BIORETENTION MODELLING USING MUSIC SOFTWARE FOR URBAN RUNOFF TREATMENT UNDER TROPICAL CLIMATE: A CASE STUDY IN UNIVERSITI SAINS MALAYSIA

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SCHOOL OF CIVIL ENGINEERING
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by

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ABSTRAK

Pencemaran air larian dan masalah banjir merupakan kebimbangan utama di kawasan bandar disebabkan oleh penambahan permukaan kedap dan aktiviti manusia. Amalan Pengurusan Terbaik untuk saliran air hujan seperti tanah bencah dan *bioretention* sudah diperkenalkan untuk menyelesaikan masalah tersebut dan aplikasi perisian model sudah dipergunakan untuk meramalkan prestasi kemudahan Amalan Pengurusan Terbaik bagi merawat air larian. Dalam projek ini, perisian MUSIC digunakan untuk memodelkan *bioretention* bagi rawatan air larian yang tercemar di kawasan bandar bawah iklim tropika. Disebabkan corak hujan di kawasan tropika yang sering dan lebat sepanjang tahun, proses hujan-aliran air dalam pemodelan akan dipengaruhi. Oleh itu, pengembangan templat meteorologi tempatan sangat penting untuk pemodelan. Model *bioretention* disimulasikan berdasarkan kajian rintis di Kampus Kejuruteraan, USM untuk menilai prestasi pengurangan kadar aliran dan pencemar seperti jumlah pepejal terampai (TSS), jumlah nitrogen (TN) dan jumlah fosforus (TP). Dua peringkat kalibrasi dilakukan dalam projek ini, iaitu peringkat pertama untuk mendapatkan aliran masuk yang sedekat mungkin dengan nilai yang diukur di lokasi perintis dan peringkat kedua untuk kalibrasi yang selanjut dengan menggunakan kombinasi pemalar kadar, k dan kepekatan latar belakang, C* bagi setiap pencemar yang sesuai dengan keputusan eksperimen. Pengesahan model dilakukan dengan menggunakan peratusan bias antara data model dan eksperimen untuk menilai ketepatan pemodelan *bioretention* mengunakan perisian MUSIC. Secara keseluruhan, prestasi model ini agak tepat kerana penilaian prestasi dikategorikan sebagai ‘sangaat baik’ atau ‘memuaskan’.

ABSTRACT

Stormwater runoff pollution and flood problem are the major concerns in urban area due to the increase of imperviousness surface and human activities. Stormwater Best Management Practices (BMPs) such as wetland and bioretention have been introduced to solve these problems and the modelling software has been developed to predict the treatment performance of those stormwater BMPs facilities. In this project, MUSIC software is used to model the bioretention to treat polluted runoff in urban area under tropical climate. Due to frequent and dense rainfall patterns in tropics throughout the year, the rainfall-runoff process will be affected in the modelling. Hence, development of local meteorological template is essential for the modelling in this study. The bioretention model is simulated based on a pilot study in USM, Engineering Campus to evaluate the flow rate and pollutants reduction performance such as total suspended solids (TSS), total nitrogen (TN) and total phosphorus (TP). Two stages of calibration were conducted, with first stage is to calibrate the inflow and runoff pollutant concentrations based on the results measured on site, and second stage to further calibrate rate constant, k and background concentration, C* combination for each pollutants which fit to experimental results. The validation of model was done using the percentage bias between modelled and experimental data to evaluate the accuracy of bioretention modelling using MUSIC software. Overall, the performance of this model is fairly accurate as the performance rating is categorized as 'very good' or 'satisfactory'.

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LIST OF SYMBOLS

C	Runoff Coefficient
C*	Background Concentration
C_{in}	Inflow Concentration
C_{out}	Outflow Concentration
E_{pan}	Pan Evaporation Data
K_p	Pan Coefficient
k	Rate Constant
Q_i^{obs}	Observed Values
Q_i^{sim}	Simulated Values
t	time

LIST OF ABBREVIATIONS

ARI	Annual Recurrence Interval
BMPs	Best Management Practices
BOD	Biochemical Oxygen Demand
COD	Chemical Oxygen Demand
CRCCH	Cooperative Research Centre for Catchment Hydrology.
CSTR	Continuous Stirred Tank Reactor
DID	Department of Irrigation and Drainage Malaysia
EIA	Effective Impervious Area
EMC	Event Mean Concentration
HEC-HMS	Hydrologic Engineering Center, Hydrologic Modeling System
MSMA	Manual Saliran Mesra Alam (Urban Stormwater Management Manual)
MUSIC	Model for Urban Storm Water Improvement Conceptualism
N	Nitrogen
NH_4^+	Ammonium
NH_4^+	Nitrate
NSE	Nach-Sutcliffe Efficiency
P	Phosphorus
PBIAS	Percentage Bias
PET	Potential Evapotranspiration data
RMSE	Root Mean Square Error
RSR	Root mean square error-observations Standard deviation Ratio
SD	Standard Deviation
SWMM	Storm Water Management Model
TIDEDA	Time Dependent Data Processing System
TN	Total Nitrogen
TP	Total Phosphorus
TSS	Total Suspended Solids
.TXT	Tab-delimited Text
USEPA	United State Environmental Protection Agency
USM	Universiti Sains Malaysia
USTM	Universal Stormwater Treatment Model

WinSLAMM	Source Loading and Management Model for Windows
WBM	Water Balance Model
WQV	Water Quality Volume
WSUD	Water Sensitive Urban Design

CHAPTER 1

INTRODUCTION

1.1 Background

Urbanisation brings negative effects to the balance of the water cycle due to the increase of the imperviousness surface. Nevertheless, the pollutants in the runoff will be transported to the water bodies in downstream and deteriorate the receiving water body. Stormwater Best Management Practices (BMPs) has been introduced since 1970s to transform conventional water quality control devices from the engineering-based approach to nature-based in water quality and quantity control (Zakaria et al., 2003). Bioretention or rain garden is one of the stormwater BMPs which can minimize the pollutants and control the flow of stormwater in a more sustainable way.

