A modelling study of the event-based retention performance of green roof under the hot-humid tropical climate in Kuching

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ABSTRACT

The influences of climate on the retention capability of green roof have been widely discussed in existing literature. However, knowledge on how the retention capability of green roof is affected by the tropical climate is limited. This paper highlights the retention performance of the green roof situated in Kuching under hot-humid tropical climatic conditions. Using the green roof water balance modelling approach, this study simulated the hourly runoff generated from a virtual green roof from November 2012 to October 2013 based on past meteorological data. The result showed that the overall retention performance was satisfactory with a mean retention rate of 72.5% from 380 analysed rainfall events but reduced to 12.0% only for the events that potentially trigger the occurrence of flash flood. By performing the Spearman rank’s correlation analysis, it was found that the rainfall depth and mean rainfall intensity, individually, had a strong negative correlation with event retention rate, suggesting that the retention rate increases with decreased rainfall depth. The expected direct relationship between retention rate and antecedent dry weather period was found to be event size dependent.

Key words | green roof, runoff modelling, storm water retention, urban stormwater management

INTRODUCTION

The city of Kuching, Malaysia, is subjected to the risk of flooding as nearly all parts of the city are located at the banks of major rivers or on their floodplains. In addition, the reduction in green spaces to accommodate the development pressures is altering the natural hydrologic cycle, including the rise in runoff volume and peak flow, and reductions in times of concentration. The existing local urban drainage system, which was designed based on ‘rapid disposal’, has led to an increase of the risk of flooding at the downstream of catchments due to increased surface runoff, peak discharges and shorter time of concentration. During the Northeast Monsoon, flash flood has become a common phenomenon within the flood-prone area in Kuching during the high intensity, short duration, and localized rainfall events, especially in the low-lying areas and natural floodplains along the river. In response, the Sarawak Urban Stormwater Management (SUStoM) guideline was published by the Department of Irrigation and Drainage Sarawak in the year 2016 (Sarawak Urban Stormwater Management (SUStoM) Guideline 2016). The guideline emphasizes ‘control-at-source’ techniques, which combine structural measures and Best Management Practices (BMPs) to control the water quantity and quality as well as erosion and sediment control.

As a source level control of stormwater, the green roof is one of the BMPs that have been recommended in most of the sustainable urban stormwater management approaches, such as Water Sensitive Urban Design (WSUD) in Australia and Sustainable Urban Drainage Systems (SUDS) in the United Kingdom. Studies have shown that the green roof is able to retain rainwater and reduce the runoff quantity from the roof surface, particularly in the European and North America regions (Prowell 2006; Fioretti et al. 2010; Chen 2011; Burszt-A damiak 2012; Carson et al. 2015). However, there is substantial variability in the reported retention performances. By reviewing the research trend and factors that affect the retention performances of the green roof from the existing literatures, Krishnan & Hamidah (2012) have identified climate as one of the factors that contribute to the variation in the retention performances seen between the studies. Köhler et al. (2001) suggested
that hot-humid tropical regions could benefit more from the green roof due to the high evapotranspiration. While the above studies have indicated the retention performance of a green roof, there are limited studies focused on their performance in the tropical climate region. Hence, it is uncertain whether the expected benefit from the high evapotranspiration could be overshadowed by the heavy and intense rainfall under the influences of the tropical climate.

Although the green roof has been recommended in most of the stormwater management approaches as a stormwater quantity control measure, the manual of SUSToM in Sarawak has yet to compile the green roof as one of the BMPs for a local urban stormwater management plan. Thus, there is no standardised guideline for the design and practice of green roofs in Sarawak. In order to fill the gap in knowledge of the retention performance of a green roof under the hot-humid tropical climate, this study is an initial attempt to investigate the retention performance of the green roof, specifically in Kuching, through a modelling approach. The retention performance of the green roof as applied under Kuching’s hot-humid tropical climate will be assessed to serve as valuable information for local designers, developers or policymakers to establish local guidelines for green roof construction and incorporate green roofs as part of the sustainable BMPs in SUSToM in future.

In the following sections, the paper is organised into literature review, methodology, results and discussion, and conclusion. By referring to the existing studies, the influences of meteorological factors towards event retention rate and the applicability of the green roof water balance modelling approach are presented in the literature review section. The methodology section gives a brief background of the studied location and describes the runoff modelling approach adopted in the present study. By using past meteorological data, the runoff generated from a given design of extensive green roof under different local rainfall scenarios was simulated. The retention performance of the green roof in Kuching under the influences of the hot-humid tropical climate is estimated and analysed in the results and discussion section. Lastly, the conclusion section summarises the findings from the modelling study and discusses the potential of the green roof to be one of the BMPs of the urban stormwater management plan in Kuching.

