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Green Roof Performance for Stormwater Management in Equatorial Urban Areas Using Storm Water Management Model (SWMM)

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Abstract

Many Low Impact Developments (LIDs) have recently been developed as a sustainable integrated strategy for managing the quantity and quality of stormwater and surrounding amenities. Previous research showed that green roof is one of the most promising LIDs for slowing down rainwater, controlling rainwater volume, and enhancing rainwater quality by filtering and leaching contaminants from the substrate. However, there is no guideline for green roof design in Malaysia. Hence, Investigating the viability of using green roofs to manage stormwater and address flash flood hazards is urgently necessary. This study used the Storm Water Management Model (SWMM) to evaluate the effectiveness of green roof in managing stormwater and improving rainwater quality. The selected study area is the multi-story car park (MSCP) rooftop at Swinburne University of Technology Sarawak Campus. Nine green roof models with different configurations were created. Results revealed that the optimum design of a green roof is 100 mm of berm height, 150 mm of soil thickness, and 50 mm of drainage mat thickness. With the ability to reduce runoff generation by 26.73%, reduce TSS by 89.75%, TP by 93.07%, TN by 93.16%, and improved BOD by 81.33%. However, pH values dropped as low as 5.933 and became more acidic due to the substrates in green roof. These findings demonstrated that green roofs improve water quality, able to temporarily store excess rainfall and it is very promising and sustainable tool in managing stormwater.

Keywords

Green Roof, Low Impact Development (LID), Storm Water Management

Model (SWMM), Storage Capacity, Pollutants Removal

1. Introduction

In many cities, especially those with dense metropolitan cores, the sight of a flash flood is all too common nowadays. It has become a more serious concern in the last decade due to climate change, increased urbanization, and obsolete stormwater management [1]. As the existing drainage system was designed to meet historical peak and volume surface runoff, it is unable to cater to the current extreme weather conditions due to the impact of climate change. Hence, floods are occurring more frequently. One of the ways to reduce the flood risk and yet save money to reconstruct the new drainage system is by adopting Low Impact Development (LID) and Best Management Practices (BMP) [2] [3]. The Storm Water Management Model (SWMM), developed by the United States Environmental Protection Agency (USEPA), is one of the essential tools for planning and designing the features of low impact development.

Low impact development (LID) is an innovative land planning and design approach that aims to preserve a site's pre-existing ecological and hydrological function by preserving, enhancing, or mimicking natural processes. There are several components of Low Impact Development (LID) in SWMM, including vegetable swale, bio-retention cell, permeable pavement, rain garden, rain barrel, infiltration trench, green roof, etc. [4] [5]. The LID type must be carefully chosen, planned, and distributed within the specified urban area to maximize its effectiveness in managing runoff and flood mitigation [6]. LID is a modern alternative to conventional stormwater management that temporarily stores rainwater during heavy rainfall and releases it after the rain stops. Some LID procedures are still new in Malaysia; however, they are not entirely novel globally. LID techniques have been used in many developed cities and nations such as Australia, the United Kingdom, Canada, New Zealand, the United States, and others. Depending on the conditions, it has been deployed with different applications [7] [8].

One of the LID techniques that has great potential but has little adapted in Malaysia is green roof system. Green roof is the man-made growing of plants on building rooftops with a mechanism that encourages their growth. Green Roof is also called vegetative roof and eco-roofs, and the roof can be either slightly sloped or flat [9]. The median green roof stormwater retention capacity can have a rate of up to 78% [10].

There are three types of green roofs: extensive green roofs, intensive green roofs, and semi-intensive green roofs [11] [12]. Green roof usually consists of a plant layer, a lightweight substrate layer, a filter membrane layer, a waterproof layer, and a drainage system [13]. The substrate layer is crucial for the green roof as the vegetation receives water and nutrients from it. An excellent green roof substrate should have a low bulk density, high water holding capacity, suitable organic material, less leaching, and high sorption of substrate. The depth of the substrates is vital to determine the stormwater retention capacity and management [14]. The type of vegetation used must also be suitable to the particular area's climate and sustain harsh climate conditions. The substrate's depth and composition and the utilized plant are crucial for green roof effectiveness. Additionally, the green roof substrate can aid in lowering stormwater pollution levels [15].

