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Green Wall for Retention of Stormwater

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ABSTRACT

Urbanisation increases the level of imperviousness in a catchment, and more runoff is converted from rainfall in urban areas. To mitigate this adverse situation, dispensed green infrastructure presents the best solution for delivering results in reducing stormwater impact. Green roofs and rain gardens are extensively studied and widely available in the literature, but this is not the case for green walls, which more often than not, are treated as ornaments. Thus, this study developed a computer-aided stormwater model that incorporates a green wall to investigate its effectiveness as an urban drainage system. The effectiveness of employing a green wall as a stormwater component is tested using USEPA SWMM 5.1 and the embedded bioretention cell interface. Four simulation models according to different conditions and precipitation input are tested, compared and discussed. The conditions include investigation of different soil types, average recurrence interval (ARI) and storm duration with design and observed rainfall. The results reveal that synthesis precipitation data, used in Scenario 1, 2 and 3, decreased runoff by more than half, at 55% on condition of one-year ARI and 5 minutes of storm duration. Meanwhile, Scenario 4 also shows a repetition of runoff reduction by half after the integration of the green wall using the observed rainfall data. Thus, it is verified that a green wall can be effectively used as an urban drainage system in reducing surface runoff.

Keywords: Bioretention, green wall, runoff, SWMM, urban stormwater management

INTRODUCTION

The process of urbanisation turns natural ground cover into urban infrastructure or utility developments. Impervious surfaces such as roofs, paved roads and parking lots have expanded significantly together with post-development progress (see Figure 1). Consequently, the infiltration of stormwater into the ground as depression storage is reduced with the gradual elimination of

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vegetation as a natural filter. Thus, overland flows tend to travel faster and a huge quantity of runoff is discharged into urban stormwater conveying systems. Surface runoff is increased in urbanised watersheds, creating greater peak discharge. As the consequence of pre-development flow regime changes, natural disasters like flash floods, occur when the capacity of a drainage system fails to sustain the overwhelming quantity of runoff.

Hence, new, exhaustive and integrated stormwater management strategies are now required to underpin the Malaysian government's target of achieving sustainable urban drainage systems nationwide (DID, 2002). These new strategies incorporate various aspects of drainage, including runoff source control, management and delayed disposal of a catchment area on proactive and multifunction bases.

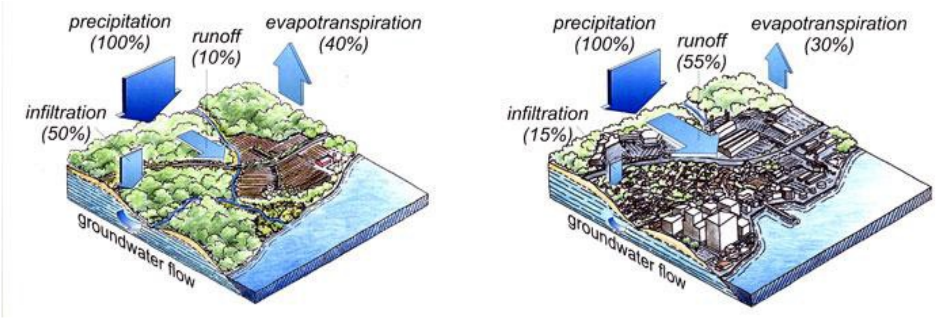


Figure 1. Typical degree of impervious areas that affect stormwater runoff, from (left) pre-development to (right) post-development (Commonwealth of Massachusetts, 2008)

Water Sensitive Urban Design

There are several well-known best practices of stormwater management used around the world that have been applied in urban developments of different countries, and one of them is Water Sensitive Urban Design (WSUD). WSUD is gaining popularity as an important element in sustainable supply planning in urban areas and has the added advantage of contributing to flood mitigation and maintaining safe water quality. Nevertheless, in order to resolve issues of high cost, land space utilisation and aesthetics of metropolitan areas, innovative stormwater management tools have emerged and been implemented. The Malaysian Urban Stormwater Management Manual (MSMA) has introduced a storage-orientated retention system that is water sensitive. The stormwater best management practices (BMPs), involving greenery and live plants, are designed to promote evapotranspiration and infiltration while minimising or delaying runoff from stormwater events (DID, 2002; 2012).