**LITERATURE REVIEW**

The hydrological performance of the green roof in term of quantity is to retain part of the stormwater. Uhl & Schiedt (2008) described that the substrate of green roof plays a similar role to the upper soil layer as the storage unit of stormwater. The volume of storage is provided by the pore volume of the substrate, the drainage system and surface of the vegetated layer. Roehr & Beck (2015) stated that for any given rainfall event, the retention capability of a green roof is highly dependent on the initial water storage capacity prior to the rainfall event. Evapotranspiration is the only mechanism to restore and optimise the water storage capacity by removing the rainwater retained by the green roof system during the antecedent dry weather period (ADWP) between two rainfall events. Theoretically, a longer ADWP associated with higher evapotranspiration rate will provide higher initial water storage capacity prior to the occurrence of a subsequent rainfall event. During the rainfall event, the green roof retains portion of the rainwater and releases excess rainwater as runoff after the water storage capacity restored during the ADWP is fully occupied. On the other hand, the green roof produces no runoff when the water storage capacity is sufficient to completely retain the rainfall. It shows that the interaction between meteorological factors under the influences of specific climate has an effect on the retention mechanism of the green roof.

As precipitation is the sole input of the green roof system, it is common that an inverse relationship is found between the event retention rate with rainfall depth (Prowell 2006; Voyde 2011; Carson et al. 2013) and rainfall intensity (Musa et al. 2011; Wai Lam & Lau 2014). Unlike a natural ground system, the water storage capacity of a green roof is finite. Thus, the proportion of rainwater retained and runoff generated by the green roof system is dependent on the amount of rainfall entering the green roof. It is often reported that a green roof performed well in retention during a light event (Prowell 2006; Hoffman et al. 2010; Chen 2011; Burszta-Adamia 2012). However, some researchers noted that events with lower rainfall depth do not guarantee a higher retention rate, as some small events were only partially retained by green roofs, while some of the large events have resulted in satisfactory retention performance (Spengen 2010; Voyde 2011).

As one of the determinants of the water storage capacity available for retention, the ADWPs is another meteorological factor that has been discussed in previous studies. The findings of Fioretti et al. (2010) showed that the overall retention performance under the event category with longer ADWP is higher compared to the event category with shorter ADWP. On the other hand, some studies revealed
that ADWP has no effect on the retention performance of the green roof, as no significant correlation was found between the variables (Spengen 2010; Voyde 2011). Spengen (2010) suggested that the water storage capacity can still be high when the ADWP is short because of a small antecedent rain event after a long dry weather period. On comparison, the influences of evapotranspiration towards the event retention performance are less obvious at the event scale. Previous studies have only discovered the influences of evapotranspiration on the retention performance after analysed the cumulative monthly and seasonal retention performances, particularly in the temperate climate region (Hoffman et al. 2010; Uhl & Schiedt 2008; Sims 2013). It appears that the accumulated effect of evapotranspiration towards the retention performance in the long term are more pronounced.

When there are limitations in instrumentation and uncontrolled climatic conditions, estimating the runoff generated from the green roof through a modelling approach is commonly practiced in previous studies. Selection of an appropriate model depends on the objective of the studies. For efficiency and responsibility of practice, the simplest model appropriate to the level of detail required or data available should always be chosen (Roehr & Beck 2015). When only the amount of runoff from a rooftop is emphasized, a green roof water balance model is an ideal approach to estimate the hydrological data from the green roof. The model accounts for all sources and fluxes of water in a defined system by balancing the inputs and outputs of water according to the water storage capacity. It is assumed that the runoff is generated from the green roof once the input exceeds the available water storage capacity of the green roof. In brief, the generation of runoff from the green roof model is determined based on the assumption as follows:

If input < available water storage capacity, then no runoff occurs

If input > available water storage capacity, then runoff occurs

A green roof water balance model has been applied in previous modelling studies that aimed to investigate the site-specific retention performance of the green roof under different climatic conditions (Prowell 2006; Sherrard & Jacobs 2012; Stovin et al. 2013; Mobilia & Longobardi 2015). By referring to the past meteorological data, the quantity of the unknown water balance component at a specific time can be estimated based on the difference between the known components. The modelling approach was proved to serve well in estimating the amount of runoff generated from a green roof according to the characteristic of local climate (Prowell 2006; Sherrard & Jacobs 2012; Stovin et al. 2013). This is because the approach required inputs from local weather data that provide a means to account for differences in climate and typology, and account for the storage changes during the ADWP in the runoff modelling process.