Green roofing has grown in popularity over time due to its advantages, especially in developed countries [16]. One of the advantages is that green roof will help reduce stormwater runoff and increase rainwater retention, which will help reduce the flash flood risk. Besides, green roof will also help reduce the building roof's temperature and prevent heat islands if the whole area adopts green roof system [17]. The green roof plants help to block direct sunlight from reaching the building's roof surface, improving the quality of the air outside and inside as well as the temperature [18]. Other than that, the plants will help remove air pollutants during their photosynthesis process and help replenish some of the oxygen. As green roof help lower the roof's temperature and the interior of the building, it will also help reduce the electricity cost for air conditioning [17]. The rainwater collected in rain barrels will be recycled for irrigating the plants or washing the housing compound.

However, green roof and rain barrel system also have some disadvantages. The substrate or soil of the green roof will put additional weight on the roof. Hence, the roof support system must be strong enough to withstand the extra load from the soil or substrate. Hence, an additional cost is incurred for a green roof system compared to a conventional one. Additional cost is also required for installing a waterproofing system on the green roof surface to avoid future leaks. Meanwhile, green roof systems also require regular maintenance to prevent clogging and the growth of other plant species.

Even though green roofs are expensive to adopt, the system is increasingly gaining popularity in Malaysia and globally nowadays. Green roof design is unavailable in both design guidelines of the second edition of Urban Stormwater Management Manual [19] and Sarawak Urban Stormwater Management (SUStoM). Therefore, it is necessary to develop a method for designing and researching the possibility of adopting green roofs to mitigate basin vulnerability and reduce flood risk, notably for Sarawak.

The rainfall-runoff model will be developed using SWMM. As the green roof facilities are yet to be installed in Sarawak, the on-site experimental data for green roofs, such as evaporation, runoff and retention, and effluent quality analysis, are unavailable. Once the rainfall-runoff model is developed, green roofs will be integrated into the model for estimating the storage capacity and water quality improvement analysis, especially in the equatorial region.

2. Study Area

The selected study area is the Swinburne University of Technology Sarawak

(SUTS) campus, as presented in **Figure 1**. It is located in the heart of Kuching, the capital of Sarawak, Malaysia. Kuching is the largest city in Sarawak and Borneo Island, with an area of 450 km^2 with a population of 812,900 (2020 census) [20]. In recent years, multiple flash floods have occurred in Kuching [21] [22]. Hence, effective and efficient modern stormwater management is required to mitigate the problem.

The temperature in Kuching can reach as high as 36˚C and as low as 22˚C during dry or drought seasons. Meanwhile, the average temperature ranges from 32˚C to 24˚C and 29˚C to 24˚C during the wet or rainy season [23] [24]. Kuching receives rainfall throughout the year, with January typically receiving the most (457 mm) and July receiving the least (156 mm) [25] [26]. The windiest month is January, with an average wind speed of roughly 6.4 km/h, while May has the lowest average wind speed at 3.9 km/h [27] [28].

Established in 2000, SUTS is operating as a joint venture between the Sarawak State Government and Swinburne Australia. The location of this campus is at 1.5329˚N latitude and 110.3572˚E longitude, on a 6.5 ha (16.5 acres) plot of land in Jalan Simpang Tiga, about 10 minutes drive from the city's center. Government offices, businesses, and residential areas surround the campus. It is conveniently close to a few shopping malls, restaurants, banks, clinics, houses of worship, supermarkets, and other amenities. SUTS is one of Kuching's most well-liked private institutions, with an approximate of 3000 students. Multi-storey car park (MSCP), lecture theatres, lecture halls, administrative buildings, and dormitories are among the principal buildings on SUTS Campus (refer to **Figure 1**).

In this study, the green roof system is proposed to install on MSCP rooftop.