Green Infrastructure

Green infrastructure (GI) manages water and creates healthier urban environments by utilising vegetation, soil and natural processes. Considering that stormwater runoff is generated across distributed areas, the application of dispensed green infrastructure presents the best approach for delivering manifold ideal results in reducing stormwater impact. At the scale of a neighbourhood or site with small linear features, GI is referred to as a stormwater management system that mimics the nature of soaking up and storing water, for instance bioretention (well-known feature that creates 'rain gardens'), green roofs or green walls (USEPA, 2014). Green roofs and rain gardens are extensively studied and widely available in the literature, but this is not the case for green walls, which more often than not, are treated as ornaments. Therefore, it was the intention of this project to look into the applicability of green walls in capturing runoff from roof tops. Computer modelling of the mentioned system provided initial results to guide the expected working of the actual model.

Green Wall

The terminology "green wall" refers to all forms of vegetated wall surfaces (GRHC, 2008). A green wall is basically a bioretention system, but it is structured in a vertical manner on a façade or wall, without the traditional requirements of space by sacrificing built-up areas. If the conventional bioretention system is a component of the urban runoff control, then theoretically, a green wall should have the same function.

Incorporated as part of a sustainable urban drainage system, green walls can mitigate water runoff and reduce stormwater flows (Green over Grey, 2009). Percolation of rainfall within modular green walls reduces the runoff rate (see Figure 2) and offers true benefits to urban stormwater management (Loh, 2008). Stormwater can be gathered for the purpose of irrigating a green wall, which in turn increases on-site infiltration and evapotranspiration. Several preliminary studies suggest that these systems retain as much as 45% to 75% of rainfall (Webb, 2010). In addition, green walls might become one of the effective stormwater management systems via vertical planting as wall area far exceeds roof area, especially in urban development areas (Kew et al., 2013). However, it is also reported that green walls hold less potential in producing much better results than green roofs (Higgs et al., 2011).

Figure 2. Modular green wall (GRHC, 2008)

METHODOLOGY

The study site was situated within Central City, which lies strategically between the Kuching and Samarahan link way (see Figure 3) in the state of Sarawak. Kota Samarahan has been on the Government's development radar screen for the past 10 years, and it seems that this will remain the case in the foreseeable future. The township experiences a high growth rate of economic development due to its function as a hub for higher education and technology. Due to rapid property and infrastructural development, flash floods often hit residential areas lying nearby. Therefore, Central City was chosen for this study to investigate ways for combating this problematic impact of urbanisation.

The main idea of this study was to propose green walls as a component of the local urban drainage system. The main goal was to devise an effective stormwater management system and to reduce the velocity of runoffs from rainfall events to downstream reaches. This gives a clearer picture of the objective of this study as it reduces the scope of the control design variables. Modular green walls were chosen as they have a sufficient volume of growing medium with retaining characteristics to control stormwater. Dependent variables in the design included the size of the modular cell, types of planting media and design rainfall.

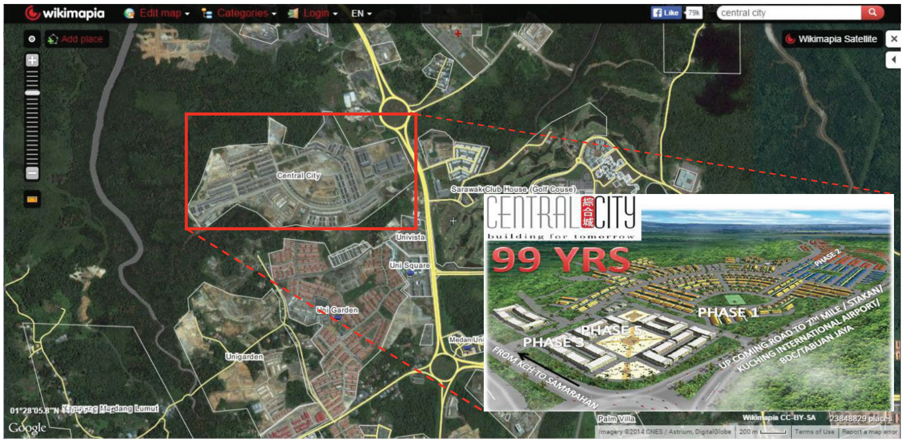


Figure 3. Aerial map of Central City via satellite image (http://wikimapia.org)