**METHODOLOGY**

**Case study**

Kuching is the capital city of Sarawak, the largest state in Malaysia (Figure 1). It is situated in the southwest region of the state and facing the South China Sea. The city has a total area of 1862.8 km² with a population of 617887 in the year 2010 (State Planning Unit of Sarawak 2010). It was reported that the gross domestic product per capita of the state was RM33307.00 in the year 2010. In the context of climate, the city, which is located closely to the north of the equator, is characterized by a hot and humid tropical climate. The air temperature is relatively uniform throughout the year, ranging from 22°C14°C early in the morning to 33°C14°C during the day (State Planning Unit of Sarawak 2010). The main variable of the local climate is rainfall, which is influenced by the two monsoons. The Northeast Monsoon (Landas season) usually falls between November and February and brings heavy rainfall. Meanwhile, the rest of the year is known as the Southwest Monsoon, with comparatively less rainfall.

![Figure 1](https://iwaponline.com/wst/article-pdf/76/11/2988/210353/wst076112988.pdf)
Modelling approach

In order to simulate the runoff generated from the green roof in Kuching according to the local climatic conditions, Equation (5) and Equation (4), developed by Stovin et al. (2013) based on the conceptual model of moisture flux within the green roof substrate layer, was adopted in the present study. All components of the model were presented in the unit area of the green roof surface in millimeters (mm). The amount of substrate moisture content, $S_t$ [mm] and runoff, $R_t$ [mm] from the green roof system at a specific time step, $t$ [hour] was determined according to the amount of precipitation or rainfall, $P_t$ [mm], maximum water storage capacity, $S_{max}$ [mm], initial substrate moisture content, $S_{t-1}$ [mm] and evapotranspiration, $ET_t$ [mm]. The model performed a moisture balance at an hourly time step that keeps track of how much rainwater is stored within the green roof system and leaves the system as runoff after the water storage capacity is fully occupied.

$$R_t = \begin{cases} 0, & S_{t-1} + P_t - ET_t \leq S_{max} \\ P_t - (S_{max} - S_{t-1}) - ET_t, & S_{t-1} + P_t - ET_t > S_{max} \end{cases}$$

$$S_t = \begin{cases} S_{t-1} + P_t - ET_t, & S_{t-1} + P_t - ET_t \leq S_{max} \\ S_{max}, & S_{t-1} + P_t - ET_t > S_{max} \end{cases}$$

By considering the feasibility and practicality of the green roof design, the virtual green roof applied in this modelling study was assumed to be a flat extensive green roof with approximately 80.0 mm growing media made of common agricultural ground in Sarawak. The main sedum species is *Axonopus compressus* (cow grass), which is commonly found in Sarawak and required little or no fertilizer and irrigation. The study of Liu (2013) indicates that the water storage capacity of typical growing media designed for extensive green roof systems in North America varies from 40.0% to 65.0% by volume. As the technology of green roof construction in Sarawak is considerably limited, the maximum water storage capacity of the 80 mm virtual extensive green roof was reduced to 25.0% or 20.0 mm to avoid overestimation of the retention capability. It was assumed that the runoff would be generated from the green roof once the substrate moisture content exceeded 20.0 mm. The initial substrate moisture content of the green roof at the first hour time step ($S_0$) was set to be 50.0% of the maximum water storage capacity (0.5$S_{max}$ or 10.0 mm). This assumption minimises the magnitude of the storage error when the initial substrate moisture content is unknown. Besides, the errors resulting from the initial substrate moisture content estimation are negligible after a long ADWP that empties that storage, or a heavy event that saturates the storage.

