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Assessing the significance of evapotranspiration in green roof modeling by SWMM

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ABSTRACT

Green roof is a low impact development (LID) practice used to mitigate imperviousness in urban areas and to reduce flood risks. In order to have sufficient designs and accurate runoff predictions, computer models should be utilized with full understanding of green roofs' hydrologic processes. Evapotranspiration is usually considered important by researchers in the water balance modeling of a green roof. The Storm Water Management Model (SWMM) version 5.1 is widely utilized rainfall-runoff modeling software which has LID controls capable of modeling green roofs. A previous study has evaluated the performance of this model in green roof simulations for single events without considering evapotranspiration in its application, but attained negative outcomes. Thus, the objective of this study is to determine the significance of considering evapotranspiration in producing accurate runoff simulations specifically using SWMM 5.1. The results of this study have shown that when evapotranspiration was not considered, simulations failed to agree with observed values, whereas when evapotranspiration was considered, simulated runoff volumes attained a very good fit with the observed runoff volumes proving the significance of evapotranspiration as an important parameter in green roof modeling.

Key words | evapotranspiration, green roof, hydrologic modeling, low impact development, single events, storm water management model (SWMM)

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INTRODUCTION

Rapid urbanization has caused an increase in impervious areas, which hinders the natural hydrologic functions of a watershed causing more sudden and frequent floods. Various low impact development (LID) and best management practices (BMP) have been developed to maintain or restore the original hydrologic and ecological functions of watersheds. Green roof is one of the emerging LID technologies used for retaining rainfall volume and attenuating storm runoff peak flows. Green roofs reduce storm water runoff through soil moisture retention and evapotranspiration (Berndtsson *et al.* 2009; She & Pang 2010; Wadzuk *et al.* 2013).

doi: 10.2166/hydro.2018.130

Green roof hydrologic processes

Green roof refers to a vegetated roof cover consisting of a root barrier, waterproof membrane, drainage layer, layer of growing medium, and vegetation (Berghage *et al.* 2009). Figure 1 shows a typical cross section of a green roof. It is generally categorized into two: extensive and intensive. Extensive green roofs typically have shallower substrates, are lower maintenance, and are more strictly functional in purpose, whereas intensive green roofs are more functional in providing recreational area and esthetics (Oberndorfer *et al.* 2007).

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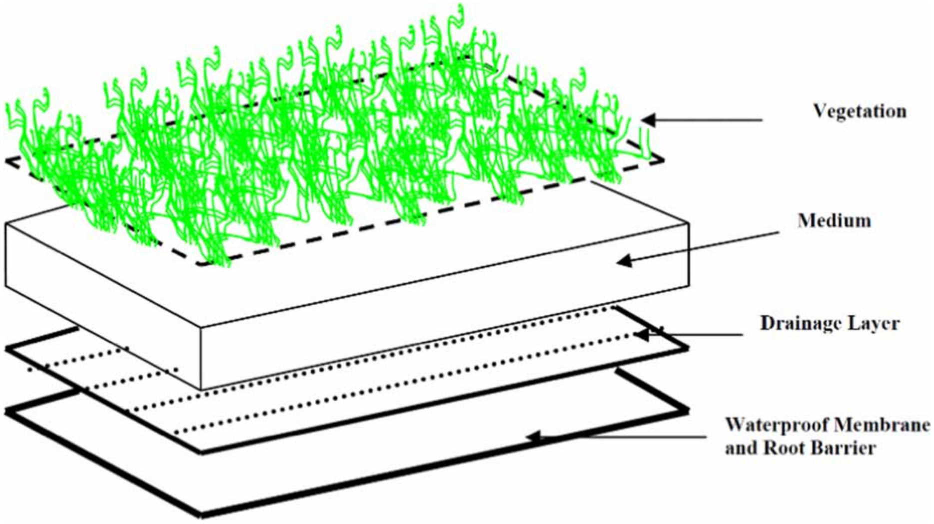

Figure 1 | Typical cross-section of a green roof system (Berghage *et al.* 2009).

A green roof functions as a stormwater control by reduction and delay of runoff. After rain falls onto the green roof, a proportion of it will be detained by the soil and the excess will flow as runoff. A proportion of this will drain into the drainage mat as runoff, and a proportion corresponding to field capacity will be retained. The retained soil moisture can be lost through evaporation and plant transpiration (evapotranspiration), creating additional storage within the soil for stormwater retention until wilting point is reached, at which evapotranspiration ceases (Berndtsson *et al.* 2009; She & Pang 2010). Evapotranspiration depends on energy, soil characteristics, moisture content, and type of vegetation (Verstraeten *et al.* 2008; Zhang & Ross 2010; Wadzuk *et al.* 2013; Limos *et al.* 2016).