Bioretention is a shallow landscaped depression which consists of filter media, vegetation, subsoils and overflow structure. It plays an important role in treating and controlling stormwater runoff. The selection of filter media, vegetation and subsoils is important as it will affect the performance of bioretention (Austin, 2012). Bioretention research was carried out in the United States at the beginning stage since 2000 and was rapidly done in Australia to evaluate the performance of bioretention (Spraakman et al., 2020). These research has proven bioretention can control stormwater and remove the pollutants effectively.

The performance on flow reduction and pollutants removal of bioretention are normally reflected by the results from both laboratory and field studies. However, it is difficult to study a complete bioretention system due to the restriction of land use (Spraakman et al., 2020). Moreover, it takes a longer time to determine the long term performance of bioretention and it is costly to have more varieties of water qualities for laboratory tests. Hence, the modelling software or simulation can be used to solve those limitations from the field-based study. The simulation models can predict the water quality or quantity of the treated runoff at the bioretention site. Modelling through software leads to the implementation of bioretention getting more popular due to the ease of predicting the performance of bioretention.

The common modelling software includes Model for Urban Storm Water Improvement Conceptualism (MUSIC), One-dimensional Richards equation model (HYDRUS-1D), Storm Water Management Model (SWMM) and HEC-HMS (Hydrologic Engineering Center, Hydrologic Modeling System). In this project, MUSIC as a conceptual modelling software is chosen to model bioretention for urban runoff under tropical climate. This is because MUSIC software able to model both water quality and quantity for a complete treatment train without complicated data input (Imteaz et al., 2013). Although MUSIC is more widely used in Australia, it has the potential to be used for bioretention (or other BMPs devices) modelling in tropical countries such as Malaysia (Elyza Muha et al., 2016).

1.2 Problem Statement

MUSIC is used as a decision-making tool and it can evaluate treatment performance of BMPs devices such as bioretention, wetlands, buffer strips, swale and Gross Pollutant Traps. The simulation of MUSIC is based on the risk-based approach associated with the hydrology effect such as the rainfall events. Therefore, meteorological data is important for the routing in MUSIC software. Although there is some meteorological data template provided for being used in MUSIC software, the provided meteorological data and evapotranspiration data were originated from various cities of Australia, such as Melbourne and Brisbane, and it may not suitable to be used in tropics. This is because the average rainfall intensity of tropical countries is relatively higher than temperate countries. Therefore, developing a local meteorological template is important to obtain more accurate analysis. MUSIC allows users to import local meteorological data for being used as the meteorological template.

In MUSIC, the selection of source node is important as it represents the runoff needed to be modelled. For the urban runoff generation, the default values adopted in MUSIC modelling are based on the calibration of the model to typical urban catchments in Australia (eWater, 2013). Hence, the calibration is needed to be done based on local condition since the urban runoff characteristics is different due to the rainfall patterns, seasons, land use, and the level of development (Goh et al., 2019). Error prediction of the size of bioretention and other parameters for the design of bioretention bring negative effects during the research. Therefore, the accuracy of modelling using the software need to be evaluated, especially in the preliminary design stage via the calibration based on the local condition.

1.3 Objectives

The objectives of this study are:

1) To develop local meteorological template for MUSIC Software using local meteorological data.

2) To evaluate the accuracy of MUSIC model for bioretention system application in tropics.

1.4 Scope of Study

This study compares the performance of bioretention towards the water quality and quantity from urban runoff based on the laboratory result from pilot site and modelling result from MUSIC. The pilot site is located at Universiti Sains Malaysia (USM), Engineering Campus. The polluted runoff is collected from main drains in Parit Buntar. The water sampling result from inflow and outflow of the bioretention site are taken as secondary data. Meteorological data includes hourly rainfall data from Bagan Serai Rainfall Station and estimation of potential evapotranspiration data (PET) from Bayan Lepas Station are required for the creation of climate template. Calibration of rate constant, k and background concentration, C^* values will be done for each pollutants. Also, validation will be done based on the experimental value. The results of flow reduction and of pollutants removal rate obtained from MUSIC will be discussed together with laboratory result in this study. The water quality parameter includes total suspended solids (TSS), total phosphorus (TP) and total nitrogen (TN).

1.5 Significant of Study

One of the benefits from this research project is to determine the readiness of MUSIC software to be used to estimate performance of bioretention system in tropics based on pilot site study. Bioretention modelling using MUSIC software is studied by developing local meteorological template. This project may help to have more understanding about the calibration done for the modelling bioretention. It will also help to guide the development of stormwater BMP’s facilities in the future study. Bioretention is one of stormwater BMP's facilities that has potential and is a more sustainable solutions for runoff pollution control and can be implemented widely in the tropical country through the aids of modelling software.

1.6 Organisation of Dissertation

This dissertation illustrates the introduction to research, literature review, as well as the methodology adopted for this study. It also presents the modelling results, discussion, conclusions, and recommendation. There are five chapters included in this dissertation: Introduction, Literature Review, Methodology, Results and Discussion, as well as Conclusions and Recommendations.