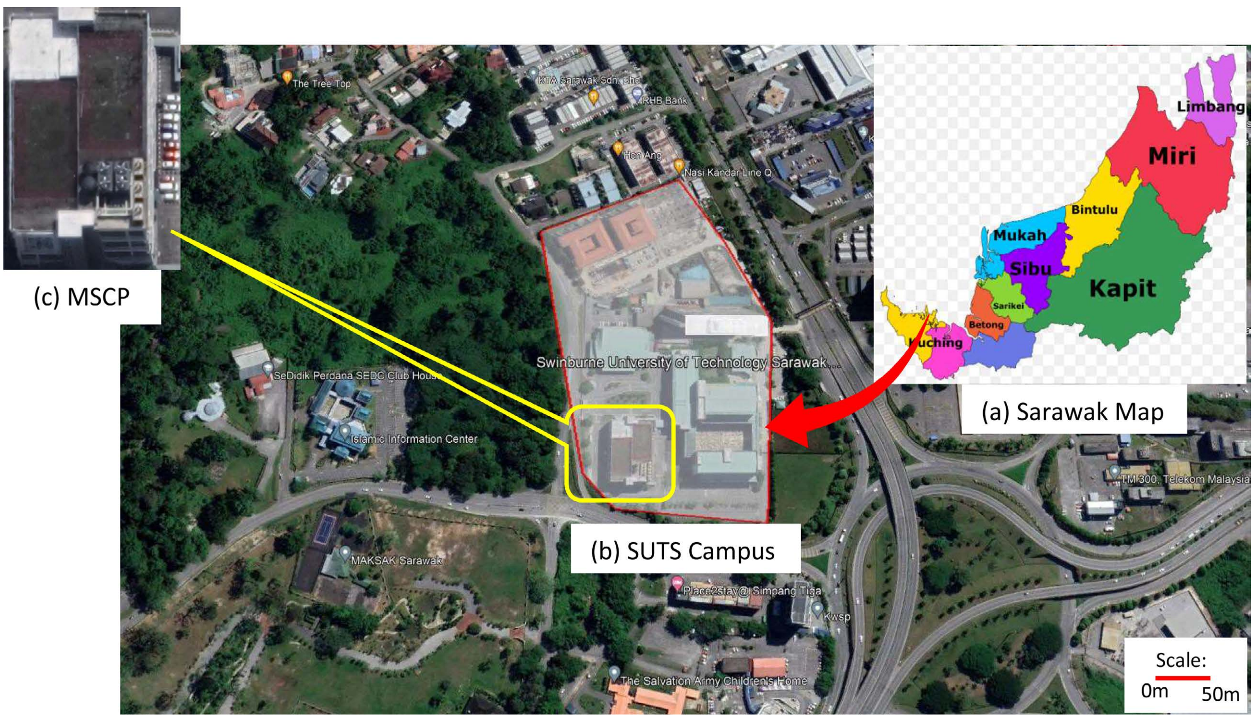

Figure 1. Locality map of MSCP in Swinburne University of Technology Sarawak Campus.

Currently, MSCP rooftop is occupied by two concrete surface tennis courts. It is proposed to transform the concrete surface tennis courts into a green roof system, and replace them with lawn grass tennis courts. The size of the MSCP rooftop is approximately 37.5 m × 60 m (approximately 0.225 Ha).

3. Methodology

The Storm Water Management Model (SWMM) from the Environmental Protection Agency (EPA) is utilized for planning, analysis, and design relating to stormwater runoff, combined with sanitary sewers and other drainage systems [29]. SWMM was created to help with stormwater management by reducing runoff through infiltration and retention and by assisting in reducing discharges that harm the water bodies. SWMM simulates the quantity and quality of water runoff in urban areas over time or for a single event. SWMM offers an integrated platform for running hydrologic, hydraulic, and water quality simulations [30]. In this study, SWMM was used to develop the green roof system. The methodology for designing green roofs is shown in **Figure 2**, from model development to simulation using SWMM.

The calibration was performed by minimizing the error between the simulated and observed runoff without considering the implementation of green roof. The model performance was evaluated using the Nash and Sutcliffe coefficient [31] [32] [33] and coefficient of correlation [34] [35] [36]. Green roofs were not included in the calibration process since they had yet to be built, and no runoff was associated with their installation. The rainfall-runoff model was calibrated using five extreme rainfall and runoff datasets collected on 6th December 2021, 5th January 2022, 8th November 2022, 22nd December 2022, and 23rd December 2022.

In order to test the possibility of mitigating the basin vulnerability and reducing flood risk, the impact of virtual green roof scenarios will be investigated using SWMM. The basin's initial representations of the SWMM model will be adjusted to accommodate the potential installation of a green roof. The potential of green roofing is estimated by combining building [37] and land use data [38]. A dedicated module that depicts the hydrological behavior of green roofs under nine scenarios as tabulated in **Table 1**, will be integrated into the SWMM