Since there were no data on evapotranspiration available from the local weather station, the value was estimated from the potential evapotranspiration (PET) rate. The PET rate is defined as the expected evapotranspiration rate associated with a crop under well-watered conditions (Berretta et al. 2014). Among the methods that have been developed for estimating the PET rate based on the meteorological data, the Hargreaves method was selected in the present study as it only requires data on air temperature that are readily available at the local weather station. The estimated average daily PET rate for each month was divided by 24 hours to obtain the average hourly PET rate. Therefore, it was assumed that every hour of the respective month had the same value of PET rate in the unit of millimeters per hour. In brief, the 1985 Hargreaves equation (Hargreaves & Samani 1985) is expressed as follows:

$$PET = 0.0023(0.408R_a)(T_{mean} + 17.8)(T_{max} - T_{min})^{0.5}$$

in which $PET$ [mm day$^{-1}$] is the potential evapotranspiration rate, $T_{mean}$ [$^\circ$C] is the daily mean air temperature, $T_{max}$ [$^\circ$C] and $T_{min}$ [$^\circ$C] is the daily maximum air temperature and daily minimum air temperature, and 0.408 is the factor to convert the unit MJ m$^{-2}$ to mm. The $R_a$ [MJ m$^{-2}$ day$^{-1}$] is the daily total extraterrestrial radiation computed from Equation (6) (Duffie & Beckman 2013), or after simplification as shown in Equation (7).

$$R_a = \frac{24(60)}{\pi} G_{SC} d_i (\omega_t \sin \varphi \sin \delta + \cos \varphi \cos \delta \sin \omega_t)$$

$$R_a \approx 37.6 \ d_i (\omega_t \sin \varphi \sin \delta + \cos \varphi \cos \delta \sin \omega_t)$$

$$d_i = 1 + 0.033 \cos \left( \frac{2 \pi}{365} I \right)$$

$$\delta = 0.409 \sin \left( \frac{2 \pi}{365} I - 1.39 \right)$$

in which $G_{SC}$ (0.0820 MJ m$^{-2}$ min$^{-1}$) is the solar constant, $d_i$ ['] is the relative distance from the Earth to the Sun, $\delta$ ['] is the solar declination, $\omega_t$ ['] is computed from arccos ($-\tan(\omega_t \tan \delta)$), $\varphi$ ['] is the latitude of the location and $I$ is the number of the day in the year (between 1 and 365).
It is important to note that the estimated hourly PET rate for each month only represents the evapotranspiration rate under well-watered conditions. Under actual conditions, it is difficult for the green roof system to be constantly maintained under well-watered conditions. Therefore, the evapotranspiration rate will eventually fall below the PET rate when access to soil moisture becomes restricted. In order to accurately estimate the change of evapotranspiration over time, the Soil Moisture Extraction Function (SMEF) model developed by Zhao et al. (2013) was adopted to estimate the actual evapotranspiration rate under the conditions of restricted moisture availability. The model considers the change in the substrate moisture condition while estimating the actual evapotranspiration from the PET value. This method describes the evapotranspiration as a function of PET multiplied by the ratio of actual moisture content to the field capacity of the substrate. By replacing the field capacity term with the maximum water storage capacity ($S_{\text{max}}$) in the denominator, the evapotranspiration rate at the time step $t$ is calculated as below:

$$ET_t = PET_t \times \frac{S_{t-1}}{S_{\text{max}}}$$

in which $PET_t$ [mm/h] is the potential evapotranspiration rate, $S_{t-1}$ [mm] is the initial water storage capacity and $S_{\text{max}}$ [mm] is the maximum water storage capacity.

**Input climate data**

In order to estimate the retention performance of the green roof under the local meteorological conditions, past rainfall data and air temperature data from 1 November 2012 to 31 October 2013 in Kuching were collected from the Department of Irrigation and Drainage Sarawak and Meteorological Department of Malaysia respectively. The past meteorological data from 1 November 2012 to 28 February 2013 represented the meteorological conditions of the Northeast Monsoon while the rest of the study period falls under the Southwest Monsoon. The continuous hourly rainfall data were recorded in the unit of millimeter depth, and individual rainfall events were separated based on a 1-hour ADWP threshold. The total rainfall depth of the individual event was calculated as the sum of consecutive hourly rainfall depth. Meanwhile, the PET were computed from the Hargreaves method based on the air temperature data.

Figure 2 displays the weather profile during the 12-month study period in Kuching. Overall, 380 rainfall events ranged between 0.5 mm to 131.5 mm with a total rainfall depth of 3466.0 mm were recorded during the 12-month study period. The data indicate that about 42.0% of the total volumetric rainfall falls within the Northeast Monsoon, even though it only spans across four months from November 2012 to February 2013. The variation in the mean daily air temperature between each month was fairly small, as might be expected due to the characteristic of a hot-humid tropical climate, with little fluctuation in air temperature. The lowest mean daily air temperature of 27.4 °C was recorded in February 2013, while the highest value of 28.8 °C was recorded in June 2013. Overall, it can be seen that the meteorological conditions during the Northeast Monsoon were associated with a higher amount of rainfall and lower air temperature compared to the Southwest Monsoon.