Chapter One included research study background, problem statement, objectives to be achieved in this study, scope of study and significance of study. Chapter Two focused on the literature review of bioretention and its application, design criteria, water quality and quantity control, review of modelling software for bioretention and also the application of MUSIC software for bioretention. Chapter Three illustrated the method of modelling the bioretention based on pilot site study using MUSIC 6 software. This chapter explained the methods used to create the meteorological template, develop the bioretention model and run the analysis. The presentation of local meteorological data's creation and results of modelling were illustrated in Chapter Four. A detailed discussion of the modelling result based on validation of laboratory tests was included in this chapter. In Chapter Five, conclusions has been made throughout this research study, along with recommendations for further research work. The suitability of MUSIC software using for bioretention modelling in tropical climate was concluded.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Urbanisation can be defined as the development of residential, commercial and industrial areas as there is an increase of human population by 60% in 2050 (United Nations, 2015). Urbanisation causes large vegetated areas converting into impervious areas, such as roads, car parks, roof and other paved surfaces (Mangangka, 2013). Thus, natural water cycle behaviour has been changed and this brings negative impacts to surface runoff in term of water quality and quantity. Also, the climate change issue contributes to the problems such as rising sea levels, increasing of runoff (Miller and Russell, 1992) and urban flooding. In addition, the increase of pollutants runoff due to human activities such as farming and the leaching of agriculture will contaminant the receiving water bodies. According to Osman et al. (2019), water pollution is a major challenge that will deteriorate our environment.

2.1.1 Stormwater Runoff Characteristics

Stormwater runoff is one of the nonpoint source pollution (Osman et al., 2019) consists of suspended solids, nutrients, organic compounds, heavy metals, pathogens, debris, trash and floatable materials (Akan, 1993). Duncan (1999) evaluated the concentration of typical pollutants such as TSS, TP and TN based on different land use as shown in Figure 2.1- 2.3. The range of concentration for those pollutants were represented in black region of bar charts. Those different values have shown that the pollutants concentration and load can be affected by land use. According to Austin (2012), the types of land use contributing high concentration of stormwater runoff include lawn, commercial streets, parking lots, highways and industrial land. However, Osman (2019) mentioned that agricultural lands contribute to more load of sediment and nutrients especially nitrogen. This has corresponded with Goh et al. (2019)'s review which is the concentration of TSS, TP and TN, in average is the highest found in agricultural lands.

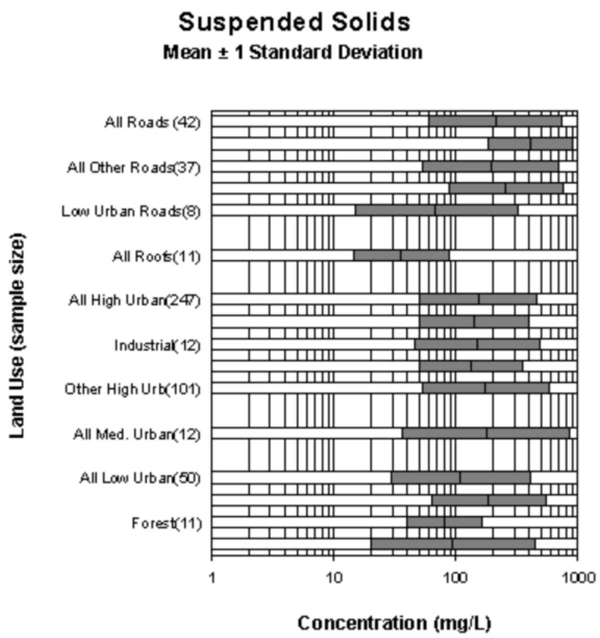

Figure 2.1: Total Suspended Solids Concentrations vs. Land-use (Duncan, 1999)

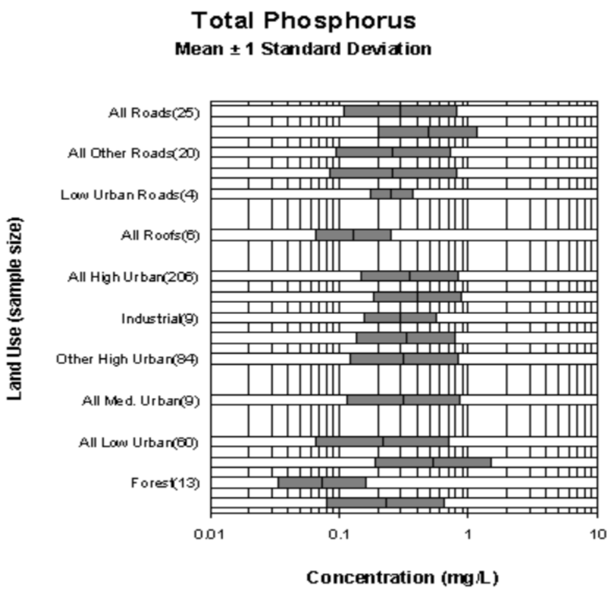

Figure 2.2: Total Phosphorus Concentrations vs. Land-use (Duncan, 1999)

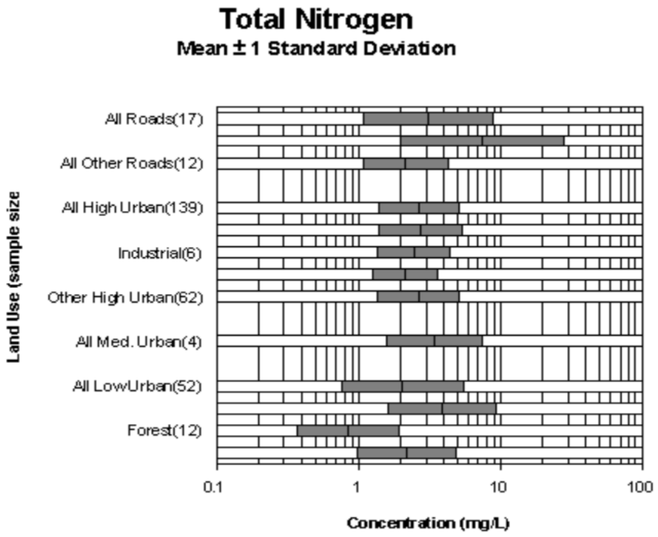

Figure 2.3: Total Nitrogen Concentrations vs. Land-use (Duncan, 1999)

