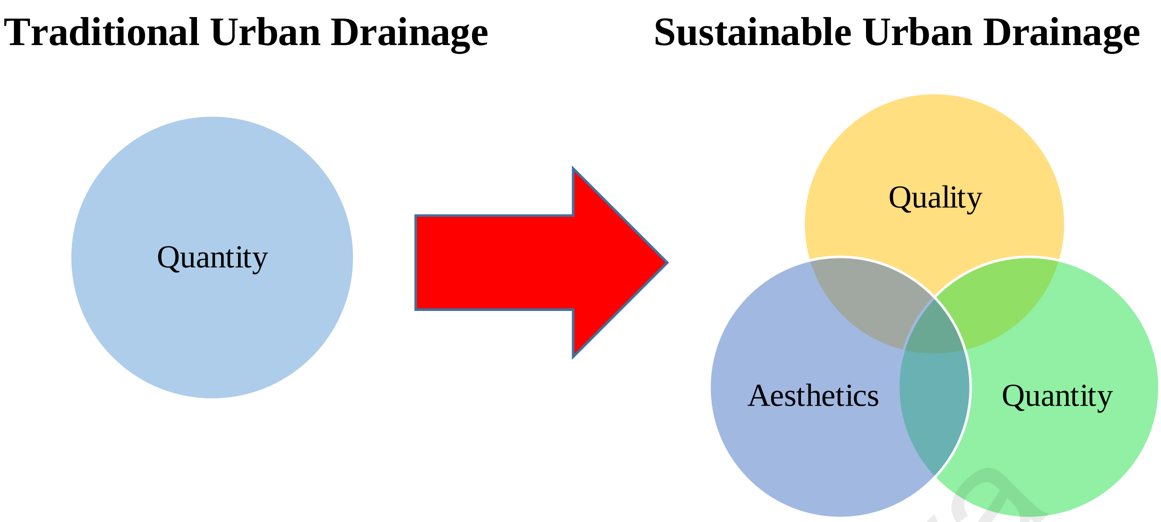


Figure 2.2: The SUDS approach in stormwater management (Jönsson, 2011)

As shown in Figure 2.2, the purposes of SUD are to minimize the effects of urbanization by improving the quantity, quality and biodiversity of the stormwater in its way to the downstream. Different techniques and structure exist for SUDS in the field.

Choosing the suitable techniques for a specific location needs detail survey about soil conditions, climate in the area, and level of urbanization. These parameters are very important in determining the appropriate SUDS techniques for a location (Falkirk Council, 2009). Because the major objective of SUDS as mentioned above is to maximize the effects of reduced flow rates, flow volumes and achieve the maximize reduction of pollutant in water body before it reach to the recipient. Achieving these objectives would be possible if a combination of different techniques used in a project or research.

There are some principles and objectives that influence the design and planning of SUDS and enabling them to mimic natural drainage by:

- Storing runoff and releasing it slowly (Attenuation)
- Allowing water to soak into the ground (Infiltration)
- Slowly transporting (Conveying) water on the surface
- Filtering out pollutants

- Allowing sediments to settle out by controlling the flow of water

Different phases of execution in a Sustainable Urban Drainage Systems (SUDS) shown in Figure 2.3 and explained briefly below.

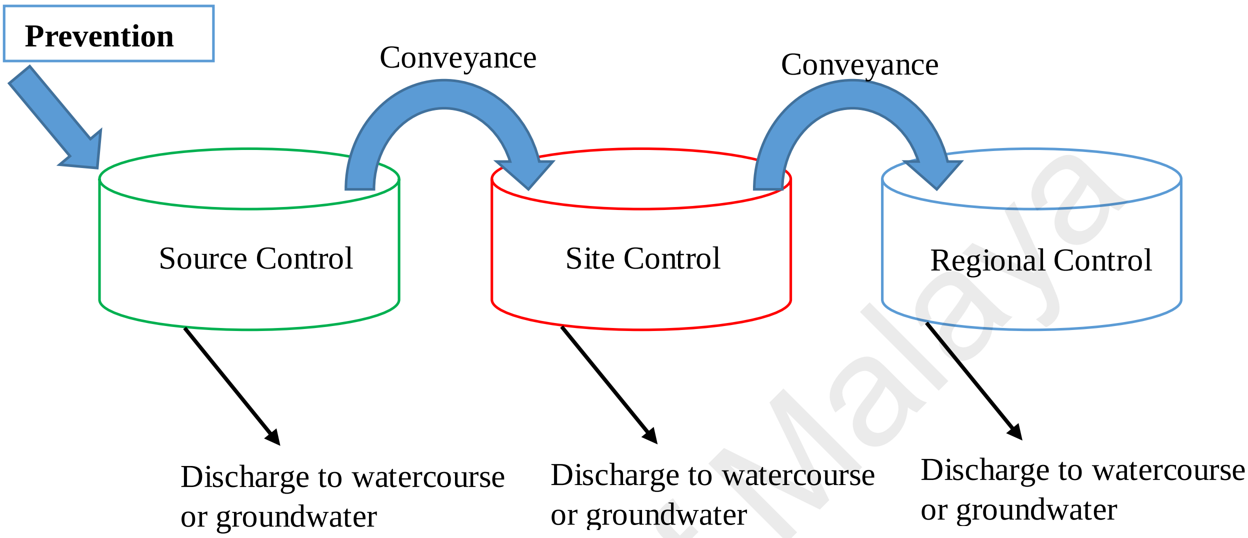


Figure 2.3: Different steps in Sustainable Urban Drainage System (SUDS) (CIRIA, 2007)

i) **Prevention**

The first action is to control the rainwater before enter into the system. If the contaminants prevented from entering into the system, the needs for other actions will be limited. Another way to reduce the pollutants percentage in stream flow and drainage systems is to raise public awareness and knowledge about impact of pollution in stormwater in their life style.

ii) **Source Control**

Dealing with stormwater at the first steps (when rainfall happen) may be the preferred, cheaper and easier option for many developments. By controlling runoff volume and potential amount of contaminants at the source, which require smaller SUDS components further downstream and is more economically.

Nowadays, the techniques of sustainable drainage system are widely recommended and applied in many countries of the world, however varies depends on the regions, but with the similar design methodologies. In Europe, Sustainable Urban Drainage System (SUDS) is used with its main focus on public health, water quality treatment and protecting valuable water resources (Willems et al., 2012; Hellström et al., 2000; Butler and Parkinson, 1997). In Australia, main focus of sustainable drainage system refers to a planning and engineering approach to minimize environmental degradation and achieve harmony between water and the urban environment (Roy et al., 2008; BMT WBM, 2009; Sharma et al., 2008). SUDS is known as Low-Impact Development (LID) in the United States and Canada, which main focus is to measure the reaction of the ecosystems for urban stormwater management (Coffman et al., 1998).

Malaysia as a developing country was not exception from this strategy. Regarding to increasing pre-developed and developed area Department of Irrigation and Drainage (DID) published a manual for Stormwater Management in Malaysia (MSMA) in 2000 to encourage the use of 'control at source' approach for urban stormwater management in Malaysia. One of these projects in Malaysia is the focus of this research.

The liability of control at source in sustainable drainage system is one of the important points of sustainable drainage design (CIRIA, 2007). Each SUDS projects according to their conditions and hydraulic design using different Best Management Practices (BMP's) components to achieve the control at source goal that will be discussed in the following section.

2.4 Best Management Practices (BMP's)

According to Parkinson and Mark (2005), stormwater best management practices (BMPs) are control actions taken to reduce the effect of landuse changes in urban areas on the both quality and quantity of urban runoff. The main objectives of BMP practices is to improve the water quality which caused by the impervious surfaces in developed areas. Besides BMPs also designed to attenuate the flow rate, flow volume through increasing the infiltration rate, filtration, detention etc.

Wood and Braune, (1999) determined that the control proceeding to improve water quality and quantity in stormwater management practices are often inappropriate and costly because of considering quality and quantity separately and without considering their interactions in the drainage system. They suggested new approach (BMPs) which already applied in US and Australia. The introduced approach can provision multi-disciplinary tasks in urban stormwater management and improve the quality and standard of life.

The use of this new approach depend on the site conditions and also different variables and parameters such as soil type, infiltration rate, etc. In different projects and case studies there are multiple actions and proceeding needed to obtain a coupled/integrated treatment in urban areas. Due to this capability, cost-effective measures can minimize the impact of urbanization on both water quantity and quality in environment.

Methods for controlling pollutant in stormwater management through BMPs can be categorized into two different categories, i) Structural and ii) Nonstructural practices. The two methods are often used together to control runoff in new developments, pre-developed, developed and construction sites. These two methods explained briefly below.

2.4.1 Structural BMPs

The Structural BMPs designed to provide temporary storage for stormwater runoff treatments (Clar et al., 2003; MWLAP, 1992; MDE, 2000). These approaches designed to control the volume and the flow rate of runoff from impervious and pervious surfaces, as well as, reducing the amount of pollutants in the discharge water through physical control, rotation or flow boundaries (Florida DER, 1988). Structural BMPs mainly improve the quality of receiving water but they also can use as control structure for quantity of surface runoff; such as constructed wetland and detention/retention ponds.

Structural BMPs continuing operation and maintenance to retain their designed efficiency. Structural BMPs can be classify into several general categories. Typical structural BMPs are presented in Table 2.1 used in the ASCE National Stormwater Database for Urban Stormwater Management.

Table 2.1. Common Structural BMPs (WEF and ASCE, 1998; U.S. EPA, 1999; U.S. EPA, 2001; NYSDEC, 2001)

Categories	**BMPs**
Ponds	Detention Ponds (Dry ponds) Retention Ponds (Wet ponds)
Wetlands	Wetlands
Biofilters	Grass Swales Filter Strip or Filter Buffer
Infiltration structure	Infiltration Trench Infiltration Basin Porous Pavement
Sand and Organic Filters	Surface Sand Filter Perimeter Filter Media Filter Underground Filter
Technology Options and Others	Water Quality Inlets

2.4.2 Non-structural BMPs

Non-structural BMPs refers to those techniques that use natural proceeding to improve water quality in surface runoff on urban areas. This method is not required and extensive construction either limits the stormwater runoff volume to reduce the pollutants in runoff (Muthukrishnan et al., 2006a; 2006b). These BMPs involve in educational, institutional or pollutants prevention practices and they improve the stormwater runoff quality by reducing the usage level, generation and accumulation the potential stormwater runoff contaminants close to the source. These practices also known as source control BMPs (WEF and ASCE, 1998; U.S. EPA, 2000).

These BMPs aims to eliminate the pollutions by avoiding their introduction to environmental. One of the disadvantages of these BMP practices is lack of data on their efficiency and performances (Clar et al., 2003; Clary et al., 2002). However, there is an increasing credit of need to primary treatment and control at source rather than treatment of pollutant of stormwater in long-term urban watershed management plans. There are two major advantages for non-structural BMPs:

- Non-structural BMPs is least-cost measures which used to treat stormwater pollutants,
- These BMPs practices are very effective in control at source approaches and thereby they are effective in reducing the cost and size of drainage system projects (WEF and ASCE, 1998; MDE, 2000).

Major categories of nonstructural practices are shown in Table 2.2.

Table 2.2. Non-structural BMPs (WEF and ASCE, 1998)

Major Categories	**Nonstructural BMPs**
Public Education	Public Education and Development
Planning and Managing	Site Design Vegetative Controls Increasing previous areas Green Roof (Consider as Structural BMPs) Low Impact Development (LID) (U.S. EPA, 2000a, 2000b)
Storm Drain Maintenance	Storm Drain Flushing BMP Maintenance
Stormwater Reuse	Landscape Watering Toilet Flushing

The main type of source control components (CIRIA, 2007):

- **Green roofs:** Green roofs define as a multi-layered system that covers the roof of the building. The roof consist of an impermeable layer, which covered with vegetation to retain the precipitation. Some of the green roofs consist a drainage layer and mainly designed to attenuating flow. This component has some disadvantage such as: cost (compared to conventional roof), it's not suitable for step roofs, and also any subsequent damage to water proof membrane is critical. According to previous research on effectiveness of this component it has best performance on, amenity potential, ecology potential and water quality treatment but less performance on peak flow or volume reduction.

Figure 2.4: Constructed green roof

- **Rainwater Collection system:** Rainwater from the impervious surfaces such as roofs, asphalts and hard surfaces can be stored and used. Appropriate design for this system can reduce the volumes and rates of runoff. Water barrels are the common structure of rainwater collection system and is suitable for small scale watershed area such as gardens. Therefore the comparative cost, performance and maintenance of barrels are less than other larger harvesting systems. But unless other components this structure also have some disadvantages such as cost of installing, potential requirement to pumping, and also has potential risks for public health. This component unless to the green roof component has best performance on peak flow and volume reduction and very poor performance on water quality treatment.

Figure 2.5: Rainwater harvesting in residential area

- **Pervious Surfaces:** Pervious surfaces can be either permeable or porous. The main difference between the two are:
  - Porous surfacing is a surface with infiltration capacity that lets water infiltrate in entire area.
  - Permeable surfacing is designed of material that is impervious to water but, by benefit of voids that designed in their surfaces allows the water to infiltrate through this pattern.

Pervious surfaces are suitable for parking lots while transporting rainwater into the underlying layers or drainage system. In these surfaces, underlying layers can be temporarily stored the water before infiltration to the ground, and can reused or transfer to drainage system. These surfaces with collecting sub layer can improve the water quality.

This component is very common now a days in parking lots but also have some disadvantages such as, this component cannot be used where there is large sediment loads, other disadvantage of this component is the risk of long-term blockage by weed and vegetation that fill the voids and decrease the infiltration rate if poorly maintenance. With all disadvantages and potential risk in long-term period, this component has a very good performance on peak flow and volume reduction and also water quality treatment but poor performance in amenity and ecology potential.

Figure 2.6: Pervious surface constructed in the parking lot

- **Permeable Surfaces:** Other permeable surfaces namely are:
  - Vegetated surfaces such as grass (suitable for the area without traffic)
  - Reinforced grass
  - Graveled areas

  The permeable surfaces allows the treatment, infiltration, transport and storage of water while the water passes through these surfaces. Graveled areas commonly used in every public and private properties areas due to low cost and high performance in amenity.

Figure 2.7: Gravelled area to increase the infiltration of surface

Objectives of source controls components are to increase the porousness within the site to achieve treatment, water quality, infiltration and attenuation. Green roof (Figure 2.4) achieves these objectives by its vegetation cover on roof, which increase attenuation, infiltration, storage and evapotranspiration helping manage flows as well as providing other benefits such as thermal comfort and biodiversity. Other components which is more important in this research are described below which considered as other source control components.

iii) Site Control: Impervious surfaces like car parks, asphalt, and roofs are the main surfaces that creating runoff. These areas conducted with different approaches such as infiltration, and detention basins with regulated outlets to control the runoff rates and volumes. This makes it possible to retain the water temporarily, reducing the worst peak-flows (SEPA, 2011). These components are described below.

- **Filtration:** one of the main treatment for water in SUDS is filtration or removing sediments or other particles from the surface runoff. The common approaches for this method are trapping, geotextile layers, and soil storage.

  According to Girling et al., (2000), vegetation has important function in the natural water cycle storing water by interception on leaf surfaces and water uptake by plants. Good root structure breaks up soils increasing permeability and allowing water to infiltrate. The use of vegetation as well as contributing towards runoff and pollution control at the same time contributing towards the preservation of natural habitats for aquatic life. The location of any filtration depend on the SUDS components. The different components that classified under filtration described below:

  - **Filter Strip:** Filter strips are surfaces that gently sloped and vegetated. Water flows onto this surface and towards the outlet, other constructed components such as soakways or main drains. The main purposes of these component is to remove any particles such as silt from the stream.

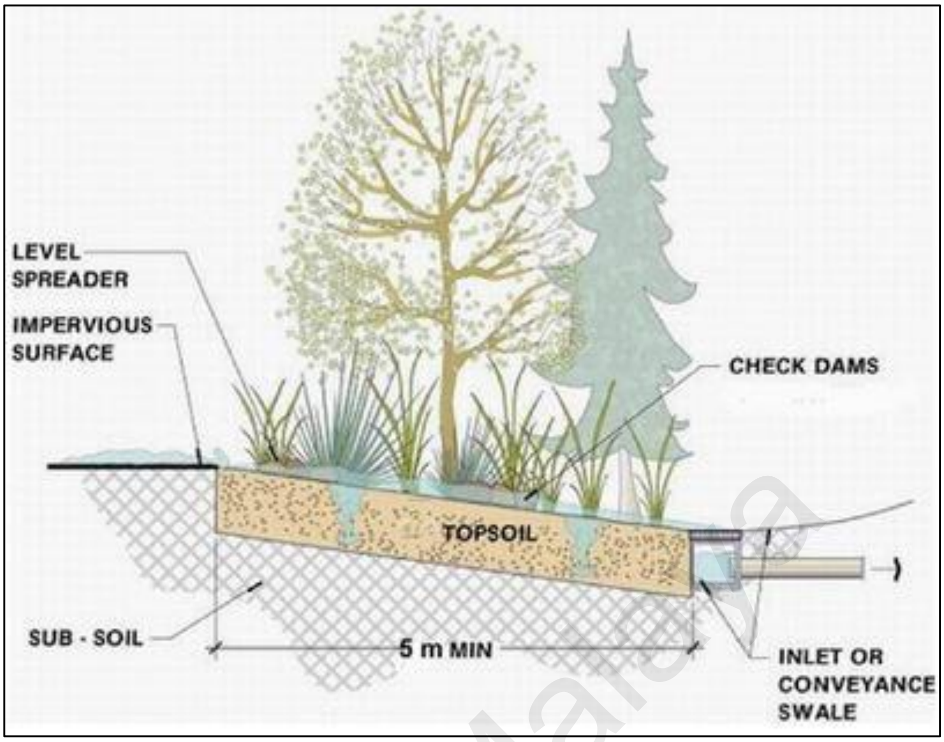


Figure 2.8: vegetated Filter strip (Landmark Design Group)

Filter strips don't have significant attenuation or reduction of extreme event flows due to this reason they should combine with other SUDS components to get high performance and achieve the objectives of this structure.

- **Filter Trench:** Filter trenches also follow the similar approach and are shallow digs filled with gravel providing temporary subsurface storage for infiltration or filtration of runoff. This trenches have high historic failure rate due to poor maintenance.

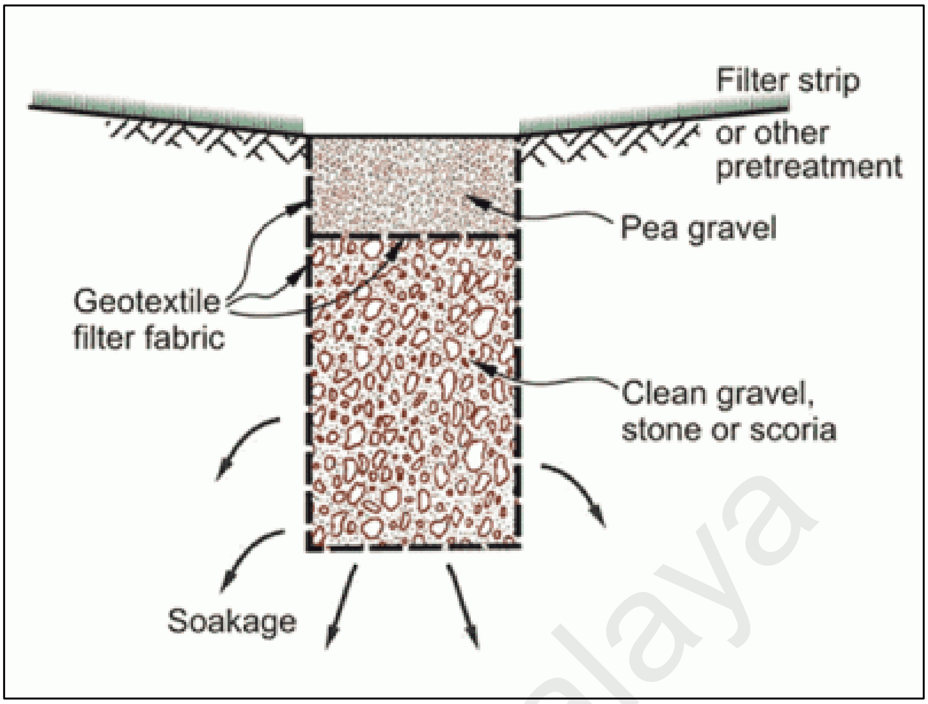


Figure 2.9: Filter trench

- **Bioretention area:** Bioretention areas are vegetated areas with specially engineered design in soil and sand layers, which filter out pollutants from surface water runoff normally associated with highways. Bioretention feature have an aesthetic and biodiversity value as they can be planted to enhance local character and are attractive landscape features. Bioretention are often depression in the ground to create opportunity to storage and attenuation and have medium performance in peak flow and volume attenuation compare to high performance in water quality treatment. Bioretention areas have requires to landscaping and management and cannot be applied for the steep slopes.

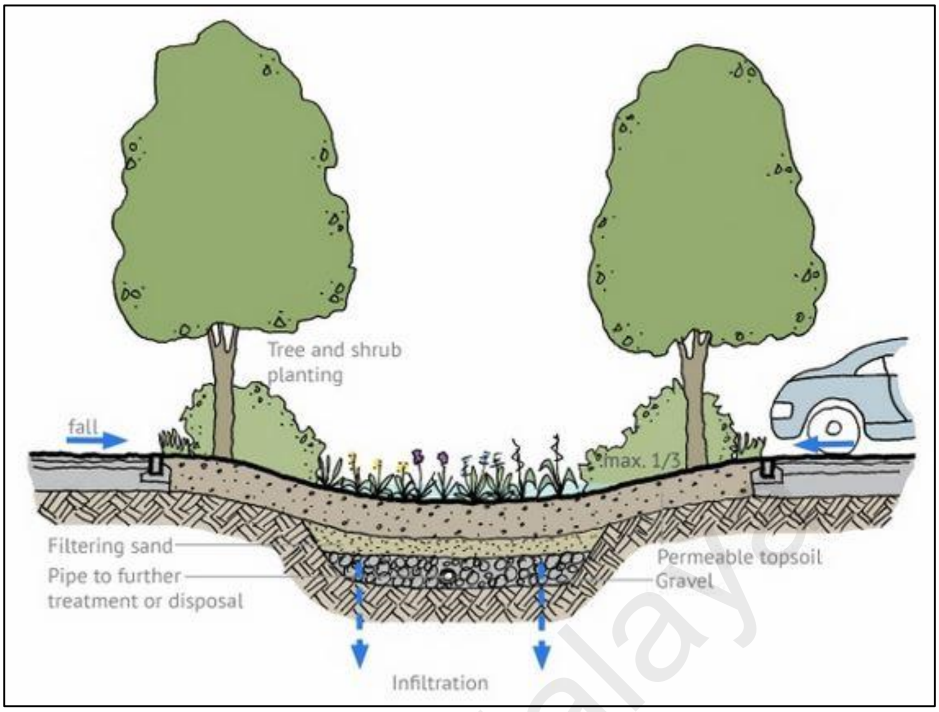


Figure 2.10: Sample of constructed Bioretention (CIRIA, 2007)

- **Infiltration:** In the infiltration components first step is capture runoff from impervious surfaces and allow it to infiltrate into the subsoil layer through the river sands or other materials that increasing infiltration rate and then improve the quality of water before returning it to the groundwater. A range of SUDS components incorporated with this approach but there are some technical considerations with using this components. One of these technical consideration is these components require maintenance same as other components. Therefore, environmental agencies should check the groundwater quality and also before surface runoff reaches to groundwater, there should be some level of treatment to increase the quality of runoff. A risk assessment also should be undertaken in the areas of contaminated lands. Infiltration components considered this section are includes:
    - **Soakaways:** Soakaways are circular or rectangular trench either filled with debris or lined with pre-cast concrete, brickwork, or polyethylene

storage structure (modular tanks) surrounded by granular backfill. Different soakways laterals can be connected to each other to cover the larger scale areas like highways. The supporting structures can be replaced with geocellular or modular structures. Soakaways have good performance on stormwater attenuation, stormwater treatment and groundwater recharge and poor performance on amenity and ecology potential. Infiltration techniques in soakaways led to the storage capability for runoff in an underground chamber which means peak flow attenuation and volume reduction. The amount of water can be drained by soakways within specific time mainly depend on infiltration rate of the surrounding soil, because of this issue soakaways have high performance only when it constructed in high drainage areas.

Figure 2.11: Soakaways

- **Infiltration Trench:** infiltration trenches are the shallow digs either filled with rubbles or sands that create temporary storage for stream runoff, thereby increasing the capacity of the ground to store and drain runoff. Infiltration trenches allow water to exfiltrate from the side and bottom to the surrounding area. The infiltration trenches also equipped with subsurface perforated pipes to increase the infiltration rate. Due to this volume reduction and flow attenuation in infiltration trench is higher than soakaways. Infiltration trench also have high historical failure due to poor maintenance and acceptable for only small catchments.

Figure 2.12: Infiltration trench constructed in highway

- **Swales and conveyance channels:** transfer the surface runoff between the SUDS components is very important in flow attenuation. There are a variety of different approaches can be used; underground pipes system with water quality treatments, or through vegetated channels that provide treatment for runoff or through designed rills or concrete channels. The preference conveyance system in SUDS components is vegetated channels or swales. This component can be used in any industrial, urban or cities areas.
    - **Swales:** swales are the shallow channel which vegetated and designed to store and/or convey runoff and remove water pollutants (CIRIA, 2004). Mohd Sidek (2002) defined swales are vegetated, open channels that have a dual function to control runoff. The shallow slopes of the side and flat bottom led to this scheme that runoff flow in thin layer and this led to increase performance of this component in infiltration and filtration of water body. The grass or vegetated swale is one of the important SUDS components which provide medium and good performance in aspect of quantity and quality of stormwater management. This component has good performance in water quality treatment because of vegetation and filtration and medium performance in peak flow attenuation and reducing runoff volume. However, this component is not suitable for steep slopes and also risk of blockage in connecting pipe work is inevitable.

Figure 2.13: Constructed grass swale

- **Channel and rills:** channel and rills are open channel with hard edges, and allows the water to flow easily and convey it to other quality control components. In channel and rills one important feature is design crossing because wrong crossing can cause structure failure and poor performance in stormwater management. Channels and rills can also include with vegetation to provide both enhanced visual appeal and water quality treatment. Channels and rills have variety of cross sections which depending on landscape.

Figure 2.14: Concrete channel constructed to transfer the water

- **Detention and Retention:** there are SUDS components that designed to either increasing water quality through the retention of runoff, or flow attenuation through store or detention of surface runoff.
    - **Detention Basin:** Detention basins known as dry detention or dry ponds, these structures are empty of water in majority of time but it depends on the watershed characteristics and provide temporary storage for runoff, delay the peak flow, reduce the stormwater runoff and also increasing the quality of stormwater runoff as well as allowing the water infiltration into the subsoil layer (CIRIA, 2004; EA, 2003i; Jefferies, 2003).

      Dry detentions have good performance of controlling flow rate by storing the stormwater runoff and releasing it slowly once the risk of flooding has passed. This capability also providing the opportunity for settlement of solids and pollutants.

Figure 2.15: Dry detention

- **Retention Pond:** known as wet ponds designed to collect stormwater runoff through swales or filter strips and allow settlement of suspended solids and biological removal of pollutants (CIRIA, 2004; EA, 2003iii). Wet ponds have water in majority of time. They are designed to support emergent and submerged aquatic vegetation along their shoreline. Runoff from each rain event is detained and treated in the pool. The retention time promotes pollutant removal through sedimentation and the opportunity for biological uptake mechanisms to reduce nutrient concentrations.

  One of disadvantages for this component is that this component has very poor performance in reducing runoff volume also may perceived health and safety risks by isolation of the ponds. Regarding to these issues maintenance, sediment monitoring, removal, and vegetation management when required is very crucial.

Figure 2.16: Constructed retention ponds

- **Geocellular systems:** These systems can be used to manage and control rainwater surface water runoff either as soakaways or as a storage tank. The modular tank is the nature of geocellular systems means that they can be tailored to suit the specific requirements of any site. This component can be used in detention ponds or swales to increase the infiltration rate and also flow attenuation but one of the major concern about this system is that very difficult to monitor and maintain but has very good performance in flow and runoff volume reduction and also water quality treatment.

Figure 2.17: Constructed Modular system as conveyance system

2.5 Bio-ecological Drainage System (BIOECODS)

In 2002, Bio-ecological Drainage system (BIOECODS) lunched in Malaysia, to meet the requirements of Stormwater Management Manual in Malaysia (MSMA). This approach of SUDS in Malaysia designed by River Engineering and Urban Drainage Research (REDAC) to increase both quality and quantity control. This pilot project was constructed in engineering campus of University of Sains Malaysia (USM). BIOECODS is a pilot project and it is an example of sustainable urban drainage system.

The aim and objectives of this project are:

- Infiltration of stormwater from buildings, roads, and other impervious areas
- Flow reduction of stormwater runoff (Quantity control)
- Stormwater quality treatment (Quality control)

Few different projects were lunched and constructed in Malaysia according to the objectives and aims of BIOECODS. According to the different projects that applied with Bio-ecological Drainage System, shows the efficiency of the system by some reduction of pollutants (Ayub et al., 2010; Ayub et al., 2005; Zakaria et al., 2003). The quality of stormwater runoff also increases from the upstream to the downstream and by control at source approaches minimizing the effect of peak flow at the downstream area (Lai and Yau, 2012; Ayub et al., 2010; Ab. Ghani et al., 2005; Ainan et al., 2004).

The BIOECODS combines three major techniques to manage stormwater based on control at source approach namely conveyance, storage, and infiltration. The concept of BIOECODS is to integrate the drainage component with ecological pond components for the further treatment of the storm water runoff. BIOECODS includes different components to achieve these objectives which namely are: Retention Pond (Wet pond), Dry detention (Dry pond), Grass swale, and also modular tanks to increase the infiltration rate and performance in runoff volume and peak flow attenuation. In combination, these increase runoffs lag time, increase opportunities for pollutant removal through settling and bio infiltration, and reduce the rate and volume of runoff through enhanced infiltration opportunities.

The BIOECODS application designed to overcome to three major problems in Malaysia namely, flash flood, river pollution and water shortage in dry season. The results shown that BIOECODS is capable of flow attenuation and removing pollutants in pre-developed and developed areas from the surface runoff.

Main components in BIOECODS namely are:

- Grass Swale with on-line subsurface detention system
- Retention Pond (Wet pond)
- Detention pond (Dry pond)
- Detention pond with on-line subsurface detention storage
- Wetland

2.5.1 Grass Swale

As it mentioned before, grass swales are one such SUDS structures that been employed for the conveyance at stormwater runoff and quality control in sustainable urban drainage system designs. Variety of research and studies conducted to evaluate the effectiveness of grass swale in peak flow attenuation and quality control (Schueler, 1994; Barrett et al., 1998; Yu et al., 2001; Backstrom, 2003; Barrett, 2005; Satgge, et al., 2012). Grass swale is one of the major components in BIOECODS and designed to cater any excess runoff while the flow from the pervious and impervious area directed to the grassed swale. Grass swale in BIOECODS defined as vegetated open channel combined with on-line subsurface module which enclosed with permeable geotextile. Grass swale has ability to reduce on-site peak flow rates by increasing the roughness of the channel and infiltration rate and time lag. Open channel vegetated by cow grass to increase the roughness and remove the low concentrations and quantities of Total Suspended Solids (TSS), heavy metals and hydrocarbons from stormwater. Cross sectional and construction of grass swale shown in Figure 2.18.

Figure 2.18: Cross sectional profile of grass swale in BIOECODS project (REDAC, 2005)

2.5.2 Retention Pond (Wet pond) and wetland

Retention pond and constructed wetland mainly constructed in downstream of BIOECODS to increase the effectiveness of quantity, water quality, and treatment.

Retention ponds are mainly full of water to provide an opportunity for sediments to settle down before the storm runoff reach to main drain. Retention pond shown in Figure 2.19.

Figure 2.19: Retention Pond

2.5.3 Detention Pond (Dry Pond)

The dry detention pond or dry pond is a SUDS component which is designed to store the excessed surface runoff permanently in developed and pre-developed areas. This is a facility that blended with the landscape for an optimum landuse. A sub-surface modular tank is placed underneath the dry pond and connected to the on-line sub-surface conveyance system of the grass swale. The surface runoff in dry pond withdraws by infiltration through the river sand and topsoil layer to the detention storage underneath then flow to the on-line subsurface conveyance system of grass swale. The dry pond functions as an off-line and on-site detention storage for flow attenuation.