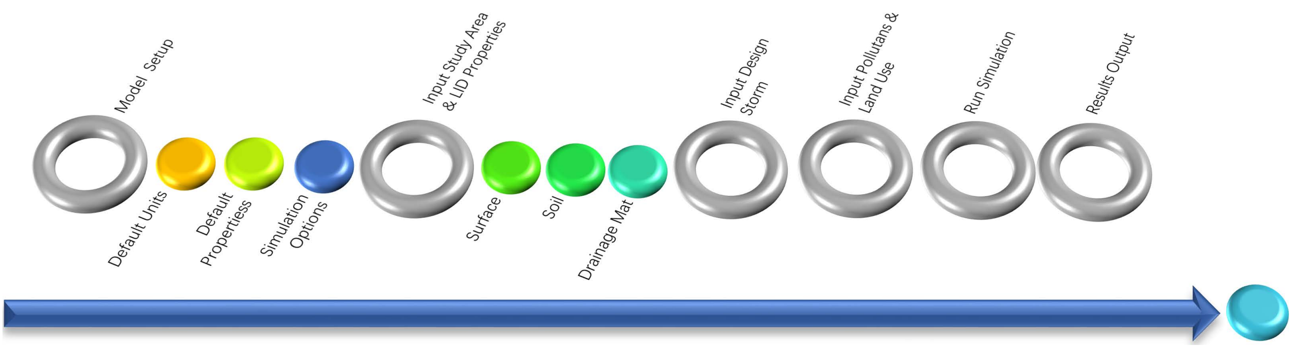

Figure 2. SWMM simulation flowchart.

framework to ascertain the impact of water retention capacity and demonstrate how a green roof may serve as an alternative to solve stormwater management issues. The selected routing method is Dynamic Wave, and the infiltration option chosen for model simulation is Horton Infiltration Model.

The input parameters for green roof consist of "surface", "soil" and "drainage mat" as presented in Figure 3. The "surface" input parameters are berm height, vegetation volume fraction, surface roughness, and surface slope. While the input parameters for "Soil" consists of soil thickness, porosity, field capacity, wilting point, conductivity, and suction head. Lastly, the drainage mat input parameters comprise the mat's thickness, void fraction, and roughness coefficient. Table 1 depicts the nine combinations of green roofs evaluated in this study, labeled as A, B, C, D, E, F, G, H, and I, based on different berm heights, soil thickness, and drainage mat thickness. Various combinations of green roof are investigated to identify the optimum configuration of green roof design for tropical regions, especially for Sarawak.

The model was then fed with rainfall data for Kuching Airport Station obtained from the Sarawak Department of Irrigation and Drainage (DID). Given that heavy rain is typically brought about by the northeast monsoon, which occurs between November and February, the model was calibrated using five extreme rainfall and runoff datasets that were collected from the Kuching Airport station on 6th December 2021, 5th January 2022, 8th November 2022, 22nd December 2022, and 23rd December 2022. These datasets were selected into the SWMM time series editor for calibration and simulation purposes.

SWMM can estimate pollutant loads related to stormwater runoff. In this study, the SWMM is employed to figure out how much pollution remains after being treated by the green roof system. Before performing the simulation, the

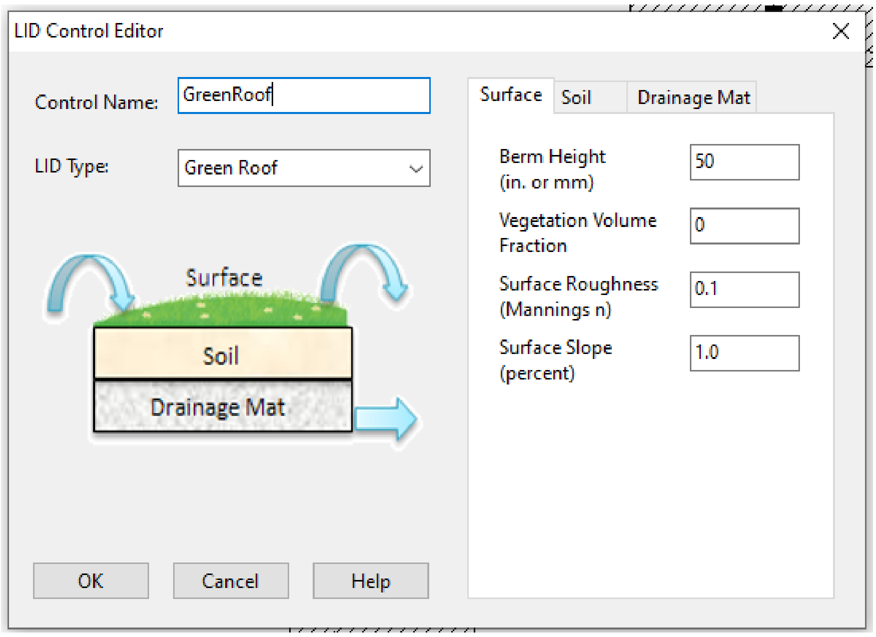

Figure 3. Green roof's LID control editor.

Table 1. Green roof parameters.