Urban runoff characteristics are different among countries due to the differences in the level of development, land use, soil properties and rainfall pattern. Compared to temperate countries such as Australia and USA, Malaysia is a tropical country which has intense and frequent rainfall throughout a whole year. As a result, low event mean concentration (EMC) and weak first flush has caused low pollutant removal rate (Wang et al., 2017). The level of development also affects the runoff characteristics within same climate region. In stormwater runoff, the most common nutrients are nitrogen and phosphorus. Those nutrients are mainly from farming, soil erosion, fuel combustion and ash from bushfires (Mangangka, 2013). The farming activities in developing countries such as China and Malaysia are in larger scale compared to developed countries' which has caused the concentration of runoff pollutants especially nutrients in developing countries is higher than in developed countries. As reported by Chow and Yusop (2014), the average concentration of pollutants in Malaysia such as TSS, TN and TP are 204 ± 182mg/L, 3.0 ± 1.2mg/L and 0.9 ± 0.2 mg/L respectively, which are higher than developed countries. According to Lucke (2018), the concentration of TSS (36.5–54.4 mg/L), TN (1.36–1.57 mg/L), and TP (0.21– 0.34 mg/L) in Australia is lower.

2.1.2 Stormwater Best Management Practices (BMPs)

Stormwater Best Management Practices (BMPs) have been implemented in urban stormwater management to restore predevelopment of hydrologic behaviour. Stormwater management can be divided into two parts, stormwater quality control and stormwater quantity control. Hence, stormwater BMPs can be considered as sustainable innovations to solve the urban flooding and runoff pollution.

The example of BMPs' facilities practised in stormwater management are gross pollutant traps, grass swales, filter strips, infiltration systems, sedimentation basins, wetlands and bioretention basins. A treatment train can be proposed with different combination of BMPs' facilities to achieve best cost-effective solutions, depends on the target pollutants found in stormwater runoff according to particle size. The performance of different facilities are closely related to the particle size range of pollutants (Wong et al., 2000). Correlation between stormwater pollutants' physical size, apporiate treatment facilities and suitable hydraulic loading are presented in Figure 2.4.

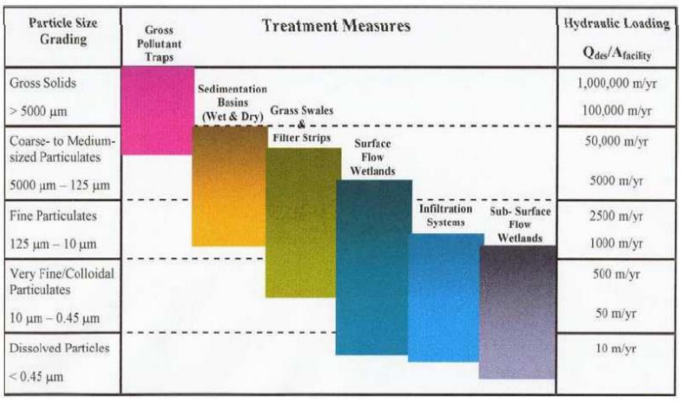

Figure 2.4: Typical Stormwater Treatment Measures, Target Pollutant Size and Hydraulic Loading (Wong, 2000)

In Malaysia, all design of stormwater BMPs' facilities including bioretention shall comply with Urban Storm water Management Manual for Malaysia (DID, 2012). According to MSMA second edition, a specified minimum overall percentage removal efficiency should be achieved for a new development area. Figure 2.5 shows the percentage pollutant reduction targets for different pollutants.

Pollutant	Reduction Targets (%)
Floatables/Litters	90
Total Suspended Solids (TSS)	80
Total Nitrogen (TN)	50
Total Phosphorus (TP)	50

Figure 2.5: Pollutants Reduction Target Based on MSMA (DID, 2012)

2.2 Bioretention

Bioretention (also referred to as rain gardens, stormwater biofilters, or bioinfiltration systems) is the landscaped depression which can cater runoff from the catchment especially from an impervious surface (Shafique, 2016). Typically, bioretention consists of engineered filter zone which includes layered soil planted with vegetation and a ponding area that allows temporary storage of excess runoff (Spraakman et al., 2020). In early 1990's, Bioretention, as one of BMP's measures, was developed by the Prince George's Country, MD, Department of Environmental Resources (PGC, 2007). The implementation of bioretention can help to replicate pre-development hydrology through the reduction of peak flow and the treatment to remove the pollutants (Wang et. al., 2017). Bioretention was firstly implemented by some developing countries such as U.S.A, Australia or New Zealand but it is getting more popular in tropical countries in these recent years. Compared to other stormwater BMPs, bioretention is commonly implemented in urban areas since it requires small spaces with smaller design annual recurrence interval (ARI) and is more flexible in the design (DID, 2012; Tirpak, 2021). It can easily fit the existing urban areas such as parking lots or housing areas, enhancing aesthetics value of urban landscape.