Cross sectional design and example of constructed dry pond project shown in Figure 2.20.

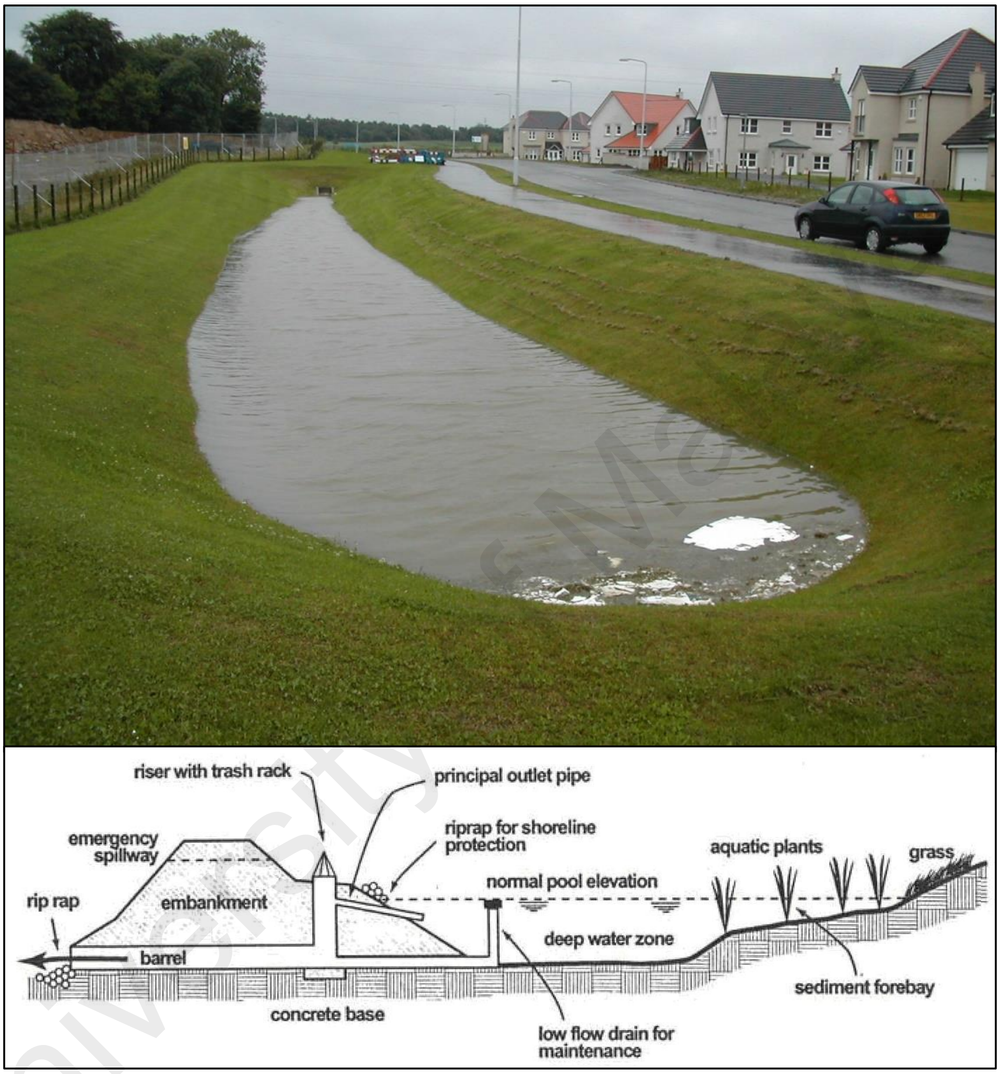


Figure 2.20: Cross sectional design and Dry Detention

2.6 Approaches for Urban Stormwater quantity estimation

The hydrological cycle begins with precipitation. Precipitation in the form of rain falling on land surface is subject to evaporation or initial loss due to interception by vegetation. The excess rainfall can appear in different forms such as infiltration, depression storage, and overland flow. Depression storages are defined as small pores and depressions on the land surface, which are able to store water temporarily. Infiltration defined as the process by which water on the ground surface enters the soil. Infiltration water may either flow through the upper layer of the soil or unsaturated zone or flow deeper into the soil reaching to ground water or saturated zone. The infiltrated water that flow in unsaturated layer and later becomes surface water, known as interflow. In some urban stormwater models, sub-surface flow are not included in model calculation. One of the reason is because in urban areas most of the land cover with impervious areas and less water infiltrate into the soil or in some cases there is no sub-surface flow and other reason is the provided data for subsurface flow is difficult to collect and in some cases impossible. This issue target model accuracy in representing hydrological cycle and this issue effects on simulation of both quality and quantity of runoff in watershed.

The most important problems associated to water quantity are flooding and water supply. High intensity of population in urban areas has led to change of land use and subsequently increasing in runoff volume, reduced time for flows to reach their peak flow rate and decreased in infiltration rate.

The concentration of human population in small areas create problems for water supply with appropriate quality. Water supply problems related to the distribution of available water resources to various type of water uses, like agricultural, industrial, and residential. This include the design of a treatment and supply facilities such as pumps, pipes, water treatment plans to meet the required demands for water supply and quality improvement. Therefore, the models that developed to simulate stormwater runoff in urban areas are different from the developed models for rural and undeveloped areas. Models for urban areas are more complicated because they must involve additional parameters, factors, and structures such as streets, gutters, overflows, closed and open conduits, pressurized flow, culverts, roof top storage, and other storage components.

2.6.1 Runoff estimation methods

Since early 1970, different urban watershed models from simple to complex are developed and introduced. Simple models require less data; calculations are not repetitive and may require simple calculations and respectively the outputs of calculation and presented information is limited. Most of urban watershed models use hydraulic and hydrologic computations to simulate rainfall-runoff response. These methods namely are Loss modelling, Overland flow routing or other variety of methods to represent catchment characterization. These methods or models can be very simple such as empirical models and very complex with variety inputs and data. In this section, several common methods are described in rainfall-runoff response modelling.

(a) Statistical and empirical models

Statistical models that have been used for rainfall-runoff response and also water quality in watershed areas are usually based on the Regression models (Zoppou, 2001). These computations measured quantities of stormwater runoff with measureable parameters that are important in particular processes.

Regression models are an example of a modelling approaches in stormwater management field. These may include, watershed or catchment characteristics such as landuse, slope, impervious and pervious areas, or climate characteristics such as rainfall intensity and rainfall patterns,

As example a non-linear regression model shown in Equation 2.1.

$$Y = \beta_0 \prod_{i=1}^{n} X_i \beta_i \qquad (2.1)$$

Where: Y, is dependent variable, X_i, are observed variables, β_i, are the unknown regression coefficients.

This is a common statistical method used in water quality and quantity modelling approaches. Different regression models also include multiple and simple linear, semi-log and log-log transform used to model water quality and quantity (Bidwell, 1971; Jewell and Adrian, 1981; Zoppou, 2001).

Jewell and Adrian (1981), they used this statistical method to simulate watershed area. Example of watershed modelling using regression model can be found in Driver and Tasker (1988), Neter et al., (1990), and Yao and Terakaura (1999).

According to Jewell and Adrian, (1981) one of the disadvantages of this statistical models is that the model developed according to given set of data with spatial arrangement. Therefore, they suggested that linear regression model is not suitable for urban catchment modelling. Other limitation for linear regression model in urban watershed areas is that for different processes and spatial patterns, new relationship and new data should be developed. Regarding to these limitation regression model has been used only for simple analysis or in situations of insufficient data or missing data. Driver and Tasker (1988) suggested that regression models are suitable for planning purposes only.

One of the regression models that used to analyzing urban runoff is based on the Antecedent Precipitation Index (API). This is a common used and very important observed parameter in surface runoff analysis. The API means summation of precipitation amounts that happening during the storm, and weighted by time of event (Betson et al., 1969). As example antecedent regression model shown in Equation 2.2:

$$C = c + (a + dS)e^{-bp}, Q = (i^n + C^n)^{1/n} - C \qquad (2.2)$$

Where: Q, is surface discharge, C, is runoff coefficient, S, is seasonal index parameter, p, is API, i, is rainfall intensity, $a, b, c, d, and\ n$, are model coefficients.

Empirical model is other statistical model that used in urban catchment modelling. Empirical models include a statistical relationship between a dependent parameter and other parameters which is important in the process. These variables are chosen according to the knowledge of the physical processes and form empirical measurements.

(b) Rational methods

Rational method is one of the empirical approach for estimating runoff and is based on the peak runoff from the drainage system happens when entire watershed area contributed to surface runoff and rainfall distributed uniformly over the watershed area (Nicklow et al., 2006). This method is the simplest method in modelling peak runoff that is important analysis in stormwater structure design. This method shown Equation 2.3.

$$Q = CiA \qquad (2.3)$$

Where: Q, is discharge or flow rate (m^3/s), A, Catchment area (m^2), i, Rainfall intensity (mm/hr), C, Runoff coefficient, where $0 \leq C \leq 1$

One of the model that is based on Statistical Rational Method (SRM) is Wallingford model and will be briefly discussed below:

Hall (1984) described a complete approaches of Wallingford procedure for the Modified version of Rational Method known as MRM for catchment areas up to 150 hectares. In this version of rational method in addition to volumetric runoff coefficient which presented in Equation 2.3, include other routing coefficient. This modified equation can be applied either for event base or designed rainfall. The Wallingford rational method, adopted to UK catchment areas (Kidd and Packman, 1979; Colyer, 1980). This method presented in Equation 2.4.

$$Q_p = 2.78(C_v C_r I A) \tag{2.4}$$

Where: C_v, volumetric runoff coefficient, C_r, routing coefficient (suggested value is 1.3), Q_p, Peak discharge (l/s), I, rainfall intensity (mm/hr), A, catchment area (ha)

And volumetric runoff coefficient calculated from the following equation.

$$C_v = \frac{PR}{100} \tag{2.5}$$

Where: PR, percentage of runoff from the catchment

The best estimate PR, and hence, runoff volume was provided by an equation derived from regression analysis (Kidd and Lowing, 1979):

$$PR = 0.829IMP + 25.0\,SOIL + 0.078\,UCWI - 20.7 \tag{2.6}$$

Where: IMP, impervious area (%), SOIL, soil index (map available for UK), UCWI, antecedent wetness index.

(c) Loss modelling

Storm loss define as the amount of the precipitation which is not transferred to surface runoff. Storm loss include, infiltration into the soil (Infiltration), stored by the surface storage (depression) and moisture captured by vegetation (Interception loss). This storm loss can be happen either from impervious or pervious surfaces.

Each storm loss that mentioned above can be modelled by different loss components that namely are, impervious and pervious area initial loss, and evaporation loss from both impervious and pervious surfaces and pervious surface continuous loss. However, in hydrograph modelling and analysis because of insignificant effect of evaporation from pervious and impervious surfaces usually this variables can be neglected.

(d) Time-Area Method

Time-area methods utilize a convolution of the rainfall excess hyetograph with a time-area diagram representing the progressive area contributions within a catchment in set time increments. Separate hydrographs are generated for the impervious and pervious surfaces within the catchment. These are combined to estimate the total flow inputs to individual sub-catchment entries to the underground urban drain network.

The time-area method first time used by Ross (1922). This computerized program known as the TRRL method was developed by the UK Transport and Road Research Laboratory (TRRL), which described by Watkins (1963). In the US, Terstriep and Stall (1974) did further develop in the method to include pervious runoff. Between 1982 and 1986, Watson's model used through extensive changes, to formulate a computerized package known as ILSAX (O'Loughlin, 1993). The sub catchment runoff estimating procedure still utilizes the basic time-area method to estimate both pervious and impervious segment of runoff. (DID, 2000). The procedure for this method used to assume separated subcatchments and storage effects characterize the flow hydrograph for any storm. To apply this method, the catchment is first should be divided into a number of time zones and separated by isochrones or lines of equal travel time to the outlet.

The translated inflow hydrograph ordinates Q_i for any selected design hyetograph can be determined. The simultaneous arrival of the runoff form areas A_1, A_2, A_3,… for storm I_1, I_2,... should be determined by properly lagging and adding contributions, or generally:

$$Q_i = I_i A_i + I_{i-1} A_{i-1} + \cdots + I_1 A_1 \tag{2.7}$$

Where: Q_i is the flow hydrographs (m^3/s), I_i is rainfall intensity (mm/hr), A_i is time-area histogram (ha), and i is number of isochrones area contributed to the outlet.

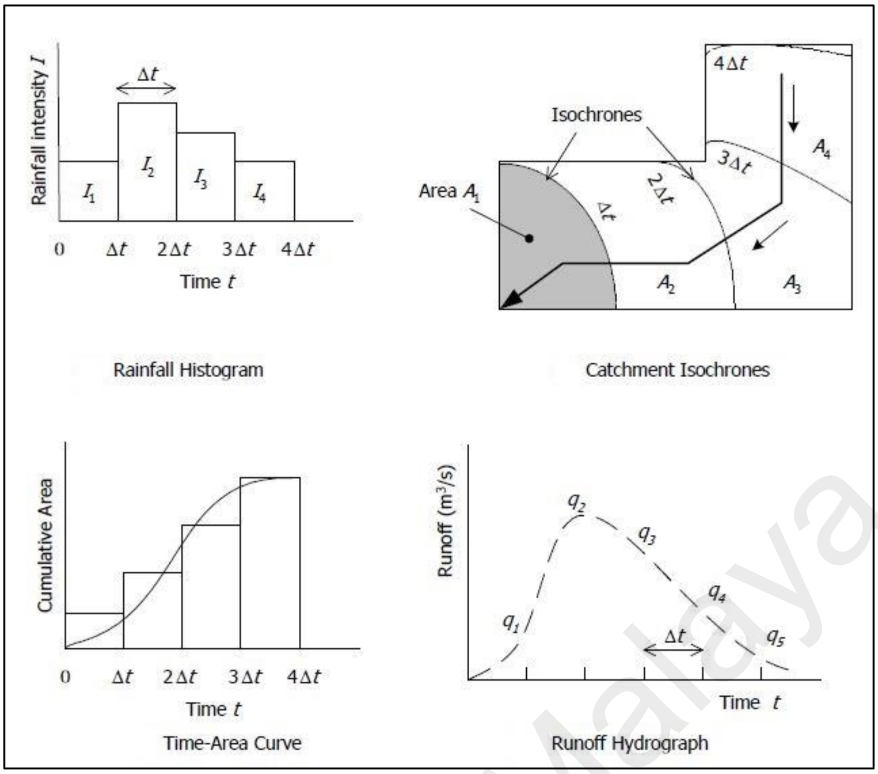


Figure 2.21: Time-Area Method

(e) Kinematic wave Model

The kinematic-wave model is one of a number of approximations of the dynamic-wave model. The dynamic-wave model describes one dimensional shallow-water waves (unsteady, gradually varied, open channel flow). In the kinematic-wave approximation, a number of the terms in the equation of motion are assumed insignificant. The equation of motion is replaced by an equation describing uniform flow. Thus, the kinematic-wave model is described by the continuity equation and a uniform-flow equation such as the well-known Chezy or Manning formulas. Kinematic-wave models are applicable to overland flow where lateral inflow is continuously added and is a large part of the total flow (Miller, 1983). For a unit width of overland flow, the formula could be expressed as:

$$\frac{\partial q}{\partial x} + \frac{\partial y}{\partial t} = i \qquad (2.8)$$

Where: q, unit width of overland flow, x, longitudinal distance, y, flow depth, t, time, i, rainfall intensity.

The terms of $\frac{\partial q}{\partial x}$ used to simulate non-uniform and $\frac{\partial y}{\partial t}$ used to simulate unsteady flow path. .

As mentioned above kinematic wave model described by uniform flow or continuity equation that mentioned below. Consider that, in uniform flow, the momentum equation could be expressed generally:

$$q = a_k y^m \tag{2.9}$$

Which a_k and m are constant and depend on a water depth and discharge. One the equation that present such a relationship is Manning's equation:

$$Q = \frac{K_m}{n} A R^{2/3} S^{1/2} \tag{2.10}$$

Where: K_m, constant coefficient that is 1.49 in U.S. units and 1.0 is SI units, n, Manning's roughness coefficient, A, effective flow area, R, hydraulic radius and depends on area and wetted perimeter, S, surface slope

Manning's roughness coefficient represents the resistance to flood flows in channel and floodplains. The results of Manning's formula, an indirect computation of stream flow, have applications in flood-plain management, in flood insurance studies, and in the design of bridges and highways across flood plains (Arcement and Schneider, 1989). Different studies conducted to suggest value for Manning's coefficient in open channels that tabulated according to factors that affect resistance of flow such as (Chow, 1959; Henderson, 1966; Streeter, 1971; Barnes, 1967).

(f) Non-linear Reservoir Model

The overland flow components over catchment could be estimated by non-linear reservoir method. In non-linear reservoir method catchment conceptualized as a very shallow reservoir. Non-linear model is based on two parameters (n, K). This model uses both storage and continuity equations that mentioned below,

(a) Storage Equation:

$$S = Kq^n \tag{2.11}$$

(b) Continuity Equation:

$$\frac{dS}{dt} = I - Q \tag{2.12}$$

Combining storage and continuity equation, the overland flow routing equation obtained in Equation 2.13:

$$I - Q - nKQ^{n-1}\left(\frac{dQ}{dt}\right) = 0 \tag{2.13}$$

Where: I is the inflow to catchment (m^3/s), Q is the outflow (discharge) (m^3/s), S is the storage (m^3), K is the storage coefficient, n is number of reservoir, t is time (s) since start of runoff

Definition for non-linear reservoir method illustrated in Figure 2.22.

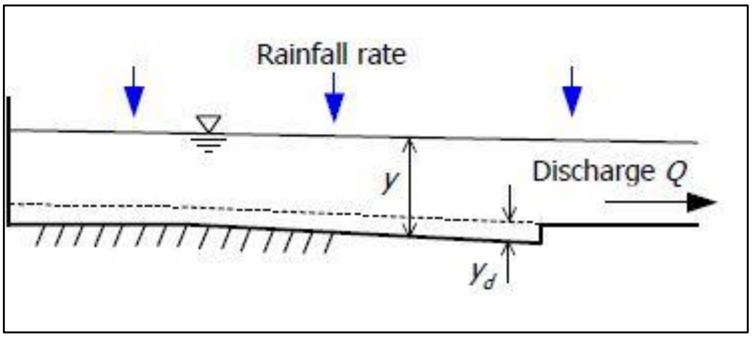


Figure 2.22: Definition of Non-linear Reservoir method (MSMA, 2001)

In Figure 2.22 Rainfall rate is as an inflow for the conceptualized catchment, and infiltration and surface discharge as outflow. The depth Y represents the average depth of surface runoff, and the depth Y_d represents the average depression storage in the catchment.

Non-linear routing used in different modelling such as RAFTS (WP Software, 1991), SWMM (U.S. Environmental Protection Agency, 1992), and WALLRUS (Hydraulics Research Ltd., 1991) for modelling overland flow routing.

2.6.2 Depression storage in pervious and impervious surfaces

Depression storage is a volume of water that stored temporarily in pores for both pervious and impervious areas. This phenomenon presented the volume of water that loss by surface wetting, ponding in the porous of the soil and interception. The depression storage calculation for impervious areas are very simple. Simply, the excess rainfall is rainfall hyetograph that subtracted from depression storage. In impervious areas depression storage is emptied by evaporation. However, as it mentioned before evaporation loss in the stormwater modelling is insignificant therefore the impervious areas depression storage is constant for modelling purposes or can be neglected in calculations. The range of depression storage for impervious areas is between 0 to 2 mm. On the other hand depression storage for pervious areas is subject to evaporation and infiltration. However, small value of evaporation in pervious surfaces compare to infiltration loss can be ignored in urban stormwater modelling (O'Loughlin, 1993).

2.6.3 Infiltration in pervious surfaces

Different equation have been developed to describe the process of infiltration of water into the soil for modelling purposes. Some of these methods are based on empirical and others based on numerical or analytical equations.

One of the equations based on empirical equation is Horton equation. On the other hands, Green-Ampt and Philip method is based on theoretical equations. The parameters for these equations should be estimated using infiltration test in the field at several points in the catchment.

Other type of infiltration models that have been developed are spatially lumped models. Because of the simplicity and ability to estimate runoff behavior in the watershed areas, spatially lumped models are used widely. Some of the most widely used models for this method is initial loss-continuing loss, constant loss rate, SCS curve model, antecedent precipitation index and proportional loss (Nandakumar et al., 1994). Between these developed models SCS methods, constant loss rate, and initial loss-continuing loss have been used in computer modeling. Some of these popular equations for infiltration loss models presented in the following sections.

(a) Horton equation

The Horton model of infiltration (Horton, 1939 and 1940) is one of the best-known models in hydrology. Horton recognized that infiltration capacity (f_p) decreased with time until it approached a minimum constant rate (f_c). He attributed this decrease in infiltration primarily to factors operating at the soil surface rather than to flow processes within the soil (Xu, 2003). Beven (2004) discovered, upon making a study of Horton's archived scientific papers that Horton's perceptual model of infiltration processes was far more sophisticated and complete than normally presented in hydrological texts. Furthermore, his understanding of the surface controls on infiltration continue to have relevance today (Beven, 2004). Horton described infiltration loss according to following equation.

$$f_p = f_c + (f_0 - f_c)^{-kt} \tag{2.14}$$

Where: f_p, infiltration capacity (m/s), f_c, minimum or ultimate value of f_p (m/s), f_0, maximum or initial value of f_p (m/s), t, time (s), k, decay coefficient (s^{-1}).

Due to this simplicity, several computer models using Horton equation in infiltration loss modelling such as InfoWorks (Wallingford UK), SWMM (U.S. Environmental Protection Agency, 1992), and MOUSE (Danish Hydraulic Institution, 1998).

(b) Green-Ampt model

Green and Ampt (GA) proposed in 1911 an approximate model that directly applies Darcy's law. The equation derived by Green and Ampt assumes that the soil surface is covered by a pool of water whose depth can be neglected. Darcy's laws could be apply to give:

$$f_p = k_s \frac{L + S}{L} \tag{2.15}$$

The basic principle of Green-Ampt model presented in Figure 2.23:

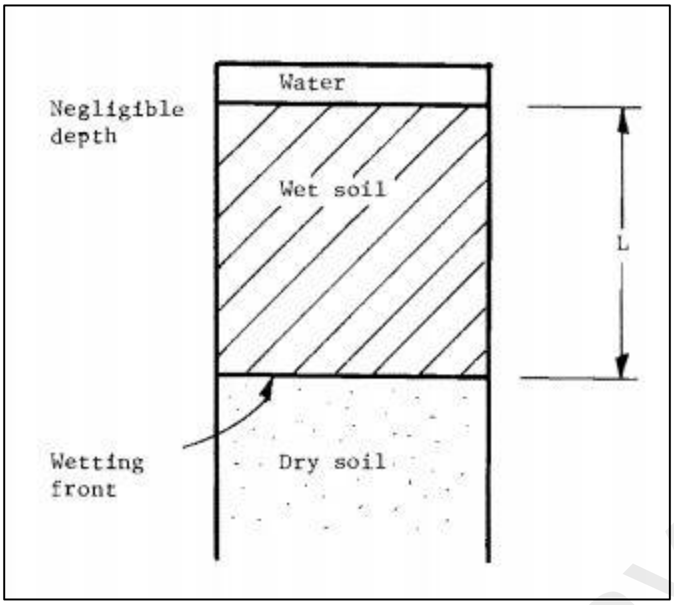


Figure 2.23: Definition diagram for Green-Ampt formula (Mein and Larson, 1971)

Where L is the distance from the soil surface to the wetting front and S is the capillary suction at the wetting front. Mein and Larson (1971) described that the Green-Ampt model have two-stage that presented by Equations 2.16 and 2.17. These equations are for the constant rainfall intensity and are not valid for ponded situation.

For F < F_s: $f = i \quad and; \quad F_s = \frac{S_u(IMD)}{\frac{i}{k_s}-1}, \quad for\ i > k_s$ (2.16)

F_s is not calculated for $I \leq K_s$,

For F ≥ F_s: $f = f_p \quad and; \quad f_p = k_s\left(1 + \frac{S_u(IMD)}{F}\right),$ (2.17)

Where: i, rainfall intensity (m/s), f, infiltration rate (m/s), f_p, infiltration capacity (m/s), F, cumulative infiltration volume (m^3/m^2), F_s, cumulative infiltration volume for saturation surface (m), k_s, saturated hydraulic conductivity (m/s), S_u, average capillary suction at the wetting form (m of water), IMD, initial moisture (m/m).

According to their findings, infiltration has direct relationship with volume of water that infiltrate and as well as soil moisture in the surface soil zone before the rain happen. Like

Horton equation, some of the parameters such as IMD, K_s, and S could be estimated based on available data such as hydraulic conductivity of soil, soil porosity, and capillarity suction. The SWMM runoff model uses the implementation of Green-Ampt infiltration equation (Mein and Lasrson, 1973).

(c) SCS method

The SCS Runoff Curve Number (CN) method is described in detail in NEH-4 (SCS 1985). The SCS runoff equation is:

$$Q = \frac{(P - I_a)^2}{(P - I_a) + S} \qquad (2.18)$$

Where: P is Rainfall (in), S is Potential maximum retention after runoff begins (in), I_a is initial abstraction, and Q is runoff (m^3/s).

Initial abstraction (I_a) is all losses before runoff begins. It includes water retained in surface depressions, water intercepted by vegetation, evaporation, and infiltration. I_a is highly variable but generally is correlated with soil and cover parameters. Through studies of many small agricultural watersheds, Ia was found to be approximated by the following empirical equation:

$$I_a = KS, \qquad 0 < K \leq 0.2 \qquad (2.19)$$

The original assumption for K is 20% for SCS method which conducted with several investigation and re-evaluation (Baltas et al., 2007; Mishra et al., 2006; Mishra and Singh, 2004; Woodward et al., 2004; Hawkins et al., 2002; Hawkins et al., 2009; Jiang, 2001), other research conducted to evaluate the value for K, for instant, Woodward et al., (2004) determined the initial abstraction K is 5% from rainfall and runoff measurements on 327 watersheds in the eastern, mid-western, and southern U.S. In addition, they found that the initial abstraction ratio K varied from storm to storm and from watershed to watershed (Woodward et al., 2004; Jiang, 2001). However, K = 20% is widely used in the world according to original evaluation from Equation 2.19:

$$I_a = 0.2S \tag{2.20}$$

In addition, the curve number (CN) value and soil moisture capacity (S) are connected by the following equation:

$$S = \frac{1000}{CN} - 10 \tag{2.21}$$

Therefore, with substituting Equation 2.20 and 2.21 into the Equation 2.18, runoff could be calculated by:

$$Q = \frac{\left(P + 2 - \frac{200}{CN}\right)^2}{\left(P + 8 + \frac{800}{CN}\right)} \tag{2.22}$$

CN value have been published for each countries based on the extensive field studies and tests for example for United States these values presented in technical report 55 (TR-55) and published by Department of Agriculture (USDA, 1986).

2.7 Urban Stormwater Models

Nowadays, more than half of the world's population has migrated to urban areas according to United Nation report (2001). Different variety of research and practices have been proven that stormwater management greatly evolved since the birth of cities, from the most fundamental objectives such as flash flood control, secure water resources to sanitation and water cycle city (Brown et al., 2009). This evolution accompanied by increasing acknowledgment of the complexity of the urban environment. As such, this development moving towards combined management of various urban water components (i.e. water treatment, distribution, storm drainage, wastewater treatment) and have become considerate of their interaction and feedbacks.

Traditional management of stormwater management considers all independent components (e.g. Rauch et al., 2005). Complexity and variety of different components in urban stormwater management has driven researcher to use computer models to ease the calculation and merged impact of different components and strategies in designing matter. There are many urban stormwater models that have been developed by different government departments, engineering consultants and academic institutions and different studies, research conducted to evaluate or analyze their effectiveness.

Zoppou (2001) reviewed some of well-known and not so well known stormwater models in aspect of both quality and quantity. In his review, he focused on different stormwater modelling approaches with common methods for flow routing and brief mathematical description in different stormwater computer models.

Burton and Pitt (2001, Appendix H) reviewed receiving water in watershed area and their relation to stormwater management. In their research, they classified the stormwater models based on their complexity, from simple models (based on event-mean concentrations multiplied by runoff volume and export coefficients) through complex models (based on spatially distributed).

McAlister et al. (2003) reviewed different stormwater models in aspect of water quality and focused on continuous simulation over one or more years and the importance of using appropriate small temporal resolution. Beecham (2002) shown important features of four different models for urban stormwater design, but he didn’t compare them to evaluate the suitability and effectiveness. Other reviews in water quality models (e.g. the review of sediment models by Merritt et al., 2003) are not related on urban stormwater.

These reviews provided an extensive background on the key principle, different approaches, methods of urban stormwater modelling, and categorizations of the models. The basic components of urban stormwater models are: (i) rainfall-runoff modelling (interaction of surface and subsurface runoff from rainfall event, and wash off of pollutants from pervious and impervious surfaces), (ii) transporting modelling (routing of runoff or pollutants through the stormwater structures, such as close and open channels, culverts, pipes system etc.). The linkage in this modelling process shown in Figure 2.24.

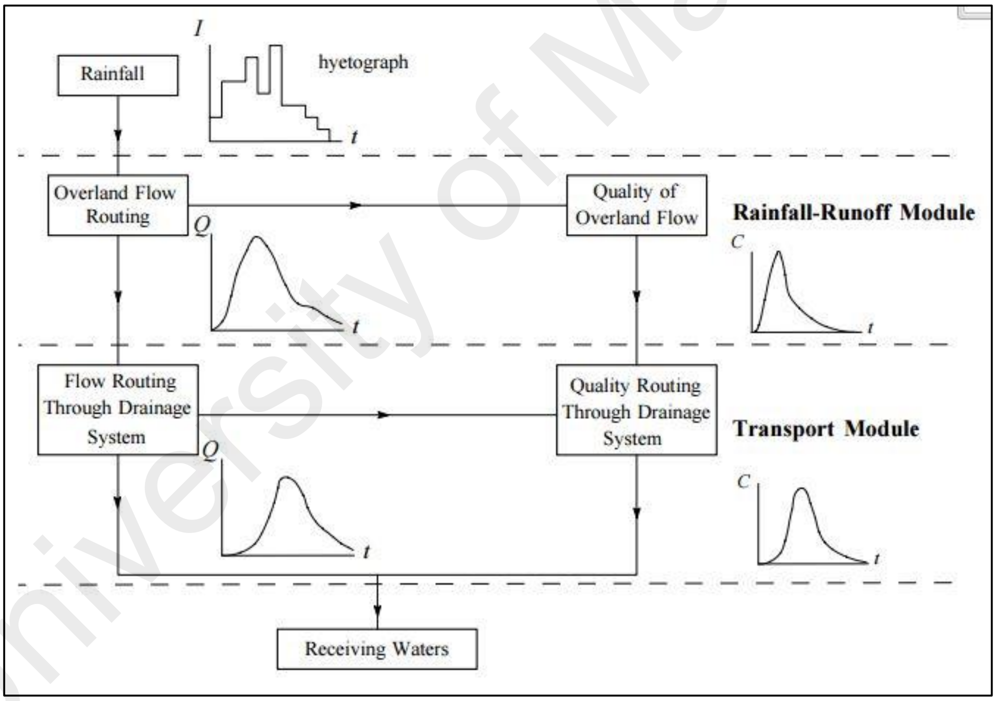


Figure 2.24: Overview of processes incorporated in Urban Stormwater Model (Nix, 1991; Zoppou, 2001)

For this study, from the widely used urban stormwater models, seven models that specifically developed to simulate urban stormwater quality and quantity were selected. These models namely are: HSPF (Bicknell et al., 1993; Johanson et al., 1980, 1984), STORM (Hydrologic Engineering Center, 1977), SWMM (Huber and Dickinson, 1988; Huber et al., 1984; Roesner et al., 1988), SWMM Level 1 (Heaney et al., 1976), DR3M–QUAL (Alley and Smith, 1982a, b), Wallingford Model (Bettess et al., 1978; Price, 1978; Price and Kidd, 1978), MIKE–SWMM, QQS (Geiger and Dorsch, 1980). These models have been classified based on their scales, water quality and quantity structures, water quality constituents, additional features can model possess, and accessibility and cost of models that described in the following sections.

(a) Modelling scale: Table 2.3 indicates the scale of different models in functionality, accessibility and capability of models in planning, operational and designing.

