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COMPARISON OF GREEN ROOF PERFORMANCE IN STORMWATER MITIGATION

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ABSTRACT

The impervious surfaces in urban areas often increase overland flow and river discharge leading to flooding issues. Green roof, being one low impact development technique, can potentially facilitate stormwater management and advert flooding problems. Although there are a number of studies examining the hydrologic behaviour of green roof, they are often limited to the monitoring periods which may not involve extreme rainfall events. They are also specific to the rainfall conditions of the study areas, making it difficult to transfer the knowledge to other countries. This study uses numerical models to quantify the hydrological behaviour of green roof and to examine the effectiveness of green roof in stormwater management. In particularly, it compares its performance in extreme rainfall events of different countries. A one-dimensional variably-saturated flow model is used. The calibrated model is subjected to the rainfall conditions of a few cities (i.e., Hong Kong, Singapore, Nagoya and London) of two-year return period. The reduction and the delay of the peak discharge, and the fraction of water retained are compared. The green roof performances (e.g., peak reduction, rainfall retained) vary due to the differences in rainfall characteristics (e.g., temporal pattern, total rainfall volume). The modeling results from different countries allow a consistent comparison, generating insights that might facilitate the transfer of results across countries. Overall, this study improves our understanding of hydrological behaviour of green roofs for stormwater management, in particularly benefiting the interpretation of green roof hydrological studies performed at rainfall conditions different from the area of interests.

Keywords: Green roof; low impact development; stormwater management; hydrological model

1. INTRODUCTION

Many urbanized areas face flooding issues, partly due to the replacement of pervious surfaces into impervious ones. To mitigate such negative hydrological impacts of urbanization and to restore the natural hydrological processes, low impact developments (LIDs) have been commonly applied in recent years. Green roof, though more commonly known for its benefits in heat mitigation and aesthetics enhancement, is one example LID practice. It is able to reduce high runoff and increase rainwater retention during rainfall (Bengtsson et al. 2005; Mentens et al. 2006; VanWoert et al. 2005). Compared to other LID practices, green roofs require no additional space (Villarreal and Bengtsson 2005) which is a significant advantage in highly urbanized cities.

There have been a number of studies about the performance of green roof in stormwater mitigation. However, the studies are mainly based on physical experiments which can be limited to the experiment duration and specific to the experiment location. For example, Gregoire and Clausen (2011) examines the effects of green roof on runoff and water quality under weekly and individual rain storm samples of runoff and precipitation in University of Connecticut, Storrs, United States. Depending on experiment duration and "luck", one might not be able to capture a large storm during the monitoring period. Furthermore, most researches were carried out in temperate regions: Germany (Köhler and Poll 2010), Sweden (Bengtsson et al. 2005), U.S Pacific North West (Schroll et al. 2011), and Estonia (Teemusk and Mander 2007), etc. Relatively little research has been performed in subtropical and tropical regions, especially regarding the hydrological behavior and thus the performance of green roof in stormwater management. Therefore, through numerical simulations, the objective of this paper is to compare the green roof performance in stormwater mitigation of a few cities that have different storm characteristics.

2. METHODS

The hydrological processes of a green roof are simulated using a generic partial differential equation solver COMSOL Multiphysics (COMSOL AB 2010). The flow through the soil layer is modeled as one-dimensional variably-saturated flow using the Richards' equation as in Eq. [1].

$$\rho\left(C_m + \rho g S e S\right)\frac{\partial H_p}{\partial t} + \frac{\partial \rho}{\partial z}\left(-\rho g \frac{\kappa_s}{\mu}\left(\frac{\partial H_p}{\partial z} + 1\right)\right) = Q_m \qquad [1]$$

where H_p is pressure head in m, C_m is specific moisture capacity in 1/m, *Se* [-] denotes the effective saturation, *S* is the storage coefficient in 1/Pa, κ_s gives the hydraulic permeability in m^2, μ is the fluid dynamic viscosity in Pa.s, κ_r [-]

denotes the relative permeability, ρ is the fluid density in kg/m^3, g is acceleration of gravity in m^2/s, and Q_m is the fluid source (positive) or sink (negative) in kg/(m^3.s).

The top boundary of the one-dimensional domain is a rainfall infiltration boundary, in which a Cauchy (mixed) boundary condition is applied. A careful choice of parameters together with conditional statements result in the boundary to behave as either a specified flux or a specified head boundary (Chui and Freyberg, 2009). When there is no water ponding on top of the green roof, the flux would be equal to the rainfall rate. However, when infiltration is smaller than the rainfall rate, water ponds and the top boundary becomes a specified head boundary with a head value that corresponds to the ponded water elevation. When a maximum ponding depth is reached, additional rainfall would become direct surface runoff bypassing the green roof system. The bottom boundary of the soil layer is a free surface boundary, in which pressure is set at atmospheric pressure.

The model is calibrated using data from Jim van Spengen's experiment (van Spengen 2010) which was carried out at National University of Singapore, Singapore. van Spengen monitored the rainfall-runoff processes that occurred on a 1 x 1 m green roof platform with a 21 cm thick soil media. Model calibration is performed using experiment data from July and September 2009, and by mainly adjusting the soil parameters. One event on 19th September is selected for time series calibration while point calibration uses the data from the first two weeks of July.