2.2.1 Design Criteria of Bioretention

Bioretention can be designed in different sizes depend on the catchment area, rainfall intensity and set goal of performance that is needed to achieve (Austin, 2012*)*. Normally, bioretention is made up of several layers that include vegetation, mulch layer, filter media, transition layer, and drainage layer. Those layers have their own functions as shown in Figure 2.6. These few elements can be factors that affect the performance of bioretention. Hydrologic performance of bioretention can be directly affected by bioretention components such as filter media and underdrain. Based on Spraakman et al. (2020), components that affect biological or ecological performance of bioretention such as selection of vegetation and plant species name were seldom described in more detail compared to other components.

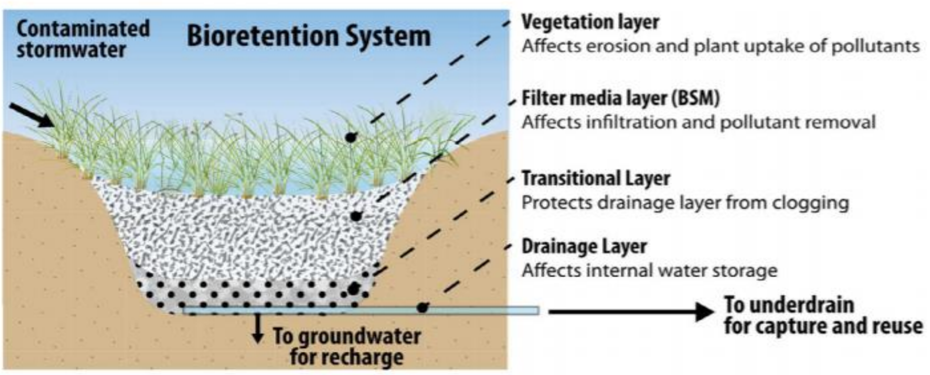

Figure 2.6: Typical Cross Section of Bioretention with Different Layers (Tirpak et al., 2021)

2.2.1(a) Bain/Ponding Area

Appropriate ponding area for bioretention design allows the space for the growth of plants and ensure the storage of stormwater runoff before filtration through the subsoils. Based on the design guidelines from United States Environment Protection Agency (USEPA), the suggested ponding area of bioretention is around 5–7% of the catchment area contributing to runoff multiplied by runoff coefficient, C with maximum ponding depth of 150mm (USEPA, 1999). According to Bratieres et al. (2008), the area of bioretention should be maximised relative with its catchment area to enhance the removal rate of both nitrogen and phosphorus. The authors further concluded that the larger bioretention should be required for regions which have high rainfall intensity such as tropics to treat high proportion of runoff. Based on MSMA (DID, 2012), the suggested ponding area should be adequate for 40mm of design storm in achieve stormwater quality control with chosen of 24 hours drain time to capture the runoff limited to 1.0 Ha of impervious area. The ponding depth is recommended in the range of 150mm to 300mm with maximum additional of freeboard. The selection of ponding area should allow the storage of stormwater in bioretention but prevent standing of water for long periods.

2.2.1(b) Mulch Layer

The mulch layer is an additional layer placed above the soil layer to provide several functions. In general, mulch layer consists of fine shredded hardwood mulch or shredded hardwood chips. It promotes the growth of microorganism, filters the pollutants and maintains the moisture and prevents the erosion (USEPA, 1999). Austin (2012) recommended that mulch layer should be 3 inches (76.2 cm) to 4 inches (101.6 cm). The recommended depth of mulch layer according to USEPA (1999) is 2 inches to 3 inches to protect from erosion. Based on MSMA (DID, 2012), the depth of mulch layer should in the range of 50mm to 100mm. However, mulch is not recommended by Payne et al. (2015) because it causes the clogging problem and exhibits the sediment removal. From the North Carolina studies with 125 bioretention configuration, Hunt (2008) found that mulch should be avoided in bioretention design as it will increase the total phosphorus in the effluent. Also, Goh et al. (2019) suggested the mulch layer in bioretention can be omitted in tropics since the frequent and intense rainfall is enough to keep moisture for the growth of plants.

2.2.1(c) Filter Media Layer

Selection of filter media in terms of depth, composition and pH is crucial in bioretention design as it will affect the performance of bioretention. The major design parameter in controlling water quality is the depth of media layer. Liu et al. (2014) suggested that the deeper media depth, the better hydrological performance. The recommended total depth of soil media is in the range of 450mm to 2000mm for adequate filtration capacity (DID, 2012). Based on USEPA's (1999) guidelines, the soil depth of 1200mm is enough to maintain moisture capacity for the plants. Meng et al. (2014) reported the depth of filter media in the range 300mm to 900mm is suitable in China by the consideration of connecting the underdrains with the municipal stormwater sewer.

In terms of filter media composition, the bioretention ideally consists of sand (50%-60%) and mix of loam/sandy loam/loamy sand (40% -50%) (Liu et al., 2014). Loamy sand and sandy loam was recommended as it allows the retention and promotes the growth of plants Meng et al. (2014). In order to promote the adsorption of pollutants, the soil media consisting of 50% sand, 30% topsoil and 20% organic material was recommended by Prince George's County (2007). Based on MSMA (DID, 2012), the recommended filter media composition includes 20%-25% top soil (sandy/silt loam), 50%-60% of medium sand and 12%-20% organic leaf compost.

Besides that, pH is also considered as a parameter for the selection of filter media as the microbial activities and the absorption of plants to remove pollutants are sensitive to the pH. The pH of soil media should be in the range of 5.5-6.5 (USEPA, 1999; DID, 2012). In short, the selection of appropriate filter media is important in bioretention design and it was emphasized by Mangangka et al. (2015) as it may cause nutrient leaching, affecting the pollutant removal rate.