The event distribution between the monsoons organised by rainfall depth, mean rainfall intensity and ADWP is displayed in Figure 3. There were 170 and 210 rainfall events recorded during the Northeast Monsoon and Southwest Monsoon respectively. As illustrated in Figure 3, both monsoons were dominated by events with a rainfall depth below 10.0 mm, occupying about 70.0% of the total events, while heavy events occurred occasionally throughout the year. The figure also shows that low-intensity events occupying about 50.0% of the total event were recorded in both monsoons. On comparison, the Northeast Monsoon had a slightly higher proportion of events with a lower rainfall depth and mean rainfall intensity. It was also noted that the Northeast Monsoon was recorded with a considerably higher frequency of events with ADWP below 7 hours (47.1%) compared to the Southwest Monsoon (28.1%).

**Interpretation of results**

By referring to the simulated runoff data, the retention depth of the rainfall event was determined based on the differences between the rainfall depth and runoff depth. The event retention rate was calculated as the proportion of the retention depth over the rainfall depth. The rainfall events were organised to illustrate how the retention performance varied under different rainfall scenarios with changing meteorological factors between the monsoons in boxplot. As the monsoons under the tropical climate in Kuching are characterised by the rainfall, the meteorological factors related to the rainfall characteristics were selected for analysis, including rainfall depth, mean rainfall intensity and ADWP. From the perspective of urban stormwater management, the retention performance of the events that potentially caused the
occurrences of flash flooding was assessed too. According to the Department of Irrigation and Drainage Sarawak (n.d), convective rain with more than 60.0 mm of rainfall depth in 2 to 4 hours’ duration may cause flash flooding.

In an attempt to determine the direction and strength of correlation between the event retention rate and meteorological factors, correlation analysis was performed between the variables. Prior to correlation analysis, the normality of the data was checked using the Anderson-Darling test. It was found that all dataset did not pass the normality test. Thus, non-parametric correlation analysis (Spearman’s rank correlation) was chosen to determine the direction and strength of the relationships, if any, between the variables. All the statistical analysis was carried out using MaxStat Lite (version 3.06).

RESULTS AND DISCUSSION

Retention performance of the green roof in Kuching

The retention rate for each rainfall event in Kuching was estimated through a green roof water balance modelling approach. The retention rates of the 380 analysed events ranged from 1.9% to 100.0%, while the overall cumulative retention rate and mean retention rate were 54.6% and 72.5% respectively. Overall, 69.5% of the total events resulted in a retention rate higher than 50.0%. In particular, 53.2% of the total events (202 events) were completely retained by the green roof. Meanwhile, 11.1% and 19.5% of the total events resulted in 30.0–50.0% and below 30.0% retention rates respectively. The preliminary results showed that the retention capability of the green roof under the hot-humid tropical climate of Kuching works for most of the events throughout the year, as there was a high proportion of events that resulted in an excellent retention rate.

Unlike the temperate climates with seasonal changes, the monsoons of the hot-humid tropical climate in Sarawak are characterised by the rainfall. In an attempt to understand the influences of rainfall characteristics towards the retention performance, Figure 4 illustrates the variation in event retention performance between the monsoons according to rainfall depth, mean rainfall intensity and ADWP. It is obvious that the event retention performances decline with increased rainfall depth and mean rainfall intensity for both monsoons. For event categories with a rainfall depth below 10.0 mm and mean rainfall intensity below 2.0 mm/hour, the boxplot indicates that the mean retention rate exceeded 80.0% during the Northeast Monsoon, whilst nearly all the events were completely retained during the Southwest Monsoon.

In contrast to expectation, the retention performances did not decline with reduced ADWP. For example, the mean retention rate of an event with ADWP shorter than 7 hours was higher than the event category with 7–24 hours of ADWP during the Southwest Monsoon. The retention performance for events with ADWP below 7 hours was considerably higher, indicating 63.2% and 81.2% of mean retention rate during the Northeast Monsoon and Southwest Monsoon respectively. It was also noted that the median retention rate for nearly all categories of ADWP was 100.0%. The modeled results indicated that most of the events with a rainfall depth below 10.0 mm performed well in retention with a very high retention rate. Thus, it is thought that the high frequency of light events within the dataset of each category of ADWP has elevated the mean and median retention rate of each category of ADWP and skewed the expected decrement in retention performance.