There is a vast amount of literature studying the retention capacity of green roofs by merely calculating the difference between the measured precipitation and the measured runoff (Moran 2004; Villarreal & Bengtsson 2005; Carter & Rasmussen 2006). However, several researchers have pointed out that evapotranspiration should be measured in order to analyze the relationship between climatic factors and retention (Berghage *et al.* 2009; Voyde *et al.* 2010; Wadzuk *et al.* 2013). A poor understanding of this hydrologic process of green roofs can lead to the underestimation of their runoff reduction capacity by failing to account for the significance of climatic factors in green roof performance.

Green roof modeling

In order to have sufficient designs and accurate runoff or retention predictions, computer models accounting for important hydrologic processes of the green roof should be developed. Researchers have developed various mathematical models and applied software in order to evaluate and analyze the performance of green roofs. One of the methods developed to determine runoff from green roofs is the curve number method, which relies on statistical analysis of runoff collected from monitoring stations (Carter & Rasmussen 2006; Palla *et al.* 2008). She & Pang (2010) developed a physically based green roof model using three submodules: an evapotranspiration module, a flow routing module which utilized Stormwater Management Model (SWMM), and an infiltration module. In late 2010, SWMM released its own LID module in which green roofs can be modeled using the bioretention cell control. This was evaluated in a field study by Burszta-Adamiak & Mrowiec (2013), with unsatisfactory results. A specific green roof module for SWMM that came out later in 2014 was studied by Palla & Gnecco (2015), and was found to be well calibrated although based on laboratory data. Evapotranspiration was not considered in these event-based simulations. However, DiGiovanni *et al.* (2010) have reported that intra-storm evapotranspiration can be important for green roof hydrology. With mixed outcomes for runoff, the significance of

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evapotranspiration based on the literature is not clear, and there are no studies relating evapotranspiration and green roof performance for single events. Hence, it is the objective of this study to determine if considering evapotranspiration would improve the quality of SWMM simulations for single events.

MATERIALS AND METHODS

Model

The United States Environmental Protection Agency's (US EPA) SWMM is a dynamic rainfall-runoff model applicable for simulating both single events and continuous performance of runoff quantity and quality of discharge from urban areas (Rossman 2015). It is widely used in civil and environmental engineering because of its broad applicability and its public availability (Burger *et al.* 2014). It has also been popularly utilized in hydroinformatics applications of urban water management (Fang & Ball 2007; Lin *et al.* 2010; Liao *et al.* 2012; Mair *et al.* 2014). In this study, SWMM 5.1 was used for the event-based rainfall-runoff simulations, using its LID control (bio-retention cell) to model the green roof site. A similar attempt utilizing the same LID control was made by Cipolla *et al.* (2016), in studying long-term hydrological modeling of an extensive green roof. The following governing equations describe the physical mechanism of green roof hydrology, consisting of three layers (Figure 2) (Rossman & Huber 2016):

$$\phi_1 \frac{\partial d_1}{\partial t} = \mathrm{i} - e_1 - f_1 - q_1 \quad \text{Surface Layer} \tag{1}$$

$$D_2 \frac{\partial \theta_2}{\partial t} = f_1 - e_2 - f_2 \quad \text{Soil Layer} \tag{2}$$

$$\phi_3 \frac{\partial d_3}{\partial t} = f_2 - e_3 - q_3 \; \text{Storage Layer} \tag{3}$$

where:

d_1 = depth of water stored on the surface (ft)
θ_2 = soil layer moisture content (volume of water/total volume of soil)

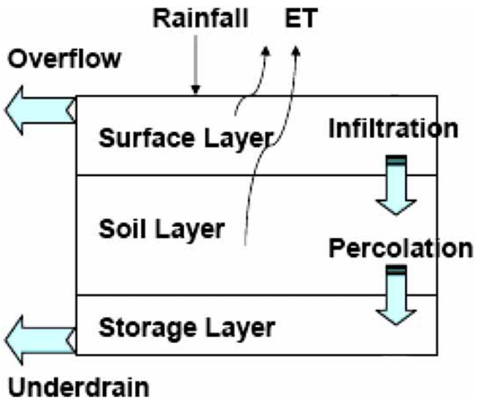

Figure 2 | A typical green roof.

d_3 = depth of water in the storage layer (ft)
i = precipitation rate falling directly on the surface layer (ft/sec)
q_1 = surface layer runoff or overflow rate (ft/sec)
q_3 = storage layer underdrain outflow rate (ft/sec)
e_1 = surface evapotranspiration rate (ft/sec)
e_2 = soil layer evapotranspiration rate (ft/sec)
e_3 = storage layer evapotranspiration rate (ft/sec)
f_1 = infiltration rate of surface water into the soil layer (ft/sec)
f_2 = percolation rate of water through the soil layer into the storage layer (ft/sec)
ϕ_1 = void fraction of any surface volume (i.e., the fraction of freeboard above the surface not filled with vegetation)
ϕ_3 = void fraction of the storage layer (void volume/total volume)
D_2 = thickness of the soil layer (ft).

