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Evaluation of Green Roof Hydrological Performance in a Malaysian Context

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ABSTRACT

Using a conceptual hydrological green roof model developed in Sheffield, UK, this article explores the potential hydrological performance characteristics of a green roof in Malaysia. The conceptual rainfall–runoff model was created from data collected on an extensive green roof test bed outfitted with a commercial green roof system. The model related the roof's performance to the hydrological processes, the roof's physical characteristics and the local climatic conditions. The developed model used both hydrological flux modelling and reservoir routing techniques to evaluate the performance of rainfall retention (volumetric control) and detention (temporal delay), respectively (Stovin et al., 2013; Vesuviano et al., 2014). Utilising the generic conceptual model, data from Batu Pahat, Malaysia was used to predict retention. The same physical configuration of the Sheffield test bed was assumed. An 11-year rainfall record was used to explore the likely effectiveness of a similarly configured green roof in a Malaysian environment, both on an annual basis and in response to specific storm events. The simulation results indicated a similarly configured roof in a Malaysian climate could reduce runoff by 84% on a per-event basis and achieved a 51% overall volumetric retention. This was comparable to UK findings despite the disparities in climate.

KEYWORDS

Evapotranspiration, green roof, stormwater management, retention, Malaysia

INTRODUCTION

An extensive green roof is a lightweight roofing system comprising an underlying drainage layer and a layer of lightweight growing media covered with a vegetated layer. A green roof is a type of sustainable drainage system (SUDS) and is also a recognized method of source control, reducing and attenuating storm runoff in order to replicate natural catchment processes (CIRIA, 2014). During a rainfall event the key hydrological mechanisms operating within the green roof are the interception and storage of rainfall by the plant layer, infiltration and storage/attenuation in the substrate and reservoir storage in the drainage layer. During dry inter-event periods, moisture will be returned to the atmosphere via evapotranspiration (ET). The ET rate describes the combined effects of evaporation from the substrate and transpiration from the plants.

Studies of full-scale green roof installations consistently show that high – though quite variable – levels of stormwater retention can be achieved, but the precise performance characteristics vary depending on the construction and local climatic conditions of the green roofs. There is an identified need for generic, process-based, modelling tools that are able to predict performance at high temporal resolutions for drainage engineering applications. Several authors e.g. Villarreal & Bengtsson (2005), Jarrett and Berghage (2008), Miller (2003), Berghage *et al*. (2007) and Palla *et al*. (2008) all recognize the importance of including ET in green roof runoff modelling.

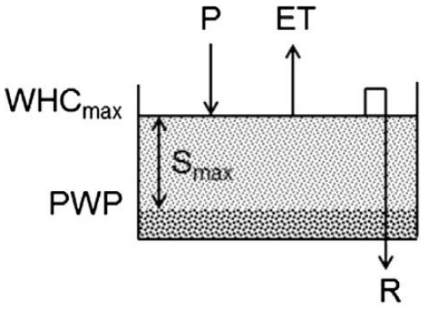
Most empirical green roof studies are based upon roofs located in seasonal climates, the majority of research being undertaken in the UK, Europe, USA, Australia and New Zealand. These countries experience seasonal changes in temperature and rainfall and the differences from season to season can be quite high (Voyde *et al*. 2010; Stovin *et al*. 2013; Wadzuk *et al*. 2013). Green roof research in tropical countries has been growing with recent developments from Singapore, Malaysia and Thailand. There are many key areas currently being investigated such as energy, thermal, urban farming (Rashid & Ahmed, 2011; Hui, 2011; Qin *et al*., 2012) and stormwater management (Qin *et al*. 2012). An evaluation study by Fauzi *et al*., (2013) on green roofs in building projects show that Malaysian stormwater studies are still lacking as opposed to those on thermal and energy efficiency (Ismail *et al*. 2011), landscape (Johari *et al.* 2011) purposes and carbon sequestration (Ismail *et al*. 2012; Rahman *et al.* 2013). However, a stormwater study on green roof test beds in Singapore has shown promising results where the test beds reduced a typical rainfall event with maximum intensity of 1 mm/min to 11.4% of total runoff and peak flow by 65% (Qin *et al.* 2013). Vergroesen & Joshi (2010) found that for similar daily rainfall depths on three consecutive days, various reductions in runoff volume (13.6% to 98.8%) and peak flow (41.9 to 98.9%) were attained. A preliminary study of green roof performance in Malaysia by Kasmin & Musa (2012) showed that retention varied between 50-100% for rainfall events with an ADWP of less than 15 hours. Several studies have emphasized that the runoff performance from green roofs is dependent on both antecedent conditions and rainfall intensity. For a tropical country like Singapore or Malaysia, these conditions are defined by a tropical climate with no significant seasonal changes (Vergroesen & Joshi 2010; NEA 2012; Qin *et al*. 2012), the impacts of which are to be studied.

