MODELLING AND SIMULATION OF BIORETENTION SYSTEM USING HYDRUS-1D

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DECLARATION

I hereby declare that the work submitted to University Malaysia Sabah is my own work except for previously published work including books, journal, and conference proceedings. All the information is properly acknowledged in the report.

05/08/2022

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CERTIFICATION

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DEGREE : **BACHELOR OF ENGINEERING WITH HONOURS (CIVIL ENGINEERING)**

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ABSTRACT

A Bioretention cell is one of the best management practices for low-impact development tools (LIDs) to reduce stormwater runoff and pollutants through infiltration. However, in tropical climate region such as Southeast Asia, higher clogging effect and overflow was observed at the pilot to field scale bioretention. This is due to high rainfall runoff volume, which significantly affects the pressure head and hydraulic conductivity parameters. In this study, 270mm and 370mm lab-scale bioretention column was constructed using plastic acrylic where the height of the engineered soil media is 150mm and 250mm, respectively. The design of the lab-scale bioretention cell column was constructed based on Urban Stormwater Management Manual (MSMA) specifications. The calculated stormwater runoff flow rate is applied to each column to model the actual scale impervious area for runoff generation. The flow sensor measurement for inflow and outflow of water was applied to understand the water movement beneath the engineered soil media. One dimensional water flow model was used to study the effect of different media depth and rainfall intensity on the value of hydraulic – pressure head parameters. The results showed that at lesser rainfall intensity of 5.3mm/min, small percentage of runoff volume reduction was observed at a low height of media (150mm) with a total of 11% compared to 55% of 250 mm media height. At higher rainfall intensity of 12mm/min, no significant deviation was observed in terms of percentage of runoff volume reduction between both heights due to increased pressure head and lower hydraulic conductivity. Root Mean Square Error (RMSE) of the model show higher efficiency between the simulated and observed values of runoff inflow from water flux analysis results generated by HYDRUS-1D. The coefficient of determination R^2 represents the highest prediction for the output of the HYDRUS-1D simulation.

ABSTRAK

PEMODELAN DAN SIMULASI SISTEM PENGEKALAN BIO MENGGUNAKAN HYDUS-1D

Sel Bioretensi ialah salah satu amalan pengurusan terbaik untuk alat pembangunan berimpak rendah (LID) untuk mengurangkan larian air ribut dan bahan pencemar melalui penyusupan. Walau bagaimanapun, di rantau iklim tropika seperti Asia Tenggara, kesan tersumbat dan limpahan yang lebih tinggi diperhatikan pada pengekalan bio skala perintis ke medan. Ini disebabkan oleh isipadu larian hujan yang tinggi, yang memberi kesan ketara kepada kepala tekanan dan parameter kekonduksian hidraulik. Dalam kajian ini, lajur bioretensi berskala makmal 270mm dan 370mm telah dibina menggunakan akrilik plastik di mana ketinggian media tanah kejuruteraan masing-masing ialah 150mm dan 250mm. Reka bentuk lajur sel bioretensi berskala makmal telah dibina berdasarkan spesifikasi Manual Saliran Mesra Alam (MSMA). Kadar aliran larian air ribut yang dikira digunakan pada setiap lajur untuk memodelkan skala sebenar kawasan kalis air untuk penjanaan larian. Pengukuran sensor aliran untuk aliran masuk dan aliran keluar air digunakan untuk memahami pergerakan air di bawah media tanah yang direka bentuk. Model aliran air satu dimensi digunakan untuk mengkaji kesan kedalaman media yang berbeza dan keamatan hujan ke atas nilai parameter kepala tekanan hidraulik. Keputusan menunjukkan bahawa pada intensiti hujan yang lebih rendah iaitu 5.3mm/min, peratusan kecil pengurangan isipadu larian diperhatikan pada ketinggian media yang rendah (150mm) dengan jumlah 11% berbanding 55% daripada ketinggian media 250 mm. Pada intensiti hujan yang lebih tinggi iaitu 12mm/min, tiada sisihan ketara diperhatikan dari segi peratusan pengurangan isipadu air larian antara kedua-dua ketinggian disebabkan peningkatan kepala tekanan dan kekonduksian hidraulik yang lebih rendah. Root Mean Square Error (RMSE) model menunjukkan kecekapan yang lebih tinggi antara nilai simulasi dan pemerhatian aliran masuk larian daripada keputusan analisis fluks air yang dijana oleh HYDRUS-1D. Pekali penentuan R^2 mewakili ramalan tertinggi untuk keluaran simulasi HYDRUS-1D.

