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Research paper

Evaluation of green roof performances for urban stormwater quantity and quality controls

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ABSTRACT
Rapid urbanization in the recent decades has quickly fuelled up the process of global warming. Many mitigation measures have been formulated and implemented in order to tackle the effect of global warming. Green roofs (roof with vegetated cover) have been proposed and implemented by various countries as one of the new environmentally friendly innovation. This paper evaluates the qualitative and quantitative performances of an extensive green roof system under tropical climate. Simulations showed that the peak discharge of stormwater run-off was reduced up to 26% in relation to concrete tile roof. Its reduction ability was decreased for storms with intense rainfall. Increment of pH was observed for the green roof run-off, and the run-off quality ranged between class I and II under Malaysia National Water Quality Index (WQI). High concentrations of phosphate were observed in the run-off samples, which showed that substrates (fertilized planting soil) might be the potential contributor. Findings indicated that there was a reduction up to around 5% for indoor temperature of the building after installation of the extensive green roof system.

Keywords: Green roof; peak discharge; run-off quality; tropical climate; Water Quality Index

1 Introduction

Depleting natural resources has appealed to sustainable developments at many countries around the world in the recent decades. Technologies or innovations which conserve the environment are gradually emerging as alternatives to mitigate consequences of climate change and rapid urbanizations. One of the prominent depleting natural resource in densely built urban areas is green spaces (vegetated spaces). Phenomenon such as urban heat island (UHI) and flash flood are pertinent to excessive impervious surfaces. In recent years, local society is aware of the importance of maintaining a balance between development and environment. Several initiatives have been suggested and initiated in order to minimize the negative impacts of urbanizations. Green Building Index (GBI) was launched in 2009 in order to evaluate the design and performance of local buildings with their responses to degree of damages to environment and energy consumption. Green roof (vegetated roof) has been suggested as one of the environmentally friendly innovation that can reduce UHI

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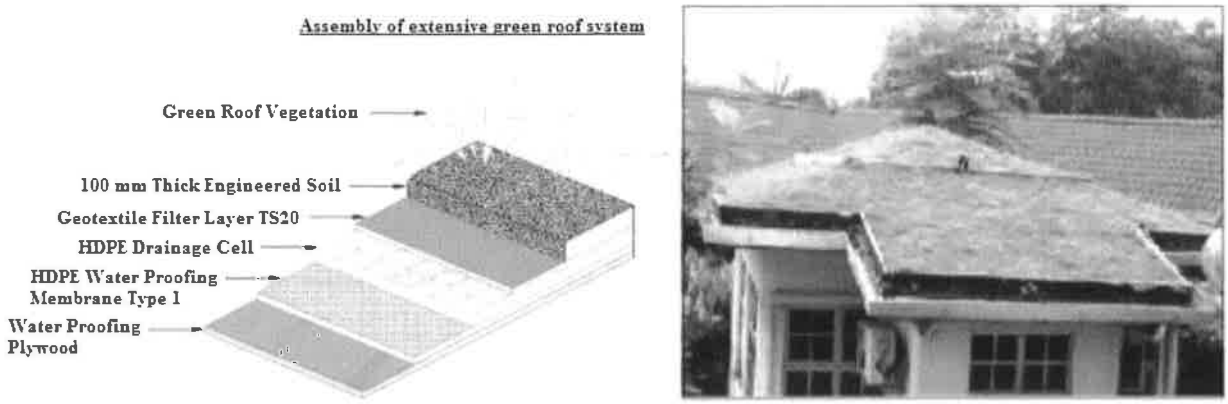

Figure 1 Configuration and details of extensive green roof system at HTC.

effect as well as minimize its impact on microclimate, human and wildlife habitat.