Local climatic conditions are assumed to affect the performance of a green roof. If rainfall depths are high then the proportion of the rain that a specific roof is able to retain will tend to be reduced compared to the same roof in a climate that experiences smaller rainfall depths. Temperature, wind speed and other meteorological factors affect ET and also therefore affect roof retention. Hotter climates experience higher ET rates, so retention capacity can be restored more quickly, resulting in greater available storage at the start of an event. These relationships are complex, making interpolation from existing research from other climatic regions difficult.

MATERIAL AND METHODS

Stovin *et al.* (2013) developed the conceptual hydrological flux model as part of efforts to explore variations in green roof performance across the varying climate of the UK. This study adds an international perspective by considering a greatly different climatic setting. An established test plot roof installed with a commercial extensive green roof system at the University of Sheffield has been used to collect data on stormwater response. Following previous model calibration under UK climatic conditions (Kasmin, *et al.* 2010), the same test plot and conceptual model is assumed to be used for the simulation of the Malaysian climate.

Figure 1 presents the conceptual model of substrate moisture flux. The substrate's maximum water-holding capacity (WHC_{max}) defines the condition when the substrate can hold no more



P	Precipitation (mm/hr)
ET	Evapotranspiration (mm/hr)
R	Runoff (subsurface) (mm/hr)
WHC_{max}	Maximum water holding capacity (mm) (equivalent to field capacity)
PWP	Permanent wilting point
S_{max}	Maximum substrate retention capacity (mm)

Figure 1. Schematic diagram of the hydrological response of rainfall retention. (Stovin *et al.* 2013).

moisture under gravity (i.e. field capacity). The moisture content at any given time will lie somewhere between field capacity and a minimum practical moisture content, which may vary in response to ambient conditions. This minimum moisture content may be considered to define the depth of non-plant-available moisture, or the permanent wilting point (PWP) (Stovin *et al.* 2013). Standard laboratory tests exist for the determination of field capacity in green roof substrates (FLL, 2008).

The difference between WHC_{max} and PWP determines the maximum stormwater retention (or storage) capacity of the green roof (S_{max}), which is clearly finite. The value of S_{max} will depend on green roof configuration. However, empirical data presented by Stovin *et al.* (2012) suggests a typical value for S_{max} on an extensive green roof with 80 mm substrate of 20 mm. In a rainfall event, the substrate will retain rainfall (P) until the point when field capacity is reached. If further moisture is added to the system, runoff (R) will occur. In reality, due to substrate heterogeneity, runoff may be initiated slightly before field capacity is reached; this may have a minor impact on the timing of runoff (detention), but can be neglected in the context of the present model. It should be noted that, as green roof substrates typically have very high hydraulic conductivities, surface runoff is not expected to occur. Excess runoff will drain vertically down through the substrate and leave the roof via the underlying drainage layer, where it will be temporarily detained. Between rainfall events, the roof’s storage capacity will be restored via ET. ET rates vary both seasonally and daily, depending upon meteorological conditions, plant species and condition, as well as the substrate’s moisture content.

Modelling ET rates in green roof systems

Potential Evapotranspiration (PET) is the expected rate of evapotranspiration associated with a crop under well-watered conditions. If access to soil moisture becomes restricted, actual ET rates fall below the PET. PET is normally estimated based on temperature-based approaches, energy-based approaches or combination approaches, which have varying levels of input data requirements. Although complex equations, such as Penmann Monteith (Razaei, 2005), have been used for PET estimation as input for rainfall runoff models (Oudin *et al.* 2005), the temperature-based Thornthwaite model was also shown to perform well (Kasmin *et al.* 2010). The Thornthwaite equation requires only the local temperature profile in order to estimate ET for short close set vegetation with an adequate water supply (Wilson, 1990). Kasmin *et al.*, (2010) suggested that a modified form of the Thornthwaite formula led to modelled runoff results that were comparable with monitored green roof runoff.

Zhao *et al.* (2013) used the Soil Moisture Extraction Function (SMEF) model for estimating actual ET under conditions of restricted moisture availability. The basic form of the SMEF method describes ET as a function of PET multiplied by the ratio of actual moisture content to the field capacity of the substrate. In accordance with the description of the conceptual hydrological flux model, it may be suggested that $S_{\max}$ should replace the field capacity term in the denominator, which leads to a temporal decay model in the form:

$$\mathrm{ET}_t = \mathrm{PET}_\mathrm{t} \times \frac{S_{t-1}}{S_{\max}} \tag{1}$$

While there is a need to further refine PET and actual ET prediction methods for green roof systems, Stovin *et al.* (2013) also presented evidence that supports a generic modelling approach based on the use of the Thornthwaite formula to predict PET and the application of the basic SMEF model to account for the decay in ET that occurs in response to restricted substrate moisture.