The calibrated model is then used to evaluate the green roof hydrological processes during the extreme events of a few cities. A few cities (i.e., Hong Kong, Singapore, Nagoya and London) covering tropical, subtropical and temperate zones are selected to represent various rainfall conditions. The cities also have certain levels of flooding risks and are interested in mitigating flooding problems through LIDs. For each selected city, the intensity-duration-frequency (IDF) curve is obtained. The alternating block method is adopted to transform the IDF curves into design storms of two-year return period with durations of 200 minutes. The one-dimensional model is then subjected to the design storms, and the following responses are evaluated and compared among the different cities:

- Peak reduction: the reduction in the peak discharge from the green roof (i.e., combining the runoff from the top of the green roof and the bottom of the soil layer) when compared to the peak of the design storm
- Peak delay: the timing of the peak green roof discharge compared with the timing of the design storm peak
- Water retained: the amount of water retained within the green roof will be compared with the total rainfall volume

3. RESULTS AND DISCUSSIONS

3.1 Design storms

For the four cities (i.e., Hong Kong, Singapore, Nagoya and London), design storms with two-year return period with duration of 200 minutes are determined. Figure 1 compares the design storms of the four cities, demonstrating the large variations among them. For example, the peak rainfall intensity in Hong Kong is almost three times than that in London.

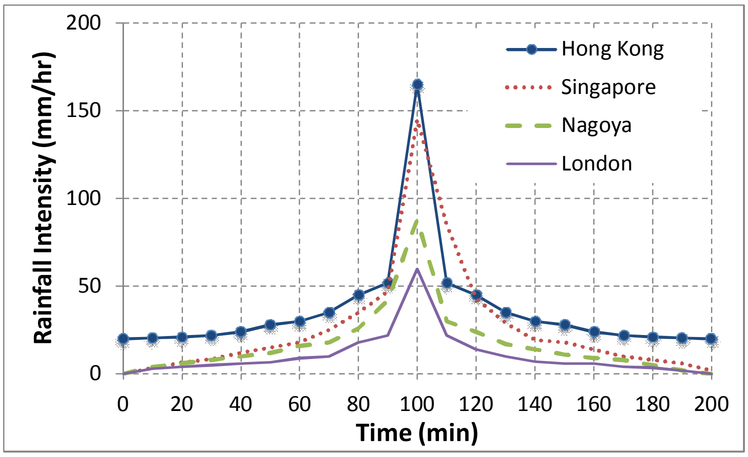

Figure 1. Design storm of two-year return period of various cities.

3.2 Performance in storm of two-year return period in Hong Kong

Taking the storm of two-year return period in Hong Kong as an example, the temporal variations of the fluxes during the storm are shown in Figure 2. The infiltration rate closely matches the precipitation rate most of the time. However, during the peak, not all the rainfall can infiltrate into the soil, generating runoff at the top of the green roof. This runoff, when combined with the drainage from the bottom of the green roof, gives the discharge shown in Figure 2. The discharge initially (e.g., first twenty minute) is significantly smaller than the precipitation and infiltration rates, implying a net gain of water within the green roof. As the green roof gets more saturated, the discharge increases. However, the peak discharge is lower than the peak precipitation rate demonstrating the reduction in peak. There is also a slight temporal delay in the discharge when compared to the precipitation, as the discharge curve is more towards the right when compared to the precipitation curve. The area under the infiltration curve is larger than that under the discharge curve. This means the total amount of water leaving the green roof is less than that entering, implying a certain amount of water is retained within the green roof.

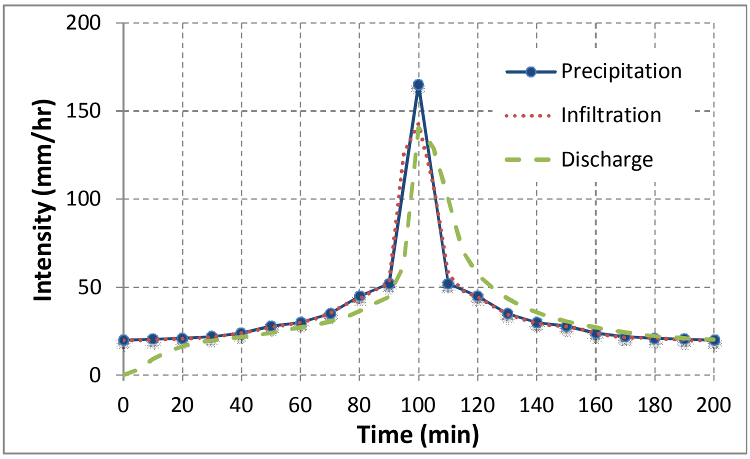

Figure 2. Inflows and outflows of green roof under storm of two-year return period of Hong Kong.

3.3 Performance comparisons among cities

With an understanding of the hydrologic processes within the green roof in response to a storm as explained in the previous section, this section compares the performances of the green roof in stormwater mitigation among the various cities. Table 1 summarizes the three key indicators, namely peak runoff reduction, peak runoff delay and water retained, together with the characteristics of the various storms.