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LIST OF ABBREVIATIONS

MSMA	-	Urban Storm Water Management Manual
DID	-	Department of Irrigation and Drainage
BMP	-	Best Management Practices
LID	-	Low Impact Development
TSS	-	Total Suspended Solids
TP	-	Total Phosphorus
TN	-	Total Nitrogen
USNDG	-	United Nation's Sustainable Development Goals
ARI	-	Average Recurrence Intervals
WQ	-	Water Quality
WSUD	-	Water Sensitive Urban Design
SUDS	-	Sustainable Urban Drainage System
FEM	-	Finite Element Mesh
DSR	-	Direct-Seeded Rice
ASWC	-	Antecedent Soil Water Content
RMSE	-	Root Mean-Square Error

CHAPTER 1

INTRODUCTION

1.1 Overview

Bioretention could be an efficient stormwater treatment, particularly in Malaysia. The Department of Irrigation and Drainage Malaysia (DID) classified it as important research specifically under the Urban Storm Water Management Manual in Malaysia (MSMA) in May 2012. (Muha et al., 2016). Although its recognition of its importance, Yang et al., (2021) stated that there is still a deficiency of systematic analysis of the effect of bioretention design parameters on hydrologic performance. In this study, we used HYDRUS-1D models to produce normal annual rainfall runoff and simulate the water balance of a bioretention system in an urban state. The investigation's objective was to identify critical design characteristics for the bioretention system and to prioritise their development.

1.2 Background of Study

The advancement of urbanization has caused pernicious effects to the well-being of aquatic ecosystems. It has caused problems like stream channelization, the declining of stream habitat, and the deteriorated water quality. To tackle this issue, it is best to understand the urbanization effects, thus to implement the mitigation actions on urban stormwater hydrology. The bioretention system is listed as a method that is regularly applied to reduce the rate of pollutants brought by impenetrable areas by stormwater (Goh et al., 2019). It is considered one of the Best Management Practices (BMPs) in Low Impact Development (LID) methods. The bioretention system also plays a significant role in green infrastructure practice and to treat urban stormwater (Waller et al., 2018). A bioretention system is generally comprised of a soil bed implanted with non-invasive vegetation, preferably native vegetation. The stormwater runoff is filtered through the soil planting bed when it enters the bioretention system. As soon as it is filtered, stormwater runoff is either moved downstream by an underdrain system or penetrated into an existing subsoil beneath the soil surface by an infiltration system. A bioretention system is often designed as a bioretention basin, which has a flat bottom, or a longer, narrower bioretention swale which has a sloping bottom. Determined by the thickness of the implanted soil bed and type of vegetation implanted bed, the Total Suspended Solids (TSS) removal rate of a bioretention system is about 80 to 90 percent (Meng et al., 2014).

A bioretention system's primary function is to retain and filter stormwater runoff that includes a diverse variety of contaminants, including suspended particles, nutrients, metals, hydrocarbons, and bacteria. The stormwater runoff will go into the surrounding soil and in time, to the groundwater aquifers. The exfiltrated runoff is also drained to receiving waters for systems with underdrains or taken up by plants in plant beds (Lisenbee et al., 2021). In other words, these processes are mainly to manage urban runoff by using vegetation or implanted soil before it is discharged into the main sewer system (Muha et al., 2016). We can assess and simulate the water flow and transport of diverse chemicals in a bioretention system by using the HYDRUS-1D software. It is a widely applied model world-wide. The HYDRUS-1D software model is also utilized to simulate the vertical water movement, heat transfer (Li et al., 2020) and the deliverance of solutes in soil solutions and wastewater effects on soil hydraulic properties, mineral nitrogen species, saline and sodic water in soil, and use of soil amendments (Ali et al., 2021). The HYDRUS-1D software also includes the evapotranspiration meteorological module, other than the hysteresis of root water absorption and water content. Moreover, this model can be implemented under various environment e.g., fixed and variable head, constant and variable flow, and atmospheric boundary (Schiavon, Michel and Boivin, Arnaud, 2006). The software model also solves the Richards equation (Richards 1931) for variably saturated water flow, heat and solute conveyance (Ali et al., 2021). The aim of this study is to determine the input data for Hydrus-1D model of bioretention which includes water content, depth of filter media, and influent volume, to simulate and optimize bioretention system using Hydrus-