Table 2.3: Functionality and accessibility of urban stormwater models (Zoppou, 2001)

Program names	Functionality			Accessibility	
	Planning	Operational	Design	Public domain	Commercial
DR3M–QUAL	✓		✓	✓	
HSPF	✓		✓	✓	
MIKE–SWMM	✓	✓	✓		✓
QQS	✓		✓		
STORM	✓			✓	
SWMM	✓		✓	✓	
Wallingford Model	✓	✓	✓		✓

(b) Water quality and quantity structures: The models for urban stormwater are able to model different components of sustainable drainage system for instant: Wallingford model is capable to model the pipes, gutter, pumps, weir, open channels, Retention/detention basins, surcharge, and rainfall-runoff interaction which make this software very suitable to model urban stormwater management.

(c) Water quality constituent: In aspect of water quality models which can simulate more pollutant are more effective in quality simulation. These pollutants mainly are: total Nitrogen, total Phosphor, suspended solids, dissolved oxygen, biochemical oxygen demand (BOD), and concentration of biochemical oxygen demand (CBOD). These are most concern parameters in water quality subjects.

(d) Additional features: some of these models have the ability for uncertainty analysis, costs and optimization. None of the selected models considered includes all these features. Only two models consider costs as an important variables in urban stormwater management (Wallingford and SWMM) and only two models includes optimization parameters (STORM and SWMM) (Zoppou, 2001).

(e) Costs and Accessibility: Most of the models developed in United States agencies. These models are available with insignificant costs but with very limited support and options. However that commercial software is expensive. Some of the models presented their source code for public domains. Some of the commercial software such as Wallingford give a very good discount to academic agencies and universities. According to all these parameters to evaluate the urban stormwater software, a suitable software for this study selected.

In this study some of most common and well-known software is described briefly below.

2.7.1 MIKE–SWMM

This software combined two well-known software that is MIKE 11(Havno et al., 1995), and SWMM (Huber et al., 1984; Huber and Dickinson, 1988; Roesner et al., 1988) models. This model developed to use the strengths of MIKE 11 in one-dimensional unsteady flow that use an implicit finite different scheme to solve the shallow water equations and replacing the EXTRAN module in SWMM model.

This combined model is able to perform in hydraulic, water quantity and quality analysis, hydrologic studies, and waste water drainage system that is include treatment plans and other water quality components. Also, different hydraulic components such as detention/retention ponds, open and closed channels, pipe drainage system and also pressurized flow can be modelled in this software.

For runoff modelling mass balance is used that include surface storage, lower soil storage and upper and lower groundwater storage. Runoff in the urban stormwater modelling include base flow and overland runoff. This model also is able to simulate two-dimensional overland flooding using shallow water wave equation.

The main parameters for water quality simulation in this software are total P, total coliform, Dissolved Oxygen (DO), total N, heavy metals, nitrate, ammonia, temperature, bed sediments, and suspended sediments. Sediments in this software defined either non-cohesive or cohesive based on their behavior and size.

This model is able to simulate water quantity and quality at any time-base or spatial scale. This software also can be used for design, operation and management of water resources problems.

2.7.2 SWMM

SWMM is other well-known software that is able to model urban stormwater drainage system. This software can model water quality and quantity either continuous or single event. Overland runoff in this software calculated based on rainfall intensity or excess rainfall, antecedent moisture condition in catchment, topography and landuse. SWMM use the simple non-linear reservoir method to simulate rainfall-runoff process that include infiltration, depression storage, and runoff from pervious and impervious surfaces.

Washoff in SWMM simulated with simple function of runoff or first order decay equation. SWMM can be used to model sewer system. Sewer runoff are generated based on landuse, density of population in watershed area and other related parameters. Infiltration in the sewer system also depend on sewer condition and groundwater levels.

For the water quality simulation pollutant routed through the sewer system using kinematic wave method. Pollutant in the storage system can be modelled as either complete mixing or plug flow. Important parameters in water quality simulation for this software are: Settle able solids, COD, BOD, suspended solids, total N, total coliforms, total P, erosion, and arbitrary pollutant.

The EXTRAN module in SWMM permits to rout the hydrographs through the open and close channels using explicit numerical solution of the shallow water wave equations. Unfortunately, sewer infiltration, dry weather flows and routing pollutant loads are not simulated.

This model is able to simulate water quantity and quality at any time-base or spatial scale. This software also can be used for design, operation and management of water resources problems.

2.7.3 Wallingford Model: InfoWorks SD

The InfoWorks SD is an urban drainage system modelling software that developed at the Wallingford in United Kingdom. This software has announced by Wallingford as a storm drainage software for the accurate, fast, and comprehensive and user friendly software in urban stormwater drainage system. InfoWorks SD is a fully dynamic, hydraulic modelling, and hydrologic modelling solution that developed to overcome the demanding problems in urban stormwater management. Modelling stormwater runoff accurately with real-world environment and urbanization problems provide an opportunity to model stormwater runoff with wide range of overland, underground and flow paths. InfoWorks SD can be used to model both free- surface and pressurized flow with high accuracy and steady quality of analysis applied to both closed and open channels. The unique feature of this software is that every frequently hydraulic components can be modelled including all details such as bypass components, culverts, open and closed cannels, pumps and their controls structures, pressurized and gravity flow, detention/retention ponds etc.

The other unique feature of this software is that can model BMP components, from design, maintenance practices and also criteria for urban stormwater components with their controls structures (using an InfoWorks Real Time Control scenario).

InfoWorks SD is able to model urban stormwater flows in complex urban area, with surface and subsurface drainage system and their control structures with high accuracy of simulation for open and close channels with the option of either real-time continuous or event based simulations. These abilities make InfoWorks SD an ideal software for project evaluation, real-time operational use and design.

InfoWorks SD contains a comprehensive set of models and tools to ensure that the network models engineers create closely match real world conditions.

- Choice of Wallingford, Fixed, New PR, SCS, Green-Ampt, Horton, constant infiltration and Horner runoff volume models.

- Choice of Wallingford, SWMM, Large catchment, SCS Unit, Snyder, SPRINT, Desbordes and Unit hydrograph runoff routing models.

Specific features, such as network and engineering validation, tracing and the Connectivity Tool, along with visual tools, such as flags, themes, 3D views and pipeline profiles, can be used to verify that models are calibrated with a high degree of confidence. InfoWorks SD incorporates a range of features that enhance the simulation of both gravity fed and pressurized networks.

- Two-dimensional (2D) modeling is available as an integrated module within InfoWorks SD, facilitating fast, accurate and detailed surface flood modeling of flows through complex urban geometries.
- Real-Time Control allows control structures to be directly programmed to respond automatically to conditions in the system during a simulation, allowing the optimization of storage and operation.
- The InfoWorks SD Water Quality Module is designed to help engineers to develop cost-effective solutions for pollution and sedimentation problems.
- A Snow Melt module, based on the SWMM continuous simulation model, calculates the melt rate, snow depth and free water depth for any subcatchments containing snow packs.

InfoWorks SD can model sewer systems or combination of stormwater drainage with sewer system using different time steps. It has been used for real time analysis, planning, design and maintenance practices in different watershed areas.

InfoWorks SD provided an option to make hyetographs as input if it was required. In InfoWorks SD determination of average spatial rainfall over a watershed area used an empirical relationship and also using rainfall intensity and a spatial smoothing factor.

The Rainfall-Runoff model in InfoWorks SD applies a modified version of rational method that is same as the rational method but it includes other parameter that is a routing coefficient. This coefficient is in conjunction with contributed area in impervious areas, evapotranspiration, antecedent conditions and soil type. The runoff estimated based on the distribution of rainfall between pervious and impervious areas. The volume of runoff from these surfaces is according to the initial loss, depression storage, infiltration rate, catchment slopes, soil type and contributed area.

The flow attenuation caused by infiltration or storage into the soil for pervious surfaces simulated by using a non-linear reservoir storage model that include upper and lower soil storage, upper and lower groundwater and base flow. This model uses slope, length, and contributed area of the catchment. The delay time model is also based on the non-linear empirical relationship that using bed slope, contributed area, and length of the catchment for simulation. These methods are suitable for the large catchments areas. For small catchments, overland runoff is routed using two equal linear reservoir model in chain with routing coefficient that is dependent on the contributing area, surface slope and rainfall intensity.

For the routing lateral flow in the drainage network InfoWorks SD using the Muskingum-Cunge method and the solution of shallow water wave equations. Both of these equations are suitable for open channels, pipes system or user-specified channels. On the other hand, pressurized pipes in drainage system can be modelled with St. Venant equations. For solving the equations an implicit finite difference scheme is used in InfoWorks SD.

For pollutant transport process advection equation is used in InfoWorks SD. The water quality pollutants that can be simulated in InfoWorks SD namely are COD, BOD, total nitrogen, ammonia, four arbitrary conservation pollutants and total P.

Deposition and erosion processes can be modelled in InfoWorks SD even sedimentation in pipes drainage system. The other structures in urban areas such as manholes, tanks, pumps, gutter, and overflows can be simulated in InfoWorks SD.

In total 12 models for stormwater management were reviewed by Zoppou (2001) and reported their advantages and disadvantages in aspects of quantity and quality of stormwater management. The results of his study mentioned below briefly reported in following tables.

Table 2.4: Characteristics of representative models (adapted from Nix, 1991; Zoppou, 2001)

Model	Model Characterization				
	Routing Level			Time modelling Scale	
	Simple Storage	Hydrologic	Hydraulic	Continuous	Event
DR3M–QUAL	✓	✓	✓		✓
HSPF	✓	✓		✓	✓
MIKE–SWMM	✓	✓	✓	✓	✓
QQS	✓	✓	✓	✓	✓
STORM	✓				✓
SWMM	1	✓	2		✓
Wallingford Model	✓	✓	✓	✓	✓

Note: 1, Flow balance only; 2: With EXTRAN module

2.8 Summary

Urban stormwater management is one of the important topics in the urbanization and flood management and other related fields. Due to increasing population in urban areas and changing in landuse (changing the pervious lands to impervious lands) in cities, controlling these runoff is major concern. Different studies conducted to suggest new strategies and sustainability approaches for runoff control, such as BMPs, LID, SUDS, WSUD, LIUDD etc. All these approaches present the control at source to prevent and control surface and subsurface runoff and increase the water quality. One of these projects that constructed in Malaysia in 2007 is a SUDS project with different BMPs component. This system combines three engineering techniques to manage stormwater based on control at source, namely infiltration, storage, and conveyance. Since the completion of the BIOECODS project, a number of studies (Lai et al., 2009; Lai et al., 2010, Lai and Mah, 2012) have been carried out to evaluate the effectiveness and performance of BIOECODS components for urban stormwater management. However, it is found that almost all the previous modelling efforts have not been very successful due to a difficulty to integrate or couple this type of drainage system (Abdullah, et al., 2004).

In view of the potential of BIOECODS or other similar projects for future implementation to overcome surface runoff problems for long-term as the urbanization increases, it is important to have a model which is capable to simulate the rainfall–runoff interaction effectively. Such a model will be very useful for further analysis, assessment, and design of similar projects where both surface and subsurface drainage system have very close interaction with each other. Many computer software models presented such as Mike11, SWMM, InfoWorks SD etc. to simulate these projects and case studies. Presented models have their differences and also techniques to model the watershed area.

CHAPTER 3: METHODOLOGY

3.1 Introduction

This chapter describes the methodology involved in this study, starting with reviewing previous study conducted by other researchers. Second part is choosing study area and site investigation which is involved in, data collection and land survey.

Data collection for study area divided in 3 parts, which are:

- Rainfall-runoff data such as rainfall data, and velocity for runoff,
- Infiltration data for study area,
- Survey data.

After collecting all the data from different monitoring stations and field data, all data analyzed and validated then InfoWorks SD software used, to develop a model for study area. Next step is calibrating and validating the model and then model assessment. The schematic sketch of mentioned steps reported in Figure 3.1.

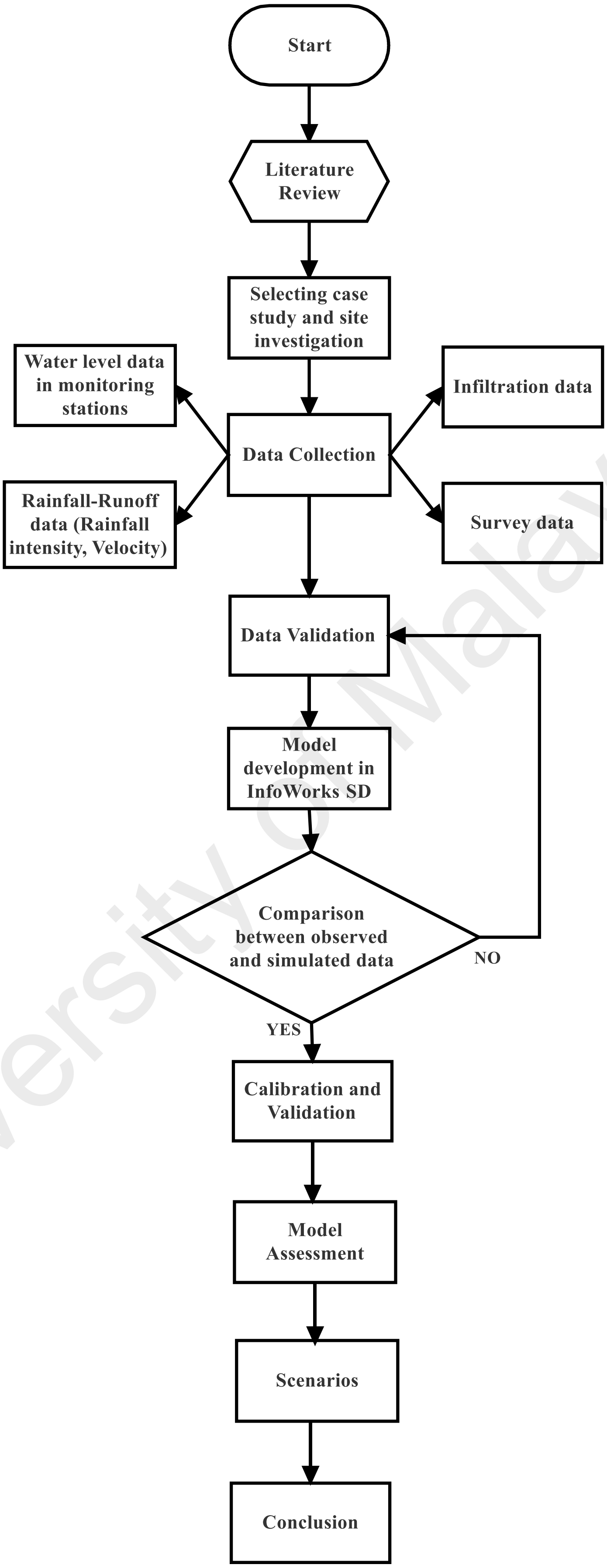


Figure 3.1: Schematic diagram of the study

3.2 Description of study area

Taiping (Latitude: +4.86 m (4˚51’36” N), Longitude: +100.72 m (100˚43’12” E)) is a small town located in Larut Matang restrict in state of Perak. Clinic Taiping built in year 2007. The drainage system in the surrounding area of this clinic is BIOECODE system and it is the first government clinic to use the BIOECODE system (Figure 3.2).

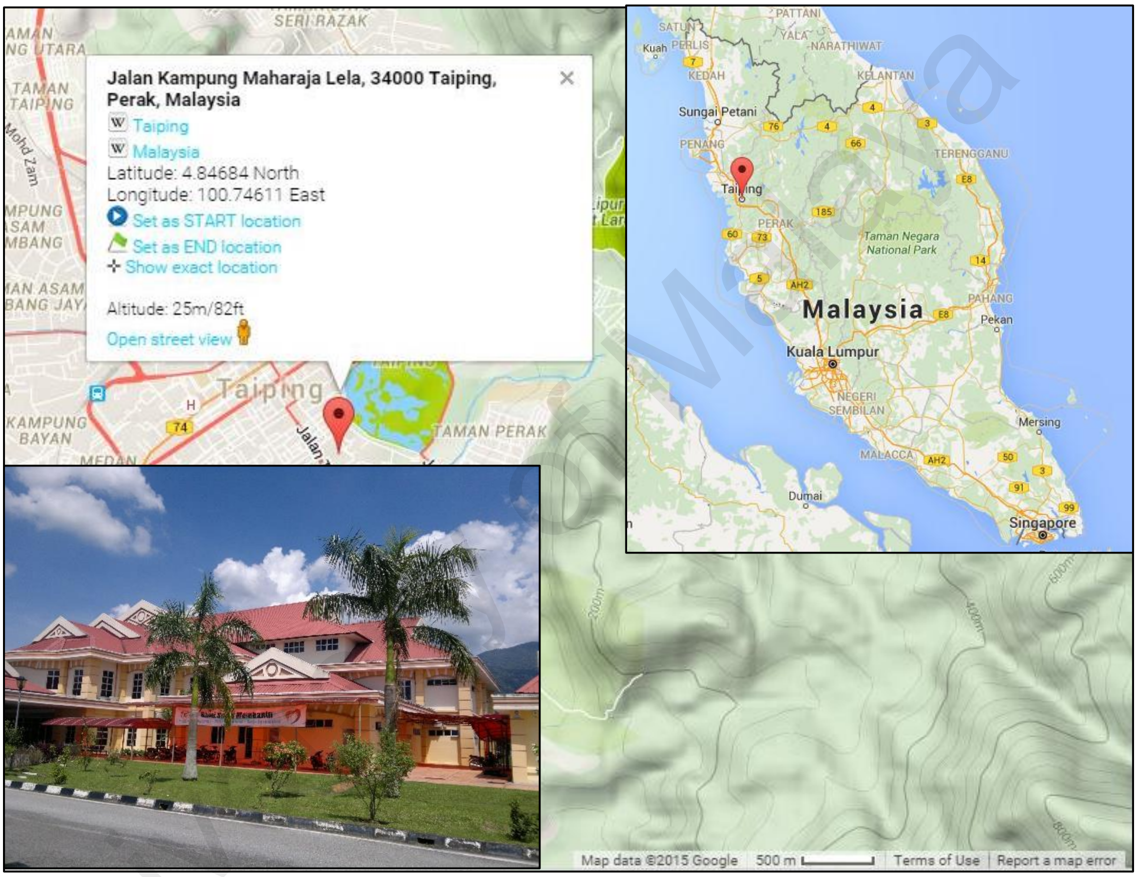


Figure 3.2: Taiping in district of Larut Matang in Perak (Source: Google map)

The 28000 m^2 study area consists of different Sustainable Urban Drainage System (SUDS) components. The main components of BIOECODS system in this study area include Retention pond (Wet Pond), mini wetland, Dry detention pond (Dry Pond), and grass swale with online subsurface conveyance system.

3.2.1 Retention Pond (Wet Pond)

This study area constructed with a wet pond with a maximum surface area of 500 m^2. The designed wet pond constructed in case study for minor storm (10 Average Recurrence Interval (ARI)) and major storm (100 ARI) and contributed with other SUDS components such as dry detention, grass swale and detention storage to increase efficiency of BIOECODS in water quantity and quality control. The designed plan of wet detention pond reported in Figure 3.3 and Figure 3.4.

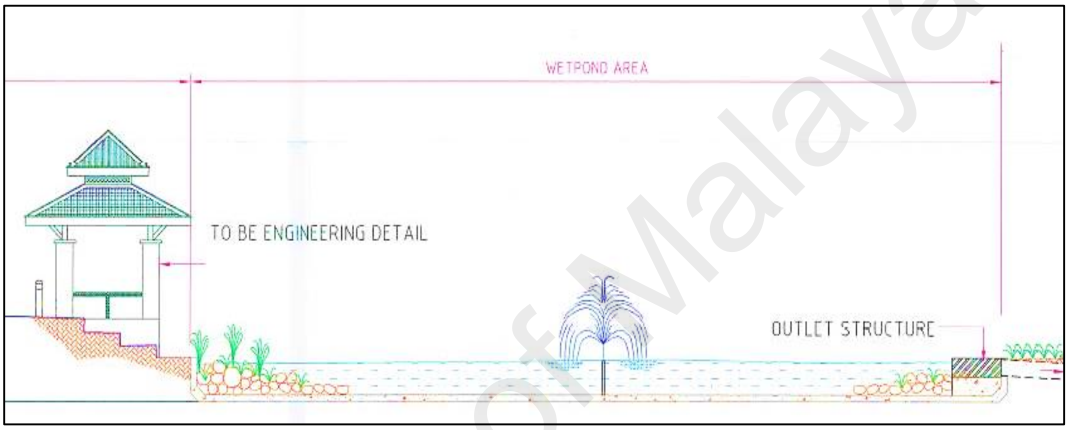


Figure 3.3: Designed wet pond for study area (Source: JKR, 2005)

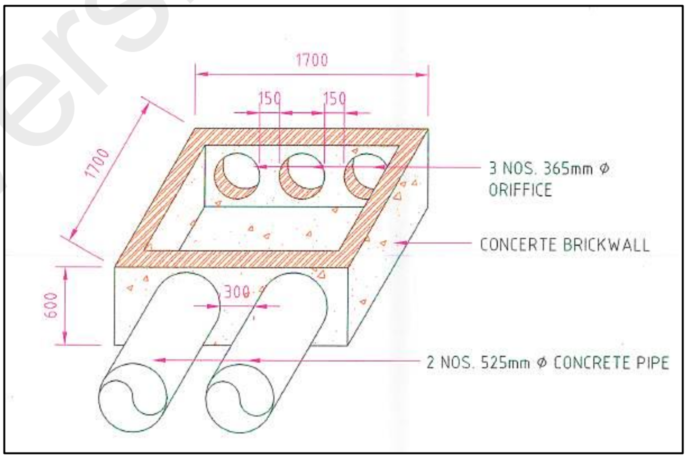


Figure 3.4: Designed outlet structure for wet pond in study area (Source: JKR, 2005)

Specific designs may vary considerably, depending on site locations or preferences but general design consideration presented below:

- **Drainage area:** the minimum recommendation catchment area is 25000 m^2 for commercial or industrial landuses 35000 m^2 for residential landuses (DID, 2012). A single wet pond should not have a contributing drainage area less than minimum recommended catchment area because it may require very small orifice that would be disposed to clogging when sized for complete drawdown of water quality volume for a specific period.
- **Location and site suitability:** It is recommended that wet ponds be located where the topography allows for maximum runoff storage at minimum excavation or embankment construction costs. Besides, wet ponds should not be located in unstable slopes or slopes higher than 15% (Iowa Natural Resources Conservation Service, 2008).

3.2.2 Dry Detention (Dry Pond)

Dry detention (Dry pond) is a SUDS component that provides quantity control in urban stormwater management by containing excess runoff in a detention basin then release it in acceptable level.

In designing a detention facility to meet the quantity control objectives it is necessary to consider the behavior of the pond storage by examining:

- The reduction of flow in the catchment area,
- The depth and duration of ponding,
- The frequency at which the overflow spillway comes into operation

The study area contains thirteen dry detention pond, where nine dry ponds (without underground detention storage) ranged between 62- 351 m^2, while four dry ponds (with underground detention storage) lies within the range of 80-198 m^2, located around the main hospital building, which the sample layout for dry pond presented in Figure 3.5. A subsurface detention storage module constructed beneath the pond and connected to the subsurface conveyance system of grass swale. The runoff in the dry pond retreats by infiltrating through river sands and top soils into the tank module underneath of dry pond and then flows downstream along the subsurface conveyance system of the grass swale. The dry ponds function as an off-line on-site detention to reduce peak flow. Design criteria for dry pond presented in Table 3.1.

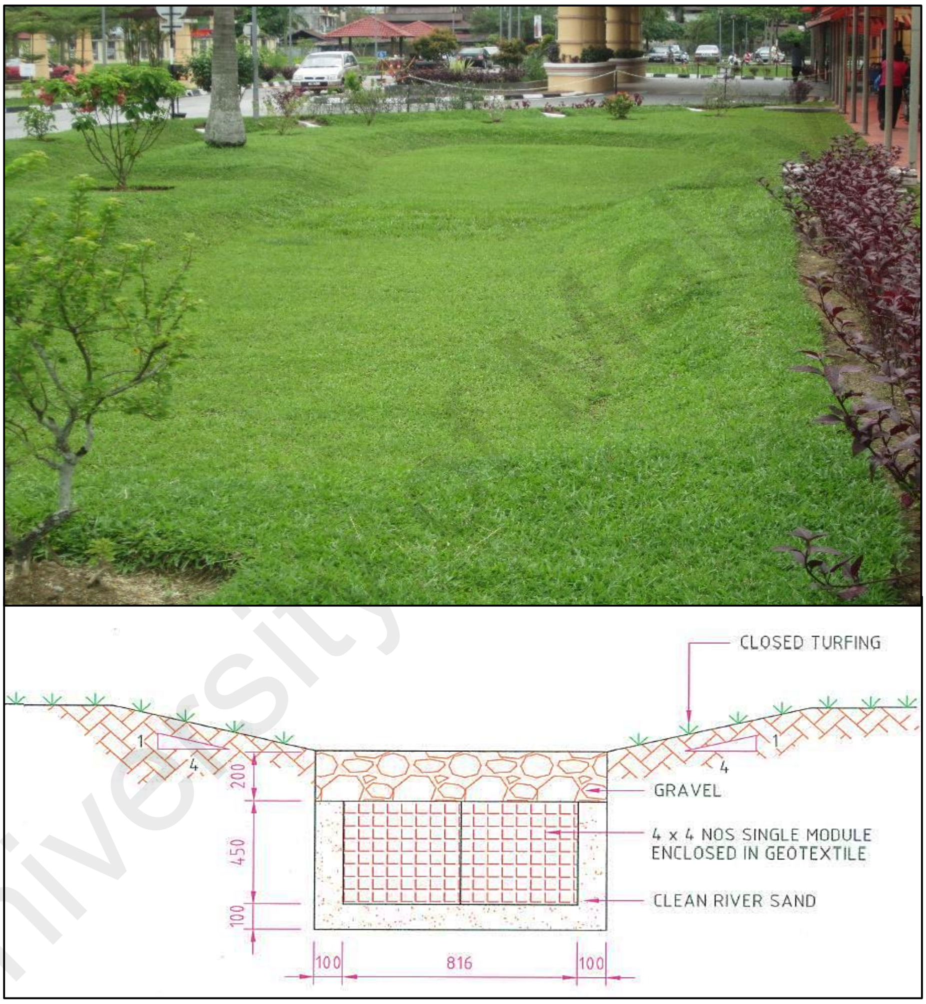


Figure 3.5: Constructed dry pond with detention storage

Table 3.1: Design criteria for dry pond

Component	Design factors	Criteria
Dry pond	Maximum period of surface water inundation	24 hour
	Maximum depth of water inundation	600 mm
	Designed rainfall	10 ARI

3.2.3 Grass swale

Grass swale are vegetated and shallow open channels designed to store and convey surface runoff at a non-erosion velocity, as well as increasing water quality through sedimentation, filtration and infiltration. Swales could covered by vegetation, which usually is grass to increase the filtration and reduce flow velocity in channel to prevent soil wash-off to downstream. The advantages and disadvantages of grass swales mentioned in literature review.

In designing swales, it is necessary to consider swales criteria and requirements that described in the following section:

- **Design Area:** grassed swales engineered for enhancing water quality and quantity but cannot effectively convey large flows. Therefore, swales are generally appropriate for catchments with small, flat impermeable areas. If used in areas with steep slopes, grassed swales must generally run parallel to contours in order to be effective.
- **Space requirement:** grassed swales must effectively incorporated with landscaping and public open spaces as they demand significant land-take due to their shallow side-slopes, due to this, grassed swales are generally difficult to incorporate into dense urban development areas (CIRIA, 2007).

- **Location and site suitability:** grassed swale should be integrated into the site planning and should take into account for location and use of other site features.
- **Subsurface soils and groundwater:** where grassed swales are designed to encourage infiltration, the seasonally high groundwater table must be more than 1 m below the base of the swale. Where infiltration is not required, the seasonally high groundwater level should be below any underdrain provided with the swales (CIRIA, 2007).

This study area were constructed with grass swales and covered with “Cow grass” to increase infiltration and reduced flow velocity. Grass swale in BIOECODS system is similar to infiltration trench so the basin of swale have high infiltration rate which cause the water infiltrate into the underneath conveyance system. Design plan and criteria of grass swale presented in Figure 3.6 and Table 3.2 respectively.

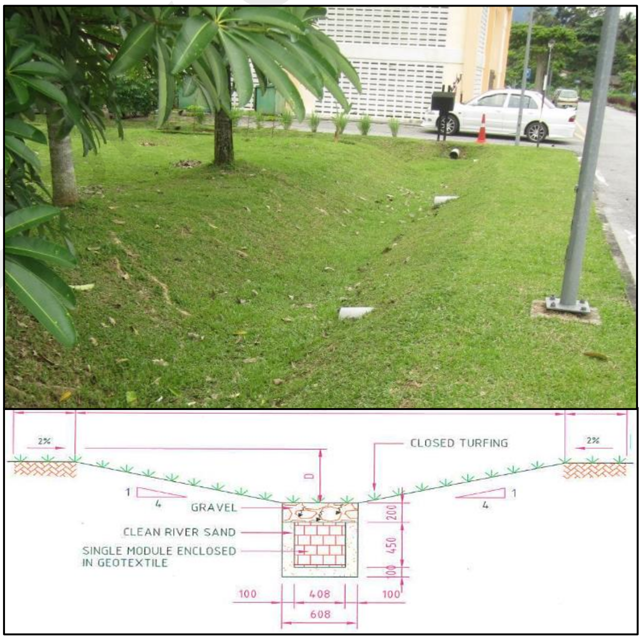


Figure 3.6: Design plan of constructed grass swale with on-line subsurface conveyance

(Source: JKR, 2005)

Table 3.2: Design criteria for grassed swale with online subsurface conveyance system (Source: JKR, 2005)

Swale Component	Criteria
Longitudinal slope	1:500
Designed rainfall	5 years ARI
Freeboard	50 mm above the designed storm water level
Average velocity	Less than 2 m/s
Manning's roughness	Grass swale: 0.035
Manning's roughness	Subsurface conveyance system: 0.1
	Grass swale: 0.035

3.2.4 Catchment and Subcatchments characteristics

The total watershed area divided into two major sub-catchments. These two sub-catchments are namely sub-catchments A and B, which shown in Figure 3.7. Sub-catchment A, has a total area of 9843.75 m^2 and total length of 482.5 m ecological swale with on-line subsurface cells covers the sub-catchment area, while sub-catchment B, has a total area of 9050 m^2 and total length of 510 m ecological swale with on-line subsurface cells, covers the sub-catchment area.

In this research, study area divided into 80 subcatchments to develop a model with high value details and accuracy. In study area each subcatchments has different characteristics such as contributing area, land-use, soil type and, slopes. The characteristics of each catchment and their subcatchments are presented in Table 3.3.

Table 3.3: characteristics of catchments A and B

Parameters and statistics	**Catchment A**	**Catchment B**
Sub-catchment numbers	14	50
Average area of subcatchments (ha)	0.049	0.035
Total length of ecological swale (m)	482.5	510
Manning's n roughness coefficient for swale	0.048	0.048
Manning's n roughness coefficient for open channel	0.014-0.016	0.014-0.016

Figure 3.7: Study site at Taiping, Larut Matang (Adopted from Google Earth)

3.3 Data Collection

For data collection purpose, five monitoring stations were installed in the study area to provide necessary data for modelling purposes. The following monitoring stations are shown in Figure 3.8.

Generally, data collection can be divided into two parts. One part is collecting data from the different installed monitoring stations and field study, which includes Rainfall data, water level and runoff velocity data, Infiltration test data; and second part is land survey, which provides vital information about topography of study area, upstream and downstream, invert levels for channels, channel slopes and other vital information. Data collection starts from September 2013 for duration of 1 year (covering raining and dry season).