The study site was then narrowed down to a specific property in Central City. A shophouse in Phase 3 was chosen as the best option to implement the study of green walls. The major reason for this preference was that the three-storey shophouse had a relatively flat plain wall in front of the building and this available space could be put into good use. Apart from stormwater management, the green wall enhanced the aesthetic view of the commercial building and significantly reduced the urban heat island effect in Central City. A corner unit of a commercial building was chosen for a maximum roof catchment area of 139.08 m^2 for the design (see Figure 4).

Figure 4. Selected corner unit of three storey shophouse painted with orange (MD Kwang Tai, 2010)

The Elmich Green Wall was adapted for use in this project. The Elmich Green Wall is a modular system that consists of Elmich Vertical Greening Modules (VGMs); each module encases a VGM bag containing planting media, metal support frames and anchoring pilasters as shown in Figure 5 (Elmich, 2008). The green wall proposed in this study was assembled in front of a column of the commercial building. The top received runoff from the roof; then, the water slowly infiltrated the modules by gravitational force to the ground level, flowing finally into the culvert and roadside drain. The proposed size for a single green wall module was: height = 700 mm, width = 700 mm and depth = 200 mm. There were a total of 17 modules to be assembled in a straight upward manner and parallel to the column, which was approximately the height of the building.

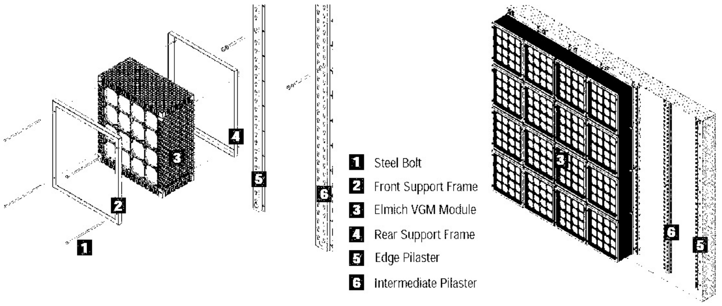


Figure 5. Elmich vertical greening modules (Elmich, 2008)

In this study, the soil for the green wall was required to allow water to pass through relatively fast. Thus, the recommended range of soil permeability was around 0.5 to 6.0 in/hr. Hence, four types of soil, namely sand, loamy sand, sandy loam and loam were chosen for analysis; the aim was to determine the best type among the four growing media for optimum performance of the green wall as an urban drainage system. Hydraulic conductivity and other useful parameters for the four selected soils are shown in Appendix A.

The performance of the green wall system was assessed within a range of ARI with 1, 2, 5, 10, 20, 50 and 100 years and storm duration of 5, 10 and 15 minutes to determine the most suitable values for satisfactory performance of the system. Design rainfall intensity (mm/hr) depends on duration (minute) and ARI (year). In this study, the intensities of different ARI and storm duration in Kota Samarahan were estimated using the computerised intensity-duration-frequency (IDF) curves generated by the Department of Irrigation and Drainage (DID) Sarawak. Apart from that, the actual data of observed rainfall (24-hour precipitation data) were used to examine the effectiveness of the green wall system as an urban drainage system. Two sets of hourly rainfall data were used for analysis: data from January 2014 represented the highest accumulated rainfall depth of the year, while data from February 2014 represented normal rainfall in Kota Samarahan, showing only about half of January's rainfall.

Using the Rational Method, peak flow, Q_1, for a 15-minute storm was manually calculated; the value derived was 0.005022 cms. Roof runoff, Q_2, for a 15-minute storm, was generated from SWMM simulation. Both results, Q_1 and Q_2, were compared, and it was found that there were no significant differences, as shown in Table 1. A comparison of 10- and 5-minute storms are presented in Table 2 and Table 3. The runoff generated by SWMM was calibrated and the performance of the green wall system was further investigated using the bioretention interface in the SWMM simulation.