Model implementation

At each time step, t, actual ET is modelled as a function of PET and substrate moisture content, S. Runoff is calculated depending on ET, the rainfall depth, P and S:

$$R_t = \begin{cases} 0, S_{t-1} + P_t - \mathrm{ET}_\mathrm{t} \le S_{\max} \\ P_t - \left(S_{\max} - S_{t-1}\right) - ET_t, S_{t-1} + P_t - \mathrm{ET}_\mathrm{t} > S_{\max} \end{cases} \tag{2}$$

Substrate moisture content is then updated:

$$S_t = \begin{cases} S_{t-1} + P_t - \mathrm{ET}_\mathrm{t}, S_{t-1} + P_t - \mathrm{ET}_\mathrm{t} \le S_{\max} \\ S_{\max}, S_{t-1} + P_t - \mathrm{ET}_\mathrm{t} > S_{\max} \end{cases} \tag{3}$$

The model has been implemented at an hourly time step. A subdaily time-step is required to characterise the system’s performance in response to individual storm events that are typically shorter in duration than one day. Note that, although in reality ET rates may vary according to a diurnal cycle, this is neglected in the model. The hourly PET value is assumed to be a constant hourly rate equivalent to the relevant monthly Thornthwaite PET rate. This simplifying assumption is justified by an appreciation that ET rates are low (in the order of 0.1 mm/h) compared with storm event rainfall intensities (1-10 mm/h). It is the cumulative effect of ET over several days prior to a storm event that impacts on the green roof’s runoff retention performance. The model has been implemented in MATLAB (2007). It should be noted that, perhaps contrary to expectations, this process-based continuous simulation approach does not require excessive computational resources. It takes less than 8 s to process an 11-year hourly rainfall time-series on a standard computer (Intel i7, 3.4 GHz).

Input climate data

Malaysia is a country with an equatorial climate, where in 2010 55% of the lived in the urban areas of Peninsular Malaysia (FAO, 2014). Peninsular Malaysia is divided into an eastern and western region by the Titiwangsa mountain range. Both regions have coastal areas, as well as various combinations of floodplains, highlands and lowlands (Suhaila & Jemain, 2007). The weather of Peninsular Malaysia is warm and humid all year round with temperatures ranging from 21°C to 32°C (Wong *et al.* 2009). The climate of Peninsular Malaysia is characterized by four rainy seasons, namely two monsoon seasons: the southwest monsoon (SWM) from May to August and northeast monsoon (NEM) from November to February; and two inter-monsoon seasons, the transitional periods between the monsoon seasons, normally in March