Parameters	Thickness	Green Roof Type
Berm Height	50 mm	
Soil Thickness	75 mm	A
Drainage Mat Thickness	25 mm	
Berm Height	100 mm	
Soil Thickness	75 mm	B
Drainage Mat Thickness	25 mm	
Berm Height	50 mm	
Soil Thickness	150 mm	C
Drainage Mat Thickness	25 mm	
Berm Height	50 mm	
Soil Thickness	75 mm	D
Drainage Mat Thickness	50 mm	
Berm Height	50 mm	
Soil Thickness	150 mm	E
Drainage Mat Thickness	50 mm	
Berm Height	100 mm	
Soil Thickness	75 mm	F
Drainage Mat Thickness	50 mm	
Berm Height	100 mm	
Soil Thickness	150 mm	G
Drainage Mat Thickness	25 mm	
Berm Height	100 mm	
Soil Thickness	150 mm	H
Drainage Mat Thickness	50 mm	
Without Green Roof	-	I

attributes of pollutants and land use are needed to model the treated water quality. The pollutants details were input into the model through the pollutants editor, while the land use editor was for land use data. SWMM can simulate five water quality parameters: total suspended solids (TSS), total phosphorus (TP), total nitrogen (TN), biochemical oxygen demand (BOD), and pH value.

4. Results and Discussion

The rainfall-runoff model was well calibrated with an average correlation coefficient and Nash-Sutcliffe efficiency of 0.93 and 0.92, respectively, using five extreme rainfall events. The calibrated parameters were then incorporated into green roof scenario studies to evaluate the effectiveness of green roofs in stormwater management. The results obtained for different types of green roofs generally can be divided into:

1) Total runoff generation, total evaporation, and total storage.
2) Pollutant removal, including TSS, TP, TN, BOD, and PH improvement.

4.1. Total Runoff Generation, Total Evaporation, and Total Storage

Figure 4 presents the observed total precipitation, simulated total runoff generation, estimated total evaporation, and expected total storage for different types of green roofs. The total amount of precipitation applied to each form of green roof is 913.00 mm. Based on the results obtained, the total evaporation of green roof types A and B are the highest that yield to 106.56 mm, followed by 105.56 mm for green roof types E and F, and subsequently, 105.25 mm for green roof type C and G. The total evaporation for green roof types D and H are 104.95 mm. Results revealed that green roof type I without berm, soil, and drainage mat has the lowest total evaporation of 34.79.

As expected, green roof type I demonstrated the highest runoff generation as no berm, soil, or drainage mat was adopted. Hence, there would be no infiltration and storage for green roof type I. Green roof type A recorded the total runoff generation of 727.65 mm, followed with 717.34 mm for green roof type E, and then 701.81 mm for green roof type C. Green roof types B, D, F, G and H had generated total runoff of 682.41 mm, 690.81 mm, 672.10 mm, 656.57 mm, and 645.58 mm, repectively.

The total runoff generation is inversely related to total storage. The total storage is proportionate with total infiltration. Hence, the best type of green roof for water storage is type H, with total storage of 162.47 mm, followed by 151.18 mm

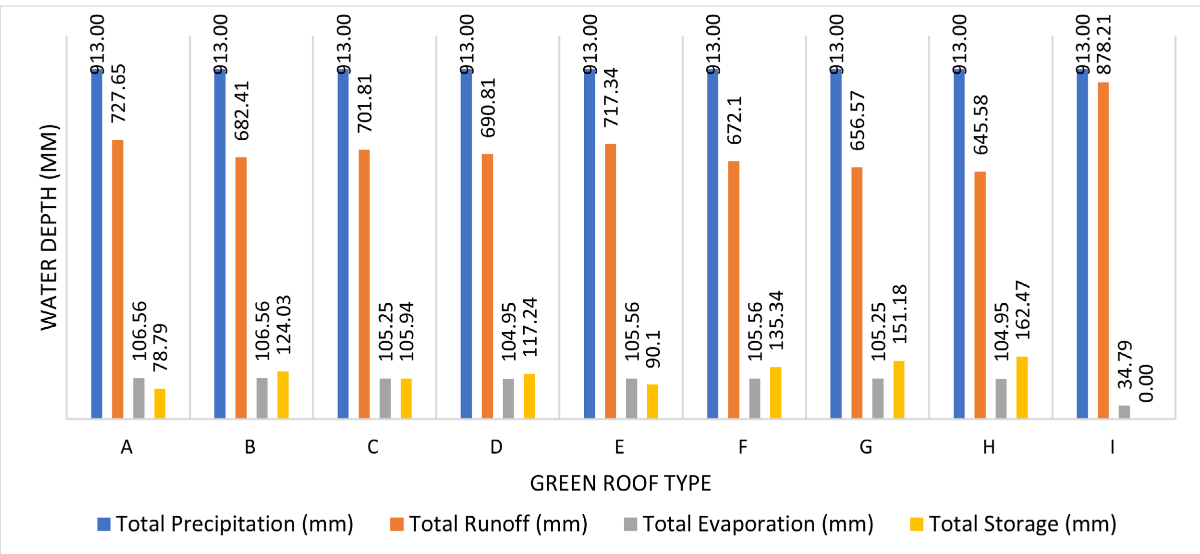

Figure 4. Total precipitation (mm), total runoff generation (mm), total evaporation (mm), and total storage (mm) for different types of green roof.