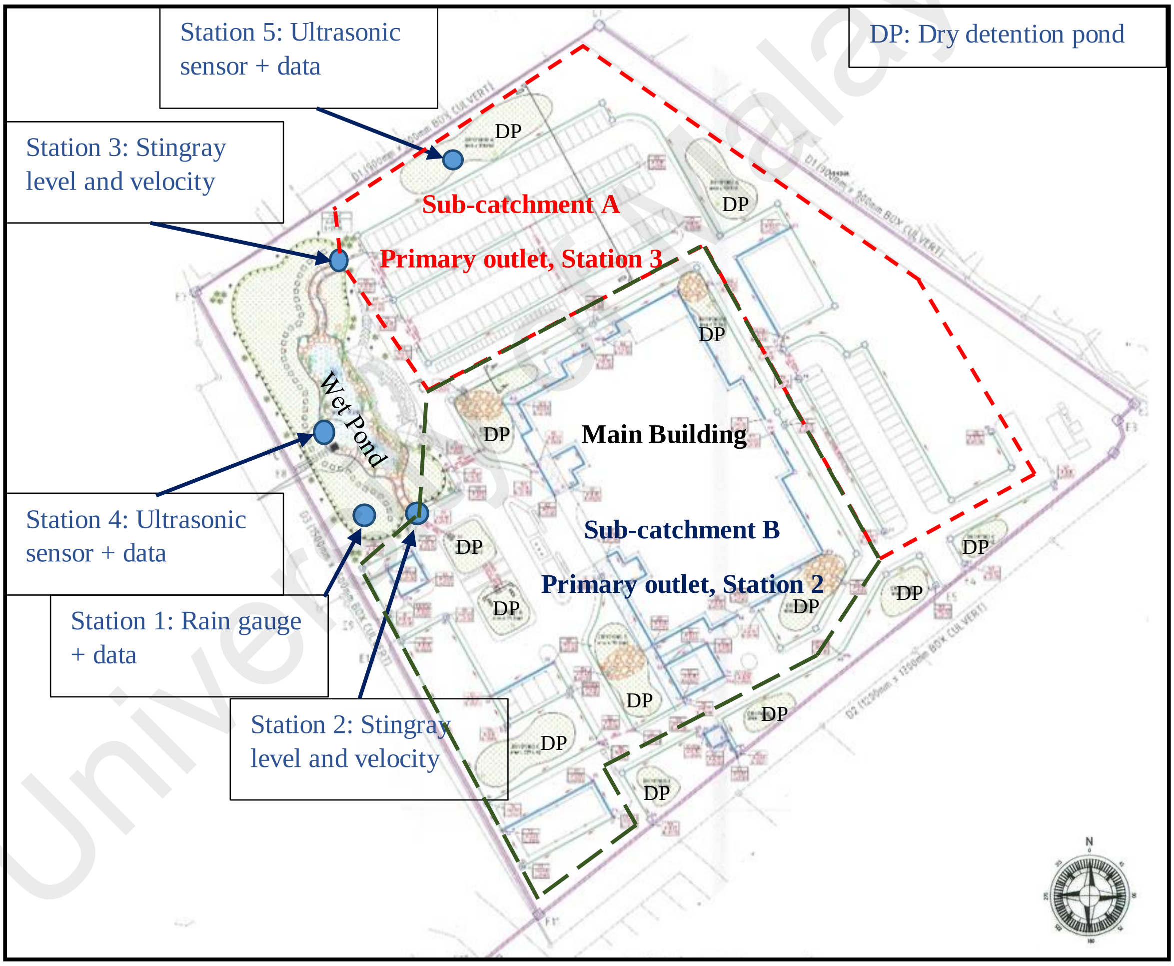


Figure 3.8: Plan view of study area and location of rainfall-runoff monitoring stations

3.3.1 Rainfall data (Rain gauge)

As mentioned in Figure 3.8, 5 monitoring stations were installed in the study area to provide information and parameters for simulation. Station number 1 is a rain gauge, which provides rainfall data. This rain gauge is Onset RG3-M, with accuracy of ±0.2 mm, which provides continuous rainfall data. This instrument calibrated on the field with a controlled rate of flow of water through the tipping bucket mechanism according to standard method provided by the company. This rain gauge automatically records rainfall data that used to determine rainfall intensity, times and duration, also records temperature when used with an optional solar radiation shield. 30 seconds time interval was set for rain gauge to collect the rainfall data in this project. Some of the specifications of this instrument provided by Onset Company are presented in Table 3.4.

Table 3.4: Rain gauge specifications (Source: HOBO rain gauge manual)

Rain Gauge	
Maximum Rainfall Rate	12.7 cm per hour
Calibration Accuracy	±1.0% (up to 2 cm per hour)
Resolution	0.2 mm
Calibration	Requires annual calibration: can be field calibrated or returned to the factory for re-calibration
Operation temperature range	0° to +50°C
Storage temperature range	-20° to +70°C
Environmental rating	Weatherproof
Housing	15.24 cm aluminum bucket
Tipping Bucket Mechanism	Stainless steel shaft and bearings
Dimensions	25.72 cm height x 15.24 cm diameter; 15.39 cm receiving orifice
Weight	1.2 Kg
Part Numbers	RG3-M (0.2 mm per tip)

3.3.2 Water level and velocity

For water level and flow velocity, four ultrasonic sensors were installed in the study area, which mentioned in Figure 3.8. Stations number 2 and 3 are two primary outlet before reach to retention pond. Two Greyline Stingray level-velocity logger with an accuracy of ±0.25% in water level and ±2% in flow velocity reading.

This portable ultrasonic sensor is very easy to work and calibration for this instrument was done in the filed according to standard method provided by the company. The sensor transmits ultrasonic pulses that travel through the water and reflect off the liquid surface. To monitor water level, the Stingray precisely measures the time it takes for echoes to return to the sensor. Velocity is measured with an ultrasonic signal continuously injected into the flow. This high frequency sound is reflected back to the sensor from particles or bubbles suspended in the liquid. If the fluid is in motion, the echoes return at an altered frequency proportionate to flow velocity. The Stingray uses this Doppler frequency shift to calculate flow velocity accurately (Figure 3.9). 10 seconds time interval was set for this instrument. Some of the specification for this sensor are presented in Table 3.5.

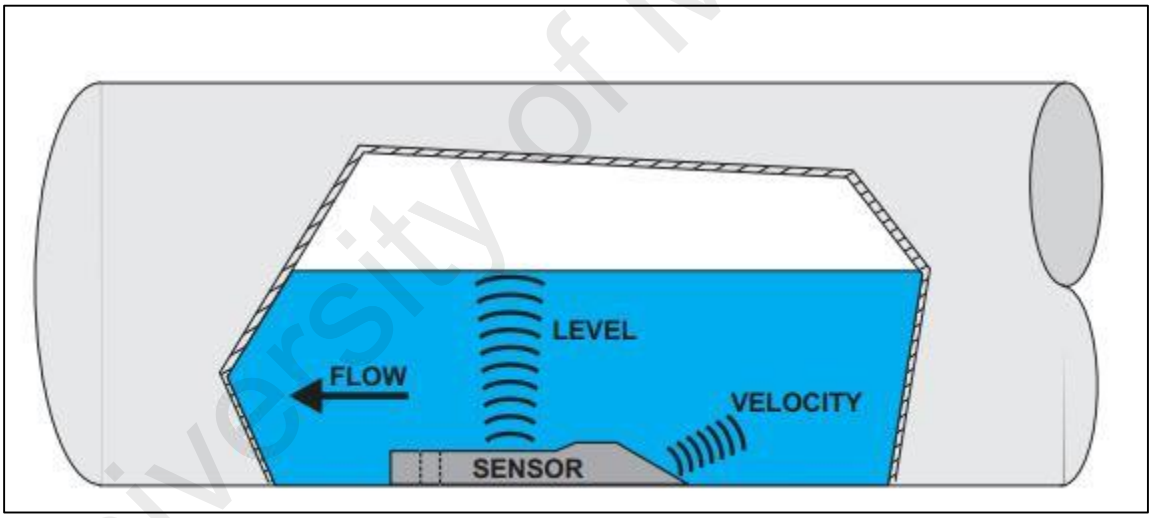


Figure 3.9: Submerged ultrasonic sensor measures water level and velocity (Source: Grayline instrument).

Table 3.5: General Specifications Greyline Stingray Level-Velocity Logger

Greyline Stingray Level-Velocity Logger	
Accuracy	Level: ±0.25% of Level. Velocity: ±2% of Reading
Operating Temp. (electronics)	-20° to 60°C
Logger Interval	10 sec (15 days), 30 sec (45 days), 1 min (3 months), 2 min (6 months), 5 min (1 year), 10 min (2 years), 20 min (4 years)
Data Logger Capacity	130,000 data points
Power	4 Alkaline 'D' cells
Weight	4.5 kg

The monitoring stations with ultrasonic sensors installed in the primary outlet before retention pond to measure the water level and flow velocity which presented in Figure 3.10.

Figure 3.10: Ultrasonic sensor in station number 2 and 3

There are two stations for collecting water level data from retention pond and dry detention stations number 4 and 5 respectively. Pulsar transducers, with an accuracy of

0.25% of the measured range or 6 mm, have been used for collect water data in these stations.

Pulsar transducer is an ultrasonic transducers that can measure level in a wide range of liquids, powders, and solids as well as open channel flow applications, which have been used to measure the depth in retention and detention pond (Figure 3.11). All of the stations were equipped with a data logger to ensure continuous measurement for further analysis and model simulation. 1-minute time interval set this instrument to measure water level in retention and dry detention pond.

Figure 3.11: Ultrasonic sensor to measure water level in Retention pond (Left) and dry detention pond (Right)

3.3.3 Infiltration test

Field experiments were also conducted at various locations (dry detentions, grass swales, empty space) in the study area to collect infiltration data. Fifteen different points to present entire study area were selected for infiltration test. Infiltration test conducted in the study area, done by using double-ring test with accuracy of ±0.2 mm (Figure 3.12).

Figure 3.12: Double-ring parts for infiltration test

3.3.4 Land Survey

The land surveying is to provide digitalized map with all elevation points, channel slopes, and cross section for entire study area. The equipment have been used for survey is Horizon total station, tripod, prism (Figure 3.13), measurement tape. Prism was set at 2m high.

The surveyed data is combined with an existing engineering drawing using AutoCAD 2014 (Version 19.1) to form a detailed topographic map of the study area. The topographic map is further transformed into a digital map using ArcGIS (Version 10.1) software.

Figure 3.13: Horizon total station HTS-582M (Source: www.horizon.sg)

Final map of study area generated in AutoCAD is shown in Figure 3.14. This map is further transformed to a digitalized map using ArcGIS (Version 10.1) software.

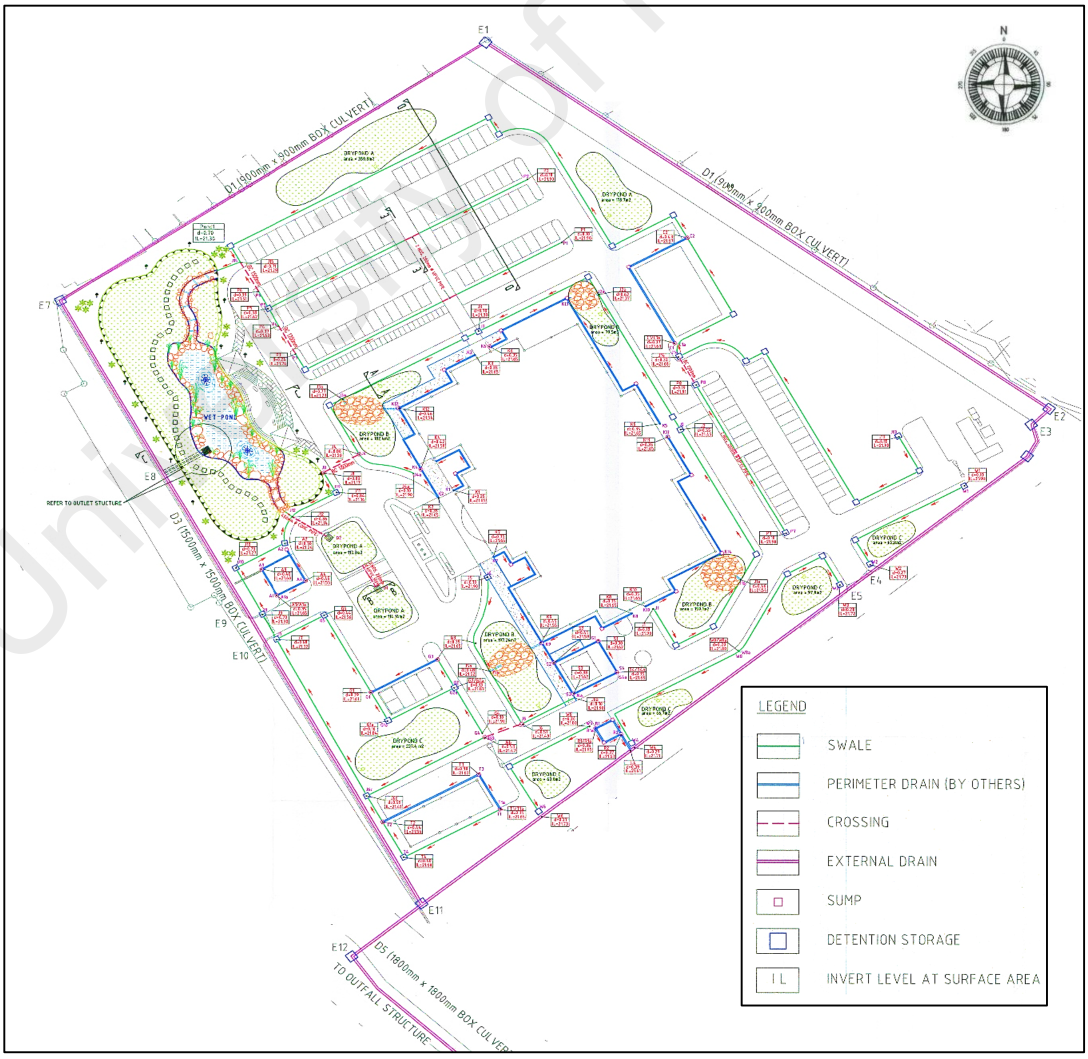


Figure 3.14: Prepared AutoCAD map according to survey data

3.4 Data Preparation and Validation

For data validation, data collection process carried on every two weeks for one year and instruments in the study area were calibrated according to standard procedures suggested by the product manufacture each time after data collection.

The reliability of all rainfall data collected, ultrasonic transducers readings, water level, and stream flow data were checked before used for analysis. Rainfall and stream discharge were crosschecked with water level and stream flow in primarily outlets. Data continuity checking, avoiding wrong rainfall, stream flow, water level reading, i.e., negative values, and deleting dates with empty data recordings which affect data sorting process were done to exclude poor quality data for modeling purpose.

3.5 Model Development

3.5.1 Modelling Software: InfoWorks SD

The selection of an appropriate hydraulic and hydrologic model was critical for this study. The selected model needed to have the ability to simulate accurately the hydrological processes in the study catchment area. Besides, convenience in importing data from other external sources to create model was also important. For instant, in this study, the drainage network data for study catchment area were obtained in Mapinfo, AutoCAD, and GIS (shape files) format while rainfall data record and water level records were obtained as an Excel file. This required that the selected model should have the capability for importing different types of data files. Furthermore, since the investigation of relationship between rainfall characteristics and urban stormwater quantity was based on individual rainfall events rather than long-term continuous rainfall records, the selected model needed to have capability to accurately simulate hydrological processes accordingly.

According to those criteria, ranges of models widely used were evaluated in order to select the appropriate model for this study. Therefore, based on a comprehensive consideration on these criteria, and literature review on these models and specifications which mention in section 2.8, InfoWorks SD was selected for this study.

In this study, InfoWorks SD software is used to create a model that present study area with SUDS components with high accuracy and closely match to real conditions. The simulation process usually involves the verification of the data and modelling approach using short-term flow surveys (based on the field measurement of sewer flow and rainfall), and subsequent use in simulating the effects of “design” events or collected rainfall events. The following sections have been developed in order to give a better understanding of the runoff estimation models that are embedded in InfoWorks SD software. The process of constructing a model and the consideration of exceedance is shown in Figure 3.15. In the following section, first urban runoff models principles and parameters will be presented.

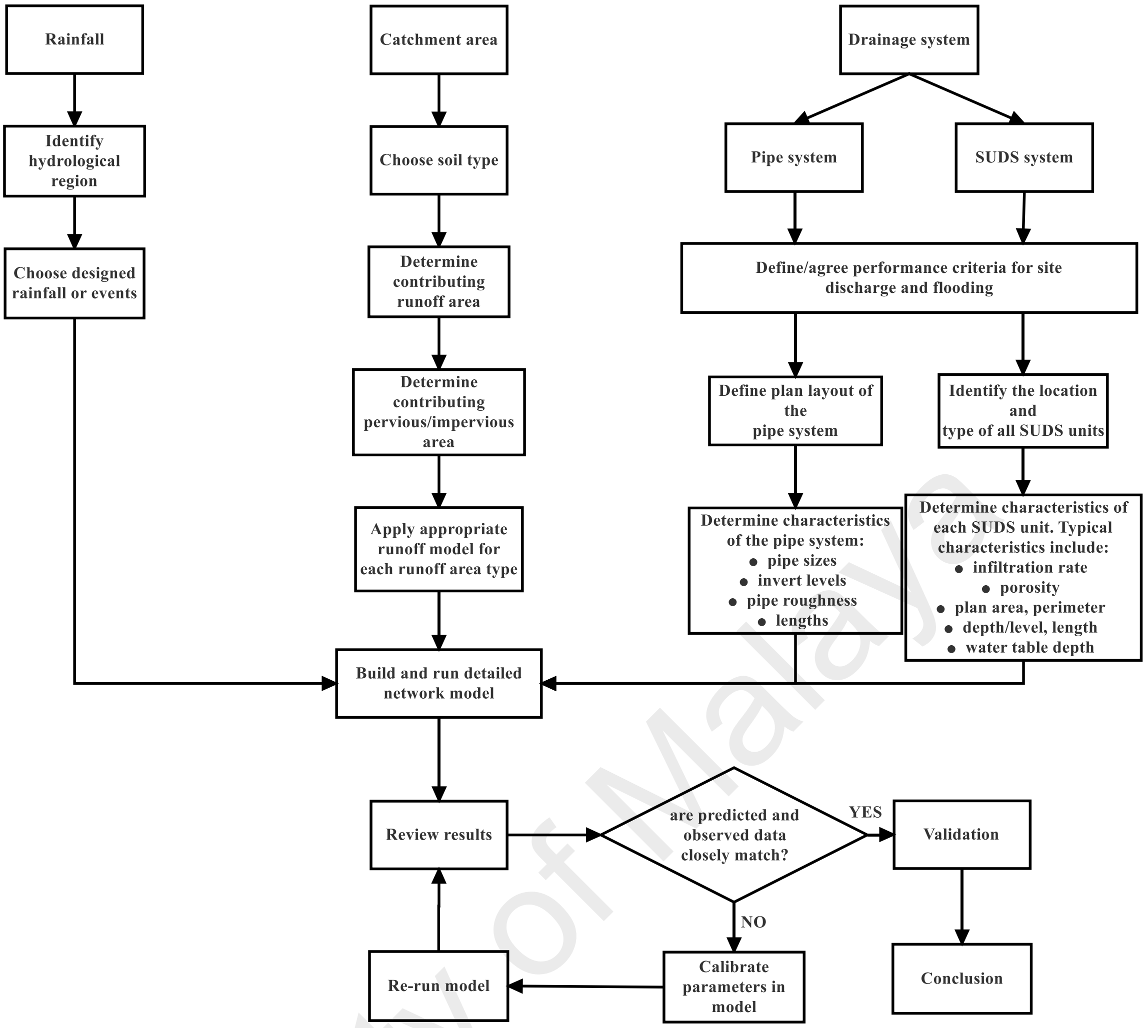


Figure 3.15: Processes for modelling urban drainage system in InfoWorks SD

In this study, the focus is to develop a model for BIOECODS drainage system with InfoWorks SD. A comprehensive review has been done about different SUDS components in BIOECODS system, design consideration and criteria, and modelling parameters. In this section the methods conducted to develop a model for BIOECODS, will presented.

3.5.2 Rainfall Characteristics

The performance of BIOECODS system may vary with different rainfall characteristics such as, duration, intensity, ARI for the study area and identifying those characteristics are important. The rainfall depth controls the volume of stormwater runoff from the catchment, and respectively the volume of water entering into the BIOECODS system. In this study, rainfall data divided into two main parts, (i) Rainfall events, and (ii) designed rainfall, which presented in the following sections.

- **Rainfall events**

Rain gauge monitoring station, provide rainfall data in mm with time interval for 30 seconds, which is required to be pre-processed and transformed into intensity (mm/hr) with time interval 5 minutes. Many rainfall data collected during the period of research and all of them evaluated and verified (prevent negative values, missing values, etc.) before proceed to next step, which is model development. For instance, some of these rainfall events presented in Table 3.6.

Table 3.6: Some of the collected rainfall data for simulation purposes

Events	Maximum Intensity (mm/hr)	Average rainfall intensity (mm/hr)	Duration (min)	Rainfall type
Event No.1 (10/9/2013)	71.4	21.2	45	Low intensity
Event No.2 (14/10/2013)	114.2	43.2	80	High Intensity
Event No.3 (23/11/2013)	102.9	42.1	50	Medium Intensity
Event No.4 (19/12/2013)	103.2	42.54	60	Medium Intensity
Event No.5 (12/1/2014)	122.3	50.2	120	High Intensity
Event No.6 (11/2/2014)	40.5	12.9	60	Low intensity
Event No.7 (21/2/2014)	30.7	10.2	55	Low intensity

This study attempted to select different rainfall patterns with different intensity and duration for model development, calibration, and validation purposes. The start and end of the simulation should be at least 1 day before rainfall event happen, so the model can analyze the data and easy to calibrate the values, which is unknown for modelling.

- **Designed rainfall**

The most common form of design rainfall data required for use in peak discharge estimation is from relationship represented by Intensity-Duration-Frequency (IDF) curves. To minimize the error in estimating rainfall intensity from this method, Empirical equation was used (DID, 2012). This equation expressed as:

$$i = \frac{\lambda T^k}{(d + \theta)^\eta} \qquad (3.1)$$

Where: i, Average rainfall intensity (mm/hr), T, Average Recurrence Interval (ARI) (0.5 ≤ T ≤ 12 months and 2≤ T ≤ 100 years), d, Storm duration (hours), 0.0833 ≤ d ≤ 72; and $\lambda, k, \theta, and\ \eta$, Fitting constants dependent on the rain gauge location (DID, 2012)

Fitting constants presented by DID (2012) for entire Malaysia, which values for the study area presented in Table 3.7:

Table 3.7: Fitting constants for the IDF empirical equation for Perak state

State	**No.**	**Station ID**	**Station Name**	**Constants**			
				λ	**k**	**θ**	**η**
Perak	1	4010001	JPS Teluk Intan	54.017	0.198	0.084	0.790
	2	4207048	JPS Setiawan	56.121	0.174	0.211	0.854
	3	4311001	Pejabat Daerah Kampar	69.926	0.148	0.149	0.813
	4	4409091	Rumah Pam Kubang Haji	52.343	0.164	0.177	0.840
	5	4511111	Politeknik Ungku Umar	70.238	0.164	0.288	0.872
	6	4807016	Bukit Larut Taiping	87.236	0.165	0.258	0.842
	7	4811075	Rancangan Belia Perlop	58.234	0.198	0.247	0.856
	8	5005003	Jln. Mtg. Buleh Bgn Serai	52.752	0.163	0.179	0.795
	9	5207001	Kolam Air JKR Selama	59.567	0.176	0.062	0.807
	10	5210069	Stesen Pem. Hutan Lawin	52.803	0.169	0.219	0.838

3.5.3 Catchment characteristics

As it mentioned in Table 3.3 study area divided to main catchment area and 80 subcatchments that cover all study area. In this study, each subcatchment has different characteristics such as contributing area, landuse, soil type, and slopes. Some of these characteristics such as slopes, and contributing area can be defined from survey data.

Each subcatchment in a model required an associated with landuse definition. The landuse allow determining surfaces for subcatchments. Landuse for studying area divided into two parts which include: pervious areas (grassed areas, dry ponds, and grass swales) and impervious areas (roads, paved parking, and roof tops).

The soil type is other important parameter which identified to the software according to conducted infiltration tests in the study area. Most of the project area covered with a soil with good drainage system so the soil class according to TR-55 documents is categorized in class B.

Other important parameter in catchment characteristics is the catchment wetness. This parameter used to calculate rainfall loses and rates of runoff. Two antecedent conditions in InfoWorks SD must be considered depending on the runoff routing and volume methods.

- **UCWI:** Used for Horton, Green-Ampt and Variable PR models and calculated according to following equation:

$$UCWI = 125 + 8API5 + SMD \quad (3.2)$$

Where, API5, is 5 days antecedent precipitation index (mm) and SMD, is Soil Moisture Deficit.

- **AMC:** Used for the Soil Conservation Service Model (SCS) which presented in Table 3.8 in InfoWorks SD.

Table 3.8: Wetness index in SCS runoff model in InfoWorks SD (Hawkins, et al., 1985)

Catchment Wetness	Wetness index	Change to storage depth
Dry	1	Multiplied with 0.281
Average	2	--
Wet	3	Multiplied with 0.427

3.5.4 Runoff Routing and Runoff volume

InfoWorks SD contains a variety of different runoff volume and routing models. Runoff volumes determine how much of the rainfall runs off the catchment into drainage system and runoff routing models determine how quickly rainfall enters the drainage system from the catchment. Details for runoff volume and routing which can be used presented in Table 3.9 and Table 3.10.

In this study according to the runoff volume and runoff routing models described in literature review, SCS model combined with Horton runoff volume model associated with SWMM runoff routing model selected for this study and modelling approach. The SCS model in conjunction with Horton model, associated by SWMM runoff routing used to model runoff from pervious and impervious areas in the catchments.

This model development can be divided into three parts: (i) Surface model (Overland flow), (ii) Subsurface model, and (iii) coupling method that described below.

- **Surface model (Overland flow):** The overland flow model is SWMM overland flow is using the non-linear reservoir and kinematic wave routing which uses simplified momentum equation for each conduit. Kinematic-wave models are applicable to overland flow where lateral inflow is continuously added and is a large part of the total flow (Miller, 1983). For a unit width of overland flow, the formula can be expressed as:

$$\frac{\partial q}{\partial x} + \frac{\partial y}{\partial t} = i \qquad (3.3)$$

Where q is the unit width of overland flow rate; x is longitudinal distance along the flow path; y is the flow depth; t is time and i is the rainfall intensity.

The terms of $\frac{\partial q}{\partial x}$ used to simulate non-uniform and $\frac{\partial y}{\partial t}$ used to simulate unsteady flow path. As mentioned above kinematic wave model described by uniform flow or continuity equation that mentioned below. Consider that, in uniform flow, the momentum equation can be expressed generally:

$$q = a_k y^m \qquad (3.4)$$

Which a_k and m are constant and depend on a water depth and discharge.

In SWMM model, the value in the Runoff routing is always the Manning's roughness whatever runoff rate selected (Engman, 1986). Therefore, maximum runoff volume from the catchment area calculated with Manning's equation:

$$Q = \frac{K_m}{n} A R^{2/3} S^{1/2} \qquad (3.5)$$

Where K_m is a constant equal to 1.49 in U.S. units and 1.0 is SI units, n is Manning's roughness coefficient, A is effective flow area, R is hydraulic radius and depends on area and wetted perimeter, and S is surface slope.

- **Subsurface model:** The SWMM model has conjunction with infiltration models Horton and Green-Ampt. In this study Horton equation is one of the well-known models in hydrology (Horton, 1939 and 1940). This model selected for this study to present subsurface model. Horton equation is an empirical formula derived from infiltrometer and is suitable for small catchments. The SCS Runoff Curve Number (CN) method is described in detail in NEH-4 (SCS 1985).

- **Coupling method:** For couple/integrate surface and subsurface model, InfoWorks SD is able to model two separate sub-systems within InfoWorks network. In general, there are two system provided by InfoWorks SD: Overland and Storm system. These two systems can modelled independently or dependently to each other and sub-catchments of these two system can be overlap. Due to this capability between two nodes, two links within the same subcatchments conducted that one link with higher invert level present surface grass swale with system type overland and one link with lower invert level present subsurface conveyance system with storm system type. This method present that when the rain happen due to infiltration capability in grass swale rainfall water directed into the soil and respectively into the subsurface conveyance system till the upper layer of soil reach to maximum infiltration capability and soil become saturated then surface flow will occurs.

Table 3.9: Runoff volume models in InfoWorks SD

Runoff Model	**Application**	**Comments**	**Suitability**
Fixed percentage runoff	Individual	Simply insert a percentage for the runoff from each surface type.	Suitable for all catchments where a good estimate of the runoff percentages can be made.
Wallingford (Fixed) PR	Total catchment	Needs to be used with care and observing the limitations of this model.	Suitable for all urban catchments in the UK. Design values of UCWI are readily available.
New UK (Variable) PR	Total catchment	This is a new UK model	UK pervious catchments where it is important to take account of the change in catchment wetness during long storms.
SCS	Individual	A rural catchment model.	Rural catchments and pervious surfaces within a catchment.
Green-Ampt	Individual	An infiltration model for pervious and semi-pervious surfaces.	Urban surfaces and pervious surfaces within a catchment. This model is associated with (SWMM) runoff routing model.
Horton	Individual	An infiltration model for pervious and semi-pervious surfaces.	Urban surfaces and pervious surfaces within a catchment.
Horner	Individual	A runoff volume model used to determine the net rainfall on urban subcatchments.	Impervious surfaces in medium sized urban subcatchments.
Constant Infiltration	Individual	The ConstInf model allows a constant infiltration to be set from the surface into groundwater. This is effectively a loss to the system but if the storage capability is exceeded a fixed runoff occurs.	

(Note: There are two types of runoff volume models, total catchment models and individual models. Total catchment models applied to all the surface types in a subcatchment. Whereas Individual model applied to one surface type in a subcatchment.)

Table 3.10: Runoff routing models in InfoWorks SD

Runoff Model	**Comments**	**Suitability**
Double linear reservoir (Wallingford) model	It is a double linear reservoir model calibrated for UK sub-catchments of less than 1 ha.	UK drainage systems where most sub-catchments are under 1 ha.
Large contributing area runoff model	A double linear reservoir model developed for UK sub-catchments of up to 100 ha.	UK systems where most sub-catchments are larger than 1 ha.
SCS Unit model	A unit hydrograph developed by the SCS (Soil Conservation Service).	Not suitable for mountainous or flat wetland areas
Snyder Unit model	A unit hydrograph using the Snyder method.	Developed using data for subcatchments in the Appalachian Highlands.
SPRINT runoff model	A single linear reservoir model developed for the European SPRINT project.	Work done under the SPRINT project for large lumped catchments.
Desbordes runoff model	The standard routing model used in France. It is a single linear reservoir model.	French systems running with event based simulations.
SWMM runoff model	A non-linear reservoir model developed in the USA.	USA drainage systems using the SWMM runoff model (in conjunction with the Horton or Green-Ampt runoff volume models for the pervious surface.
Unit	A unit hydrograph.	Depends on the method of calculation selected.

3.5.5 Drainage system characteristics

The selected area is a Sustainable Urban Drainage System (SUDS) and environmental friendly drainage system. For the modelling purposes each components of this system simulated and the important parameters for modelling described in the following sections. Main concern of this study is to model BIOECODS system, which has innovative drainage system that is combination of grass swale with on-line subsurface conveyance system. Therefore, the main part in modelling approach is to present both surface and subsurface runoff in the single drainage system or integrated network drainage system.

As it mentioned before Rainfall-Runoff has three model components: initial loss (depression storage), runoff volume, and runoff routing. A proportion of this percolation flow (the percolation percentage infiltrating) infiltrates directly into the drainage network while the remainder penetrates deeper to feed the groundwater storage reservoir. This rainfall-runoff relation is shown in Figure 3.16.

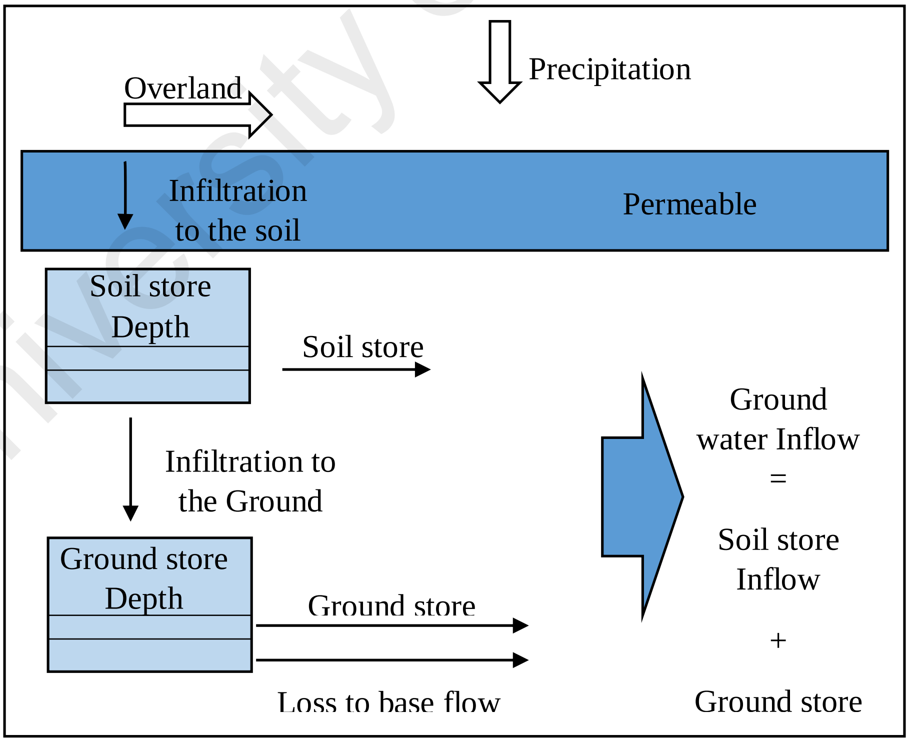


Figure 3.16: Integrated rainfall-runoff model in InfoWorks SD

Next step in model development by InfoWorks SD is to model the BIOECODS components such as wet pond, grass swales, detention ponds etc. therefore, drainage network links (conduits) and nodes for surface and subsurface drainage system in BIOECODS presented in the following section.