Surface infiltration into the soil layer, f_1, is modeled with the Green–Ampt equation:

$$f_1 = K_{2S}\left(1 + \frac{(\phi_2 - \theta_{20})(d_1 + \psi_2)}{F}\right) \tag{4}$$

where:

f_1 = infiltration rate (ft/sec)
K_{2S} = soil's saturated hydraulic conductivity (ft/sec)
ϕ_2 = porosity (void volume/total volume) of the soil layer (used later on)
θ_{20} = moisture content at the top of the soil layer (fraction)

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ψ_2 = suction head at the infiltration wetting front formed in the soil (ft)
F = cumulative infiltration volume per unit area over a storm event (ft).

Percolation through the soil layer (f_2) is modeled using Darcy's law, and the resulting equation is:

$$f_2 = \begin{cases} K_{2S} exp(-HCO(\phi_2 - \theta_2)), & \theta_2 > \theta_{FC} \\ 0, & \theta_2 \leq \theta_{FC} \end{cases} \tag{5}$$

where K_{2S} is the soil's saturated hydraulic conductivity (ft/sec), HCO is a decay constant derived from moisture retention curve data that describes how conductivity decreases with decreasing moisture content, and θ_{FC} is the soil's field capacity moisture content.

Data

Readily available monitoring data were taken from the International Stormwater BMP Database (WERF 2017). Portland Building Ecoroof, which is located in Portland, Oregon, USA, was chosen as a study site because the available data were sufficient for simulating green roof hydrology. Sedum species and blue oat grass were planted as vegetation for the green roof (Kurtz 2010). Data include general descriptions of the site, total depths of precipitation, and total runoff volumes per event. Hourly precipitation data were taken from the City of Portland HYDRA Rainfall Network (USGS 2017). More specific design data were taken from the 2010 Stormwater Management Facilities Monitoring Report by the Bureau of Environmental Services of the City of Portland, Oregon, USA (Kurtz 2010). Parameter values not available in the report were calibrated from ranges of values recommended by green roof literature (She & Pang 2010; Taylor 2010), default values from SWMM, or from recommended ranges from the SWMM 5.1 Manual (Rossman 2015).

Model applications

Sensitivity analysis

Sensitivity analysis was carried out in order to determine which model parameters should be prioritized or neglected in the calibration procedure. The procedure utilized parameter perturbation, which involves adjusting one parameter value by a certain percentage while keeping all other parameters constant (Hamby 1994). A ±20% variation was used for this study. An event from September 27, 2007 was chosen for the analysis because it was representative of the available rainfall events in terms of duration and average intensity. The influence of the parameters on the simulated runoff volume was measured by the condition number (CN):

$$CN = \frac{k}{c}\frac{\Delta c}{\Delta k} \tag{6}$$

where k is the base parameter value, c is the corresponding base runoff, Δk is the change in parameter, and Δc is the change in runoff prediction (Chapra 2008). A larger value of CN means that the parameter has a greater influence on the simulated runoff volume. A positive CN implies that there is a direct relationship between the parameter and the output, whereas a negative CN implies that there is an inverse relationship.

Aside from the parameters in the LID Control Editor, evapotranspiration was also considered, as literature indicates that it is an important component of the water balance for green roofs (Wadzuk *et al.* 2013). Evapotranspiration is a complex process depending on soil moisture and energy factors. However, by simplification, evapotranspiration can be represented using the evaporation rate tool in SWMM. Due to lack of evapotranspiration related data, the constant evaporation option in the SWMM model was used based on the evapotranspiration rate range (1 to 10 mm/day) derived from a monitoring study conducted in Pennsylvania, USA (Wadzuk *et al.* 2013). We then considered it as a calibration parameter to be determined appropriate for use when it helps to achieve overall satisfactory fit for the runoff prediction. Table 1 lists the considered parameters and their corresponding base values.

Calibration and validation

After sensitivity analysis, calibration of influential parameters was performed. Two calibrations were done: one did not consider evapotranspiration in the simulation, whereas the other did. Parameter values were manually

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Table 1 | Initial parameters and base values

Parameter	Base value
Surface roughness	0.15[a]
Soil porosity	0.5[b]
Field capacity	0.3[b]
Wilting point	0.15[c]
Conductivity	3 in/hr[b]
Conductivity slope	10[d]
Suction head	3.5 in[d]
Storage void ratio	0.75[d]
Flow exponent	10[e]
Evaporation rate (evapotranspiration)	0.2 in/d[f]

[a] SWMM 5.1 Manual.
[b] She & Pang (2010).
[c] Taylor (2010).
[d] SWMM default value.
[e] Assumed.
[f] Wadzuk *et al.* (2013).

adjusted until the agreement between the observed and simulated runoff volumes was maximized. Using the calibrated parameter values and a different data set, the model was then validated. The data set used for calibration includes 23 rainfall events occurring from March 2007 to February 2008, whereas the data set used for validation includes 22 rainfall events occurring from March 2008 to February 2009.