1D model based on the volume reduction rate performance, and to validate the Hydrus-1D model of the bioretention cell in accordance with the MSMA requirements which was obtained from previous experimentation results.

1.3 Problem Statement

Hydrological aspect plays a significant role in the overall performance of bioretention system. The major issues with bioretention system are the clogging effects and overflow, which is always encountered. This affects the stormwater runoff where it cannot be treated well in field scale with the encounter of the stated issues above. So, a critical analysis should be made with the idea of using HYDRUS-1D software. The optimization of the bioretention system by using HYDRUS-1D software should predict which value from the selected parameters of water content, depth of filter media, and influent volume will reduce the clogging and overflow issues, based on volume reduction rate. In addition, since the hydrological analysis of bioretention system in Malaysia is lacking, as the analysis is mostly based on the pollutant removal efficiency, this study provides significant data input for the analysis of hydrological performance of the bioretention system. This is crucial for the future of bioretention performance in the future, especially for tropical countries like Malaysia.

1.4 Objective of Study

1. To determine the input data for Hydrus-1D model of bioretention which includes water content, depth of filter media, and influent volume.
2. To simulate and optimize bioretention system using Hydrus-1D model based on the volume reduction rate performance
3. To validate the Hydrus-1D model of the bioretention cell in accordance with the MSMA requirements which was obtained from previous experimentation results.

1.5 Scope of Work

This study is to model a lab-scaled bioretention system using HYDRUS-1D software. The scope of work for this study is to simulate the volume reduction rate performance of the lab-scaled bioretention system. So, to attain this objective, firstly, the parameters of data input for HYDRUS-1D shall be obtained from the lab-scaled bioretention system and also default values from the HYDRUS-1D software. The parameters that will be manipulating the output data from HYDRUS-1D software are water content, depth of filter media, and influent volume, hydraulic conductivity. This will then help in evaluating the hydrological performance which is the volume reduction rate of bioretention system based on MSMA standard design specification. Material used for the filter of the lab-scaled bioretention system are sandy loam soil, gravel, and local plants. Optimization of the manipulating factors using HYDRUS-1D are limited to 2 levels only. This research area is extended to more tropical climate condition compared to other tempered climate study on bioretention.

1.6 Significance of Study

The data obtained from this study will aid the existing MSMA design specifications of bioretention system this study focuses more on the hydrological aspects of the system. Moreover, with the existing and newly added data parameters from this study, the community may be more aware about the benefits of bioretention system, especially, in terms of water quality treatment. In line with the United Nations Sustainable Development Goal (UNSDG) of countries such as Malaysia, Singapore, and Brunei Darussalam, bioretention system falls under the 6th and 11th goal of the UNSDG which is Clean Water and Sanitation and Sustainable Cities and Communities respectively (United Nations , 2021).

Stated in the UNSDG 6th goal, points 6.3 “By the year of 2030, water quality must be significantly improved globally by decreasing rate of pollution, removing dumping, and evading the release of dangerous chemicals and materials, halving the share of untreated wastewater, and significantly increasing recycling and safe reuse” and 6.4 “By the year of

2030, water efficiency must be significantly boosted across sectors and guarantee sustainable freshwater withdrawals and supply in effort to relieve water shortage and significantly reduce the many people affected by it", clearly means we need sustainable, clean and treated water to live. Meanwhile, the UNSDG 11^{th} goal mentioned in points 11.3 "By the year of 2030, all countries should expand their capability for participatory, integrated, and sustainable human settlement planning and management" and 11.A "By increasing national and regional development planning, we can foster reliable economic, social, and environmental ties between urban, peri-urban, and rural communities". This shows that the bioretention system supports the sustainable urbanization and positive environmental relationship between urban, peri-urban and rural areas.