- **Drainage network links (Conduits)**

A link presents the physical connection between two nodes in the network system and may be one of the following:

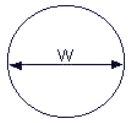
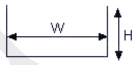
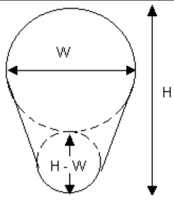
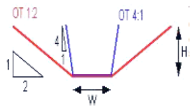
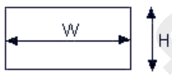
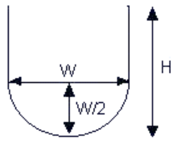
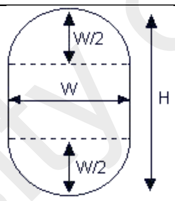
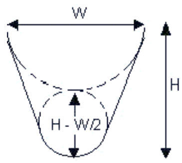
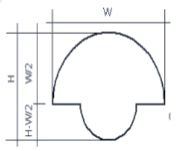
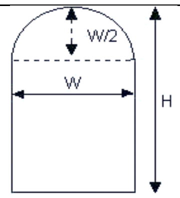
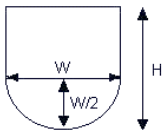
- A conduit can joining two nodes either closed pipe or an open channel.
- A control structure, such as a weir, pump, or other flow control device.

In the InfoWorks network, each node must be connected by a link to at least one other node; a single node may have several links to other nodes. Any pair of nodes can be connected by only one link. A conduit that changes direction can be represented by two links, with a node at their junction. The boundary condition between the link and a node is either of the outfall or headloss type. The gradient of a conduit is defined by invert levels at each end of the link; this does not preclude discontinuities in level at nodes or negative gradients.

For each link, one of the nodes must be specified as the 'upstream' end. This identifies the nominal direction of flow but is not necessarily the direction in which the water will always flow. The upstream node in combination with the invert level at the upstream end is used by the system for allocating a unique label to the link. The link's downstream node is given for information.

A variety of pre-defined cross-sectional shapes may be selected for both closed pipes and open channels in InfoWorks SD. Circular pipes are defined by one dimension (the diameter) and all others by the height and width; in the case of open channels the height will be to the top of the channel lining. Non-standard cross-sectional shapes may be modelled by defining a non-dimensional height/width relationship. Two different values of hydraulic roughness may be assigned, one for the bottom third of the conduit and one for the remainder. Available cross section shapes for conduits presented in Table 3.11.

Table 3.11 Available cross section shapes in InfoWorks SD

Name	Parameters	Shape	Name	Parameters	Shape
Circle	Full Height or width		Open rectangular	Full height, width	
Egg	Full Height, width		Trapezoidal channel	Full Height, Base Width, Side Slopes	
Rectangular pipe	Full Height, width		U-shape channel	Full Height, Top width	
Oval pipe	Full height, width		Egg shaped channel	Full Height, width	
Cunette pipe	Full height, width		Arch-shaped pipe	Full height, width	
U-shape pipe	Full height, width		User defined shapes		

The necessary parameters for hydraulic modelling in InfoWorks SD are conduit length, upstream and downstream invert level (either open or closed). The lengths and invert levels to specify upstream and downstream were obtained from conducted survey work in study area. In this study, Trapezoidal channel selected to present the grass swales in the study area that is presented below.

Grass swale in InfoWorks SD presented as a link and the following parameters are required to model this surface conveyance system:

- Base height: This defines nominal base area, which the infiltration coefficient (base) applied.
- Infiltration coefficient (Base): Infiltration rate from the conduit base to the ground.
- Infiltration coefficient (Side): Infiltration rate from the conduit side to the ground.

Required parameters in InfoWorks SD presented in Figure 3.17.

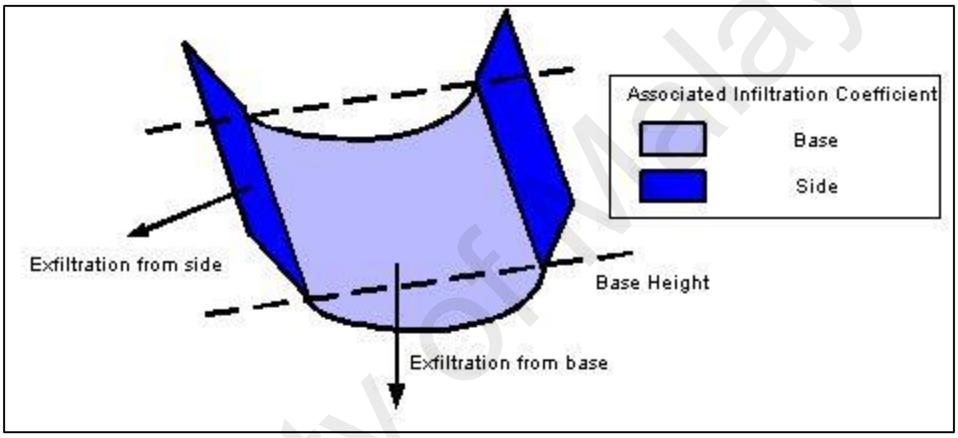


Figure 3.17: schematic plan of required parameters in modelling swale

The use of the SUDS parameters allows flow to leave the conduit via exfiltration at a uniform rate along the length of the swale. InfoWorks calculates a loss rate based on the wetted perimeter. The loss is applied to the node immediately downstream of the swale. The needs of swales contributing in the length of swale, which constructed along the impervious areas such as car park or road inflow to the swale presented as lateral inflow, which means as water runs off the area, the flows in the link will uniformly increase.

As it mentioned before to increase the infiltration rate, grass swale filled with permeable materials such as gravel and river sand. Regarding to this capability, InfoWorks SD provided some options to model the permeable materials.

Inflows to the permeable conduit are lateral inflows from subcatchments draining to the conduit, plus any inflow. Discharge, Q, is calculated using Darcy's Law: rate of flow of water through a permeable formation is proportional to the change in elevation between points (Δh), the distance between the points (L), cross sectional area (A) and the hydraulic conductivity (K) of the material the water flows through. Discharge, Q is calculated as:

$$Q = -KA\frac{\Delta h}{L} \quad (3.6)$$

- **Drainage network nodes**

A node represents a physical structure in the drainage system; structures include:

- A manhole or other point at which water enters the system
- A storage structure, e.g. a tank
- An outfall, where water leaves the system
- A pond
- A break

In this study, nodes are used for modelling the retention and detention ponds that the required parameters for the ponds presented below:

- Level (m), plan area (m^2), and perimeter (m): These parameters help InfoWorks SD to specify the shape of the ponds. Also defines how the volume of the pond increases as the ponds fill.
- Vegetated level or normal water level: specify level that infiltration will be start.
- Linear level: This level specifies that below this level infiltration rate is zero.
- Infiltration loss coefficients

In this study, vegetated level, linear level, area and perimeters provided from survey data and infiltration loss coefficient also conducted from infiltration test in the study area.

3.6 Sensitivity analysis, model calibration and verification

In all modelling procedure calibration and verification is the most vital action. This procedure need a full knowledge about the modelling process and also parameters which used in the modelling. One of the methods to identify these important parameters which play the important roles in modelling is sensitivity analysis. Sensitivity analysis is a method to determine which parameters of the model have the greatest impact on the model results. It ranks model parameters based on their contribution on overall error in model predictions. This method can be local or global. In the local sensitivity, the effect of each input parameter is determined separately by keeping other parameters constant and in global sensitivity analysis all model inputs are allowed to vary over their ranges at the same time. In this project local sensitivity was selected and the parameters which have greatest impact on the results identified for the calibration and verification procedure. After this step next step is calibration and validation.

The calibration and validation for the studies that involves with field measurements is very critical and important in model development and simulation. According to Schnoor (1996) calibration can be defined as a statistically acceptable comparison between simulated and observed data (field measurements).

The simplest form of optimization is iterative trial and error whereby model parameters are changed and a measure of goodness-of-fit between model results and calibration dataset is noted. However, many models include numerous parameters that also are interdependent and this will confound the definition of an optimum parameterization (Mulligan and Wainwright, 2003). In these cases with using of sensitivity analysis those parameters determined for further calibration and validation analysis.

Several calibration and uncertainty analysis techniques have been applied in previous research work, such as the first-order error analysis (FOEA) (Melching and Yoon, 1996), the Monte Carlo method (Kao and Hong, 1996) and the Generalized Likelihood

Uncertainty Estimation method (GLUE) (Beven and Binley, 1992). The FOEA method is based on linear-relationships and fails to deal adequately with the complex models (Melching and Yoon, 1996). The Monte Carlo method requires repeating model simulation according to the parameter sampling, resulting in tremendous computational time and human effort (Gong et al., 2011). However, the GLUE methodology determines the performance of the model focus on the parameter set, not on the individual parameters (Beven and Binley, 1992). The GLUE method can also handle the parameter interactions and non-linearity implicitly through the likelihood measure (Vazquz et al., 2009). In addition, GLUE is a simple concept and is relatively easy to implement. Therefore, GLUE is used in this study for parameter uncertainty analysis

In InfoWorks SD calibration process for surface runoff was carried out for the parameters which not measured or decided by observation of catchment area such as land use, Curve number, and Manning's n roughness coefficient. For the subsurface flow calibration following procedure conducted for study area.

Each Ground Infiltration record contains 10 parameters. Of these, the Porosity of Soil, Porosity of Ground and the Soil Depth have a physical basis and been estimated or measured. The remaining 7 parameters were calibration coefficients and these have been obtained by hand, or by using an appropriate optimization routine.

The recommended procedure for calibrating the infiltration model by hand is to first calibrate the rainfall induced infiltration and then calibrate groundwater infiltration. The other important parameters which calibrated for this modelling are timing, base flow and maximum peak flow. All these parameters calibrated according to the recommended procedure and sensitivity analysis for the model.

- **Calibrate the rainfall induced infiltration:** The first phase of the calibration involves finding the following parameters:

    1. Percolation Percentage Infiltrating

2. Percolation Threshold
3. Percolation Coefficient

To finding these parameters calibration have been performed on single storms occurring when ground water infiltration is known (or expected) to be zero and the following steps was carried out to calibrate the rainfall induced infiltration:

- A ground infiltration record was created and infiltration event using initial estimates of Percolation Percentage Infiltrating, Percolation Coefficient, and Percolation Threshold. In this procedure, to ensure that no groundwater infiltration enters into the drainage network initial groundwater level was assumed lower than baseflow/ infiltration thresholds.
- Model was run.
- Measured and predicted flows compared. For calibration, the infiltration model toggled the three unknowns. For this purpose: increasing the percolation threshold increase the lag between when the storm starts and when infiltration starts, increasing percolation coefficient increases the duration of infiltration flow and increasing percolation percentage infiltrating increase the volume infiltrating.
- Steps 2 to 3 repeated until the measured and modelled curves compare well.

The main purpose of validation is to determine that the existing model is suitable for intended purpose or not. Van Horn (1971) described that validation can be defined as any process, that is design to evaluate the correspondence between modelled and observed data. The validation process includes the statistical techniques for testing the merit of experimental data. The experimental data usually are the field measurements data. Model evaluation requires these field measurement to determine the accuracy of developed model with actual condition (Mulligan and Wainwright, 2003).

3.7 Model Assessment

In model assessment different methods or techniques were used to evaluate the efficiency, accuracy and the impacts of the model compare to actual condition. Some of these statistical techniques that is used to calibrate and validate the model discussed below.

(a) Root Mean Square Error (RMSE): this is a statistical estimator to show the accuracy of developed model compare to observed data. RMSE is the mean square difference between the modelled and the measured value as:

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(O_i - M_i)^2} \quad (3.7)$$

Where: O_i, Observed value, M_i, predicted or simulated value, n, number of observation.

(b) Square of the Pearson's Product Moment Correlation Coefficient (r^2): is a simple statistical techniques that commonly used in model evaluation (Mayer and Butler, 1993). The Peterson's (r^2) determine the proportion of the total variance in the observed data that can be explained by the model. It ranges from 0 (poor model) to 1 (perfect model) and is given by

$$r^2 = \left[\frac{\sum_{i=1}^{n}(O_i - \bar{O}).(M_i - \bar{M})}{\sqrt{\sum_{i=1}^{n}(O_i - \bar{O})^2}.\sqrt{\sum_{i=1}^{n}(M_i - \bar{M})^2}}\right]^2 \quad (3.8)$$

Where: M_i, model outputs, $\bar{M}$, mean model outputs, O_i, observed outputs, $\bar{O}$, mean observed outputs, n, number of outputs.

(c) Nash-Sutcliffe efficiency (NSE): is a normalized statistic that determines the relative magnitude of the residual variance ("noise") compared to the measured data variance (“information”) (Nash and Sutcliffe, 1970). NSE indicates how well the plot of observed versus simulated data fits the 1:1 line. NSE is computed as shown in equation 3.5:

$$NSE = 1 - \left[\frac{\sum_{i=1}^{n}\left(Y_i^{obs} - Y_i^{sim}\right)^2}{\sum_{i=1}^{n}\left(Y_i^{obs} - \bar{Y}\right)^2}\right] \quad (3.9)$$

Where: Y_i^{obs}, ith observation value, Y_i^{sim}, ith simulated value, $\bar{Y}$, mean of observation data, n, number of observations.

NSE statistical model has fluctuated between the range of $-\infty$ and 1.0 (1 inclusive), and NSE = 1 is optimal value. Values between 0 and 1 described the developed model is acceptable however, negative values indicate that the mean observed value is a better predictor than simulated values which means simulated results compare to observed data is not acceptable and the developed model is unable to present actual condition.

This statistical technique recommended by different researcher for the hydrological studies and simulation of hydrological watershed because it provides an extensive information on the reported values and developed model (ASCE, 1993; Legates and McCabe, 1999; Sevat and Dezetter, 1991).

3.8 Scenarios

For model assessment different scenarios developed to emphasize on the efficiency and functionality of the BIOECODS and SUDS components in peak flow attenuation, increasing infiltration rate through the SUDS components during the rainfall. These scenarios explained briefly below:

- **Scenario 1:** To evaluate the effectiveness of BIOECODS drainage system in flow attenuation the calibrated model was used to consider that scenario where the

BIOECODS is replaced with a traditional drainage system consist of concrete drains (without on-line subsurface conveyance system) but with the same hydraulic and hydrologic parameters as the actual site condition.

- **Scenario 2:** In this scenario calibrated model was used to evaluate the BIOECODS system in peak flow attenuation during the rain event, that present how the infiltration and peak flow attenuation behave from the time that rain started since the end of the event.
- **Scenario 3:** This scenario is use design rainfall to evaluate the effectiveness of ecological swale in BIOECODS system. Due to this, observed data replaced with design rainfall with different annual recurrence interval (ARI).
- **Scenario 4:** This scenario developed to evaluate the effectiveness of entire projects with all BMP components. For this purpose the calibrated model was used to consider that BIOECODS system replaced with traditional drainage system with concrete drains and no BMP components and evaluate the effects in downstream.
- **Scenario 5:** This scenario developed to determine the optimum size for the subsurface modular conduit and characteristics of subsurface flow during the rainfall events.

CHAPTER 4: RESULTS AND DISCUSSION

4.1 Introduction

Increasing impervious surfaces associated with urban environments extremely alter the water quantity and quality characteristics of stormwater runoff (Section 2.2). To protect urban environments, mitigation techniques are required to manage these impacts. The performance of the SUDS systems can be evaluated in terms of quality and quantity improvement. This study mainly focus on the quantity aspects of urban stormwater management.

The performance of BIOECODS system in conjunction with SUDS components can be evaluated according to their capability to reduce the impact of urbanization on stormwater runoff characteristics. In particular, SUDS objectives is to mimic impact of pre-development/development flows by reducing peak flow, stormwater volumes, delay in runoff. The performance of the monitored BIOECODS system was evaluated in terms of these objectives.

This chapter presents the results for AutoCAD, ArcGIS, and InfoWorks SD software that used to evaluate the performance of BIOECODS system at the Taiping Clinic, in Larut Matang restrict, Perak, Malaysia. Firstly, AutoCAD map created according to survey data presented and then transferred to ArcGIS for further exploring. Secondly, necessary data for modelling purposes such as, rainfall data, designed rainfall, infiltration results were presented. Thirdly, created model was compared with observed data for calibration and validation. In the final step, calibrated model was investigated for evaluating the efficiency and functionality of BIOECODS system and SUDS components in peak flow attenuation

4.2 AutoCAD

The survey data converted to AutoCAD (Version 2013) to create a map for more investigation about the study area. The created map in AutoCAD presented in Figure 4.1.

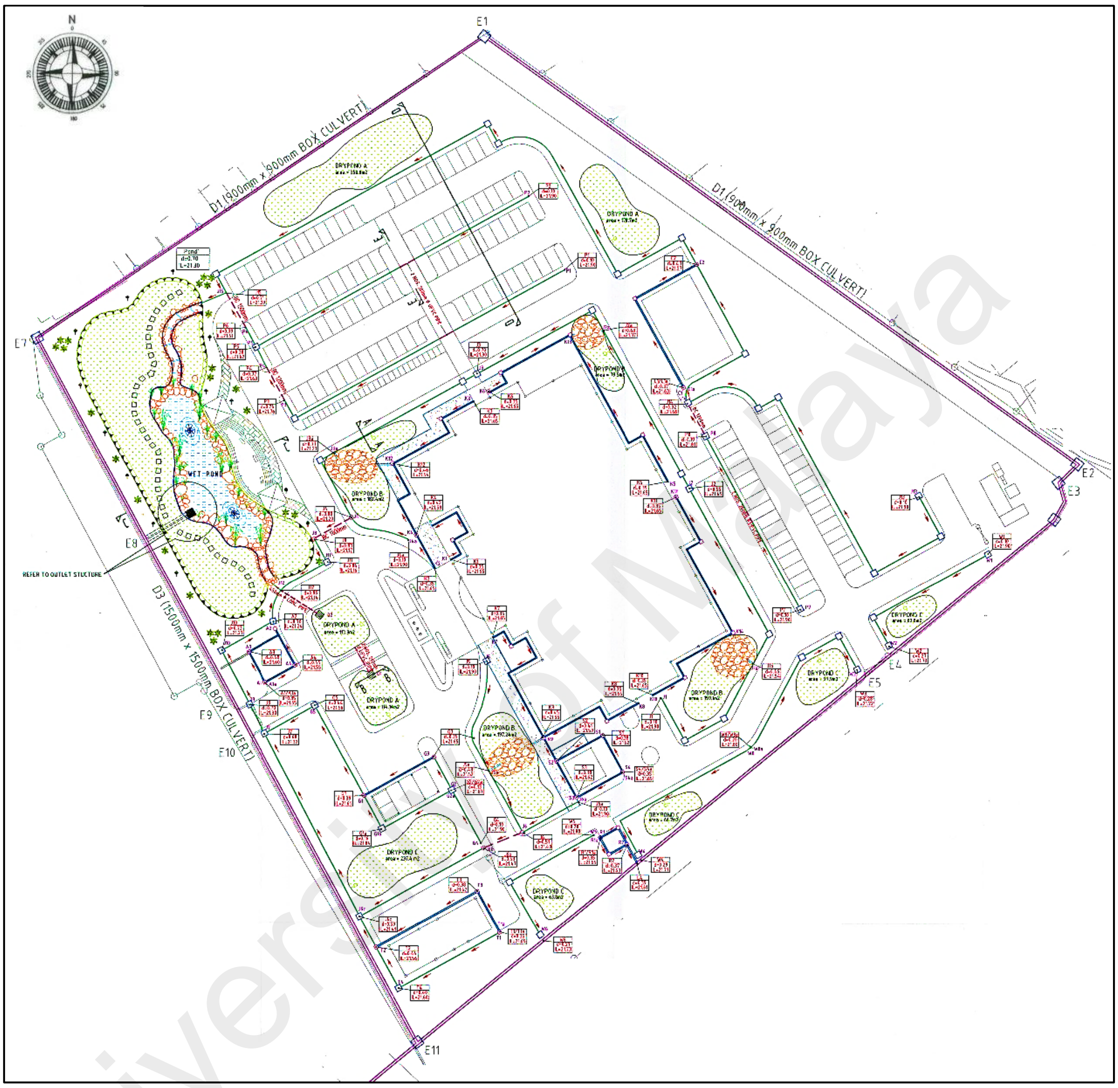


Figure 4.1: Plan map from study area in AutoCAD

4.3 ArcGIS

All survey data and plan map created in AutoCAD transferred to ArcGIS to create TIN layer and digitalized map with projected coordinate UTM 47N for Malaysia and presented in the data as attribute of separate points that geometrically connected to the conduits downstream by another layer of polyline feature. The downstream invert level for open and closed channel and digitalized map for study area presented in Figure 4.2 and 4.3 respectively.

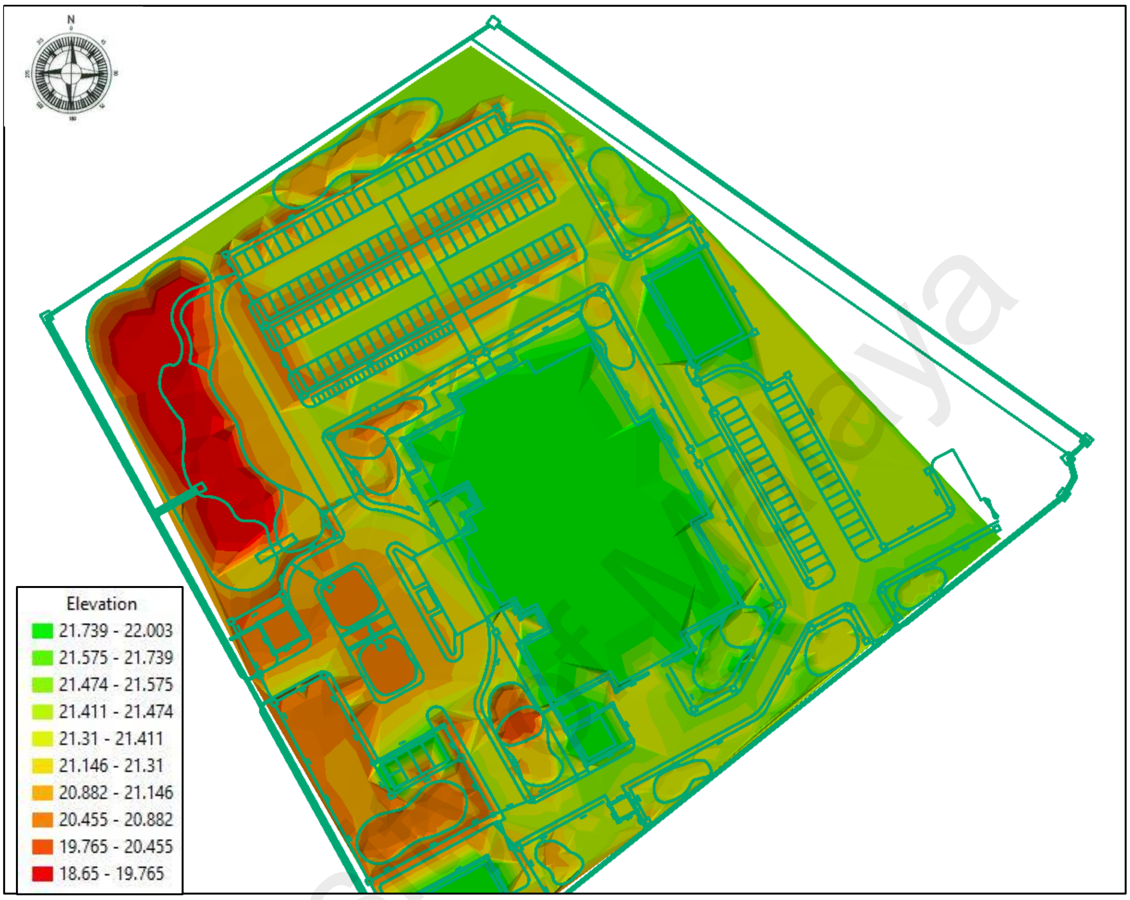


Figure 4.2: Created TIN layer for study area in ArcGIS

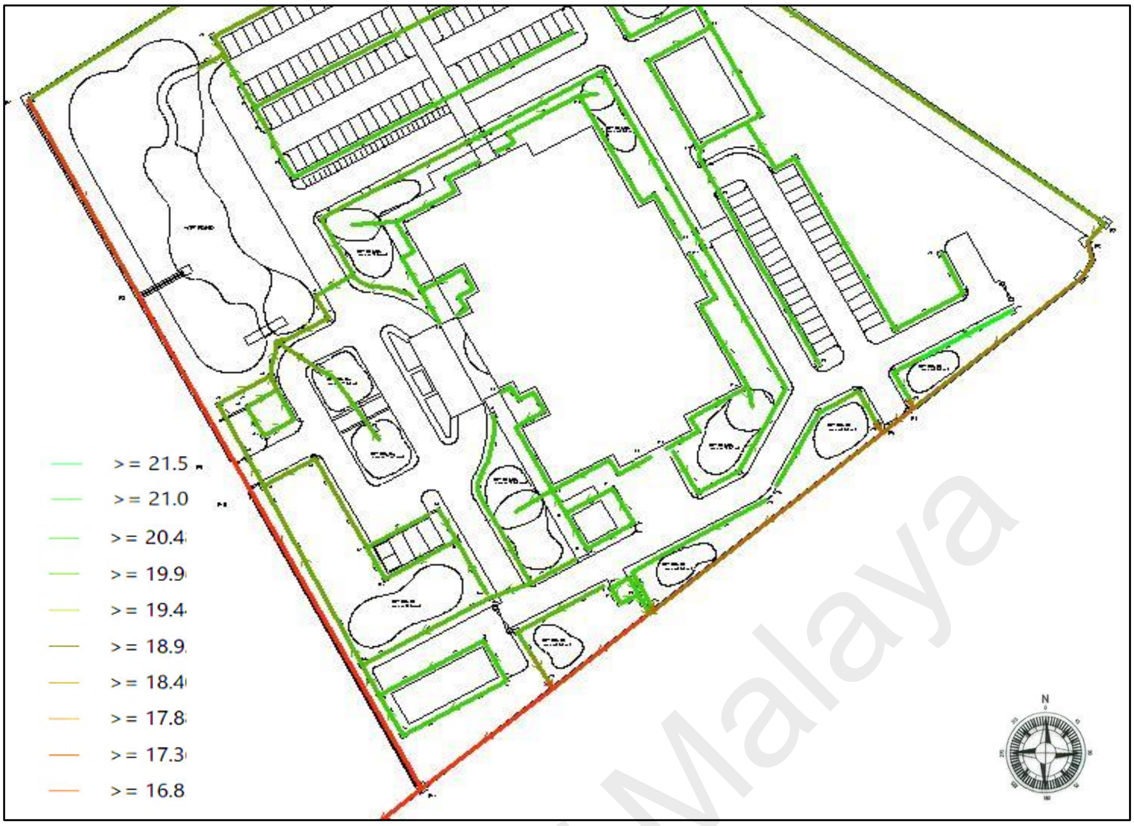


Figure 4.3: Changing in invert level in conduits in the study area

4.4 InfoWorks SD ground model

According to the collected data from survey data and created digitalized map in ArcGIS, all data transferred to the selected software, model developed and their results analyzed. In the existing of adequate runoff measurements, and rainfall data, calibration and validation for model was done by comparison between observed and predicted values in BIOECODS components. The final model for BIOECODS drainage system presented in Figure 4.4.

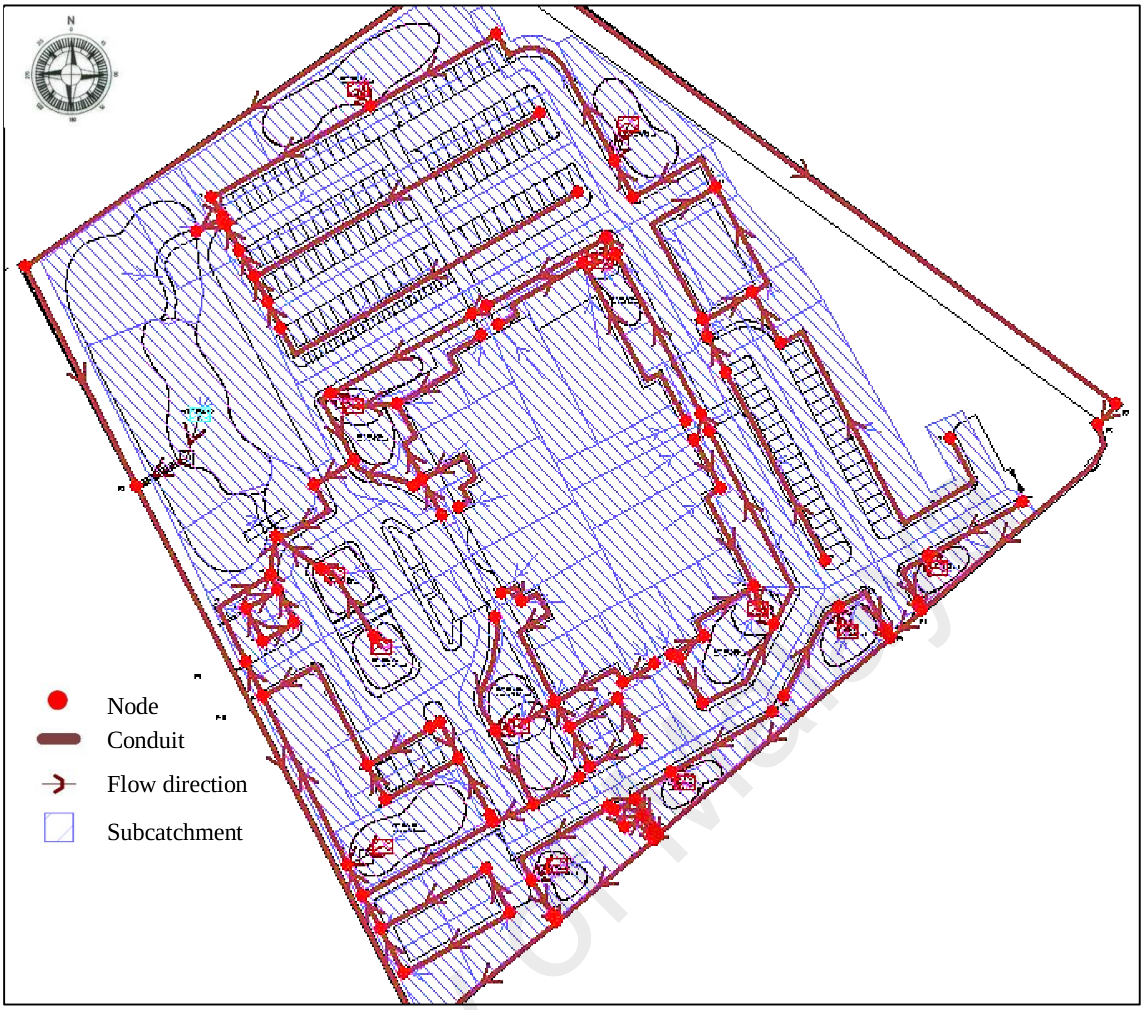


Figure 4.4: Drainage network and subcatchments map for BIOECODS system modelled in InfoWorks SD

All the required data such as subcatchment data, infiltration test results, rainfall data transferred to InfoWorks SD to develop a model with proper details. The other necessary parameters such as CN values, soil class etc. calibrated. All the required data presented for model shown in the following section.