When compared to the retention performance during the Northeast Monsoon, it was revealed that the mean retention rates for an event category with similar rainfall
depth and mean rainfall intensity were higher during the Southwest Monsoon. Most studies attributed the seasonal variations in retention performance to the changes in evapotranspiration rates between the seasons (Uhl & Schiedt 2008; Hoffman et al. 2010; Sims 2015). However, the PET rate in Kuching during the study period only ranged from 0.17 mm/hour in January 2013 to 0.20 mm/hour for most of the months during the Southwest Monsoon. Hence, it is unlikely that the variability in retention performances of similar events between the monsoons is due to the differences in evapotranspiration rates. By referring to the rainfall pattern between the monsoons, it is most likely that the reduced retention performance of similar rainfall events during the Northeast Monsoon was due to the shorter

![Figure 3](image_url)
ADWP. The rainfall data indicate that most of the rainfall events during the Southwest Monsoon had longer ADWP. On average, the ADWP of the rainfall events during the Southwest Monsoon (26.0 hours) were nearly twice the value in the Northeast Monsoon (14.0 hours). It is believed that longer ADWP between rainfall events provides more time for the evapotranspiration mechanism to restore the water storage capacity. Moreover, the variation in ADWP has a stronger effect on the regeneration of the water storage capacity due to the high evapotranspiration rate under hot-humid tropical climates. Hence, similar rainfall events have resulted in different retention performance between the monsoons due to the variation in initial water storage capacity.

The modeled result indicates that the overall retention performance of the green roof in Sarawak was satisfactory and comparable with the previous studies. However, these data must be interpreted with caution because evaluating the retention performances of significant events will ultimately determine whether a green roof system is preferred for managing urban stormwater in Kuching. During the Northeast Monsoon, the modeled results revealed that the mean retention rate declined to a minimum with a mean retention rate of 10.2% and 18.5% only when the rainfall depth exceeded 40.0 mm and mean rainfall intensity exceeded 10.0 mm/hour respectively. The reduction in retention performance with increased rainfall depth and mean rainfall...
intensity is expected, as the water storage capacity is finite. Based on the criteria of the Department of Irrigation and Drainage Sarawak, there are a total of five rainfall events that were identified as extreme events that could potentially trigger the occurrences of flash flooding in Kuching. The results indicated that the retention rate of these events ranged from 2.4% to 24.8%, with a mean retention rate of 12.0% only.

Having considered that the water storage capacity of the green roof is finite, the improvement in retention performance with higher initial water storage capacity could be minimal. The maximum water storage capacity will determine the amount of runoff produced from the green roof as well as the retention rate if the rainfall exceeds the water storage capacity. In other words, any event categorized as a significant event by DID Sarawak with a minimum 60.0 mm of rainfall will produce at least 40.0 mm runoff from the green roof, even though the water storage capacity was fully restored. The findings suggested that the virtual green roof’s retention capability is less effective during the heavy and high-intensity events that are responsible for flash floods, but it can be enhanced with increased maximum water storage capacity.

**Relationships between event retention rate and meteorological factors**

The variation in event retention performance in relation to event rainfall depth, mean rainfall intensity and ADWP is displayed in Figure 5. The results from correlation analysis between event retention rates with different meteorological factors are summarised in Table 1. When the event retention rate was plotted against rainfall depth and mean rainfall intensity, the scatterplots show a decrement trend in retention rate with increased rainfall depth and mean rainfall intensity. However, large dispersions within the data were also noted from the scatterplots. The result from Spearman’s rank correlation analysis showed that the correlation between event retention rate with rainfall characteristics were strong and statistically significant. In particular, the retention rate had the strongest correlations with rainfall depth followed by mean rainfall intensity. The significant influence of rainfall depth on retention rate is expected, as it is the sole input to the green roof system. The negative correlations indicate that the event retention rate had an inverse relationship, individually, with rainfall depth and mean rainfall intensity. The inverse relationship found between the variables is generally consistent with the findings from previous studies (Prowell 2006; Musa et al. 2011; Voyde 2011; Carson et al. 2015; Wai Lam & Lau 2014).