Hand calculation using Rational Method can be represented as:

$$Q_1 = \frac{CiA}{360} \tag{1}$$

where

Q_1 = Peak flow (cms);

C = Runoff coefficient;

i = Average rainfall intensity (mm/hr); and

A = Drainage area (ha)

Given that at the existing condition,

- ARI = 1 year
- Rainfall intensity, i, corresponding to a 15-minute storm = 130 mm/hr
- Roof runoff coefficient, C = 1.0
- Roof catchment area, A = 139.08 m^2 = 0.013908 ha

thus, peak flow, $Q_1 = \frac{CiA}{360} = \frac{1.0(130)(0.013908)}{360} = 0.005022$ cms

Table 1
SWMM calibrations for a 15-minute storm

ARI (year)	Rainfall Intensity, *i* (mm/hr) corresponding to 15-minute storm	Peak Flow, Q_1 (cms)	SWMM-generated Roof Runoff, Q_2 (cms) for 15-minute storm
1	130	0.005022	0.005017
2	160	0.006181	0.006176
5	170	0.006568	0.006562
10	180	0.006954	0.006954
20	190	0.007340	0.007334
50	210	0.008113	0.008106
100	230	0.008886	0.008879

Table 2
SWMM calibrations for a 10-minute storm

ARI (year)	Rainfall Intensity (mm/hr) corresponding to 10-minute storm	Peak Flow, Q_1 (cms)	SWMM-generated Roof Runoff, Q_2 (cms) for 10-minute storm
1	130	0.005022	0.005015
2	160	0.006181	0.006174
5	170	0.006568	0.006560
10	180	0.006954	0.006952
20	190	0.007340	0.007333
50	210	0.008113	0.008106
100	230	0.008886	0.008879

Table 3
SWMM calibrations for a 5-minute storm

ARI (year)	Rainfall Intensity (mm/hr) corresponding to 5-minute storm	Peak Flow, Q_1 (cms)	SWMM-generated Roof Runoff, Q_2 (cms) for 5-minute storm
1	130	0.005022	0.005006
2	160	0.006181	0.006167
5	170	0.006568	0.006554
10	180	0.006954	0.006941
20	190	0.007340	0.007328
50	210	0.008113	0.008102
100	230	0.008886	0.008875

However, SWMM used another equation based on nonlinear reservoir representation (see Figure 6). Each subcatchment surface was treated as a nonlinear reservoir. Inflow came from precipitation and the runoff from any designated upstream subcatchment areas. Outflow consisted of infiltration, evaporation and surface runoff. The capacity of this 'reservoir' was the maximum depression storage, which is the maximum surface storage provided by ponding, surface wetting and interception. Surface runoff, Q, occurred only when the depth of water, d, in the 'reservoir, exceeded the maximum depression storage, d_p, in which case the outflow was given by Manning's equation:

$$Q = W\frac{1.49}{n}\left(d - d_p\right)^{5/3}S^{1/2} \qquad [2]$$

where

W is the subcatchment's characteristic width;

S is slope;

n is Manning roughness value; and

Depth of water, d_p, over the subcatchment was continuously updated with time by solving numerically a water balance equation over the subcatchment. Therefore, the hand calculation is not shown here.

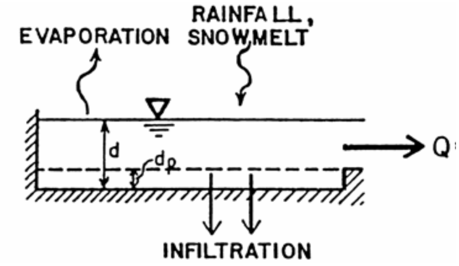


Figure 6. Nonlinear reservoir representation of a subcatchment (Huber & Dickinson, 1988)

RESULTS AND DISCUSSION

The process of employing a green wall as a stormwater component to reduce rainfall runoff was tested using Storm Water Management Model (SWMM) 5.1, which was carried out utilising an embedded bioretention cell interface. Four simulation models set to different conditions and precipitation input are shown in Table 4.