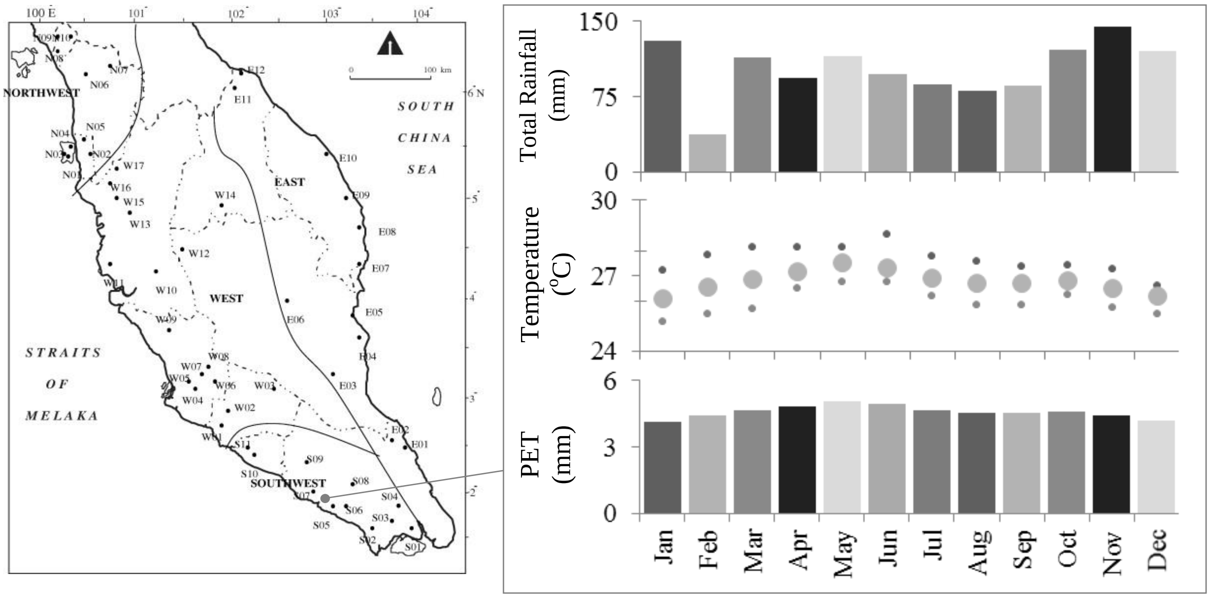


Figure 2. Left: Map of Peninsular Malaysia showing the geographical regions (Suhaila & Jemain, 2007). Right: The average monthly climate profile for Batu Pahat.

to April and September to October (Suhaila *et al.* 2010; Suhaila & Jemain, 2007). In general, SWM events are less intense than NEM events. Additional heavy rainfall normally occurs between monsoon seasons in the form of convective rains where the west coast generally sees more rainfall than the east (Suhaila *et al.* 2010).

Malaysia receives around 2000 mm to 4000 mm rainfall annually between November-March and May-September. Since 1988 the mean flood discharge of the Klang River has increased from 148 m^3/s to 440 m^3/s (Mohd Fauzi, 2013). This increase in discharge coincides with the tremendous urbanization of its catchment area. Rivers all across Malaysia whose catchment areas are undergoing various degrees of urbanization are seen to exhibit a similar trend (Mohd Fauzi, 2013). The implementation of sustainable drainage systems is critically needed to help protect Malaysia’s continuing development from the threat of flooding.

The data used in this paper is from Batu Pahat in southern Malaysia. Batu Pahat is one of the districts on Johor with a latitude of 1° 52' 0" N and longitude of 102° 59' 0" E. Batu Pahat has experienced extreme flood events with an ARI larger than 100-yr between December 2006 and January 2007 (Mohd Fauzi, 2013). Continuous 11 year rainfall and temperature data records were obtained from the Department of Irrigation and Drainage; and the Malaysian Meteorological Department, respectively. Figure 2 shows the average monthly rainfall, temperature and PET for the 11-year record. The region experienced an average monthly temperature of between 25-28^{o}C, and average monthly rainfall varied from 35 to 100 mm.

Data Analysis

Based on the conceptual water balance-based retention model, estimation on the runoff values have been determined using two input data; the daily rainfall time-series and the monthly PET rates. Runoff from the green roof was modelled using identical assumptions to those presented in Stovin *et al.* (2013). The roof was assumed to have a maximum storage capacity of 20 mm. Actual ET was modelled as a function of PET and soil moisture content, to reflect the fact that ET rates will fall when moisture supply is restricted.

All the rainfall data was read into MATLAB to identified the data gaps. Some data between 2005 and 2007 was missing due to the malfunction of the rain gauge at the Batu Pahat station. Where gaps were identified in the data the missing data was replaced with zeros. This leads to underestimations in total rainfall and runoff values but conserves the temporal characteristics of individual storm events and dry periods. The data was then aggregated into hourly time-steps using MATLAB, for comparability with Stovin *et al.* (2013). It should be noted that higher temporal resolutions than this are not required for retention analyses, which depend on (longer-term) ET processes.

ET was predicted at each time step based on PET and the current level of moisture available in the substrate moisture store (Stovin *et al*. 2013). Use of the Thornthwaite formula to predict PET for 2004 gave predicted PET values of between 3.99 and 5.30 mm/day, with a mean value of 4.55 mm/day, hence the PET was estimated to be constant at 4.55 mm/day. This assumption is justified by the extremely constant climatic conditions experienced throughout the year, with monthly mean temperatures varying only between 25-28 °C. The rainfall-runoff record was discretised into storm events (1192 in total), based on an inter-event dry period of 6 hours. Various performance statistics have been derived for all events and for significant events. In this case the ‘significant events’ are simply taken to be the 11 largest rainfall events, i.e. approximately 1 in 1 year return period events.

RESULTS AND DISCUSSION

Table 1 highlights the characteristics of rainfall, runoff and retention depth for the simulated green roof in Batu Pahat area. For 11.4 years rainfall data, 1192 rainfall events were observed with a maximum event rainfall of 147 mm over 44 hours with intensity of 3.3 mm/hr. Mean rainfall intensity for the Batu Pahat area was 2.3 mm/hr. Those events identified as significant may represent the type of rainfall that could produce flash floods in urban areas, and have a return period of approximately 1 in 1 year. Figure 3 shows the full modelled runoff response for the first year of data. It can be seen that the volumetric retention exceeds 60% in this case, which is higher than the mean volumetric retention of 51%.