In fact, Urban Stormwater Management Manual for Malaysia (MSMA) was firstly introduced in 2001 as a guideline to adopt and design Best Management Practices (BMPs) in controlling stormwater in terms of quantity and quality to achieve least impacts of post-development. BMPs such as infiltration basin, swale and constructed wetland are suggested as alternatives of soft engineering structures to deal with stormwater instead of having hard structures such as concrete channel and concrete detention pond. Such BMPs are capable of augmenting coverage of green spaces in urban areas. MSMA second edition was released in 2012, whereby additional BMPs such as bio-retention/bio-filter has been featured and revised into the manual. However, green roof was not featured in MSMA, although it is one of the BMPs as well. As other stormwater manuals applied at overseas, such as Sustainable Urban Drainage System (SUDS) (UK), Low Impact Development (LID) (USA), and Water Sensitive Urban Design (WSUD) (Australia), have been suggesting that green roofs can be used as a practice for stormwater quantity and quality controls, thus there is an urge to study the performances of green roof under local tropical climate. Though there are buildings with green roofs in Malaysia, their performances are not monitored and scientifically proved in local environment. Only limited studies/works had been done on green roof system in Malaysia (Ismail *et al.* 2008, Aziz and Ismail 2011, Ismail *et al.* 2011, Johari *et al.* 2011). Thus, the scientific data obtained from this study can be applied to develop design guideline of green roof system for Malaysia in future. Thus, this paper focuses on evaluating the hydrological (quantity and quality) and thermal performance of an extensive green roof system in Malaysia.

1.1 *Green roof concept*

Green roofs are made of a system of manufactured layers deliberately placed over roofing structures which support growing medium and vegetation. Green roof systems can be generally divided into extensive green roof (Eco-roofs) and intensive green roof (Podium Garden & Sky Gardens) (Derek 2007). Extensive green roof is low-weighted and requires only minimal maintenance. Its growing media depth is usually lesser than 150 mm and the growing medium mostly consists of a high portion of lightweight inorganic materials (expanded shale, slate, sand and gravel) and a small portion of organic matter (humus and compost). On the contrary, intensive green roof is much heavier and requires a higher construction cost and constant maintenance. Its substrate layer over 150 mm is common. Due to deeper growing medium, intensive green roof system allows a complex ecosystem to be developed, which the vegetation may range from shrubs to small trees. In contrast, extensive green roof system has limited plants species due to constraint of shallow growth media. The basic components of a green roof system regardless of extensive or intensive are vegetation, growth media, drainage layer, filter layer, water proofing layer, and protection layer. Figure 1 shows the configuration of green roof components in Humid Tropics Center (HTC), Kuala Lumpur. The bottom layer of the green roof is composed of water proofing plywood and high-density polyethylene (HDPE) water proofing geo-membrane type 1 with a minimum thickness of 20 mm was laid upon it. Above the water proofing membrane is HDPE drainage cell and a layer of geotextile TS500 was inserted between the membrane and drainage cell. About 100 mm depth of engineered soil with approved fertilizer was compacted and it was placed on the drainage layer. The soil was lined with geotextile TS500 with a thickness of 1.2 mm. The type of vegetation selected for the green roof system is *Zoysia japonica* (Japan Grass).