for type G, 135.34 mm for type F, 124.03 mm for type B, 117.24 mm for type D, 105.94 mm for type C, 90.10 mm for type E, and lastly, 78.79 mm for type A. There is no infiltration rate and storage capacity for green roof type I. The results revealed that green roof type H with a berm height of 100 mm, soil thickness of 150 mm, and drainage mat of 50 mm provides the best performance in terms of water storage, which is 51.50% increment compared with green roof type A and it is able to reduce the total runoff up to 26.49%.

4.2. Pollutants Removal for Different Green Roof Types

The effectiveness of different green roof types in treating the pollutants, including Total Suspended Solids (TSS), Total Phosphorus (TP), Total Nitrogen (TN), Biochemical Oxygen Demand (BOD), and PH values, are investigated in this study. The pollutants found on green roofs are originated from fertilization [39] [40] [41] (Köhler *et al.*, 2002; Berndtsson *et al.*, 2009; Gregoire & Clausen, 2011). The primary nitrogen source in the soil is organic matter, which primarily arises from plant residues. Nitrogen found in organic matter is in organic forms that are indigestible by plants. Bacteria were utilized to transform the organic nitrogen into the inorganic form so that the inorganic nitrogen would be uptaken by plants to grow, develop, and produce seeds. Nonetheless, Gregoire and Clausen [41] discovered that the green roof retained more than 65% of the zinc from precipitation.

Moreover, the findings from Köhler *et al.* [40] revealed that green roof is able to decrease the loads of nitrogen pollutant. Apart from that, green roofs can also help lessen the impacts of acid rain by increasing the pH of runoff water from 5 to 6 to above 7 to 8. Plants that grow on green roofs can absorb air pollutants such as carbon dioxide and generate oxygen. In addition, Yang *et al.* [42] also found that green roofs are able to reduce air pollution by allowing plants to absorb ozone. In this study, contaminated water with TSS of 150.697 mg/L, TP of 0.592 mg/L, TN of 4.680 mg/L, BOD of 90.897 mg/L, and PH of 7.098 was chosen to assess the efficacy of green roofs in pollutants removal.

Figure 5 revealed that the TSS was reduced significantly for all types of green roof. The TSS level was reduced significantly to 89.75%, to the lowest level of 15.452 ng/L for type H green roof. The second lowest TSS level reduction is green roof Type B with a value of 15.719 mg/L, followed by 16.096 mg/L for green roof type D. Meanwhile, the TSS level was reduced to 16.396 mg/L, 16.543 mg/L, 16.810 mg/L, 17.186 mg/L and 17.435 mg/L for green roof types B, D, E, and A, respectively. Results revealed that green roof system is extremely effective in removing TSS in water.

The effectiveness of washing off TP for all types of green roofs is presented in **Figure 6**. For types G and H green roofs, the TP level was lowered to the lowest level of 0.041 mg/L, with a total removal of 93.07%. The green roof type F had the second-lowest TP level drop, with a value of 0.042 mg/L, followed by 0.043 mg/L for types B and D. For green roof types C and A, the TP level was reduced

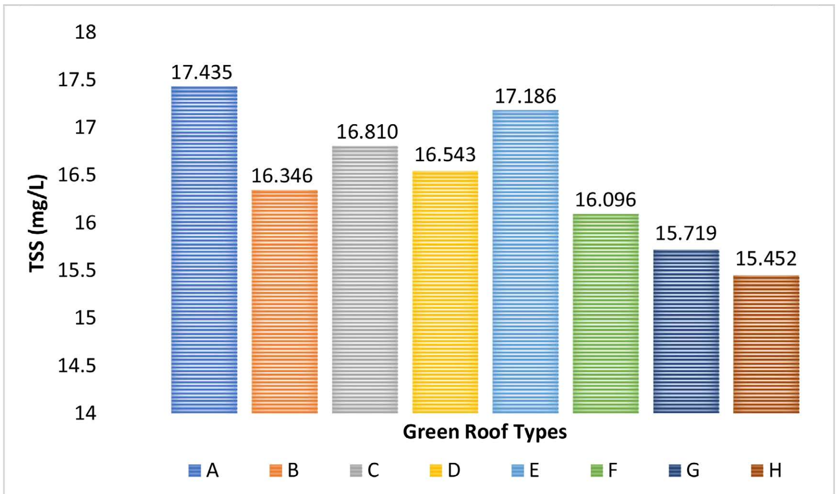

Figure 5. TSS (mg/L) Washoff for different types of green roof.