4.4.1 Subcatchment Parameterization

Subcatchments require a wide range of parameters until they can be modelled in InfoWorks SD. Some of these parameters (e.g. subcatchment area, contributing area) are easier to obtain, although uncertainties may be involved. In contrast, other parameters (e.g. soil class, CN values) required try and error parameter estimation and calibration. Before going into the detail on the subcatchment specific parameters, some general parameter settings area mentioned: (i) each subcatchment was manually assigned to a correct outlet node in the drainage network, (ii) subcatchments were named with numbers, (iii) runoff from both pervious and impervious fraction of a subcatchment was set to routed directly to the outlet, (iv) all subcatchments were linked to the same rainfall profile in study area, (v) subcatchments are valued by overland system type in drainage network and drained to the links (grass swales).

The imperviousness parameter describes the percentage of impervious surfaces in relation to the total area of a subcatchment. It is often used as a calibration parameter (Choi and Ball, 2002) as it is not quite straightforward to physically define, due to the fact that many surfaces are in reality impervious. Other ways to define the values of imperviousness are to estimate them based on land use data, or by automated or manual image processing of aerial or satellite orthophotos. In this study, the value of imperviousness estimated according to land use data and Curve number (CN) value for the study area. In this study as it mentioned in section 3.7.3.1 (Table 3.10), five different land use ID was introduced to InfoWorks SD and runoff from pervious and impervious surfaces was estimated. The landuse map for the study area is presented in Figure 4.5.

Figure 4.5: Land use map for study area

As it shown in Figure 4.5, 68% of the study area covered with impervious area that include paved parking lots, buildings, roof and only 30% pervious areas include vegetated detention ponds, grass swales and open spaces. This issue highlights the important of control runoff in the study area. The contributed area for each landuse calculated according to the survey data and presented in Table 4.1.

Table 4.1: contributed area for pervious and impervious surfaces in study area

Surfaces	Contributed area (m^2)	Percentage of entire area ($m^{2)}$
Impervious surface	19134	68%
Pervious surface	8406	30%

All survey data collected from study area converted into an elevation map in InfoWorks SD to evaluate the average gradient of each subcatchment at which the subcatchment drain to the node that presented in Figure 4.6. According to Figure 4.6, study area has gentle slope which different between highest and lowest point is 1 m approximately.

Figure 4.6: Subcatchment slopes for study area

As it mentioned before in this study SCS model combined with Horton runoff volume model to simulate runoff from pervious and impervious in the catchment. In SCS model, CN value is an important character to calculate the runoff from pervious and impervious area.

The Curve Number (CN) values were evaluated and calibrated in 12 individual classes according to site observation and also previous studies (DID, 2012; Lai and Mah, 2012; Chow, 1959) for each subcatchment which shown in Figure 4.7.

Higher value presenting impervious areas such as roofs, paved parking, asphalts which has more runoff from surface and lower value presenting pervious areas such as open space, vegetated areas, grass swales which has more infiltration and less runoff.

Figure 4.7: CN values for individual subcatchment for study area

After invert level and channel lengths were obtained from survey data, the Manning's n roughness had to be defined. The designed Manning's n roughness for grass swales in the study area were obtained from previous studies (See section 3.2.3) and calibrated for study area (Table 3.2)

4.5 Data collection

4.5.1 Infiltration test

The Horton infiltration model with conjunction to SWMM model to account for infiltration involves two soil-dependent parameters: (i) Horton initial, f_0, (ii) Horton limiting, f_c, (iii) Horton Decay, K, which is calculated from equation 2.6 (See section 2.7.2.2). Infiltration test conducted for study area in 10 different locations such as open space, dry detention ponds with subsurface detention storage, dry detention without subsurface detention storage, and grass swales. Typical infiltration parameters values for field test presented in Table 4.2.

Infiltration test conducted in the study area cover entire area and sample of infiltration test result for different place in the area presented in Figure 4.8.

Table 4.2: Sample of conducted infiltration test in different catchment

Symbol	Variable	Unit	Range of infiltration in Dry pond without detention storage	Range of infiltration in Dry pond with detention storage	Range of infiltration in grass swale
f_0	Initial	mm/hr	26-75	100-150	130-212
f_c	Limiting	mm/hr	3	3	3

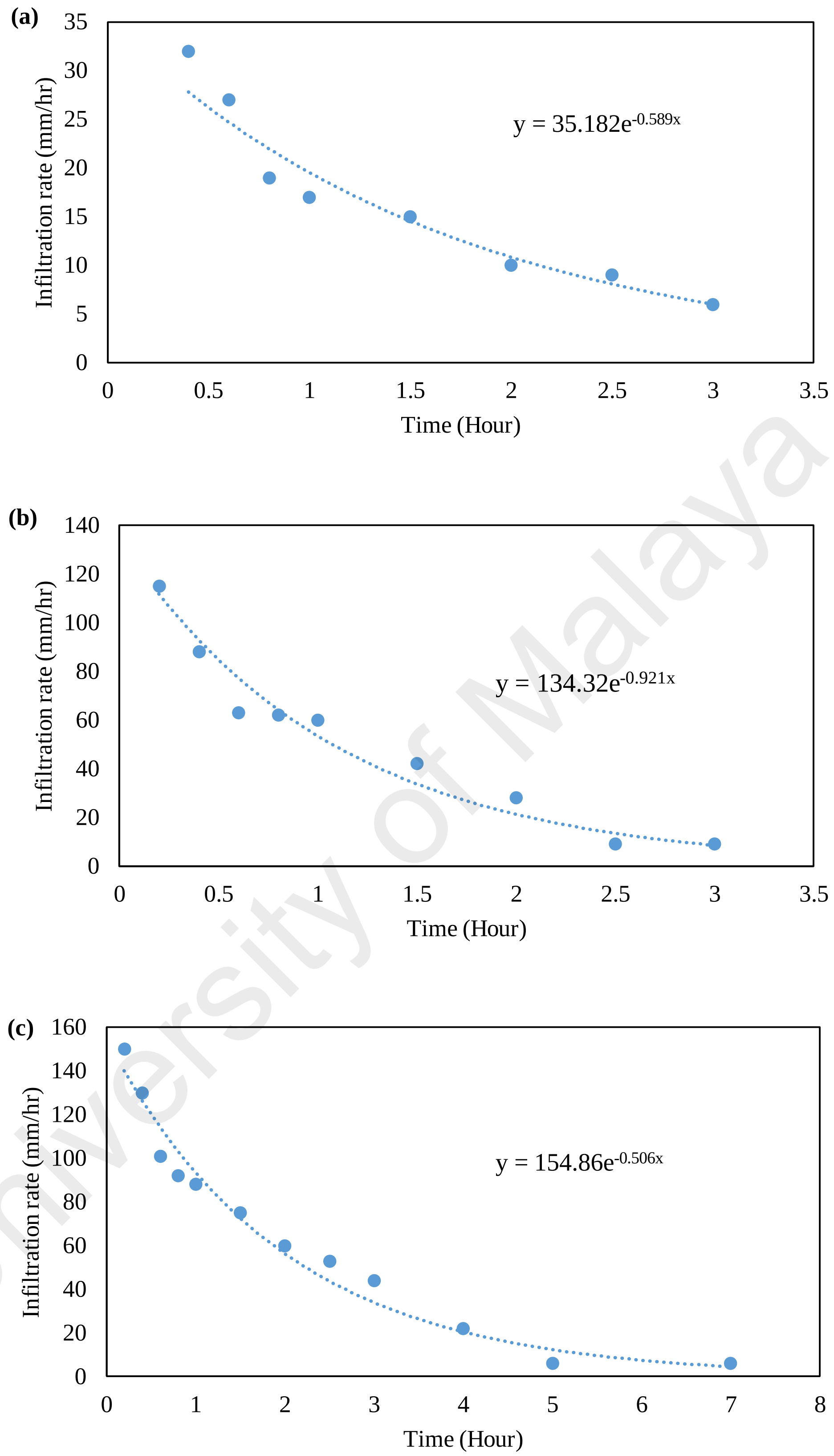


Figure 4.8: Conducted infiltration test: (a) Dry pond without detention storage, (b) Dry pond with detention storage, (c) Grass swale

Infiltration results revealed that the grass swale with an on-line subsurface conveyance system has highest infiltration rate compare to other SUDS components in the study area such as detention pond and retention pond.

4.5.2 Rainfall data

- **Rainfall Event**

During data collection, rainfall data collected and after validating data 7 sets of data was used for modelling purposes that presented in Table 4.3.

Table 4.3: Rainfall events for simulation purposes

Events	Maximum Intensity (mm/hr)	Average rainfall intensity (mm/hr)	Duration (min)	Rainfall type
Event No.1 (10/9/2013)	71.4	21.2	45	Low intensity
Event No.2 (14/10/2013)	114.2	43.2	80	High Intensity
Event No.3 (23/11/2013)	102.9	42.1	50	Medium Intensity
Event No.4 (19/12/2013)	103.2	42.54	60	Medium Intensity
Event No.5 (12/1/2014)	122.3	50.2	120	High Intensity
Event No.6 (11/2/2014)	40.5	12.9	40	Low intensity
Event No.7 (21/2/2014)	30.7	10.2	55	Low intensity

The raw time step for collecting data for rain gauge monitoring station was set for 30 seconds. All the collected rainfall data after verification (prevent negative values, missing values, etc.) was converted to 5 minutes time interval and collected height converted to intensity for further analysis. Therefore, rainfall data processed and transferred to InfoWorks SD as rainfall event data with time interval of 5 minutes.

The selected rainfall events have different patterns, intensity, and duration and in different months happen to cover all the dry and wet season for the study area. The selected rainfall events with different characteristics presented in Figure 4.9-4.11.

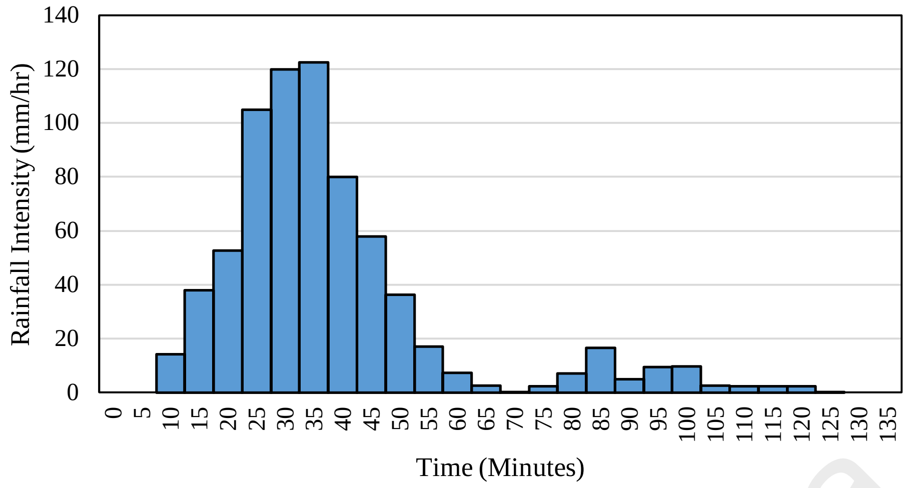


Figure 4.9: Rainfall patterns and characteristics for selected rainfall event No. 5 (12/1/2014), High intensity

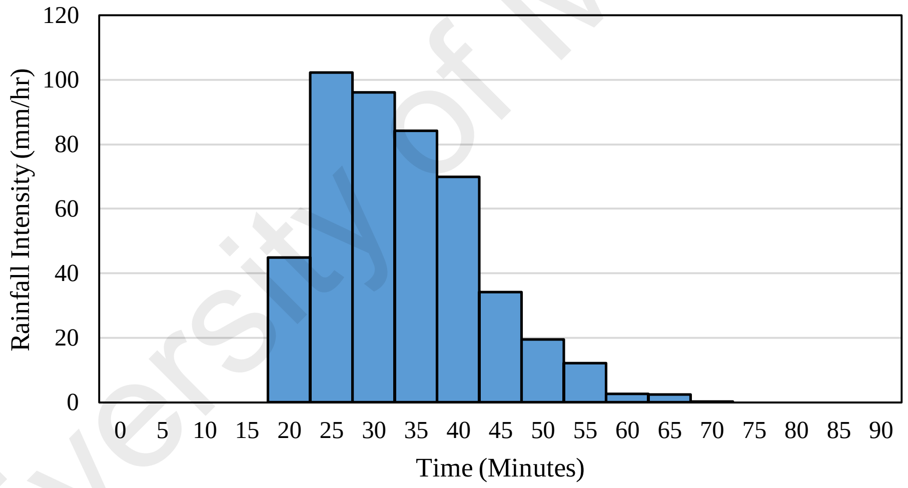


Figure 4.10: Rainfall patterns and characteristics for selected rainfall event No. 4 (19/12/2013), Medium intensity

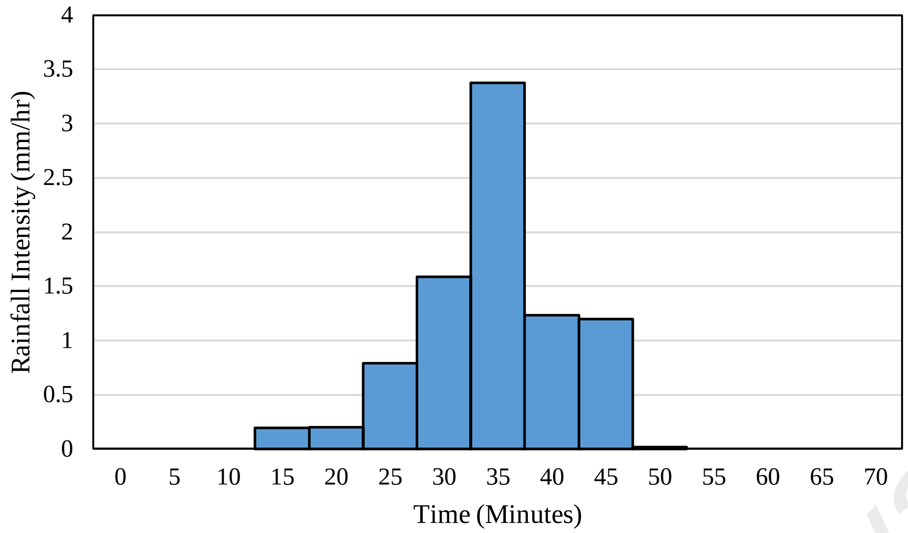


Figure 4.11: Rainfall patterns and characteristics for selected rainfall event No. 6 (11/2/2014), Low intensity

For accuracy in simulation start and end of the simulation is at least 1 day before rainfall event happen, so the model can analysis the data and also its easy to calibrate the values which is unknown for modelling. From the collected rainfall in monitoring station, five rainfall events with high, medium and low intensity was selected that shown in Table 4.4.

Table 4.4: Selected rainfall events with different patterns for simulation purposes

Event	**Maximum Intensity (mm/hr)**	**Observed Maximum level (m)**		
		Station No.4	**Station No.3**	**Station No.2**
Event No.2	114.2	0.79	0.1	0.12
Event No.3	102.9	0.81	0.12	0.11
Event No.4	103.2	0.81	0.11	0.12
Event No.5	122.3	0.89	0.15	0.14
Event No.6	40.5	0.60	0.03	0

- **Designed rainfall**

According to Manual Stormwater for Malaysia (MSMA), IDF curve for the study area calculated. Empirical equation was used to minimizing the error in estimating rainfall intensity. The data was used to generate 2-100 years ARI events as shown in Figure 4.12.

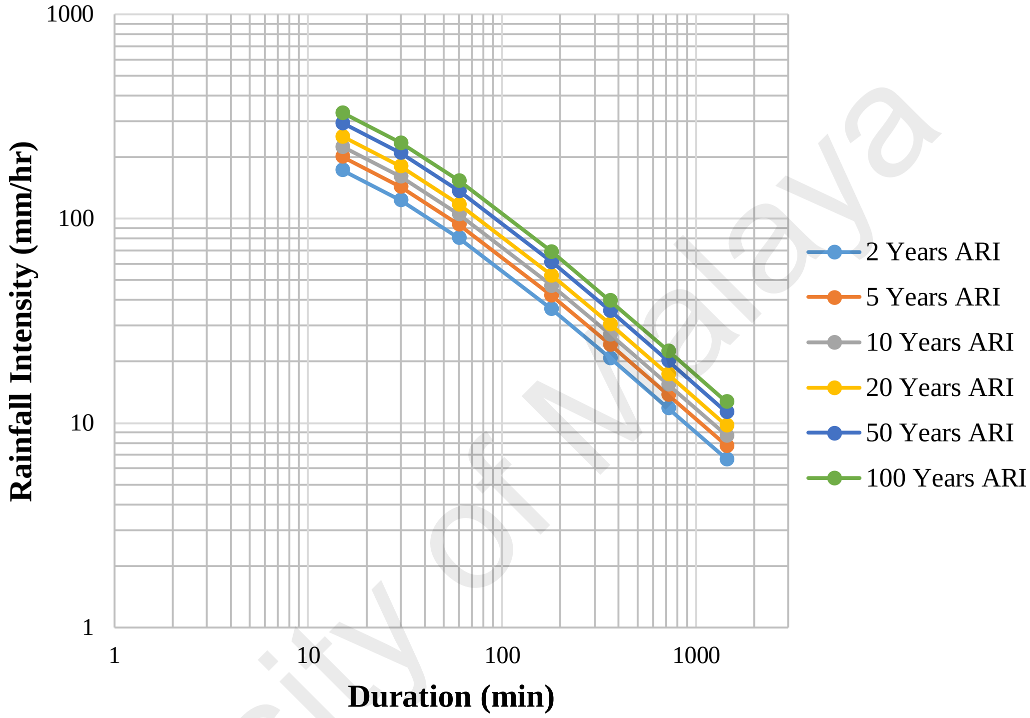
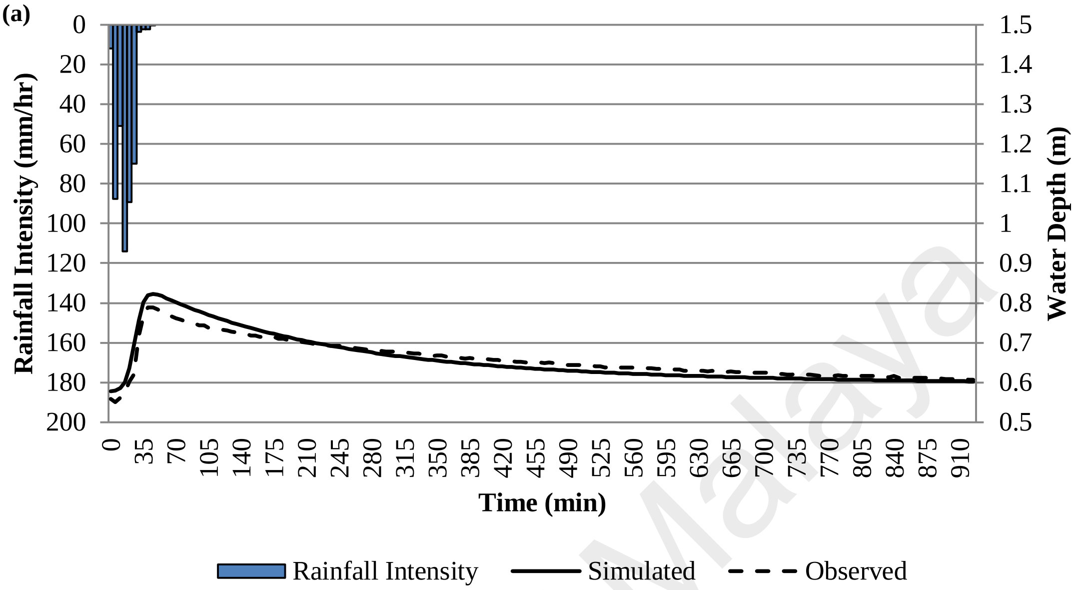


Figure 4.12: IDF Curve for Taiping, Perak

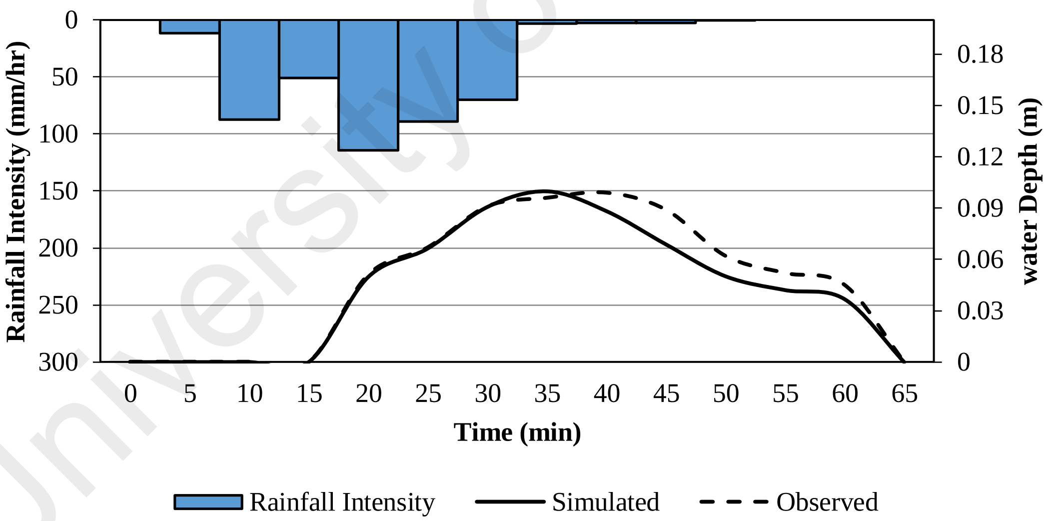
4.6 Model simulation

The model was run for five single rainfall events with 5 minutes time interval with different patterns and intensity (See Table 4.4). For validation purposes modelling results in terms of water level for each of the component were compared with the measured data in the monitoring stations (See Table 4.4). The measured values in terms of water level for retention ponds, and primary outlets for selected rainfall events presented in Table 4.4 and sample of results in terms of water level for rainfall event No.2 (14/10/2013), rainfall event No.5 (12/01/2014) and rainfall event No. 3 (23/11/2013) presented in Figure 4.13, 4.14, and 4.15 respectively.

(a)



(b)



(c)

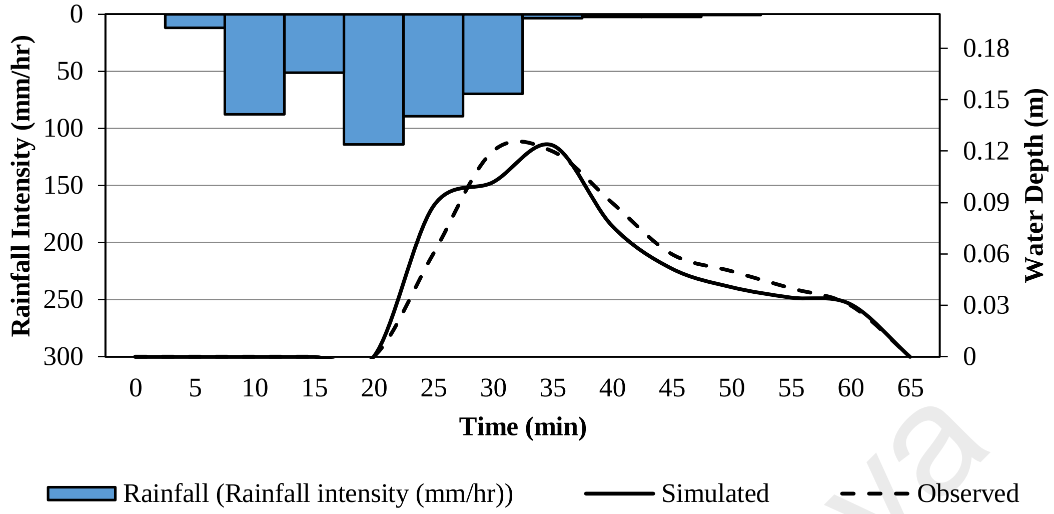
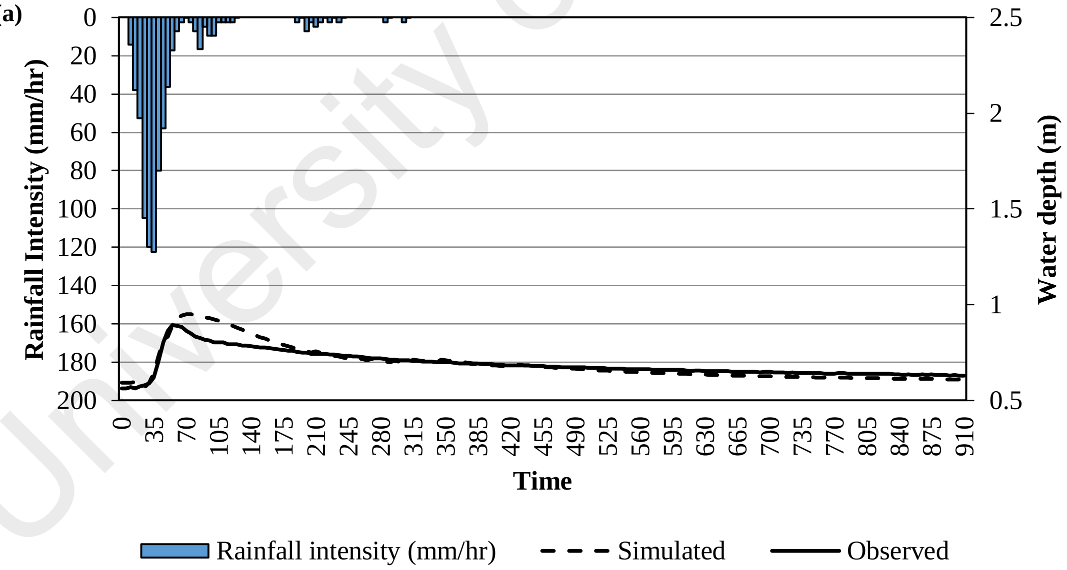
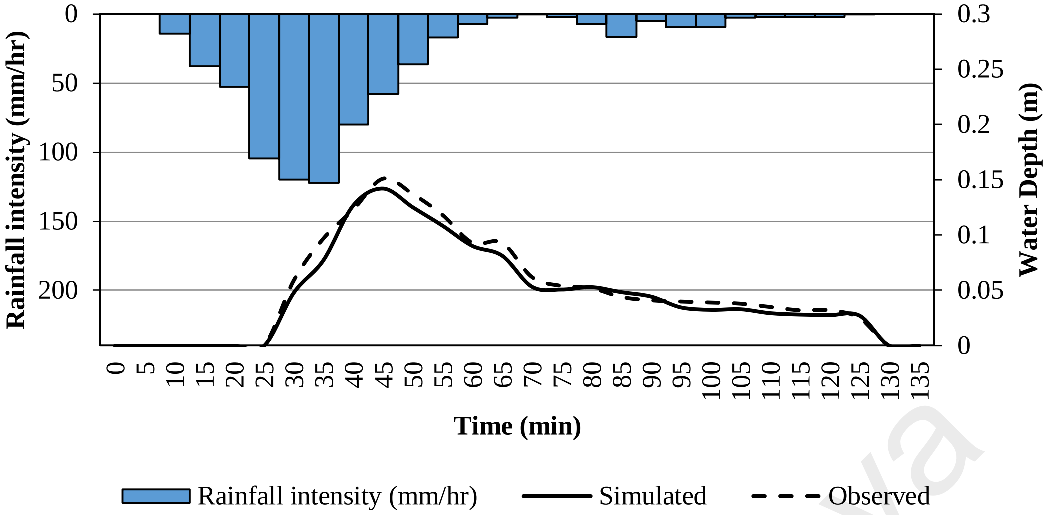


Figure 4.13: Comparison of modelled (BIOECODS) and observed water level for rainfall event 14/10/2013, (a) Retention pond station No.4, (b) Primary outlet station No. 3, (c) Primary outlet station No.2

(a)



(b)



(c)

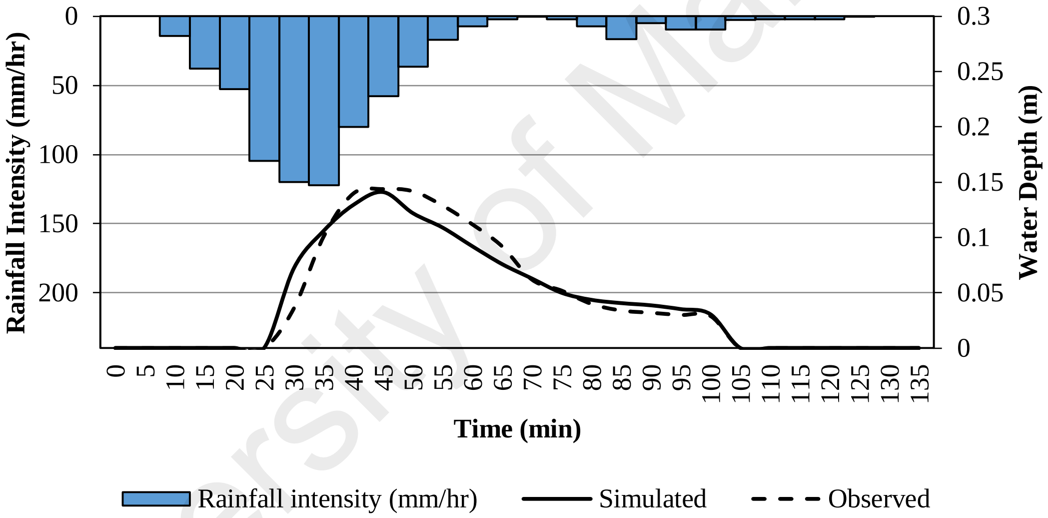


Figure 4.14: Comparison of modelled (BIOECODS) and observed water level for rainfall event 12/01/2014, (a) Retention pond station No.4, (b) Primary outlet station No. 3, (c) Primary outlet station No.2

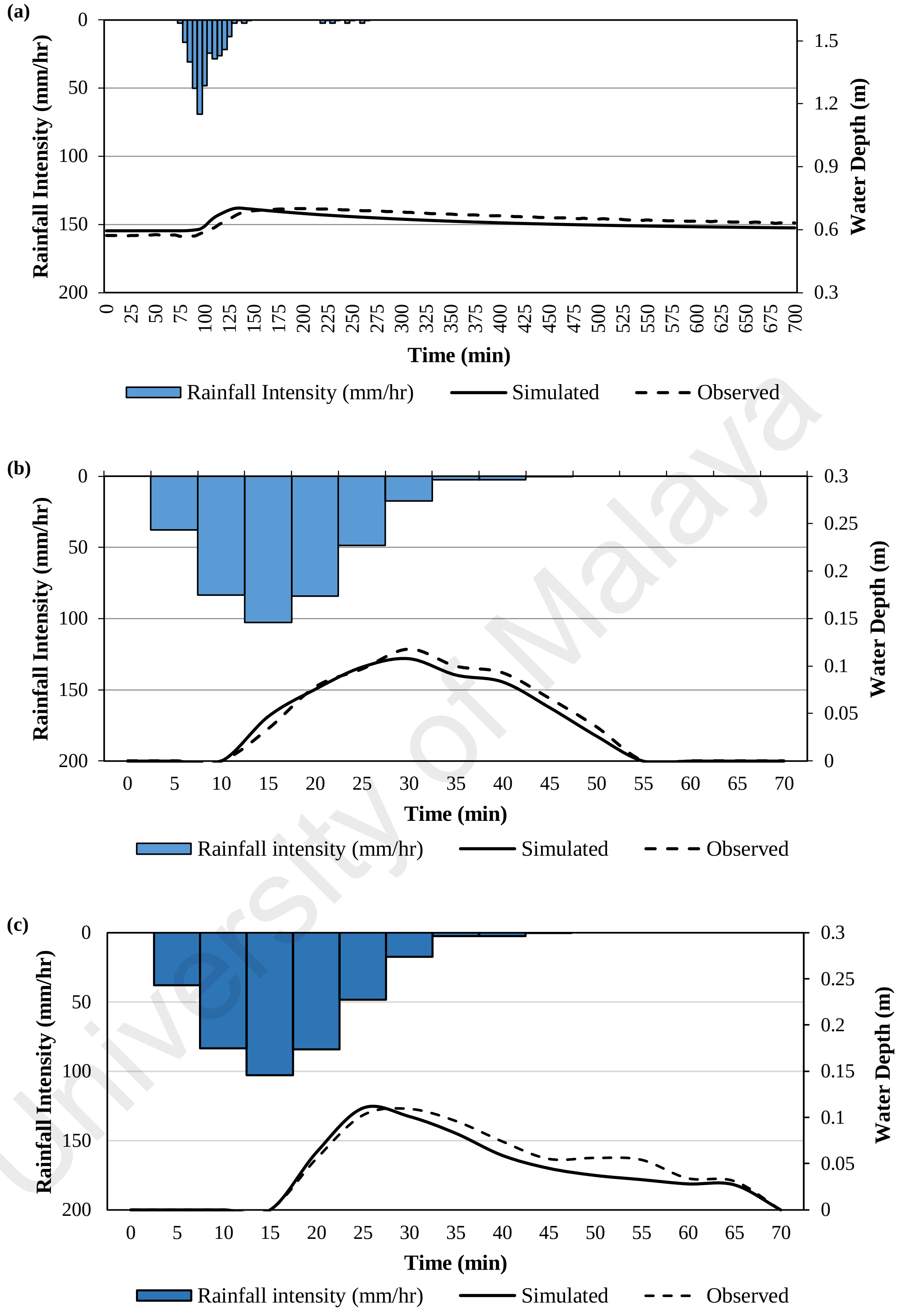


Figure 4.15: Comparison of modelled (BIOECODS) and observed water level for rainfall event 23/11/2013, (a) Retention pond station No.4, (b) Primary outlet station No. 3, (c) Primary outlet station No.2

4.7 Sensitivity analysis

Rainfall-runoff modeling predicts the hydrological response (runoff) to a certain input (precipitation), usually as a function of time. The mechanisms of prediction differ. So-called 'black-box models' (or the systems view) seek for an abstract function relating the input and output functions, whereas physically-based models try to thoroughly describe the underlying processes. In practice, most rainfall-runoff models fall between these two extremes (Dingman, 2008).