1.2 *Green roof performances*

Numerous studies and research conducted overseas have proved that extensive green roof gives positive effects on peak discharge reduction and thermal reduction. Green roofs reduce run-off by delaying the initial time of run-off due to absorption of water in the green roof, reducing the total run-off by retaining part of the rainfall, and spreading the residual run-off over a long time period through a relatively slow release of the excess water that is stored in the substrate layer. Mentens *et al.* (2006) found that extensive roof greening on just 10% of the buildings already results in a run-off reduction of 2.7% for the region and of 54% for the individual buildings. Gregoire and Clausen (2011) reported that the studied extensive green roof in University of Connecticut retained 34% more precipitation than predicted and 51.4% of the precipitation when extrapolated to total coverage of the watershed. There are several factors that affect the hydrological performance of a green roof, which includes rainfall intensity, slope and coverage of vegetation. Teemusk and Mander (2007) found that a lightweight-aggregate (LWA)-based green roof could retain light rain events up to 86% in condition that the rain events do not occur too soon after one another, but it could not retain water for heavy rainstorm. Water storage capacity or stormwater retention ability has close relationship with rainfall intensity (Villarreal-Gonzalez and Bengtsson 2005, Carter and Rasmussen 2006). Study by Hilten *et al.* (2008) in Georgia, USA revealed that rainfall depth per storm strongly influences the performance of green roofs for stormwater mitigation. Green roof can delay initial time of run-off by retaining the rain water through the substrate layer before it is saturated. Once the growth media reaches its point of saturation, the rainwater fall on the green roof will be directed as surface run-off. Carter and Rasmussen (2006) noted that the studied green roof induced an average increase of 17.9 min for average run-off lag times when compared with the control roof. Installation of green roof in steep slope is not advisable since it will create problems regarding stability and erosion. FM Global (2007) suggests not using slopes greater than 22°. Toronto Green Roof Construction Standard Supplementary Guidelines mention that for slopes above 30°, the vegetation may present performance problems due to poor root resistance to shear. Van Woert *et al.* (2005) concluded that roof slope did affect the stormwater retention ability of green roof. However, Carter and Rasmussen (2006) stated in other way that slope of a green roof did not affect the peak flows and stormwater volumes.

Performance of green roof in enhancing water quality is debatable since it sometimes can be a source of nutrients/pollutants to the outflow. Green roofs did remove phosphorus concentration during moderate storms but not the efficient filter for pH, BOD7, and COD (Teemusk and Mander 2007). Green roof was able to neutralize acidic stormwater and acted as a filter for pollutant particles from atmosphere (Ni 2009). However, higher concentration of total nitrogen and total phosphorus were observed in the green roof outflow during the first two years of green roof's life and its media was the origin of the nutrients (Moran *et al.* 2005). There are several factors dominating the green roof run-off water quality, which includes type of material used (composition of soil, material of drainage), soil thickness, type of vegetation, local climate, dynamics of precipitation, local pollution sources, and physico-chemical properties of pollutants (Berndtsson 2009, Vijayaraghavan *et al.* 2012). Green roof contributes to building insulation and energy efficiency by trapping air layer within the plant mass so that the building surface is cooled in summer and warmed in winter (Derek 2007). Vegetation of green roof act as a cooling agent by dissipating portion of city heat via evapotranspiration, thus green roof is applied as a way to combat UHI effect and to conserve more energy, which is initially used to cool the buildings. Green roofs were able to reduce solar energy gained up to 90% when compared with non-greened-top buildings; indoor temperature for green roof's buildings was reported to have a reduction of 3–4°C as outdoor temperature ranges between 25°C and 30°C (Peck *et al.* 1999).

2 Methodology

2.1 *Study site*

The roof system of *surau* (prayer hall) at the HTC of Department of Irrigation and Drainage (DID) Malaysia was retrofitted by replacing the existing tile roof with an extensive green roof which occupies an estimated catchment area of 80 m^2 with inclined slope of about 20° (Figure 1). Besides green roof, other components such as constructed wetland, permeable pavements, bio-retention system, rainwater harvesting system, and greywater reuse system were also installed in HTC. These components combine as an integrated stormwater management called MSMA Stormwater Management Eco-hydrology (SME) that allows sustainable management and improvement of water quality entering water bodies from urban regions and reductions in potable water demand. The hydrological performance of green roof in HTC was studied by monitoring the run-off hydrographs that the green roof produced in the specified storm events. The run-off produced by the green roof was gauged by *ISCO 2110* ultrasonic flow module and a run-off collection tank with 30° V-notch weir. Green roof hydrographs were then simulated using stormwater modelling software (XP-SWMM). The simulated green roof hydrographs were calibrated to the observed green roof hydrographs to ensure that the output data generated by the modelling software was closely matched to the actual hydrographs (observed). The simulated green roof run-off hydrographs were compared to the simulated brown roof run-off hydrographs in order to determine the reduction of peak discharge of green roof in relation to the conventional impervious roof. Simulation was done both for actual storm events and design storms. For design storm events, the simulation was done based on the local rainfall temporal patterns derived for HTC. The specific design storms' durations were 10, 30, and 60 min in 2 years average recurrence interval. Run-off water samples from the green roof were collected as grab samples for randomly selected storm events. A total of three water samples were collected from the outlet of green roof for each storm event. The water samples were collected at the early, middle, and late stage of the storm event. This will represent the average run-off quality from green roof for each storm. The water samples were collected using a 2-l plastic bottle and sent to certified laboratory immediately for water quality analysis. An *in situ* water quality probe also installed at the run-off collection tank for measurements of the physical properties of the run-off such as pH, temperature, and conductivity. Water Quality Index (WQI) was calculated for each of the green roof run-off sample. Indoor temperature of the green roof building was measured by a digital thermometer which was attached to the inner wall of the building. Differences in maximum temperature recorded before and after installation of the green roof were evaluated.