As expected, the green roof handles smaller storms better and thus performs better in London and Nagoya than in Singapore and Hong Kong. The peak reductions of all cities are all over 15%, suggesting good performance. However, many urban drainage systems are designed for larger storms and thus further simulations should be performed with storms of larger return periods. Only Nagoya and London experience some peak delays. Simulation outputs are however at five-minute intervals and delays shorter than 5 minutes are therefore not detectable. The delays after all are only in the orders of a few minutes and are minimal except in small urban catchment which can have very short time of concentrations. Finally, the amount of water retained by the green roof is also compared. The higher the amount of water retained, the smaller the amount of discharge and thus the better the performance. Furthermore, the water retained can support evapotranspiration during dry times, reducing water requirements in irrigation. The absolute amounts of rainfall retained are larger for Hong Kong and Singapore which have larger total amounts of rainfall. However, the percentages retained are higher for Nagoya and London.

Table 1. Performance comparisons among cities.

	HONG KONG	SINGPOARE	NAGOYA	LONDON
Peak rainfall (mm/hr)	165	145	88	60
Peak discharge (mm/hr)	141	107	69	42
Peak reduction (%)	15	26	22	30
Peak delay (min)	0	0	5	5
Total rainfall (mm)	1267	944	572	357
Rainfall retained (mm)	26	24	23	20
Percentage retained (%)	2.1	2.5	4.0	5.6

4. CONCLUSIONS

The design storms of various parts of the world, e.g., tropical, subtropical and temperate zones, are very different. The performance of green roof in stormwater mitigation therefore varies. This study simulates the hydrological processes of a green roof under the two-year storm of Hong Kong, Singapore, Nagoya and London. The performances in peak runoff reduction, peak delay and water retained are compared. As expected, the green roof is more effective in mitigating the peaks of smaller storms of London and Nagoya. However, the absolute amounts of rainfall retained are larger for Hong Kong and Singapore given the larger total amounts of rainfall. The design guidelines of green roofs that focus on hydrological aspects in generally are lacking worldwide. For locations that are new to LIDs or in using green roofs to mitigate stormwater, they often take reference to guidelines published elsewhere such as those in U.K. and U.S. The simulation results of this study can provide some basis for engineers to interpret guidelines and/or results that are derived elsewhere. However, this study is preliminary and has only considered a storm of two-year return period. However, urban drainage systems are often designed to handle more extreme events such as those of ten, fifty and even a hundred year events. Therefore, green roof by itself would not be sufficient to handle those extreme events especially in Hong Kong and Singapore, and should be combined with other LID techniques (Trinh and Huong, 2013) or traditional drainage systems.

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REFERENCES

Bengtsson, L., Grahn, L., and Olsson, J. (2005). Hydrological function of a thin extensive green roof in southern Sweden. *Nordic Hydrology*, 36:259-268.

Chui, T., and Freyberg, D. (2009). Implementing hydrologic boundary conditions in a multiphysics model. *Journal of Hydrologic Engineering* , 14:1374-1377.

COMSOLAB. (2010) *COMSOL Multiphysics reference guide* (Version 4.1). Stockholm, Sweden.

Gregoire, B.G., and Clausen, J.C. (2011) Effect of a modular extensive green roof on stormwater runoff and water quality. *Ecological Engineering*, 37:963-969.

Köhler, M., and Poll, P.H. (2010) Long-term performance of selected old Berlin greenroofs in comparison to younger extensive greenroofs in Berlin. *Ecological Engineering*, 36:722-729.

Mentens, J., Raes, D., and Hermy, M. (2006) Green roofs as a tool for solving the rainwater runoff problem in the urbanized 21st century? *Landscape and Urban Planning*, 77:217-226.

Schroll, E., Lambrinos, J., Righetti, T., and Sandrock, D. (2011) The role of vegetation in regulating stormwater runoff from green roofs in a winter rainfall climate. *Ecological Engineering*, 37:595-600.

Teemusk, A., and Mander, Ü. (2007) Rainwater runoff quantity and quality performance from a greenroof: The effects of short-term events. *Ecological Engineering*, 30:271-277.

Trinh, D. H., and T. F. M. Chui (2013). Assessing the hydrologic restoration of an urbanized area via integrated distributed hydrological model. *Hydrology and Earth System Sciences*, 17: 4789-4801.

van Spengen, J. (2010). The effects of large-scale green roof implementation on rainfall-runoff in a tropical urbanized subcatchment. A Singapore case study. Faculty Civil Engneering and Geosciences. Deft, The Netherland: Delft University of Technology (TuDelft).

VanWoert, N.D., Rowe, D.B., Andresen, J.A., Rugh, C.L., Fernandez, R.T., and Xiao, L. (2005). Green roof stormwater retention: effects of roof surface, slope and media depth. *Journal of Environmental Quality*, 34:1036–1044.

Villarreal, E.L., and Bengtsson, L. (2005) Response of a Sedum green-roof to individual rain events. *Ecological Engineering*, 25:1-7.