As it mentioned watershed model for this study were applied on a single-event basis. Mainly, the objectives of single events basis modelling are to determine the timing, peak flow, recession curve and flow volume (ASCE, 1993; Van Liew et al., 2003).

According to Ramírez (2000), accurate estimation of peak flow and the time to peak is very vital for the flood forecasting and estimation. It is also important for evaluating the capacity of urban structure to avoid flash flood. Time-to-peak (lag time) is affected by differen factors such as, catchment slopes, cahnnel roughness, drainage network density, infiltration rate and soil type and peak flow affected by antecedent soil moisture content before rainfall happen, rainfall intensity, soil type, drainage system density etc.

The simplest techniques that suggested by ASCE (1993) is simple precent error in peal flow rates (PEP). In this statistical method PEP calculated by dividing the differences of peak flow between simulated peak flow and observed peak flow by the observed peak flow rate. Model validation for time to peak can be determined by the same procedure.

Boyle et al. (2000) suggested for the single event simulation, hydrograph be divided into three phases based on different catchment behavior during rainfall and dry periods. Each phase should be evaluated by rating. If the perfomance ratings are similar to each other, then a single perfomrance rating can be applied for hydrograph. The model evaluation for retention pond, grass swale in primary outlets in BIOECODS system for rainfall event

14/10/2013 and rainfall event 12/01/2014 presented in Table 4.5 and 4.6 respectively as sample.

From the presented results of comparison between observed and simulated data to be a perception that this model can simulate the study area with all SUDS components with close match to the observed data and low error. Table 4.5 and 4.6 presenting the accuracy of this model with different methods.

Table 4.5: Evaluating the accuracy of modelling BIOECODS components for rainfall event 14/10/2013 in InfoWorks SD

Components	Raising limb			Falling limb			Baseflow		
	R^2 %	RMSE %	NSE %	R^2 %	RMSE %	NSE %	R^2 %	RMSE %	NSE %
Retention Pond Station No.4	98	3.7	99.4	99	2.4	99.7	98	1.2	99.9
Primary outlet Station No.3	99	0.2	99.9	97	1.3	99.7	99	0.3	99.7
Primary outlet Station No.2	98	1.2	99.1	94	1.2	99.8	99	0.4	99.9

Table 4.6: Evaluating the accuracy of modelling BIOECODS components for rainfall event 12/01/2014 in InfoWorks SD

Components	Raising limb			Falling limb			Baseflow		
	R^2 %	RMSE %	NSE %	R^2 %	RMSE %	NSE %	R^2 %	RMSE %	NSE %
Retention Pond Station No.4	99	4.9	98.9	95	10.9	93.8	98	1.9	99.8
Primary outlet Station No.3	99	0.91	99.7	98	0.64	99.9	99	0.51	99.8
Primary outlet Station No.2	91	1.5	98.9	98	0.97	99.8	98	0.64	99.9

As it mentioned before in order to use model outputs for tasks ranging from regulation to research, models should be scientifically sound, and defensible. Sensitivity analysis is the process of determining the rate of change in model output with respond to change model input (parameters). It is a necessary process to identify the key parameters which required in model calibration. Due to this matter sensitivity analysis was conducted for current model and key parameters in this study determined. The first step for sensitivity analaysis is to specify the input parameters. Input parameters in InfoWorks SD presented in Table 4.7.

Key input parameters in InfoWorks SD divided into two sets of data (i) catchments, and (ii) stormwater conveyance system (Nodes and links). As it mentioned, the watershed area divided into two main catchments with different subcatchments. Some of these parameters (e.g. subcatchment area, contributing area) are easier to obtain, although uncertainties may be involved. In contrast, other parameters (e.g. soil class, CN values) required trial and error parameter estimation and calibration. Conduit length, upstream and downstream invert level (either open or closed) and also cross sectional shape are necessary parameters for hydraulic modelling in InfoWorks SD and other parameters (e.g. manning's n roughness) required trial and error estimation and calibration.

In order to evaluate the effectiveness of the adopted modelling approach concerning the BIOECODS modelling, the uncertainty analysis has been evaluated by means of the GLUE methodology (Beven and Binley, 1992) which shown in Figure 4.16. The GLUE methodology transforms the problem of searching for an optimum parameter set into a search for sets of parameter values that give reliable simulations. Several modelling runs are performed adopting Monte Carlo simulation for evaluating model performance, varying parameters value in a specified range.

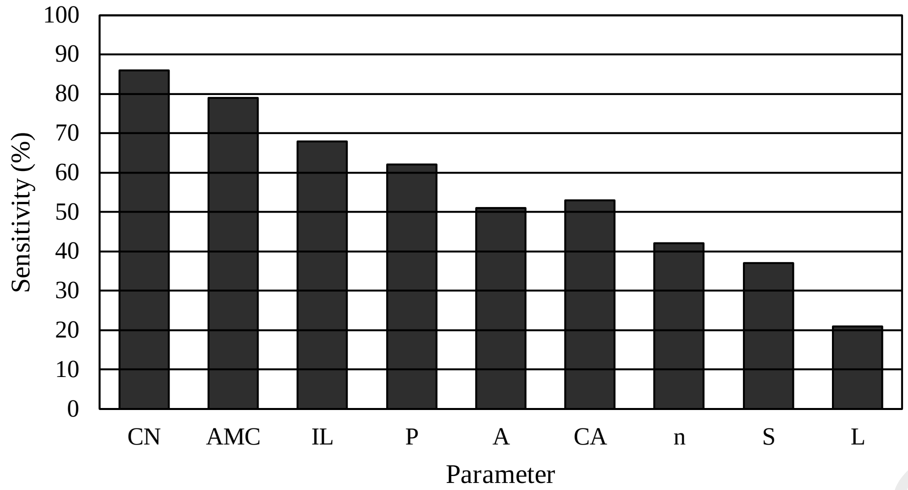


Figure 4.16: Graphical representation of the sensitivity ranking of models parameters

The following results present that in single event base modelling the key paramaters are curve number (CN), wetness index (AMC) and infiltration rate (I_L). Calibrated parameters presented in Table 4.7.

Table 4.7: Calibrated parameters for BIOECODS system

Parameters	Description	Values
n	Manning's coefficient	1) Grass swale = 0.048 2) Concrete = 0.012-0.014
CN	Curve number value	1) Roofs, paved parking lots, asphalts = 97 2) Grass swales with subsurface detention storage = 20-40 3) Grass swales without subsurface detention storage = 40-60
Porosity	The percentage void	1) The value is between 0 – 100% which according to the observation from the study site calibrated.

The rest of input parameters such as areas, infiltration rates, length, and slopes determined by field measurments and survey study.

4.8 Calibration and validation

For calibration and validation purposes two events with minimum and maximum rainfall intensities and period selected as calibrating data and three events as validation. The events No.2 (14/10/2013) and No.3 (23/11/2013) selected for calibration and event No.4 (19/12/2014), No.5 (12/1/2014) and No.6 (11/2/2014) selected for validation.

The calibration and validation results in aspect of error show that model has adapted to real situation and important parameters for modelling well done calibrated. Due to insufficient observed runoff for primary outlet station No.2 in event No.6, this event did not count for model calibration and validation, which presented in Table 4.8. The results for calibration and validation for Primary outlet station No.2, Primary outlet station No.3 and retention pond station No.4 duplicated in Table 4.8, 4.9 and 4.10 respectively.

Table 4.8: Calibration and validation results for Primary outlet station No.2

Station NO.2		**Peak Flow (Volume/Minute)**			**Entire rainfall hydrograph**		
		Observed	**Simulated**	**Error (%)**	**Observed level (m)**	**Simulated level (m)**	**Average Error (%)**
Calibration	**Event 2**	0.12	0.12	2.9	0.030 - 0.120	0.030 - 0.124	3.8360
	Event 3	0.11	0.11	1	0.031 - 0.109	0.027 - 0.110	5.6548
Validation	**Event 4**	0.12	0.11	1.9	0.032 - 0.115	0.030- 0.112	5.8780
	Event 5	0.14	0.14	1.9	0.029 - 0.144	0.030 - 0.141	8.8510

Table 4.9: Calibration and validation results for Primary outlet station No.3

Station NO.3		**Peak Flow (Volume/Minute)**			**Entire rainfall hydrograph**		
		Observed	**Simulated**	**Error (%)**	**Observed level (m)**	**Simulated level (m)**	**Average Error (%)**
Calibration	**Event 2**	0.099	0.100	0.784	0.045 - 0.099	0.036 - 0.1	2.0020
	Event 3	0.118	0.108	8.575	0.036 - 0.118	0.026 - 0.108	5.6670
Validation	**Event 4**	0.108	0.102	4.902	0.053 - 0.11	0.0436- 0.1021	4.5890
	Event 5	0.151	0.142	5.788	0.025 - 0.151	0.0273 -0.1423	7.3230
	Event 6	0.029	0.028	2.188	0 – 0.0293	0 – 0.0287	6.8123

Table 4.10: Calibration and validation results for Retention pond station No.4

Station NO.4		Peak Flow (Volume/Minute)			Entire rainfall hydrograph		
		Observed	**Simulated**	**Error (%)**	**Observed level (m)**	**Simulated level (m)**	**Average Error (%)**
Calibration	**Event 2**	0.79	0.85	7.87	0.54 - 0.79	0.56 - 0.85	6.16
	Event 3	0.81	0.95	17.28	0.54 - 0.81	0.56 - 0.95	15.64
Validation	**Event 4**	0.81	0.85	5.26	0.52 - 0.81	0.56- 0.85	2.44
	Event 5	0.89	0.92	3.55	0.54 - 0.89	0.56 – 0.92	1.20
	Event 6	0.6	0.65	8.16	0.55 – 0.60	0.46 – 0.65	6.30

The results for calibration and validation for each station shows that current model has closely match to actual situation and able to simulate the case study area with high accuracy.

4.9 Model Assessment

The results show that the current model can predict the hydraulic and hydrologic parameters in each BIOECODS components compared with collected observed data by installed monitoring stations in study area.

For further study and exploring BIOECODS system in aspect of water quantity, different scenarios were developed to evaluate the BIOECODS system and in general SUDS components in control at source approach, flow attenuation and stormwater management. The scenarios developed and discussed in this section and the results of these scenarios analyzed for each component.

(a) Scenario 1

In this section, consider a scenario to further explore and functionality of BIOECODS in peak flow attenuation. The calibrated model is used to consider that scenario where the BIOECODS is replaced with a traditional drainage system consist of concrete drains (without on-line subsurface conveyance system) of the same hydraulic and hydrologic parameters as the actual site condition.

This scenario emphasize on the main aspect of grass swale with on-line subsurface conveyance system which is increase the water quality, flow attenuation by increasing infiltration rate through the swale during the rainfall.

A sample of simulated result for the study area with traditional drainage system is shown in Figure 4.17. It can be seen that the flow rate and flow velocity for most of the drain are much higher (v up to 0.8 m/s, Q up to 0.1 m^3/s) when compared with BIOECODS system, this means that much bigger volume of runoff will reach to the retention pond at downstream, overflow is found as expected on floodplain region around the retention pond, with a maximum flood depth of 0.746 m.

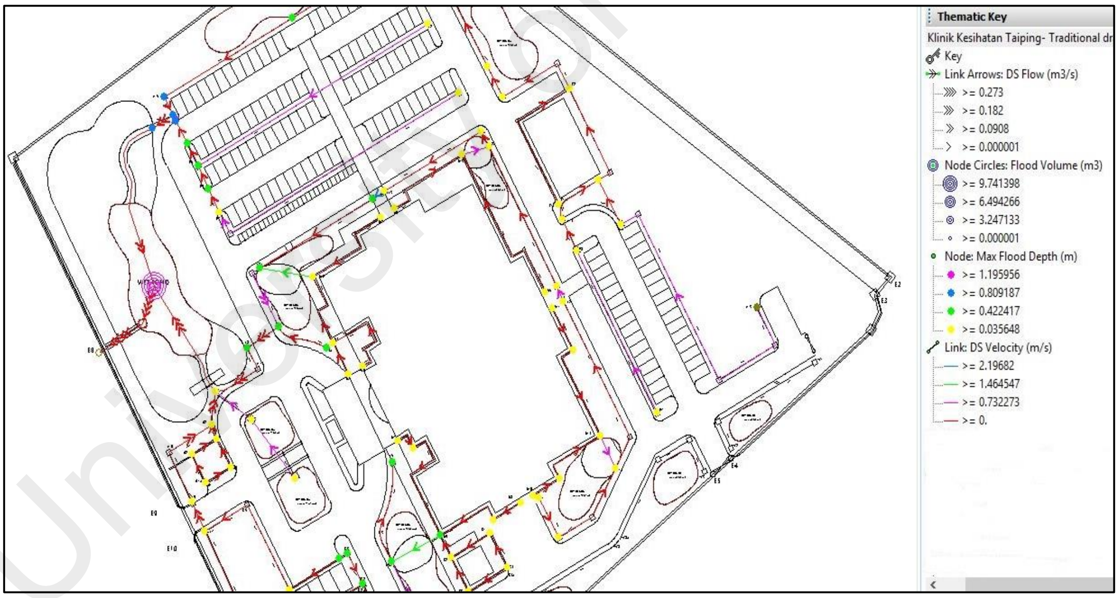


Figure 4.17: Flow simulation (traditional drainage system) for event NO.1 using InfoWorks SD

The model was run for selected rainfall events. As a sample the simulation results for two primary outlet stations (Stations No.2 and No.3) for event number two (14/10/2013) were presented in Figure 4.18. The results presented in Figure 4.18 shows that BIOECODS system delay time to peak because of high infiltration rate of ecological swale with subsurface conveyance system. This situation continues until the soil becomes saturated and then rainfall will change to be a very gradual flow.

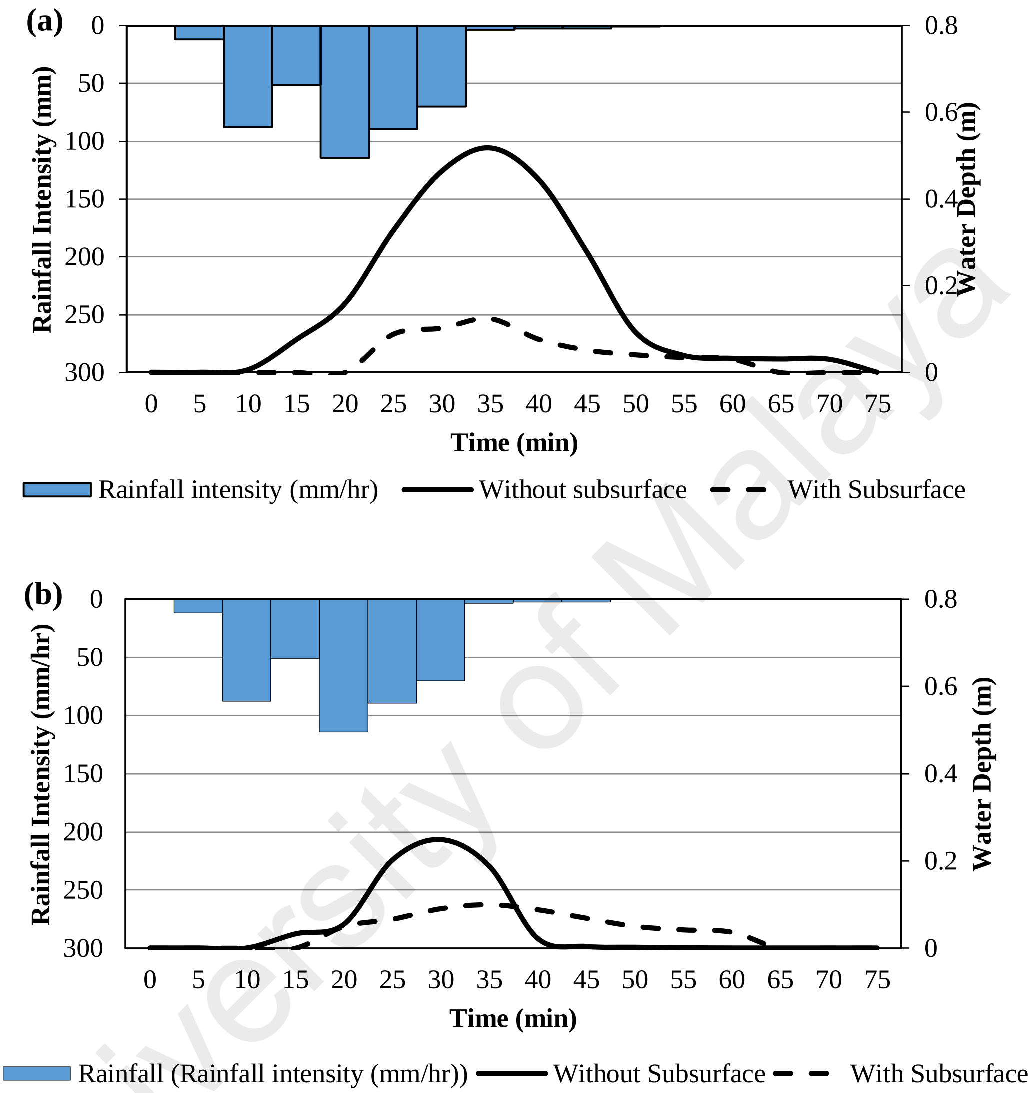


Figure 4.18: Evaluation of ecological grass swale for event number one (14/10/2013): (a) primary outlet station No.2; (b) Primary outlet station No.3

It is shows the grass swale has high infiltration rate before the soil saturated so compare to concrete surface (no infiltration capability) at the moment rainfall happen. Due to the scheme no water level detected in grass swale, the other concept of ecological swale is to increase the water quality of water with decreasing the velocity of flow and increasing the rate of infiltration that is very clear in the Figure 4.18. Comparison results between these two conditions presented in Table 4.11.

Table 4.11: Comparison results for two different scenarios

Stations	**Without ecological drainage system**		**With ecological drainage system**	
	Maximum Water level	**Time to Peak flow**	**Maximum Water level**	**Time to Peak flow**
Primary outlet station No.2	0.5178	60 min	0.1235	75 min
Primary outlet station No.3	0.2487	35 min	0.099	55 min

The result in Table 4.11 present in Primary outlet station No.3 that ecological drainage system with subsurface module expect to reduce maximum water level by 60% in 20 minutes after the rain start and for Primary outlet station NO.2 reduce maximum water level by 76% in 15 minutes after the rain start (Benisi et al., 2016).

(b) Scenario 2

This scenario mainly focused on the concept of ecological swale with on-line subsurface conveyance system that is infiltration capacity. The calibrated model was used to evaluate the BIOECODS system in peak flow attenuation during the rain event, which details how the infiltration and peak flow attenuation behave from the time it started raining since the end of the event and emphasize on the contribution of subsurface conveyance system in flow attenuation. Due to this issue, the model was run for selected rainfall events. The sample of the simulated flow rate and water depth in both surface and subsurface conveyance system in the downstream for three rainfall events with small, medium and high intensity are presented in Figures 4.19, 4.20 and 4.21.

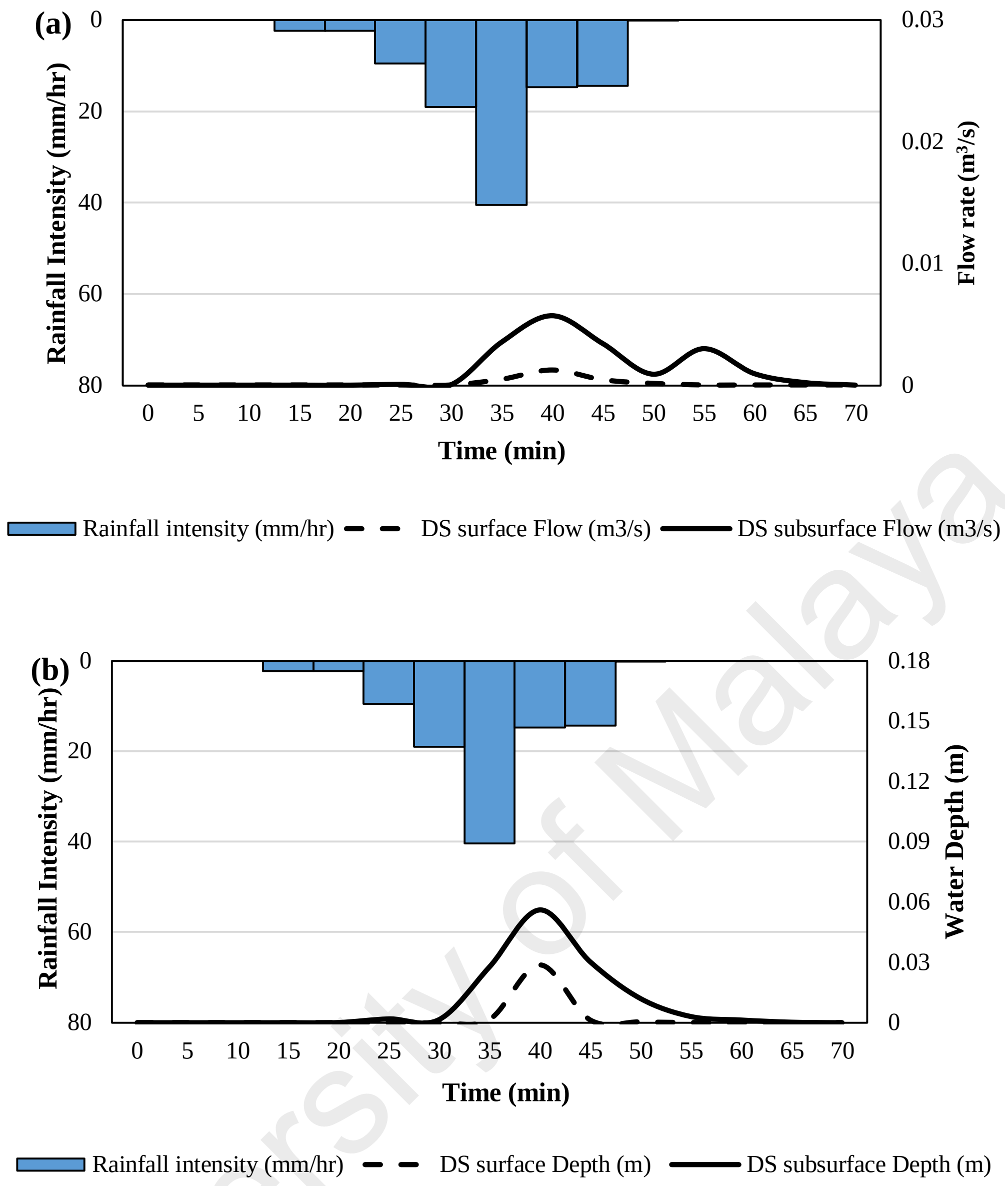
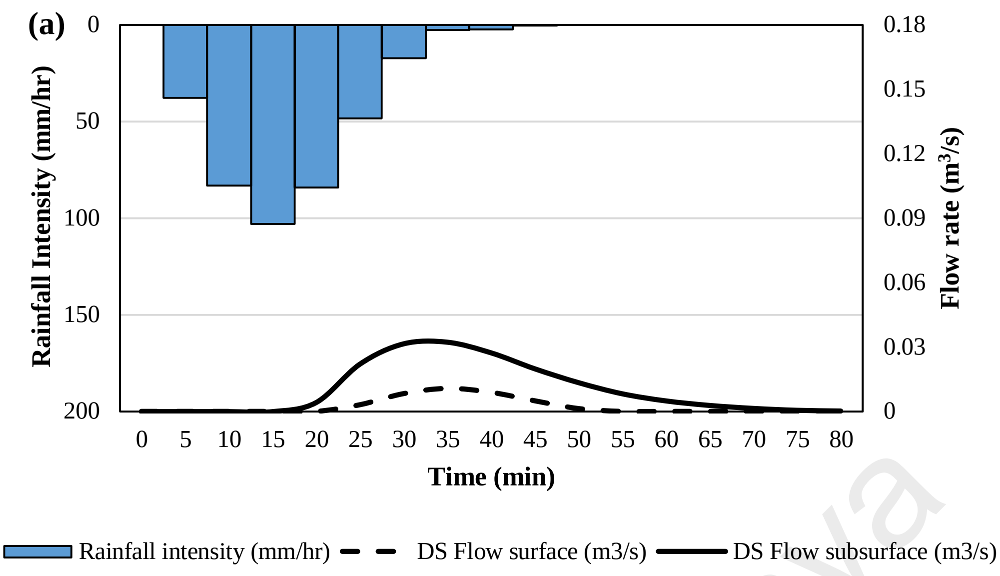


Figure 4.19: Simulated result for low intensity rainfall event No.6 (11/02/2014) in primary outlet monitoring station No.3: (a) Flow rate, (b) Water depth



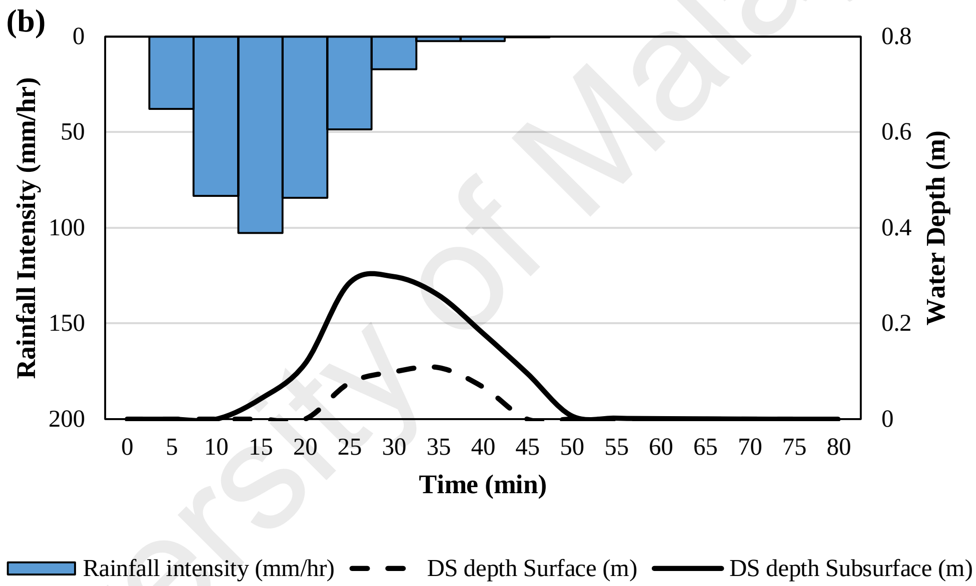
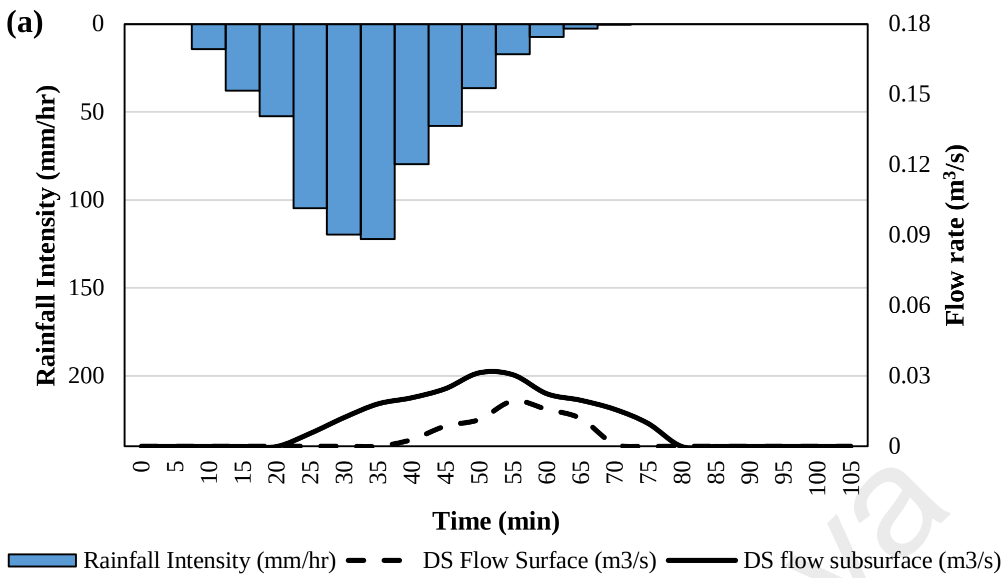


Figure 4.20: Simulated result for medium intensity rainfall event No.3 (23/11/2013) in primary outlet monitoring station No.3: (a) Flow rate, (b) Water depth



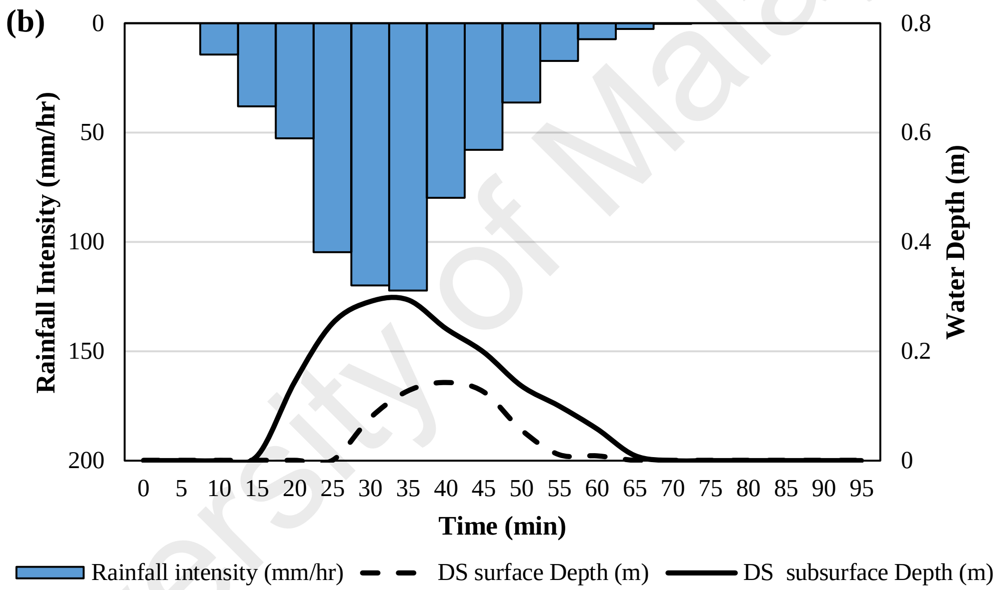


Figure 4.21: Simulated result for high intensity rainfall event No.5 (12/1/2014) in primary outlet monitoring station No.3: (a) Flow rate, (b) Water depth

From the presented figures it is obvious that in all rainfall events with similar patterns and site condition, subsurface conveyance system contribute more than the surface ecological grass swale in peak flow attenuation, due to the high rate of infiltration in ecological swales with on-line subsurface conveyance system through upstream to downstream.

A sample of the simulation result of the study area for the flow ratio ($Q_{Subsurface}/Q_{total}$) of subsurface flow was compared to total flow discharge in the station No.3, presented in Figure 4.22.