Table 4
Scenarios for modelling

Scenario	Precipitation Input	Condition
1	Design rainfall	Examine different soil media
2	Design rainfall	Examine average recurrence intervals (ARIs)
3	Design rainfall	Examine storm duration
4	Observed rainfall	Examine the effectiveness of green wall as an urban drainage system

After examining all the criteria in Scenario 1, 2 and 3 using design rainfalls, three soil types i.e loamy sand, sandy loam and loam showed equally good ability in surface runoff reduction, excluding sand, which acts as the control item. The following sizes were the design parameters that give the best result for optimum green wall performance: 12000 mm thickness, 1 year ARI and 5 minutes of storm duration (see Figures 7 to 9).

In Scenario 1, the thickness of the green wall was fixed at 12000mm and roof runoff was fixed at one-year ARI, while storm duration was 5 minutes for a single unit of corner shophouses. Hence, the types of growing media for a green wall are the dependent variables that determine the performance of the green wall. As shown in Figure 7, sand is expected to have the highest percentage of runoff reduction, followed by loamy sand, sandy loam and loam. The range is from 55.1% to 54.6%, which is a difference of only about 0.5%; thus all the soil types were considered equal in terms of runoff reduction.

All the soil types under study had higher composition of sand, which brought about a faster rate of storm water absorption. Although the permeability of clay and silt was low, their water-holding capability for retaining water was for a long period. The larger the soil particle size, the higher the conductivity. As a result, water infiltration rate increases in tandem with an increase in porosity or void between soil particles.

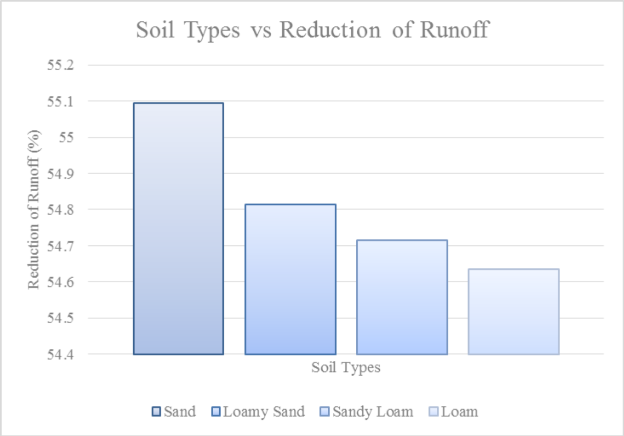


Figure 7. Reduction of runoff based on soil types for 5 minutes of one-year ARI event

In Scenario 2, the variables were given the following values: the thickness of the green wall was fixed at 12000 mm and storm duration was fixed at 5 minutes for a single corner shophouse. The ARIs were the dependent variables used to measure the performance of the green wall. Figure 8 shows the ARI traits for all the soil types, giving similar declivitous patterns from ARI year 1 until 100. The range of drop in runoff reduction was around 55% to 20%.

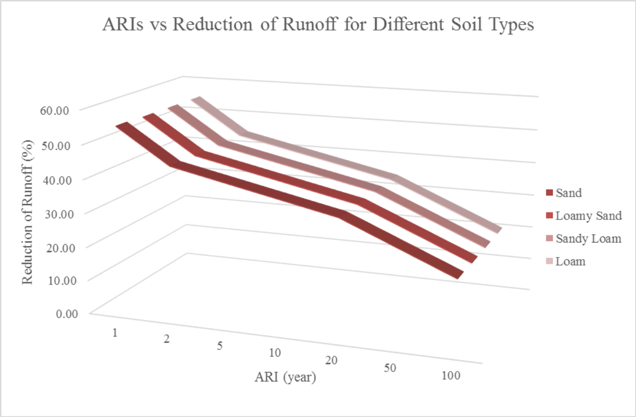


Figure 8. Reduction of runoff based on soil types and ARIs

According to DID (2010), a green wall (bioretention) is a minor system intended to collect, control and convey runoff from facilities in areas with relatively frequent storm events (recommended up to 10-year ARI) that minimises inconvenience and nuisance of flooding. The rationale of adopting a higher standard for minor systems in large commercial, business and industrial areas is that a minor system has a greater potential to cause damage and disruption in the event of flooding.