2.2.1(d) Transition Layer

Transition layer is the layer between filter media layer and drainage layer. The transition layer is recommended if the fine gravel is used for drainage layer. The installation of transition layer is to prevent the fine particle migrating from filter layer to drainage layer. Typically, the transition layer is made up of 100 mm -150 mm thick of sand (DID, 2012). From the study carried out by Yang et al. (2020), the filter materials with particle size of range 0.16 – 0.63mm tended to moved down. The study revealed transition layer with 100mm of coarse sand can prevent the losing of filler in the filter layer. The specific particle size for materials used in transition layer is mentioned as Table 2.1 below.

Table 2.1: Typical Particle Size Distribution for Transition Layer (Moreton Bay Waterways & Catchments Patnership, 2006)

Particle Size (mm)	Passing (%)
1.4	100
1.0	80
0.7	44
0.5	8.4

2.2.1(e) Drainage Layer

Drainage Layer is important to carry treated water from the base of media into collection pipe or infiltrate into surrounding soils. It provides the pore space to store water temporarily with its high porosity (Payne at el., 2015). According to MSMA , the thickness of the drainage layer is normally 200mm to 400mm (DID, 2012). Basically, the drainage layer consists of perforated underdrains surrounded by either 1 mm of coarse sand or 2-5 mm of fine gravel (Moreton Bay Waterways & Catchment Partnership, 2006).

2.2.1(f) Vegetation

Vegetation is one of major component for a bioretention design. Microbial action and plant uptake normally take place in the treatment process of runoff due to the presence of the vegetation (Liu et al., 2014). The most significant role of selected plants in bioretention design is to replicate the natural ecosystem which can control peak flow and treat pollutant. Column studies conducted by Bratieres et al. (2008) showed that vegetated columns especially *C. appressa* and *M. ericifolia* have better performance in nutrients removal compared to non-vegetated columns. Also, the selection of vegetation can be done based on aesthetics value, site layout and maintenance and the arrangement can be in irregular interval to mimic a natural plant growth condition (USEPA, 1999).

2.3 Stormwater Runoff Treatment Using Bioretention

Treatment performance of a bioretention can be evaluated in terms of quantity and quality treatment. There are two important criteria in quantity treatment, which are the reduction in peak flow and the reduction in runoff volume. According to Mangangka (2013), peak flow reduction helps to protect the ecosystem at the downstream waterways because peak flow can causes hydraulic pressure and physical disturbance to the aquatic life.

For water quality treatment, the reduction of pollutant concentration or pollutant loading are used as terms to evaluate the bioretention performance. Besides the hydraulic factors such as inflow and outflow parameter of bioretention, the water quality treatment performance of bioretention is also affected by hydrologic factors such as rainfall characteristics (Mangangka et al., 2015).

Several studies have focused on pollutant reduction especially nutrients such as nitrogen and phosphorus because excessive of nutrients in stormwater runoff may lead to eutrophication which deteleriotes the receiving water bodies (Skorobogatov et al., 2020). Based on Wang et al. (2017), the required pollutants removal rate of bioretention are 80-92% of TSS, 30-90% of TP, 30% -65% of TN in various parts of world. Figure 2.7 below shows bioretention has good performance in removing pollutant especially suspended solid and nutrients. Liu et al. (2014) stated that the performance of bioretention can be affected by the clogging problem due to the large quantities of sediment because of the decrease of surface infiltration rate. Hence, maintenance of bioretention is important to maintain the long-term performance of bioretention.

BMPs Type	Pollutant Removal Efficiency			Other factors			
	Gross Pollutants	TSS	Nutrient (TN & TP)	Maintenance	Land Required	Treatable Catchment Area	Cost
Infiltration	Low	High	High	Medium	High	Medium	Low
Bioretention	Low	High	High	Low	Medium	Medium	Medium
Swale	Low	Medium	Medium	Low	Low	Low	Low
GPT	High	Low	No	Medium	Medium	Medium	Medium
Water Quality Pond	Medium	Medium	Medium	Medium	High	High	High
Wetlands	Medium	High	High	High	Medium	High	High

Figure 2.7: Selection of BMPs for Various Pollutants (Melbourne Water, 2005)

2.3.1 Stormwater Quantity Control Mechanism

Stormwater quantity control using bioretention can be attributed via two processes which are exfiltration and evapotranspiration. Both processes play vital roles in reducing the runoff and allowing enough groundwater to discharge. Up to 31% of stormwater runoff is discharged through exfiltration, whereas up to 19% of stormwater runoff is discharged through evapotranspiration (Liu et al., 2014). Exfiltration happens when the bioretention is designed in unlined condition as the runoff can be lost to surrounding soils and flows to the groundwater table.

Meng et al. (2014) found that evapotranspiration played a crucial role in the hydrology performance of bioretention because plant evapotranspiration during interstorm periods provided a larger available soil water storage capacity. However, there was only 8% of bioretention studies reported about the evapotranspiration rate (Spraakman et al., 2020). This indicates that evapotranspiration process was always omitted in the past bioretention study compared to infiltration. He also mentioned that the evapotranspiration can be measured via weighing lysimeter or estimated via evapotranspiration models. Skorobogatov et al. (2020) emphasizes that the evapotranspiration process can be interpreted by having more understanding about plant-media interaction.

2.3.2 Stormwater Quality Control Mechanism

As mentioned previously, one of the functions of bioretention is to control the quality stormwater by treating the pollutants. The stormwater quality control can refer to the pollutant removal using bioretention through biological, chemical and physical process. Bioretention can treat the pollutants by several mechanisms such as filtration, adsorption, denitrification and plant uptake. The mechanisms to be discussed in this section focused on the removal of total suspended solids (TSS), nitrogen (N) and phosphorus (P).