During simulation, ET is assumed to continue during storm events, it is therefore possible for retention depths in excess of the defined retention capacity (in this case 20 mm) to occur. For example, an event lasting 44 hours will have almost 29 mm maximum possible retention if the moisture store is empty at the start of the event and ET is 4.55 mm/day. This explains why a maximum retention depth in excess of 20 mm has been recorded.

Table 1: Retention performance characteristics for Batu Pahat Station.

		Duration (Hours)	Rainfall depth (mm)	Runoff depth (mm)	Retention depth (mm)	Retention proportion
All Events [1192]	Mean	3.54	10.38	5.09	5.29	0.84
	Median	2.00	4.60	0.00	3.87	1.00
	Maximum	44.00	147.00	142.92	26.40	1.00
	Minimum	1.00	0.10	0.00	0.10	0.03
Significant Events [11]	Mean	16.36	104.72	91.29	13.42	0.13
	Median	9.00	96.00	85.28	11.16	0.13
	Maximum	44.00	147.00	142.92	26.40	0.23
	Minimum	5.00	76.80	65.64	4.08	0.03

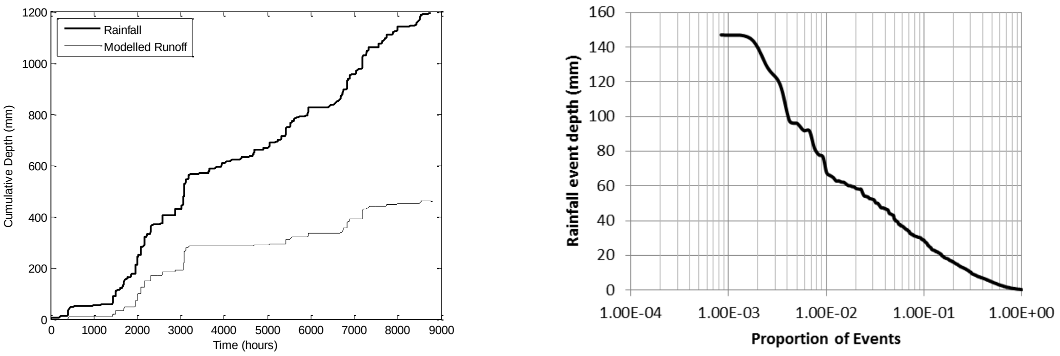


Figure 3. *Left*: Cumulative rainfall and runoff profiles for the first year of data in Batu Pahat. *Right*: Rainfall event frequency.

The mean retention proportion of 0.84 is very high. This reflects the predominance of relatively small rainfall events (mean rainfall depth 10.38 mm), combined with the high ET rates that deliver 4.55 mm retention capacity per day. i.e. the daily recharge is close to 50% of the average storm depth. The median retention proportion of 1 indicates that there are a large number of small events which it is easy for the roof to fully retain. As indicated in Figure 3, the rainfall series is characterised by many relatively small events and fewer large events. 1% of events > 70 mm; 10% events > 28.5 mm; 50% of events > 4.6 mm.

Stovin *et al.* (2013) noted that for all four UK locations the per-event retention was greater than the overall volumetric retention. This is also evident in the Malaysian data. The observed spread between the per-event and per-significant-event data is very high in the Malaysian data. This reinforces the fact that the effectiveness of green roofs in major rainfall events is limited by the roof's finite capacity. Per-event and overall retention is most comparable to the East Midlands region of the UK, but with more than double the annual rainfall.

CONCLUSION

The ability to simulate the application of an 11 year Malaysian rainfall record to the Sheffield test bed has shown the potential effectiveness of a similarly configured roof within a Malaysian environment. The application of the UK-derived conceptual hydrological flux model highlights the usefulness of a generic model for determining green roof performance. Whilst the model used here is limited to simulating the Sheffield test bed, further efforts to generalise green roof models will aid drainage engineers in determining runoff for a range of roof specifications in a variety of locations and climates. The simulation showed that a Malaysian climate is capable of supporting elevated ET rates when compared to the UK. This increase in ET enables faster regeneration of the roof's storage capacity and so the initial available storage for each event is increased, leading to a mean per-event retention of 84%. However the heavy convective rainfall events may still exceed the available storage within the roof and create runoff, as seen from the significant events where mean per-event retention was just 13%. The total volumetric reduction of 51% over the 11 year simulation represents a significant reduction in rainfall runoff.

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