3 Results and discussions

3.1 *Model calibration and validation results*

Time–Area run-off generation model was used to transform the effective rainfall to run-off hydrograph. This model was chosen to simulate the run-off hydrographs since higher value of r^2 (regressive analysis) was obtained as calibrating the simulated flow to the observed flow. The value of r^2 obtained from this run-off generation model in several randomly selected storm events ranged from 0.7 to 0.8. High value of r^2 indicates that the modelling software with the specified run-off generation model (time–area) is able to simulate the run-off rate produced by the green roof adequately. Table 1 summarizes the results of calibrations of the simulated flow to the observed flow in the specific storm events. Verifications were done for other independent storm events. The variations for the simulated peak flow relative to the observed peak flow in the specified storm events were −3.50% and 2.19%. Table 2 shows the details of verification for the run-off simulation.

3.2 *Design storm simulation results*

The calibrated and verified hydrologic parameters were applied to simulate run-off hydrograph for green roof and impervious roof. The peak discharges obtained for green roof were then

Table 1 Calibrations for hydrological simulation

Storm event	Total rainfall (mm)	Rainfall Intensity (mm/h)			R^2
		5 min	60 min	24 h	
20/7/2012	26.2	12.0	16.8	1.1	0.7786
16/8/2012	25.2	12.0	25.2	1.1	0.8393
21/8/2012	35.6	4.8	17.6	1.5	0.7959

Table 2 Verification for run-off simulation

Storm event	Observed peak flow (l/s)	Simulated peak flow (l/s)	Variation (%)
6/7/2012	0.913	0.881	−3.50
8/7/2012	0.456	0.466	2.19

Table 3 Reduction of peak discharge for green roof in different design storm duration

Design Storm (min)	Rainfall intensity (mm/h)	Reduction of Q_{peak} (%)
10	146.6	24.4
30	86.0	40.7
60	59.9	47.3

compared to impervious brown roof in order to determine the ability of the green roof in HTC in reducing the peak discharge. Table 3 summarizes the reduction of peak discharge for green roof in three different design storm durations. For design storm with 60 min duration, the reduction of peak flow can reach up to 47.3% for our green roof system.

Results show that the simulated green roof hydrographs yielded lower peak discharge than the impervious concrete tile roof in each specified duration of design storm and the reduction ability increased for storms with lower rainfall intensities. Simulations have also been carried out for actual storm events (Figure 2) and the results were summarized in Table 4. Average peak discharge reduction of 23.6% was estimated from the specified storms. Moran *et al.* (2005) in North Carolina of USA stated that their extensive green roof showed a reduction in average peak flow by more than 75%. Voyde *et al.* (2010) also found that their green roof can retain a median of 82% of rainfall received per rainfall event, with a median peak flow reduction of 93% compared to rainfall intensity. Study by Musa *et al.* (2008) found that their vegetated roof model was able to retain 17–48% of storm water run-off from rainfall. Meanwhile, Kasmin *et al.* (2014) in their study reported that a similarly configured green roof in a Malaysian climate could reduce run-off by 84% on a per-event basis and achieved a 51% overall volumetric retention. The extensive green roof system in our study is found to be less capable of reducing the peak flow when compared to that in other studies. The rainfall depths and intensities in our study are higher when compared with the study by Voyde *et al.* (2010) in Auckland, in which 95% of their monitored rainfall depths are less than 25 mm. Higher rainfall intensity in tropical climate will reduce the peak flow reduction ability in the extensive green roof system in Malaysia.