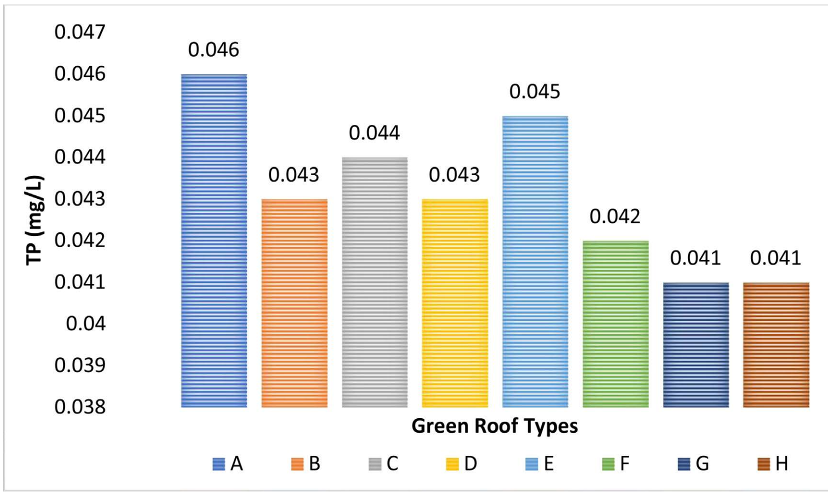

Figure 6. TP (mg/L) Washoff for different types of green roof.

to respective 0.044 mg/L and 0.046 mg/L. The results showed that the green roof system successfully eliminates TP in water.

Figure 7 illustrates how well each type of green roof eliminates TN. The TN level is removed by type H green roof to a maximum value of 0.320 mg/L, which is 93.16%, followed by type G green roofs at 0.326 mg/L and type F green roofs at 0.328 mg/L. The TP levels were also reduced to 0.339 mg/L for type B green roof, 0.343 mg/L for type D green roof, 0.349 mg/L for type C green roof, 0.362 mg/L for type D green roof. Generally, the outcome of this experiment demonstrated that the green roof effectively removes TP from water.

Figure 8 displays the effectiveness of removing BOD for all green roofs. Green roof type H is most effective in removing BOD level to 16.971 mg/L with 81.33% reduction, followed by type G green roof with BOD level of 17.254 mg/L and 17.679 mg/L for type F green roof. The BOD levels were also reduced significantly to 17.953 mg/L, 18.170 mg/L, 18.464 mg/L, and 19.149 mg/L for the green roof types B, D, C, and A, respectively. Once again, this results simulation

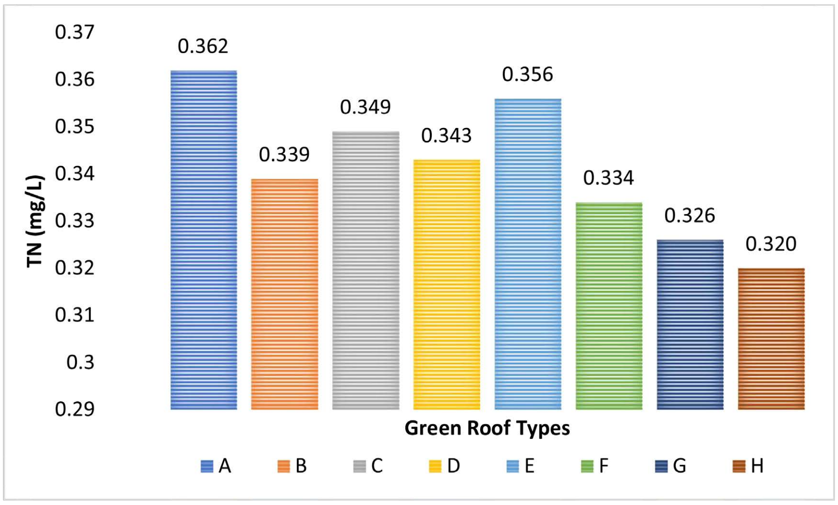

Figure 7. TN (mg/L) Washoff for different types of green roof.