CHAPTER 2

LITERATURE REVIEW

2.1 Bioretention System

The bioretention system is considered a type of stormwater best management practises (BMPs) that treat stormwater runoff by combining the processes of biological uptake and porous media filtration. They incorporate plants such as shrubs and grass as well as layered media composed of soil, sand, and mulches to create an ecosystem of sorts. Runoff from small rainstorms is captured, temporarily detained, and treated in these structures before being released back into the receiving waters. A shallow excavated site along a proposed drainage channel or swale should have its runoff pre-treated and diverted into systems that can be built from there. Bioretention systems can be divided into two designs, which are permeable and impermeable system design (Department of Irrigation and Drainage (DID) Malaysia, 2012). The permeable system (Figure 2.1) draws water through the filtration media and sand bed layer before distributing it to the neighbouring native soil and finally recharging the groundwater supply. On the other hand, the impermeable system (Figure 2.2) This method also clears out water from the filtration media through transition layers, but it is interrupted by a subsoil pipe or underdrain that is located in the draining layer. For people living in an area where native soils have a low infiltration capacity or where higher rainfall intensity is frequently experienced, they will need an underdrain to transport excess water away from the site so that it can be used for storage capacity during the next storm. A bioretention system is made up of several components, including pre-treatment, an inlet, an excavated basin area with plants and an underlying mulch layer, a soil bed, a sand bed, a drainage and outlet structure, and a drainage and outlet layout (Department of Irrigation and Drainage (DID) Malaysia, 2012).