No significant peak run-off was observed during storm with low rainfall intensity. This implied that as the rainfall intensity/volume of a storm was low, the green roof system (vegetation and substrate layer) was able to retain all the effective rainfall and then the run-off was gradually released out from the system as time lapsed. Table 5 depicts the observed peak run-off during storms with low rainfall intensities.

3.3 *Assessment of green roof run-off quality*

There were a total of 15 run-off water samples collected from April 2012 to September 2012. These samples were sent to

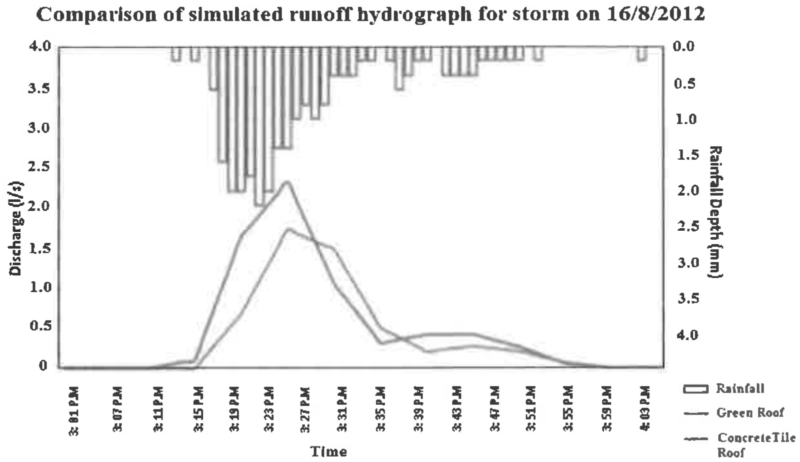

Figure 2 Comparison of simulated hydrographs for storm on 16/8/2012.

Table 4 Comparison of peak flows between green roof and concrete tile roof

Storm event	Peak flow, Q_{peak} (l/s) Green roof	Concrete tile roof	Reduction (%)
6/7/2012	0.881	1.156	23.7
8/7/2012	0.466	0.629	25.9
20/7/2012	0.639	0.840	19.1
16/8/2012	1.720	2.315	25.7

Table 5 Observed peak discharge for green roof during low rainfall intensity/volume

Storm event	Total rainfall (mm)	Rainfall Intensity (mm/h) 5 min	60 min	24 h	Observed Q_{peak} (l/s)
24/6/2012	2.0	21.6	2.0	0.1	0.020
26/6/2012	5.6	24.0	5.6	0.2	0.101
4/7/2012	5.8	9.6	3.4	0.2	0.035
11/7/2012	3.6	2.4	2.2	0.2	0.031