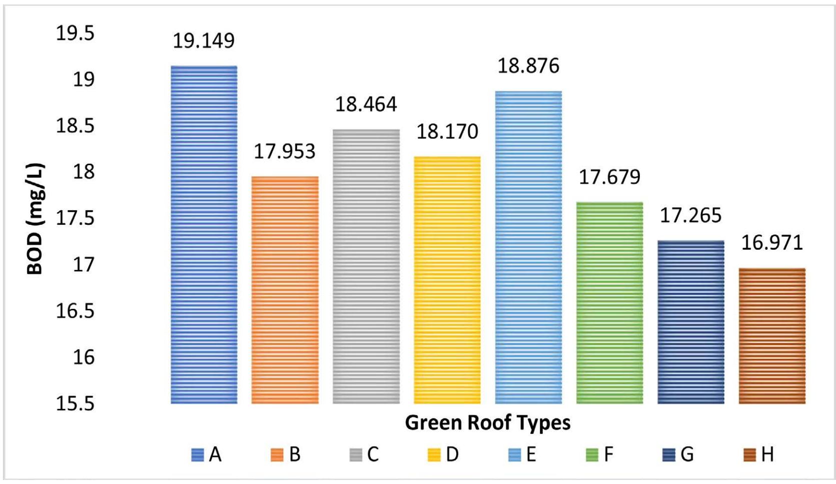

Figure 8. BOD (mg/L) Washoff for different types of green roof.

demonstrated that the green roof system effectively removes BOD from water.

Figure 9 presents the PH values after the polluted water was treated on all types of green roof. The PH value for original untreated water is 7.098. The PH values were dropped to 5.986, 5.958, 5.970, 5.963, 5.979, 5.951, 5.941 and 5.933 after treatment at green roof types A, B, C, D, E, F and G, respectively. The pH value is more acidic after filtering through the green roofs due to the substrates [43].

5. Conclusions

The adoption of green roof successfully reduced the runoff generation, and increased storage capacity and pollutant removal. Green roof type H with a berm height of 100 mm, soil thickness of 150 mm, and drainage mat thickness of 50 mm, has the overall best performance when compared to the other green roof types. Green roof type H has demonstrated its ability to reduce the runoff generation by 26.49%, and increase the storage capacity by 51.50% more than green

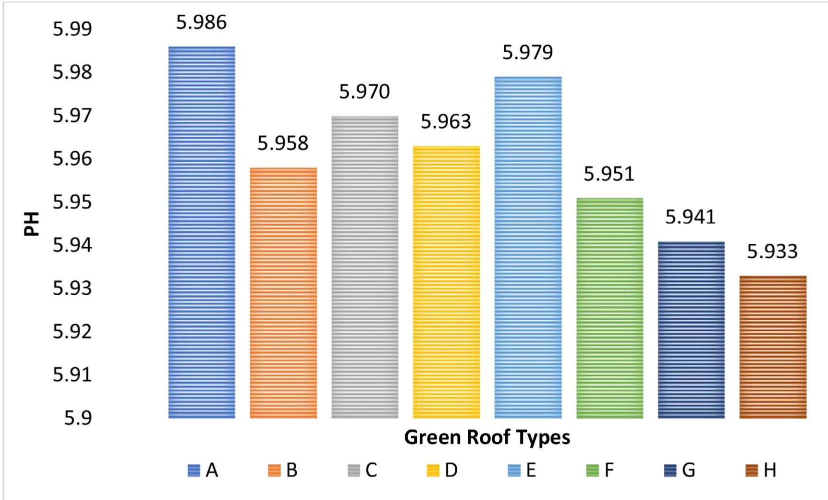

Figure 9. PH Values for different types of green roof.

roof type A. Meanwhile, green roof type H also performed well in removing 89.75% of TSS, 93.07% of TP, 93.16% of TN, and 81.33% of BOD. The main reason might be the combination of berm height, soil thickness and drainage mat for green roof type H is the thickest compared with other types of green roof. It can be concluded that the capability of green roof in water storage and pollutant removal is proportionate with the total thickness of berm height, soil thickness, and drainage mat. Therefore, the total thickness of the berm height, the soil thickness, and the drainage mat are crucial to figuring out how much and how quickly stormwater runoff is generated. Additional research is necessary to determine how much this helps with flood mitigation.

The inability of this SWMM to analyze various soil types is one of its drawbacks in terms of building green roof. Therefore, only the default values for soil attributes were used for analysis. In addition, this analysis does not include the cost of implementing a green roof system.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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