The trend of Scenario 1 was repeated for analysis, reiterating that the performance of the three soil types was the same. However, even at the extreme event of 100-year ARI, the three soil types were shown to be able to reduce about 20% of peak runoff.

In Scenario 3, the thickness of the green wall was fixed at 12000mm and the storm ARI was set at 1 year for a single corner shophouse. Hence, storm duration became the dependent variable that showcased the performance of the green wall. As shown in Figure 9, the storm duration traits for all the soil types showed similar declivitous patterns from 5 until 15 minutes. The drop in runoff reduction ranged from 55% to 22%.

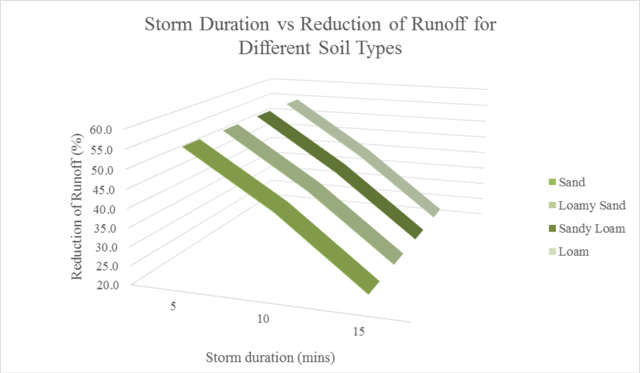


Figure 9. Reduction of runoff based on soil types and storm durations

Duration of storm is an important parameter that defines the intensity for a given ARI and thus, affects the resulting runoff peak. The storm duration that produces the maximum runoff peak traditionally is defined as the time of concentration – the sum of the travelling time to an inlet plus the time of travel in the stormwater conveyance system (DID, 2002). Although travel time from individual elements of a system may be short, the total nominal travel time of flow for all individual elements within any catchment to their points of entry into the stormwater drainage network should not be less than 5 minutes (DID, 2002).

The analysis of Scenario 3 showed that it was acceptable to use 5 minutes as the critical storm duration in order to enhance the performance of the green wall system; this was to prolong the serviceability period of the minor urban drainage system and to reduce the volume of storm runoff.

In Scenario 4, the observed rainfall data were used to test and determine the effectiveness of the green wall as an urban drainage system. Appendix B and Appendix C, respectively, show the rainfall-runoff simulations of the existing drainage system without the integration of the green wall for two months, namely January and February 2014, using two sets of actual observed rainfall data for Central City, Kota Samarahan. The simulation of roof runoffs with and without the green wall with respect to the three selected soil types (loamy sand, sandy loam and loam) were carried out and the results were compared and analysed. The performance of the green wall was not solely dependent on rainfall pattern, but also on the interval between storms for particular rainfall events. Therefore, four specific periods of storm duration with various intensity levels were extracted from January and February 2014 and analysed, as shown in Figure 10.