certified laboratory for water quality analysis. WQI of each sample was then calculated based on the results obtained from laboratory and *in situ* probe. The results of WQI for each storm event were shown in Table 6. An average WQI of 92 (Class I) was obtained out of 15 samples for the run-off generated from the green roof, which indicated that the run-off produced was clean (not polluted). Although the run-off samples achieved a high WQI and considered not polluted, but results revealed that the green roof was a source of phosphate (PO_4−P). Average concentration of 2.40 mg/l was obtained from the run-off samples collected. The substrates (fertilized planting soil) were recognized as the origin of this nutrient contained in the run-off. However, the concentration of PO_4−P presented in the run-off samples was noticed to be reducing as time lapsed due to uptake by the vegetation. Immature vegetation during the early stage caused the nutrient to leach into the run-off. Vijayaraghavan *et al.* (2012) also found significant amounts of NO_3 and PO_4 in the run-off from their extensive green roof system in Singapore. Study by Rosli *et al.* (2014) also indicated that green roof system became the source of contaminant for NO_3 and Zn. Berndtsson *et al.* (2006) in southern Sweden and Gregoire and Clausen (2011) in the USA also found a similar result that vegetated roofs contribute phosphate phosphorus to the run-off.

Average pH value of 7.823 was obtained for the collected water samples, which might explain that the outflow produced by the green roof was basic. As fresh rainwater is usually

Table 6 WQI for run-off samples in monitored storm events

Event	TSS	BOD	COD	DO	pH	NH_3−N	WQI	Class
2/5/2012	94	93	70	95	93	89	89	II
7/5/2012	95	93	80	96	95	95	93	I
10/5/2012	96	95	80	94	94	91	92	I
11/5/2012	95	94	75	94	94	90	90	II
26/6/2012	93	94	75	100	93	84	90	II
Average	94	95	80	95	94	90	92	I

Table 7 Comparison of mean indoor temperature before and after installation of green roof

Month	Monthly mean temperature, 2010 (°C) before	Monthly mean temperature, 2011 (°C) after	Reduction (°C)	Percentage of reduction (%)
January	30.3	28.7	1.6	5.28
February	32.2	30.7	1.5	4.66

acidic, it could be said that green roof has been acting as a buffer zone to increase the alkalinity of the run-off which it produced. This finding is similar to the study conducted by Kohler and Schmidt (2003), which found out that the run-off from substrates of green roof was up to 7.5 as the median pH for precipitation was just 6.2. Thus the rise of pH in the run-off might be due to basic constituents contained in the substrates consisting of fertilized planting soil. Same statement was drawn from study conducted by Ni (2009) that green roof was able to neutralize acidic stormwater. The increase of average pH during rainwater passage through the intensive vegetated roof indicated rapid neutralization of the acid depositions (Berndtsson *et al.* 2009).

Thermal performance of the green roof was monitored by comparing the maximum mean temperature recorded prior and after installation of green roof. Indoor temperature of the green roof building was measured in every interval of 15 min daily. In order to succeed the comparison, an assumption was made that the local climate in HTC before installation and after installation of green roof was about the same and fluctuation of surrounding temperature was negligible. The temperature data were available only for January and February in 2010 and 2011. Thus, comparison can only be made on these two months.

Reductions of mean temperature were noticed in both months of January and February after installation of green roof. The amount of reduction was listed in Table 7. The installed green roof was able to reduce the mean room temperature to 5.28% and 4.66% for January and February, respectively. Tabares-Velasco and Srebic (2011) in Pennsylvania, USA found that the uninsulated green roof samples with plants showed an average heat flux reduction of 25% compared to samples without plants under the laboratory conditions.

4 Conclusions

This study was carried out to evaluate the hydrological (quantity and quality) and thermal performance of an extensive green roof system in HTC, Malaysia. Findings show that the performances of extensive green roof system are promising under local tropical climate. Simulations conducted in this study indicated that the extensive green roof system could reduce the peak discharge up to 47% for design storms and 26% for actual storm when compared to concrete tile roof. However, its reduction ability decreased for storms with intense rainfall. The water quality of the outflow produced by the green roof was generally good and achieved high WQI (Class I). However, the studied green roof was a source of PO4 and acted as a buffer zone to neutralize the precipitation. Substrates of the green roof could be the essential factor in affecting the quality of the outflow. Cooler environment was created inside the green roof building since reduction of indoor temperature up to around 5% was observed after installation of the green roof system.

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Disclosure statement

No potential conflict of interest was reported by the authors.

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