The removal of TSS is always the main concern and closely associated with the other pollutants such as nutrients, hydrocarbon and metals due to the ability of TSS to adsorb such pollutants (Mangangka, 2013). Settling and filtration process help to capture TSS and the removal of those pollutant can be done through sedimentation in the bioretention media. Longer filtration time due to the increase of rainfall duration enhances the retention of particulate matter and results in an increased TSS removal rate (He Qiumei et al., 2020). As the result, it also improves the removal rate of P and N through filtration under same condition.

In stormwater, TN can be found in various form such as ammonium (NH_4^+) and nitrate (NO_3^-) and the concentration of TN effluent was mainly affected by NO_3^- (He K. et al, 2020). The mechanism of TN removal is more complex and it involves ammonification, volatilization, nitrification, denitrification, and vegetative uptake (Bratieres, 2008). Ammonification is the conversion process to break organic N chemicals into ammonium whereas the loss of ammonia in bioretention systems is via volatilization process. (Liu et al., 2014).

The main processes for the removal of P involved in bioretention are precipitation, adsorption, filtration, and vegetation uptake. Precipitation can be an important removal process in stormwater high in metal ion content. P ions can be adsorbed readily by many soils through the process of ion exchange. The proportion of plant roots exposed to P, plant and root age, as well as environmental factors such as temperature and soil pH, all affect the rate of P uptake in plants (Liu et al., 2014).

2.4 Urban Stormwater Modelling

Modelling or simulation softwares were developed since there is increasing need to predict the performance of stormwater BMP's facilities including bioretention. The development of modelling software is also due to the restriction of test condition and unexpected results from the experimental study (Meng et.al, 2014). Also, computational models simplify the complex process of bioretention by using mathematical equations and help to evaluate the performance of bioretention. (Liu et al., 2014). Models can help to convert laboratory result to field scale, allowing us to have more understanding about process involving in bioretention such as the flow of water, retention and transport of pollutants (Spraakman et al., 2020). There are several approaches used for stormwater modelling and those modelling software can be classified based on different aspect as shown in Figure 2.7. The modelling software can be selected based on the needs and the purposes.

Aspect	Options			Recommendation
Modelling period	***Event-based*** models simulate single rainfall events, normally design events	***Continuous simulation*** models simulate a long rainfall data series, which may cover months or years.		Continuous simulation is preferred, as it is better able to approximate the range of conditions which may be encountered in reality, and to simulate cumulative and long-term impacts on receiving waters.
Modelling approach	***Empirical*** models relate runoff quality and quantity directly to catchment and rainfall parameters, without modelling the various processes occurring. Sizing curves presented in the Practice Guide are essentially an empirical model	***Conceptual*** models use interlinked storage and process components to represent the system. Parameters usually need to be determined through calibration and verification. MUSIC is a conceptual model	***Process-based*** models use fundamental equations to represent the system. The model parameters have a direct physical meaning and can be measured in the field.	Empirical models are simple to use and require relatively little data input. Process based models are complex and require significant data input. For the purposes of sizing stormwater treatment measures as part of a WSUD Strategy, conceptual models represent a good balance between simplicity and accuracy.
Spatial resolution	***Spatially-lumped*** models use a single set of parameters to represent the whole catchment	***Distributed*** models divide the catchment into a series of smaller subcatchments, each having different properties.		Distributed models are able to represent heterogeneity within a catchment and provide a more accurate result. Most modelling packages allow the model set up to be either spatially lumped or distributed, and the model set up can be refined over time as more information is available to define the properties in a distributed set up.
Parameter type	***Deterministic*** models always produce the same results for a given set of input parameters	***Stochastic*** models contain one or more parameters with random behaviour, usually with a statistical distribution. Stochastic models may include both deterministic and probabilistic components. Stochastic models do not always produce the same results for a given set of input parameters		Stochastic models allow more realistic simulation of parameters such as pollutant concentrations in runoff, which are log-normally distributed when measured in the field.
Purpose	***Planning*** models are normally used to compare the outcomes of different management options for a catchment	***Design*** models are normally used to optimise the size and configuration of stormwater treatment measures for to achieve best practice pollutant removal performance	***Operational*** models are normally used to optimise the performance of stormwater drainage and wastewater networks once they are operational	All three types of models are important at different stages.

Figure 2.8: Modelling Options with Differences Aspects
(Darwin Harbour WSUD, 2009).

2.4.1 Modelling Software for Bioretention

There are different models can be used to simulate the performance of bioretention. Different modelling software has its own capabilities and limitation and the summary of modelling software for simulation of bioretention is summarised in Table 2.2. These softwares include Model for Urban Stormwater Improvement Conceptualism (MUSIC), Storm Water Management Model (SWMM), Hydrologic Engineering Center, Hydrologic Modelling System (HEC-HMS), RECARGA, HYDRUS, Source Loading and Management Model for Windows (WinSLAMM) and DRAINMOD. Based on the review of 10 models by Elliott and Trowdale (2007), bioretention can be modelled only in MUSIC 2.0 and Water Balance Model (WBM) but WBM is limited to water quality aspects. The review stated that softwares such as MOUSE 2004 and SWMM5 can model indirectly using infiltration device. Although DRAINMOND was originally used for agriculture modelling, it was recently used to simulate bioretention due to the similarity between subsurface drain tiles and underdrain of bioretention (Liu et al., 2014). Spraakman et al. (2020) reported the most popular model used was SWMM (31%), followed by RECARGA (7%) and HYDRUS-1D or 2D (5%) among 7 models which also including MUSIC and HEC-HMS. Models can be classified as event based or continuous models. Normally, a single rainfall-runoff event is used for event based models whereas a series of rainfall-runoff event is used for continuous models (Mangangka, 2013). The RECARGA is widely used for bioretention simulation because it allows for both event based and continuous modelling (Meng et al., 2014).