The evapotranspiration rate and ADWP both play important roles in determining the initial water storage capacity of the green roof. Since the local evapotranspiration rate is fairly stable, it is reasonable to expect that the ADWP will exert a stronger effect on the water storage capacity as well as the event retention rate. However, it is obvious that there were no clear associations seen between the retention rate and ADWP after the retention rates were plotted against the ADWP, as shown in Figure 5. Although the Spearman’s rank correlation analysis revealed that the event retention rate is directly related to ADWP, it was found that the correlations between the variables were relatively weak. The poor correlations found between the variables indicate that the ADWP has limited or no effect on the retention rate, and the result concurs with the findings of Spengen (2010) and Voyde (2011), which also found a weak correlation between the variables.

There are several possible explanations for this result. For example, ADWP would not be in full effect if the ADWP was only reset by a small antecedent event after a long dry weather period (Spengen 2010). The water storage capacity will still remain high after a short ADWP, as the small antecedent event did not cause a drastic change in the antecedent moisture content. In other words, ADWP is not a good indicator of the water storage capacity of the green roof. Since the local rainfall events in Kuching were dominated by light events, it is likely that most of the analysed events with short ADWP were reset by light events, and thus resulted in a higher retention rate. In addition, Stovin et al. (2012) found that the retention rate tends to be low with short ADWP, yet a long ADWP does not necessarily yield higher retention as the water storage capacity is finite. For example, the water storage capacity of the green roof was nearly optimised prior to the event on 7 March 2013 due to the long ADWP (167 hours) provided for the evapotranspiration mechanism. However, the retention rate was only 17.6% and a huge amount of runoff (47.0 mm) was produced from the green roof. This is due to the extremely high amount of rainfall (103.5 mm) that entered the green roof and exceeded the maximum water storage capacity (20.0 mm).

These shortcomings suggest that the unclear relationship between retention rate and ADWP could be partly due to the variations in event size. In order to examine whether the influences of ADWP towards retention rate are masked by the event size, Spearman’s rank correlation analysis was further performed to determine the associations between ADWP and retention rate within the dataset categorized by rainfall depth. As expected, it was found that the strength of correlations between the ADWP and retention rate were
more pronounced among the events with similar rainfall depth. The result revealed that the correlation coefficients found between the retention rate and ADWP were 0.413, 0.593, 0.525, 0.610 and 0.706 for event size categories below 10.0 mm, 10.0 mm – 20.0 mm, 20.0 mm – 30.0 mm, 30.0 mm – 40.0 mm and above 40.0 mm respectively. The moderate to strong positive correlation indicated that the event retention rate of rainfall events with similar rainfall depth tends to increase with longer ADWP. In addition, the strong to moderate correlations found between the retention rate and ADWP under the rainfall depth categories are thought to explain the variations in retention rate among events with similar rainfall depth. Overall, the result from correlation analysis suggested that the influence of ADWP towards retention rate is event size dependent.

**CONCLUSIONS**

The current paper is an initial attempt to explore the retention performance of an extensive green roof under the influences of hot-humid tropical climate specifically in Kuching through a modelling approach. The overall retention performance of the green roof was found to be satisfactory, with an estimated mean retention rate as high as 72.5% from a total of 380 analysed rainfall events. The preliminary
Findings showed that the retention capability of the green roof under the tropical climate of Kuching works for most of the events. Rainfall events with a smaller rainfall depth and mean rainfall intensity were highly retained by the green roof. It was also found that the retention performance of the green roof during the Southwest Monsoon was higher compared to the Northeast Monsoon due to the longer ADWP. However, the retention performance declined to a minimum when the rainfall depth exceeded 40.0 mm and mean rainfall intensity was higher than 10.0 mm/hour. From the aspect of urban stormwater management, the retention capability of the green roof during the events that were responsible for flash flooding was found to be less effective, with a mean retention rate of 12.0% only.

The correlation analysis revealed that, individually, the event retention rate had strong and statistically significant negative correlations with rainfall depth and mean rainfall intensity. The results also showed that ADWP, previously thought to play an important role in determining the retention performance, accounts for little of the variance in retention rate, with a weak correlation found between the variables. However, the retention rate had moderate to strong positive correlations with the ADWP after the events were organised by rainfall depth, depending on the event size. The finding suggests that the ADWP has a more pronounced effect on retention performance when the rainfall depth is taken into account. In brief, it is clear that the event retention rate of the green roof in Sarawak has an inverse relationship with rainfall depth and mean rainfall intensity, while the direct relationship between retention rate and ADWP is event size dependent. As has been noted from the strengths of correlation, it is suggested that the rainfall depth is the primary factor that affects the event retention rate of the green roof in Sarawak.