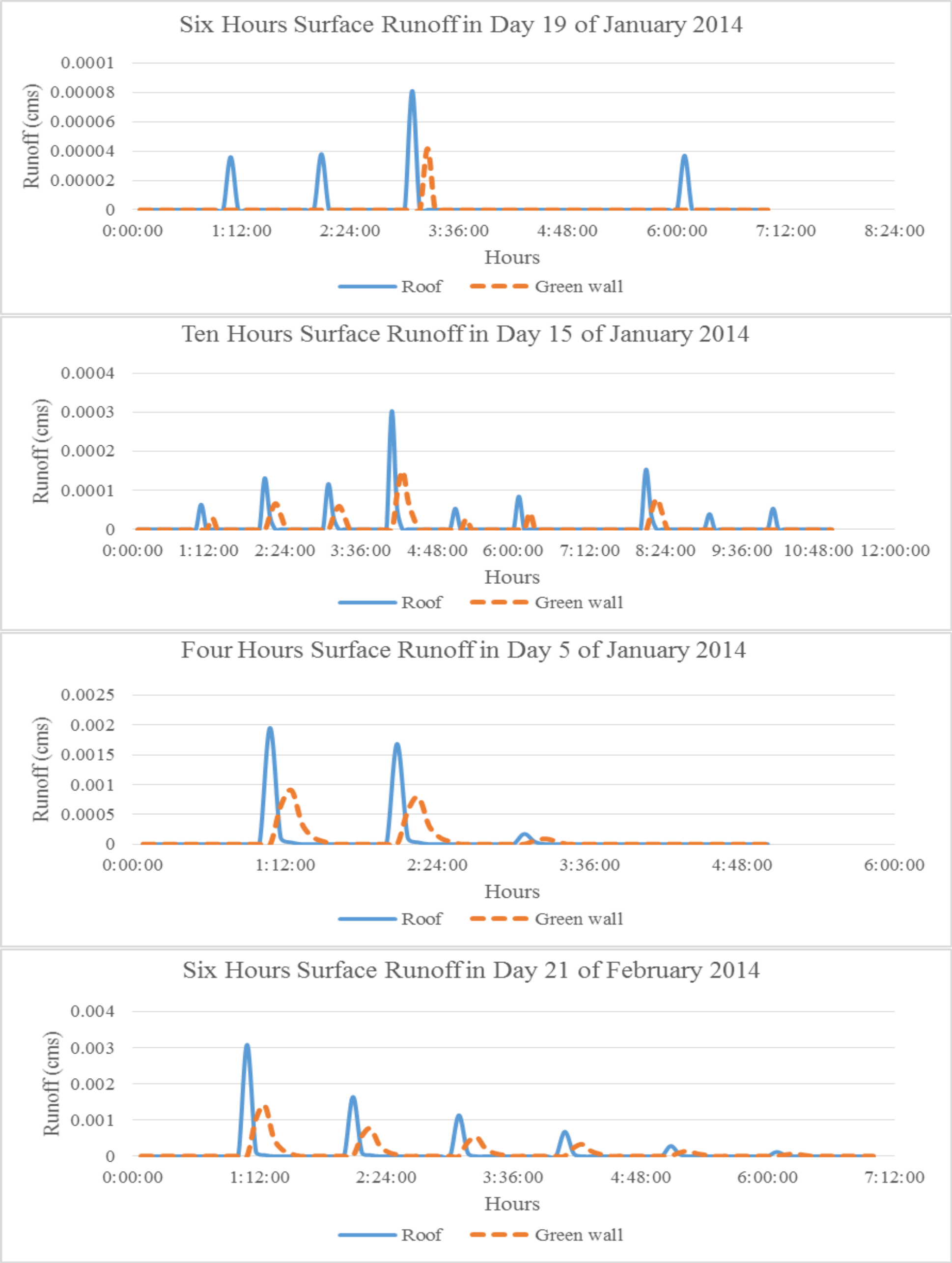


Figure 10. Four analyses of specific periods of storm duration with various intensity levels in January and February 2014

In this project, the effectiveness of a green wall as an urban drainage system was summarised by measuring hydrologic performance, which mainly focusses on deviation of runoff, with integration of the green wall system as shown in Table 5.

Table 5
Summary of hydrologic performance incorporating green wall

Scenario	Date	Continuous Storm Time Span	Intensity (mm/hr)		Average Runoff Reduction (%)
			Range	Average	
4	19 Jan	6 hrs	0.5-3.5	2.0	87
	15 Jan	10 hrs	1.5-9.5	5.5	55
	5 Jan	4 hrs	1.5-51.5	26.5	52
	21 Feb	6 hrs	4.5-80.5	42.5	52
1, 2 & 3	-	Single storm at 5 mins for one year of ARI	-	100.0	55

Scenario 4 showed the average runoff reduction gradually going down from 87% to 52% as the average rainfall intensity rose from 2.0 to 42.5 mm/hr. The increment of storm duration also degraded the performance of the green wall; changes in continuous storm time spanned from 6 to 10 hours, significantly reducing runoff reduction. With the same continuous storm time span of 6 hours, both events on 19 January and 21 February, with the intensity of 2.0 mm/hr and 42.5 mm/hr respectively, showed large gaps in runoff reduction at 35%. Thus, it is evident that when both storm duration and rainfall intensity increase, runoff reduction decreases and so does the effectiveness of the green wall as an urban drainage system facility.