Calibration is an important process in modelling. Mangangka (2013) calibrated the models based on the inflow and outflow result. The purpose of that calibration is to ensure the prediction of outflow can be done under several conditions using the same models. Gülbaz at el. (2019) developed the calibration for non-point source pollutants to model bioretention and observed the pollutant removal's performance using SWMM. The pollutants build-up and wash off coefficients were achieved for TN, TP, zinc (Zn), copper (Cu) and lead (Pb) from the model's calibration. Meng et.al (2014) simulated the hydrologic performance of bioretention facilities by HYDRUS-1D and suggested that the simulation of water quality improvement could be done in the future study via the solute transport function of HYDRUS-1D. From the findings of Bailey et al. (2018), the MUSIC modelling showed a more accurate result after the calibration had been done based on local climate data and Avon River's catchment land use parameters.

The simulation of water quality results can be done based on event mean concentration (EMC). A simple "build-up/wash off" approach is adopted for some models such as WinSLAMM, SWMM and MUSIC to evaluate the water quality performance of bioretention (Dehais, 2011).

Table 2.2: Summary for Bioretention Modelling Software

Modelling Software	Description	Capabilities	Limitations
*MUSIC (Model for Urban Stormwater Improvement Conceptualism)	Conceptual design tool for stormwater management. Helps in decision making for selection of BMPs to treat runoff	• Predict the both water quality and quantity performance of BMPs in stormwater management without the complex input • Develop a suitable BMPs treatment train based on the goals to achieve • Estimate life cycle costs stormwater management system	• Unable to perform detailed analysis such as hydraulic analysis of urban stormwater system • Require of actual data for calibration and validation for the accuracy of model based on local condition
SWMM (Stormwater Management Model)	Planning design tool for wide range application, combining with hydrology, hydraulics, wastewater and stormwater control models	• Perform detailed hydrology and hydraulic analysis in both single and continuous event. • Aid to determine the most sensitive parameters with regarding to water quality issue. (Niazi et al., 2017)	• Lack of user guidance for the selection of parameters and automated calibration
HEC-HMS (Hydrologic Engineering Center, Hydrologic Modelling System)	Conceptual design tool to model hydrologic response, developing standard hydrograph based on precipitation input (Liu et al., 2014)	• Simulate rainfall-runoff process and provide analysis of overland flow run off and channel routing	• Limited to simulating storage (Liu et al., 2014)
RECARGA	Design and analysis tool for evaluate hydrologic performance	• Provide hydrologic analysis of bioretention and runoff retention, allowing both	• Parameters such as depth and type of filter media cannot be specified. (Meng et al., 2014)

		single event and continuous modelling	• Unable to evaluate stormwater quality performance
HYDRUS	Model to develop standard hydrograph based on precipitation input	• Allow complex simulation for ponding and subsurface process such as infiltration (Meng, 2014) • Capable for inverse modelling and calibration (Kaykhosrav, 2018)	• Inhibit any import data as input in HYDRUS-1 (Kaykhosrav, 2018)
*WinSLAMM (Source Loading and Management Model for Windows)	Preliminary and analysis tool for hydrologic model based on pollutants wash off from source according land type (Liu et al., 2014)	• Evaluate the sizing requirement and effectiveness of stormwater management strategy	• Temporal resolution of modelling only limited to daily or hourly (Kaykhosrav et al., 2018)
DRAINMOD	Hydrologic model for agriculture field drainage management	• Able to simulate bioretention due to the similarity between subsurface drain tiles and underdrain of bioretention	• Limitation in stormwater quality simulation (Liu, 2014)

*Proprietary Software, the remaining are freely available

2.4.2 Statistical Performance Evaluation for Modelling

To evaluate the performance of modelling, there are three common statistical methods that can be used, which includes Root mean square error-observations Standard deviation Ratio (RSR), Nach-Sutcliffe Efficiency (NSE) and Percentage bias (PBIAS). The lower RSR value with the lower value of Root Mean Square Error (RMSE) indicates a better model performance. If the value of RSR is equal to zero, it means there is no residual variation and the modelled value is fit with observed value (Bailey et al., 2018). RSR can be calculated by using equation below:

$$\text{RSR} = \frac{RSME}{STDEV_{\cdot obs}} = \frac{\sqrt{\sum_{i=1}^{n}(Q_i^{obs} - Q_i^{sim})^2}}{\sqrt{\sum_{i=1}^{n}(Q_i^{obs} - Q_i^{mean})^2}} \qquad \text{Eq(2.1)}$$

NSE coefficient can be computed by using equation below:

$$\text{NSE} = 1 - [\frac{\sum_{i=1}^{n}(Q_i^{obs} - Q_i^{sim})^2}{\sum_{i=1}^{n}(Q_i^{obs} - Q_i^{mean})^2}] \qquad \text{Eq (2.2)}$$

whereas for PBias can be calculated by using equation below:

$$\text{PBIAS} = \frac{\sum_{i=1}^{n}(Q_i^{obs} - Q_i^{sim})^{*}100}{\sum_{i=1}^{n}(Q_i^{obs})} \qquad \text{Eq (2.3)}$$

Figure 2.9 shows the common performance rating of models using three different statistical methods. The performance rating for RSR and NSE is same for all elements but there is different percentage bias for specific elements. This difference is due to the recent availability of information (PBIAS) on the uncertainty of measured streamflow and water quality. Moreover, PBIAS is suitable to be used to evaluate the model whether is underestimated or overestimated. PBIAS is more suitable used to evaluate the performance of bioretention modelling as the bioretention modelling includes both flow reduction and pollutants removal parameters.