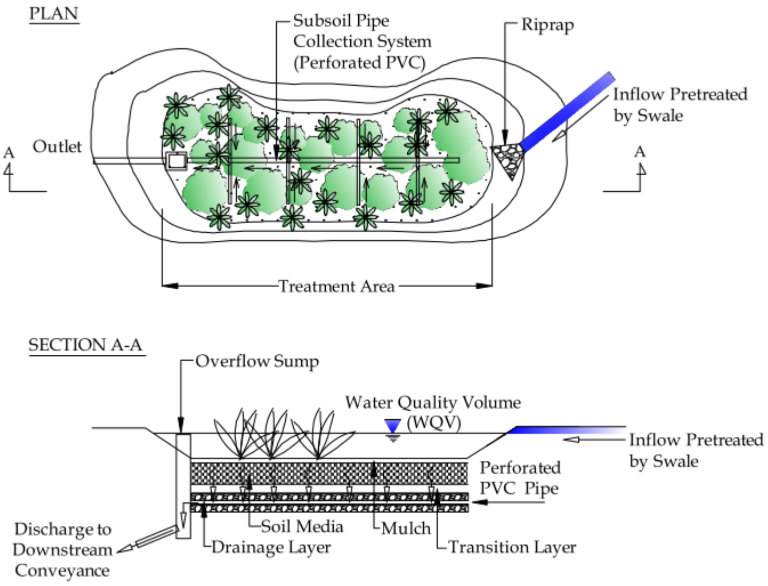

Figure 2. 1 : Impermeable Bioretention Basin

Source : MSMA 2nd Edition

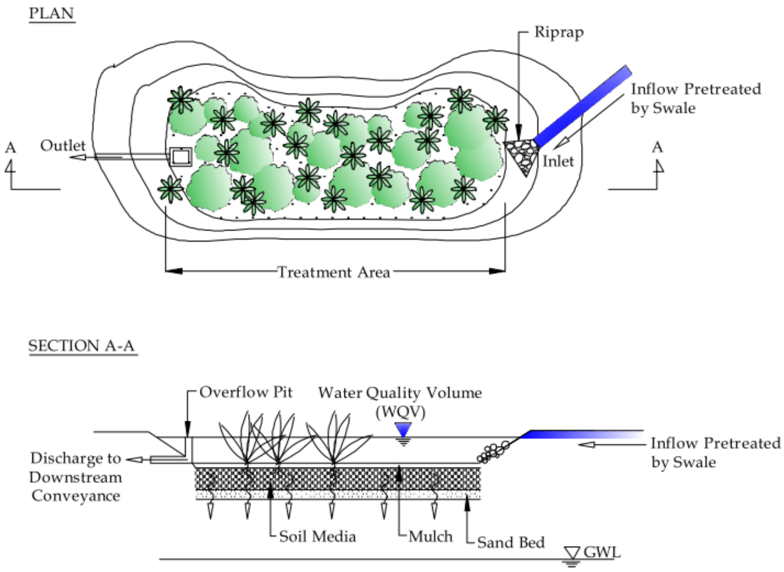

Figure 2. 2 : Permeable Bioretention Basin

Source : MSMA 2nd Edition

The selection of various plant species can result in a plethora of landscape designs that can be created. Organic matter such as compost, plants, soils, and a mulch layer all play an important role in the treatment of runoff by breaking down pollutants and removing them from the environment. The underlying gravel beds (drainage layer) are used to temporarily store and infiltrate treated stormwater after it has percolated through the organic soil layer (filter media), and they are also used to discharge treated stormwater through beneath-ground drains. Using a diverse type of pollutant removal mechanisms, which includes filtration, extended detention treatment; adsorption to soil particles, denitrification; and biological uptake by plants, they increase the quality of water by removing fine sediment and trace metals from it, as well as nutrients and bacteria, as well as organics from it (Department of Irrigation and Drainage (DID) Malaysia, 2012).

A high degree of treatment is provided by the systems due to the increase in the organic content of the soils used in the bioretention cell, which promotes removal of pollutants from the water as well as absorption of runoff. The organic soils act as a sponge, retaining water and increasing the amount of storage capacity available in the cell. Table 2.1 shows the removal efficiency of a bioretention system for a selection of stormwater pollutants.

Table 2. 1 : Removal Efficiency of Bioretention System

Pollutant	Removal Efficiency (%)
Total Suspended Solids (TSS)	80 (High)
Total Phosphorus (TP)	60 (Medium)
Total Nitrogen (TN)	50 (Medium)
Metals	80 (High)

Source : MSMA 2nd Edition

The treated stormwater is accumulated in an underdrain system or permitted to infiltrate into the ground after it has been filtered through vegetation and soil media. Stormwater runoff that exceeds the design stormwater Average Recurrence Intervals (ARIs) bypasses the bioretention system entirely.

Since this study is based on a lab-scaled bioretention system, it is crucial to have the knowledge of the cell's filter bed area. The filtering treatment criteria should be as follows:

- Leading up to infiltration, the entire treatment system (including pre-treatment) must always temporarily hold the Water Quality Volume (WQ_v) derived from 40mm (i.e., three-month ARI) design rainfall.
- Any bioretention system must adhere to the specified requirements. This is shown in Figures 2.3 and 2.4. In table 2.3, it shows the physical specification and geometry of a bioretention system, whereas in table 2.4, it provides the coefficient of permeability (k) for different kinds of filter media.

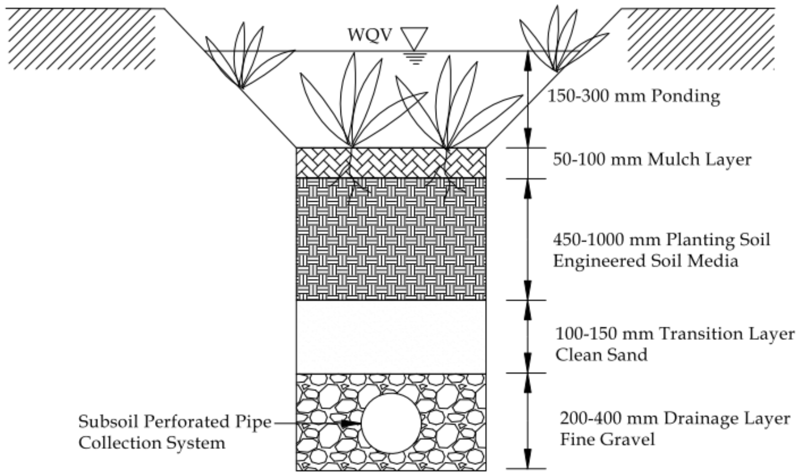

Figure 2. 3 : Specification for Impermeable Bioretention System

Source : MSMA 2nd Edition