CONCLUSION

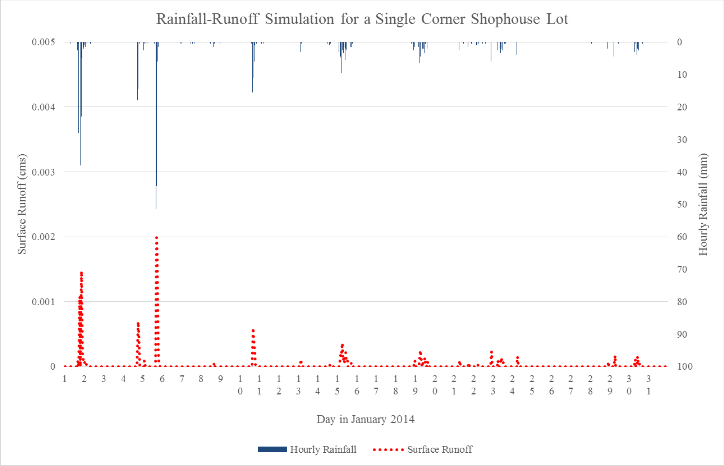
This project demonstrated green wall simulation for a commercial shophouse in Central City, Kota Samarahan. The experiment was carried out using synthesised or actual precipitation data and it tested four scenarios set up on different conditions. The simulation model on the hydrologic condition for the study area was developed to verify the effectiveness of using a green wall as an urban drainage system for reducing surface runoff using USEPA SWMM 5.1. Initially, when using synthesised precipitation data, the runoff decreased by half at 55% on the condition of one-year ARI and 5 minutes of storm duration. The results obtained in Scenario 4 showed repetition of runoff reduction by half after the integration of a green wall using the observed rainfall data.

The green wall model proposed in this study demonstrated the effectiveness of using a green wall as a component of the stormwater management system through four scenarios using SWMM simulation. The results and data displayed can be a guide for future practical design and the building of an actual model.

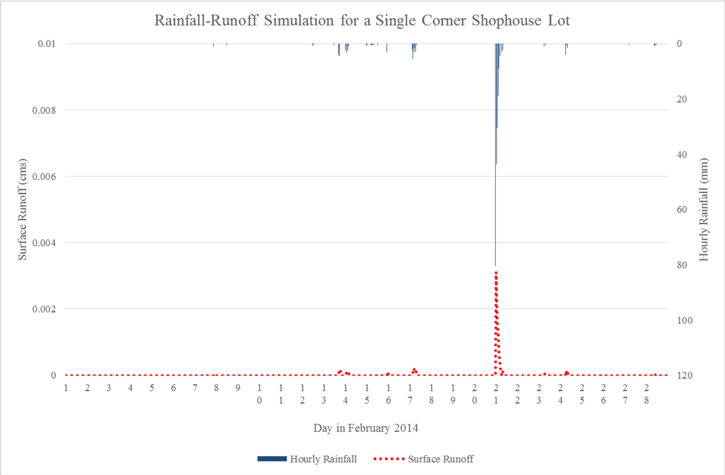
APPENDIX A

Soil Texture Class	Saturated Hydraulic Conductivity (in/hr)	Suction Head (in.)	Porosity (fraction)	Field Capacity (fraction)	Wilting Point (fraction)
Sand	4.74	1.93	0.437	0.062	0.024
Loamy Sand	1.18	2.40	0.437	0.105	0.047
Sandy Loam	0.43	4.33	0.453	0.190	0.085
Loam	0.13	3.50	0.463	0.232	0.116

APPENDIX B



APPENDIX C



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