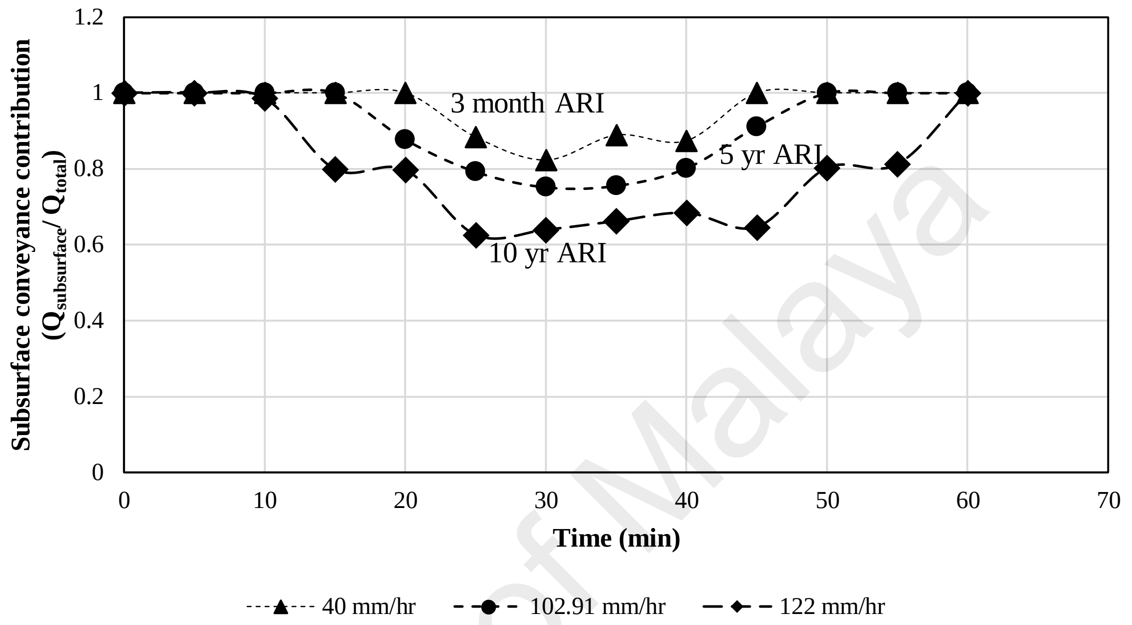


Figure 4.22: Subsurface flow ratio ($Q_{Subsurface}/Q_{total}$) during rainfall events with different intensity and patterns

Figure 4.22 pointed out that when the rainfall intensity increases, the ratio of the infiltration and exchange of water flow between surface drainage and subsurface conveyance system changes. This change depends on the pattern of the rainfall, infiltration capacity of soil, and land use.

As shown in Figures 4.19, 4.20, and 4.21, when the rain intensity increases, the exchange of water flow to the subsurface conveyance sharply decreases due to land wetness, along with the infiltration capacity, especially when the intensity is very low (Event No.6, 40 mm/hr), where approximately the received rain water will infiltrate the subsurface drainage system. This proves that the subsurface conveyance drainage system react differently to different intensities in reducing peak flow attenuation.

From the results, it is clear that small events (low intensity), merged grass swale with the subsurface conveyance system, reduces the peak flow by 82%, while medium events (medium intensity) is capable of reducing downstream peaks by 75-78%, and in heavy events (high intensity), the flow rates will be reduced by 62% (Benisi and Lai, 2016). The results showed that increasing ARI subsurface drainage system would decrease the contribution in flow attenuation, while decreasing the subsurface conveyance system in all these four events will never result in maximization, and based on this, the flow in the subsurface drainage system is regarded as an open channel. The results showed that this system is very effective in flow attenuation for different events for multiple patterns and intensity.

(c) Scenario 3

The next step in evaluating the effectiveness of ecological swale is to replace the observed rainfall data with the designed rainfall to evaluate of effectiveness of swale in different Annual Recurrence Interval (ARI). For this purpose, 5 different design rainfalls with ARI of 2, 5, 10, 20, 50, and 100 years are generated according to Stormwater Manual for Malaysia (DID, 2012) for the study area. Empirical equation used to minimize error in estimating the rainfall intensity values from the IDF curves Empirical equation (DID, 2012).

$$i = \frac{\lambda T^k}{(d + \theta)^\eta} \tag{4.1}$$

Where, i = Average rainfall intensity (mm/hr), T = Average recurrence interval – ARI ($0.5 \leq T \leq 12$ month and $2 \leq T \leq 100$ year), d = Storm duration (hours), $0.0833 \leq d \leq 72$, and λ, k, θ and η = fitting constants dependent on the rain gauge location.

It is important to emphasize that the rainfall temporal patterns are intended for use in the hydrograph generation design storms. Fitting constants for the IDF empirical equation and also the designed rainfall data presented in Table 4.12 and Table 4.13 respectively.

Table 4.12: Fitting constants for the IDF Empirical equation (DID, 2012)

State	No.	Station ID	Station Name	Constants			
				Λ	k	θ	ɳ
Perak	6	4807016	Bukit Larut Taiping	87.236	0.165	0.258	0.842

Table 4.13 Designed rainfall for study area

Rain Duration (hr)	**ARI**											
	2 year		**5 year**		**10 year**		**20 year**		**50 year**		**100 year**	
	i (m/hr)	**P (mm)**	**i (mm/hr)**	**P (mm)**	**i (mm/hr)**	**P (mm)**	**i (mm/hr)**	**P (mm)**	**i (mm/hr)**	**P (mm)**	**i (mm/hr)**	**P (mm)**
1	80.6	80.6	93.7	93.7	105.1	105.1	117.9	117.9	137.1	137.1	153.7	153.7
3	36.2	108.5	42.1	126.3	47.2	141.6	52.9	158.7	61.5	184.6	69	207
6	20.9	125.3	24.3	145.7	27.2	163.4	30.5	183.2	35.5	213.1	39.8	238.9
12	11.9	142.3	13.8	165.5	15.5	185.5	17.3	208	20.2	242	22.6	271.3
24	6.7	160.2	7.8	186.3	8.7	208.9	9.8	234.2	11.3	272.4	12.7	305.4

A sample of simulation result for the study area for the flow ratio for subsurface flow compare to total flow discharge ($Q_{Subsurface}/Q_{Total}$), in the Primary outlet monitoring station No.3 presented in the Figure 4.23.

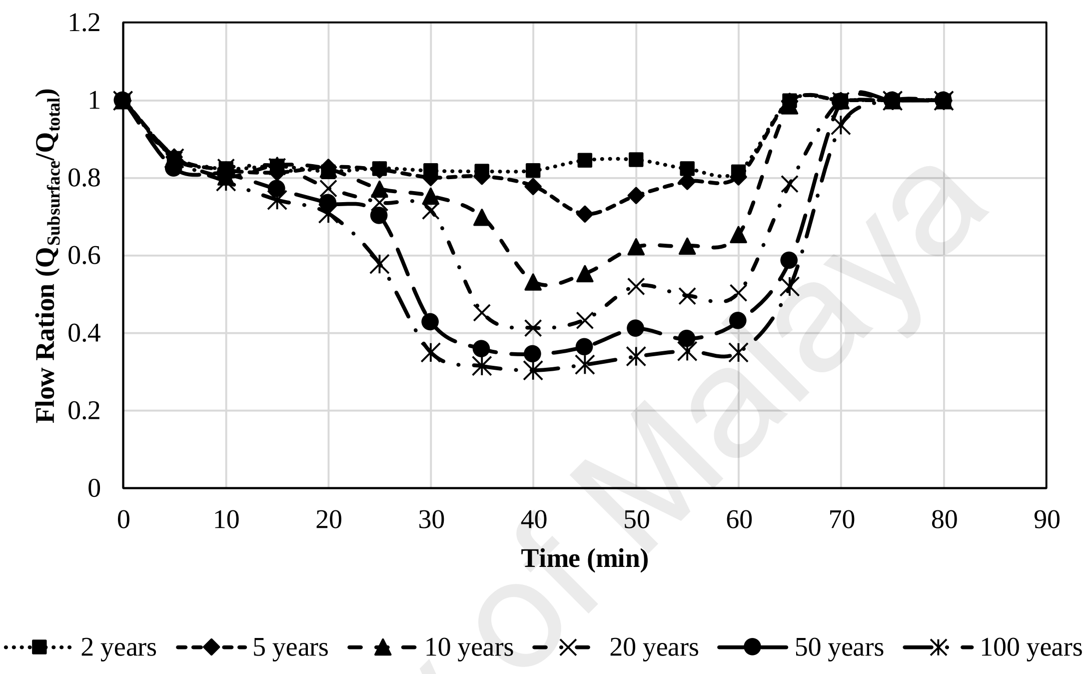


Figure 4.23: Subsurface flow ratio during 1 hour rainfall events with different ARI

The result from the graph presenting that after the rain finished (after 60 minutes), grass swale with online subsurface conveyance still have water flow and almost after 80 minutes from starting rain for rain event with 100 year ARI all the water transferred to subsurface conveyance system. The graph also presents that the lowest and greatest contribution between surface and subsurface flow belong to rainfall event with 100 year ARI and 2 years ARI respectively. The results for other rainfall events presented in following Figures:

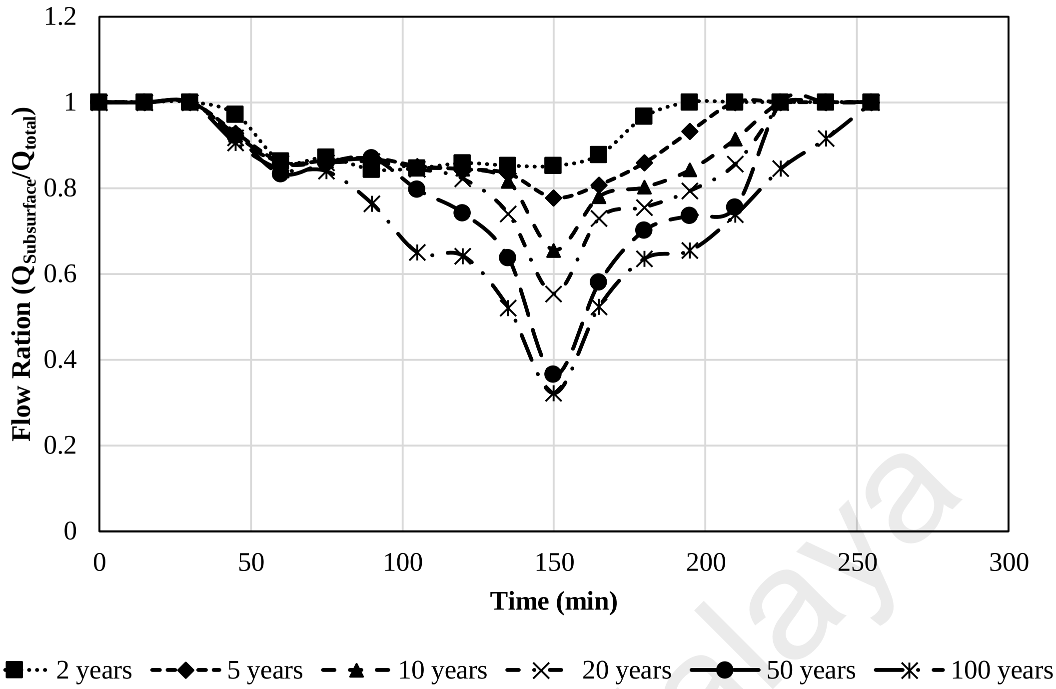


Figure 4.24: Subsurface flow ratio during 3 hours rainfall events with different ARI

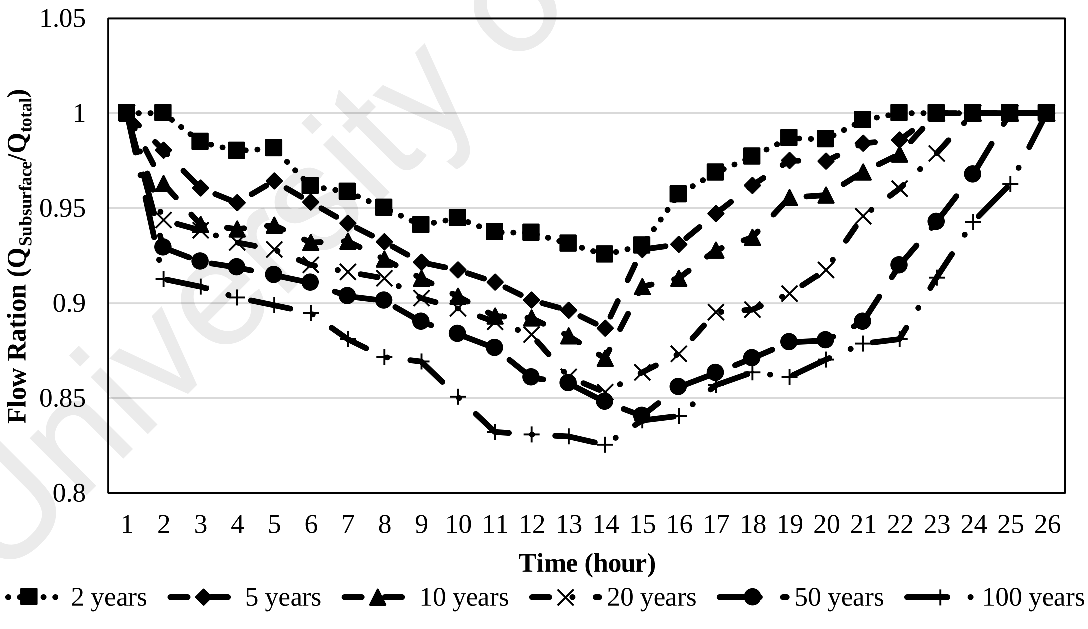


Figure 4.25: Subsurface flow ratio during 24 hours rainfall events with different ARI

As the average rainfall intensity reduce, in other word the rainfall duration increasing contribution of subsurface conveyance system in flow attenuation increasing significantly and all the rainwater due to high infiltration rate infiltrate to subsurface drainage system.

This shows how subsurface conveyance drainage system behaves in different intensities to reduce peak flow attenuation.

The results shows that with the increasing the ARI subsurface drainage system contribution in flow attenuation decreasing and subsurface conveyance system in all these events never became full and according to this matter flow in the subsurface drainage system consider as an open channel. These results demonstrate that this system is very effective in flow attenuation in different rainfall events by different patterns and intensity that presented in Figure 4.26.

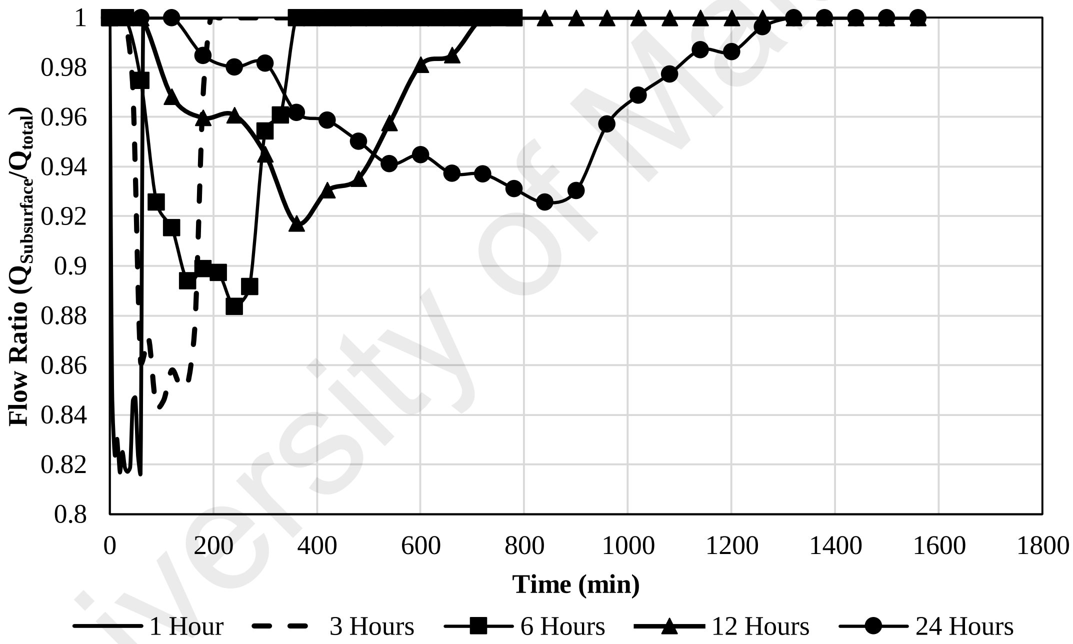


Figure 4.26: Subsurface flow ratio for rainfall events with 2 year ARI and different duration

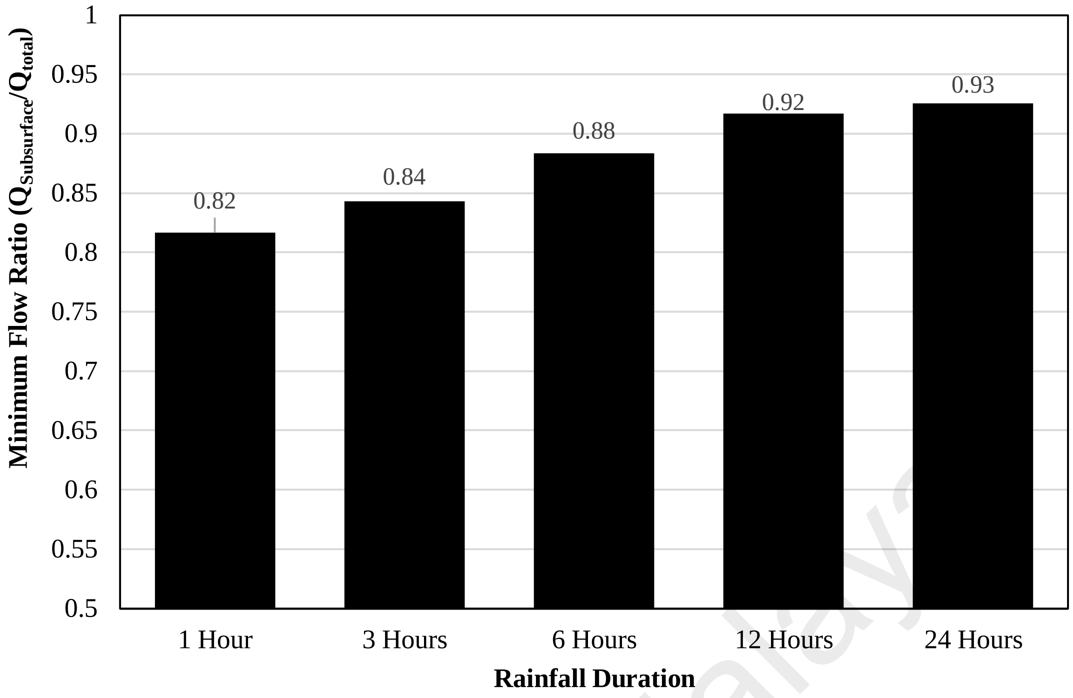


Figure 4.27: Minimum contribution of online subsurface conveyance system in different rainfall duration with 2 years ARI

(d) Scenario 4

This scenario developed to evaluate total system of BIOECODS with all constructed SUDS components and measure the effects of these components in retention pond that is last point before runoff reach to outlet. For this purpose the calibrated model is used to consider that scenario where the BIOECODS is replaced with a traditional drainage system consist of concrete drains and without any SUDS components of the same hydraulic and hydrologic parameters as the actual site condition and evaluate the effects in downstream which in this case is constructed retention pond.

Simulation was run for the study area with traditional drainage system. It reported that the flow rate and flow velocity for most of the drain were much higher (v up to 0.8 m/s, Q up to 0.1 m3/s) when compared with BIOECODS. This means that much bigger volume of runoff will reach the retention pond downstream. An overflow was found as expected on the floodplain region around the retention pond, with a maximum flood depth of 0.746 m.

The results show happening of flash flood in the node that present retention pond during the simulation. Flood depth according to simulation is more than 1.2 m, and flood volume is more than 9.74 m^3. The sample result for rainfall event number two (14/10/2013) presented in Figure 4.28.

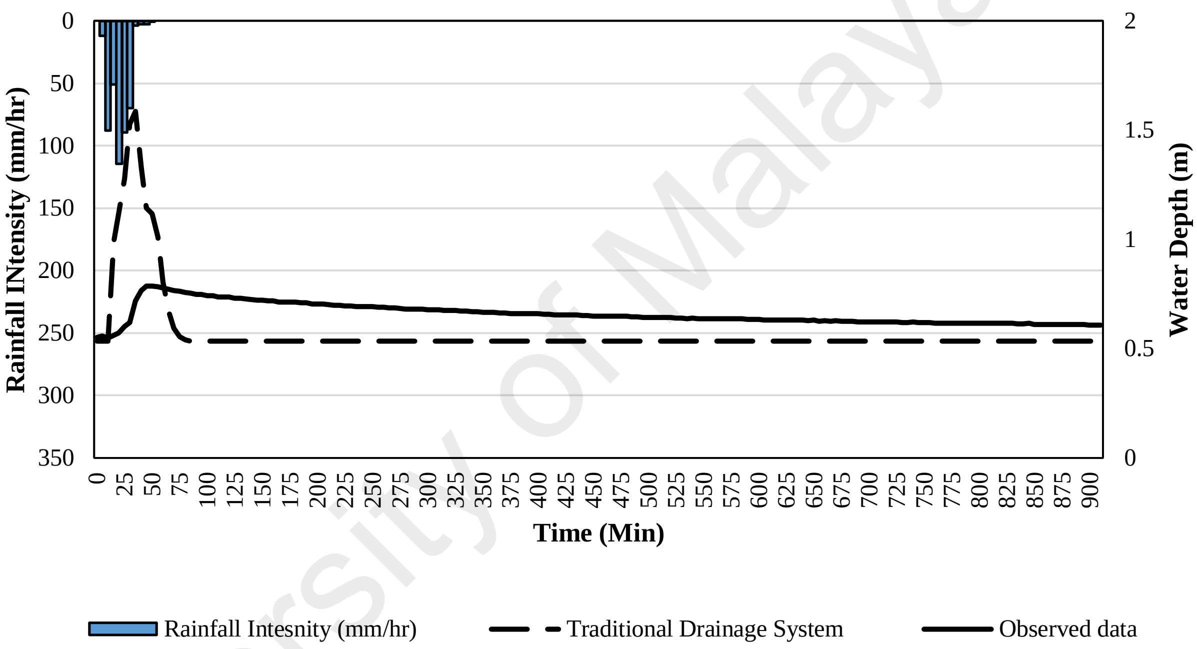


Figure 4.28: Comparison of modelled traditional drainage system and observed water level in downstream (retention pond) for rainfall event number two (14/10/2013)

The results indicated that the water level peak reduction in event number 6 (low intensity rainfall event) was more than 100% and in rainfall event number 5 (high intensity rainfall event), in rainfall event number 2 (medium intensity rainfall event), water level reduction was in range of ±60%-100%, and the delay time for event with medium intensity (event number 2), and high intensity event (event number 5) was ±15 minutes for a catchment area of 28000m^2.

(e) Scenario 5

This scenario developed to determine the optimum size for subsurface conveyance system and characteristics of subsurface flow during the rainfall event. For this purpose the calibrated model is used to consider that scenario with different size of subsurface conduit module and the compare it with flow ratio for the rainfall event 2 to determine the optimum size for subsurface conduit module. Furthermore, the optimum size was used to characterize the subsurface flow. The results for this scenario presented in below:

Table 4.14: Different size of subsurface conveyance system and the flow ratio for rainfall event 2

height (cm)	**Flow ratio**
65	0.630912
60	0.629875
55	0.628755
50	0.626538
45	0.625595
40	0.561341
35	0.497465
30	0.403649
20	0.247974

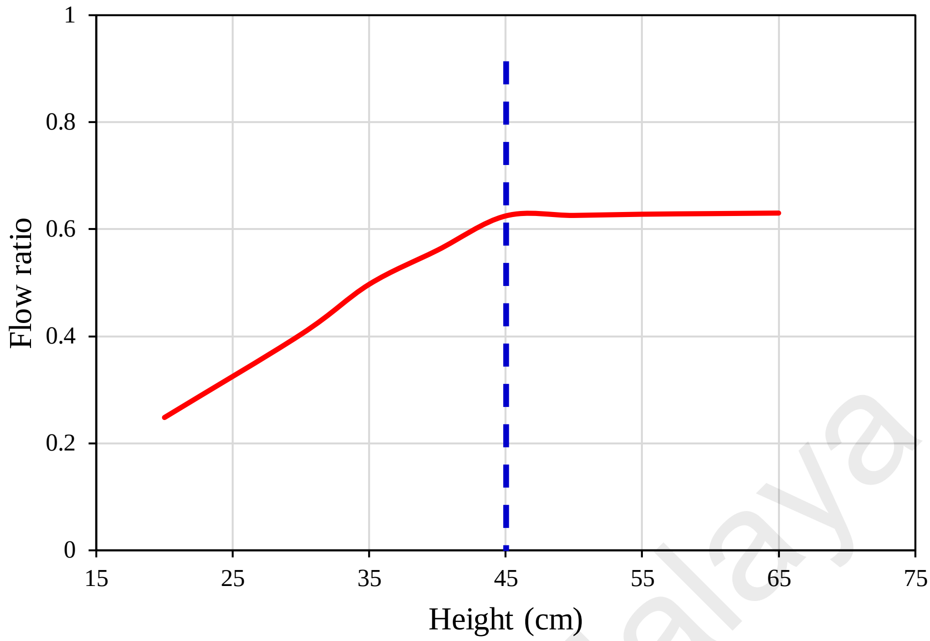


Figure 4.29: The determination of optimum size for subsurface conduit module for rainfall event 2

The results shows that the optimum size for subsurface conveyance system is the module with height of 45 cm, because increasing the size doesn't have significant effects on the flow ratio in subsurface drainage system.

For the next step, rainfall event with highest rainfall intensity (rainfall event 5) to investigate the characteristics of subsurface flow. The result for this achievement presented in Figure 4.30.

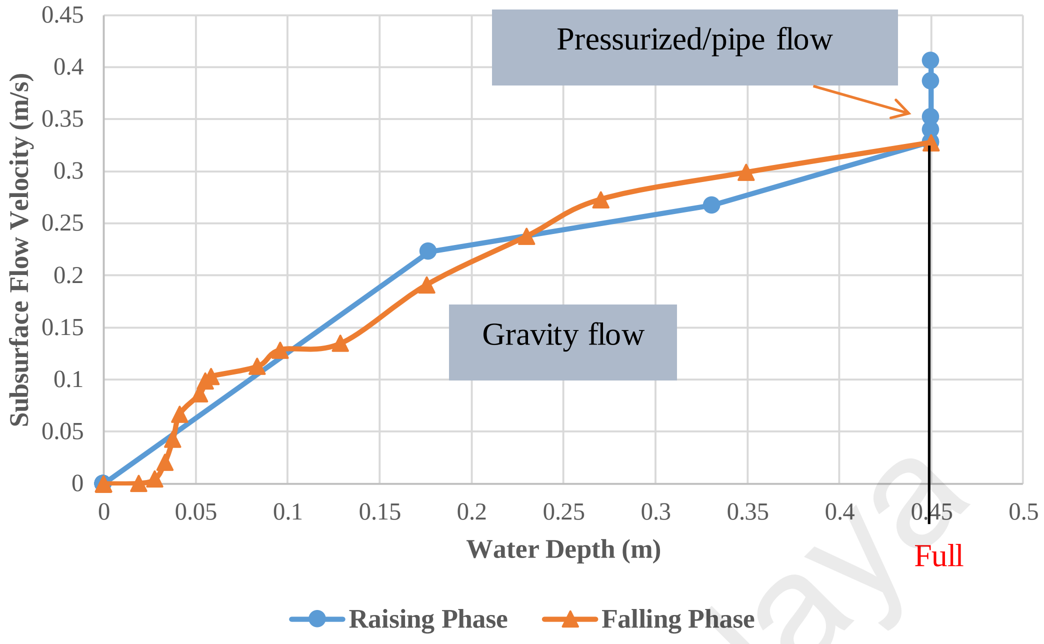


Figure 4.30: Flow characteristics for subsurface conveyance system for rainfall event 5

The result from the Figure 4.30 present that for the rainfall event 5, water level in the subsurface drainage component increase until it's become full and in that time speed of water in subsurface drainage system increase dramatically which present the pressurized or pipe flow and after the water reduce in subsurface the speed of flow decrease as well and behave as gravity flow.

The result present that the subsurface flow can behave as pressurize or pipe flow when it becomes full and when it has free surface behave as gravity flow.

4.10 Summary

This study based on the field study and the results from model simulation, it can be concluded that the SUDS components simulation in InfoWorks SD is able to successfully simulate the rainfall-runoff relationships for BIOECODS. It is able to predict water level in the study area with an average error of 5.66% for maximum water level, and 3.36% for water level fluctuation for total rainfall event. With the combination of various SUDS components such as dry detention, subsurface detention, and others in the study area, the results further strengthen the effectiveness of each SUDS components and BIOECODS drainage system in flow attenuation and delay the runoff that reach to water body. Through this study, the technique being utilized to define the surface and on-line subsurface conveyance system is proved successful to integrate the flow in both components and their interactions. Although to evaluate and emphasize on effectiveness of SUDS components and on the other hand BIOECODS system in small catchments different scenarios were developed and the presented results shown the effectiveness of this sustainable drainage system in different conditions in flow attenuation and stormwater management approaches.

CHAPTER 5: CONCLUSION AND RECOMMENDATION

5.1 Introduction

The innovative drainage system in this research is a Bio-ecological Drainage System (BIOECODS). The main components of BIOECODS system are grass swale (Ecological swale), Dry Detention (Dry ponds), retention pond (Wet pond) and etc. The novelty of this project is that the constructed grass swale coupled with on-line subsurface conveyance system with module tanks. The aim of this study is to develop a model that present surface and subsurface conveyance system simultaneously in single model platform and then evaluate the effectiveness of this system in aspect of water quantity in stormwater management.

A new technique was adopted for BIOECODS system to model surface and subsurface drainage system and constructed SUDS components. The presented results from developed model compared with the observed data that collected from different installed monitoring stations in the study area. Data collection can be divided into two parts, (i) monitoring stations, (ii) field study such as survey and infiltration test. All the collected data was used to develop a model with high accuracy, which is able to model the system compare to actual situation. The model is used for further advanced analysis such as:

- Developing different scenarios to evaluate the SUDS components
- Analyze the functionality of various SUDS components
- Model construction for BIOECODS system

This study shown that a computer simulation model for estimation rainfall-runoff response in urban area can be efficiently developed to provide important information for analyzing reductions of runoff and preventing flash flood in urban watershed area. Based on the obtained results in Chapter 4, the following conclusions can be drawn:

- The computer simulation model called InfoWorks SD, used for rainfall-runoff response analysis of urban drainage system (BIOECODS), has the ability to model surface and subsurface conveyance system in single system successfully.
- A new techniques that used to model both surface and on-line subsurface conveyance system in the urban area can simulate study area with high accuracy.
- The results shown the InfoWorks SD performed well in predicting the hydraulic and hydrological parameters with high accuracy.
- InfoWorks SD is an appropriate computer model to analyze, simulate, and evaluate the effectiveness of the BIOECODS drainage system components and in general BMP's components.
- The BIOECODS system and in general BMP's components in this study area are very effective in peak flow attenuation and flood control in small catchment such as study area.
- Grass swale with on-line subsurface conveyance system is very effective BMP component which is capable to decrease water level by 60%-70% and delay the peak flow between 10-20 min for different rainfall.
- The results indicate a peak water level reduction for the total catchment area of 28000m^2 of more than 100% during low intensity events, and in the range of ±60-100% for events of medium and high intensity. They also show that the lag time to peak for events of medium and high intensity were ±15 minutes.
- The model shows that ecological drainage system is very effective in terms of decreasing peak flow and improving the infiltration characteristic of an urban land. Also subsurface drainage module integrated with swale is able to cater a percentage of surface runoff volume approximately 60% to 76% for rainfall events.

5.2 Recommendation for future studies

As it mentioned before, needs a model that can analyze the impact of future climate and urban conditions is necessary for urban areas as population increase. This study used new techniques to model the SUDS components, which are widely used in developed and pre-developed areas. This study can be extending to other project same as BIOECODS system. The modelling effort in terms of quality and quantity of urban runoff could be used for entire world and all SUDS or BMP's components. Effort of this modelling can illustrate the new idea to the designing, planning, and strategies for preventing flash flood in urban areas with considering the increasing population in urban areas. In other hand, to ensure the SUDS system will work properly during rainfall events and evaluate the effectiveness of constructed projects.

Some of the recommendation for further studies mentioned below:

- Further exploring in simulation SUDS, in terms of quality that now a days play an important roles in control at source approaches.
- Using the validated and calibrated parameters form this study for developing a 2D model for SUDS components and compare 1D & 2D model in terms of accuracy, efficiency, and error.
- Using other software to simulate the SUDS components and comparison between these software to identify the most effective and accurate computer model.
- Using of this techniques in other projects with different conditions or climate.

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