The preliminary findings add to our understanding that the effectiveness of using green roofs for stormwater runoff quantity control in Kuching is conditional. The reduced retention rate of the green roof during the events responsible for flash flooding can be enhanced with increased maximum water storage capacity, but it should be noted that it will also result in higher construction costs and rooftop loading. There are other hydrological benefits provided by the green roof towards urban stormwater management, such as detention and peak flow reduction (Chen 2011; Voyde 2011). In addition, the runoff reduction benefits provided by green roofs could also help to reduce the riverbank erosion problem, which has been included as one of the major focuses in the SUSToM guidelines. Instead of increasing the maximum water storage capacity, the green roof should be designed to achieve the best balance between various hydrological benefits offered by the green roof based on the meteorological conditions, local rooftop loading restrictions and the budget.

Due to the land size restriction, it is suggested that green roofs could be another alternative BMP to the detention/retention pond in the SUSToM guidelines. The opportunity for the installation of green roofs in Kuching is ample compared to other BMPs, as the rising number of local shopping

Table 1 | Spearman rank’s correlation analysis between event retention rate and meteorological factors

<table>
<thead>
<tr>
<th>Correlation coefficient</th>
<th>Rainfall depth</th>
<th>Mean rainfall intensity</th>
<th>ADWP</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>NE</td>
<td>SW</td>
<td>NE</td>
</tr>
<tr>
<td>Number of data pairs (XY)</td>
<td>170</td>
<td>210</td>
<td>170</td>
</tr>
<tr>
<td>r</td>
<td>-0.741</td>
<td>-0.759</td>
<td>-0.67</td>
</tr>
<tr>
<td>Statistic</td>
<td>&lt;0.0001</td>
<td>&lt;0.0001</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Correlation significant?</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Significance level: 95%</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
</tbody>
</table>

Anderson-Darling test

| Col (Meteorological factor) | p-value | <0.0001 | <0.0001 | <0.0001 | <0.0001 | <0.0001 | <0.0001 |
| Col (retention rate)        | p-value | <0.0001 | <0.0001 | <0.0001 | <0.0001 | <0.0001 | <0.0001 |
| Pass normality test (p > 0.05)? | No | No | No | No | No | No |

The preliminary findings add to our understanding that the effectiveness of using green roofs for stormwater runoff quantity control in Kuching is conditional. The reduced retention rate of the green roof during the events responsible for flash flooding can be enhanced with increased maximum water storage capacity, but it should be noted that it will also result in higher construction costs and rooftop loading. There are other hydrological benefits provided by the green roof towards urban stormwater management, such as detention and peak flow reduction (Chen 2011; Voyde 2011). In addition, the runoff reduction benefits provided by green roofs could also help to reduce the riverbank erosion problem, which has been included as one of the major focuses in the SUSToM guidelines. Instead of increasing the maximum water storage capacity, the green roof should be designed to achieve the best balance between various hydrological benefits offered by the green roof based on the meteorological conditions, local rooftop loading restrictions and the budget.

Due to the land size restriction, it is suggested that green roofs could be another alternative BMP to the detention/retention pond in the SUSToM guidelines. The opportunity for the installation of green roofs in Kuching is ample compared to other BMPs, as the rising number of local shopping
malls and hotels constructed in recent years has provided plenty of suitable yet vacant rooftop space. Although it is clear that green roofs alone will never fully solve the urban stormwater problems, the average 12.0% runoff reduction contributed by the green roof alone during the events responsible for flash flooding could still be significant when it is associated with other sustainable BMPs at parcel scale. Thus, the need to identify the most practical and effective combination of various BMPs in mitigating local stormwater issues is duly crucial. It is hoped that the estimated retention performances of the green roof in this paper can be referred as the potential contribution of the green roof alone in runoff reduction under different rainfall scenarios when it is incorporated with other BMPs in large scale modelling.

REFERENCES


Prowell, E. S. 2006 An Analysis of Stormwater Retention and Detention of Modular Green Roof Blocks. Master Thesis, Department of Forest Resources, University of Georgia, USA.


Sarawak Urban Stormwater Management (SUStoM) Guideline 2016 1st edn, Department of Irrigation and Drainage, Sarawak, Malaysia.


State Planning Unit of Sarawak 2015 Sarawak Facts and Figures 2015, State Planning Unit, Chief Minister’s Department, Malaysia.


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