The Nash–Sutcliffe efficiency coefficient (NSE) was selected as the statistical performance metric:

$$NSE = 1 - \left[\frac{\sum_{i=1}^{n}(Y_i^{obs} - Y_i^{sim})^2}{\sum_{i=1}^{n}(Y_i^{obs} - Y^{mean})^2}\right] \tag{7}$$

where Y_i^{obs} is the i-th observed value, Y_i^{sim} is i-th simulated value, Y^{mean} is the mean of observed values, and n is the total number of observations (Moriasi *et al.* 2007). Using NSE is extremely common in the evaluation of the performance of simulation models, and is recommended by the American Society of Civil Engineers. The coefficient ranges from negative infinity to 1.0. A value of 1.0 indicates perfect fit, whereas negative values show that the observed mean is a better predictor of the runoff volume. Table 2 lists the criteria given by Donigian & Love (2003) used to interpret NSE.

Table 2 | NSE criteria

Performance statistics	Poor	Fair	Good	Very good
NSE for simulation	<0.60	0.60–0.70	0.70–0.80	>0.80

RESULTS AND DISCUSSION

Sensitivity analysis

The sensitivity analysis has shown that the only parameters that have an effect on the simulated runoff volume are field capacity, wilting point, and evaporation rate. Table 3 lists the CN of the influential parameters. Field capacity (FC), having the greatest CN value, has the greatest influence on the simulated runoff volume, followed by wilting point (WP), and evaporation rate (ER). Calibration of parameters was prioritized in this order. An increase in field capacity and evaporation rate causes a decrease in runoff volume, whereas an increase in wilting point causes an increase in runoff volume.

Field capacity is described as the soil moisture content after all free water has drained off after saturation; wilting point is the soil moisture at which plants cannot survive (in SWMM, this is the minimum allowable soil moisture); and lastly, evaporation rate represents evapotranspiration, which is the drying process of soil due to both evaporation and transpiration of plants. These three parameters describe the processes in which runoff volume can be reduced: retention and drying. The other parameters (e.g., porosity and conductivity) that were initially considered may have an effect on peak flow and hydrograph, but not on the total runoff volume.

As was seen in three governing equations for green roof hydrology (Equations (1)–(3)), total runoff from the green roof is affected by the initial soil moisture condition, retention capacity, and evapotranspiration. Of the sensitive

Table 3 | CN values for ER, FC, and WP

Parameter	CN
Evaporation rate	−1.774
Field capacity	−16.051
Wilting point	8.439

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parameters identified from the sensitivity analysis, field capacity and wilting point are the parameters that characterize retention capacity and the initial available storage in the soil layer. Field capacity as appeared in Equation (5) sets the limit for percolation to occur, below which it becomes zero. Therefore, the larger the value, the more soil moisture can be retained. This explains the sensitivity analysis result where increasing field capacity decreases the runoff as a result of increasing retention capacity. As for the wilting point, it is used in SWMM to define the initial soil moisture condition which represents the initial degree of saturation (Rossman & Huber 2016). This explains the results of the sensitivity analysis indicating that increasing wilting point increases total runoff, as the more saturated the soil becomes, the greater the total runoff. Lastly, the evaporation rate appears directly as a sink term in the governing equations for three layers. This explains the sensitivity analysis results showing that increasing evaporation rate decreases total runoff. In summary, the sensitivity analysis results obtained are synonymous with what the governing equations tell us in terms of how they are related to the total runoff from green roofs.

Calibration and validation

When evapotranspiration was not considered in calibration, the best NSE value obtained was 0.508, which is considered a poor fit. During calibration, NSE was increased by increasing field capacity or decreasing wilting point. The calibrated parameter values are 0.49 and 0 for field capacity and wilting point, respectively. 0.49 is the largest possible value of field capacity that can be used in SWMM and 0 is the smallest value of wilting point possible, yet the combination still yielded a poor fit. Moreover, these parameter values are unrealistic and outside the ranges recommended in green roof literature. In Figure 3(b), it can be observed that both overestimations and underestimations occurred in the best calibration. Adjusting parameters to minimize overestimations worsened underestimations and vice versa.

When evapotranspiration was considered, better results were attained. The calibrated values of field capacity, wilting point, and evaporation rate were 0.25, 0.18, and 0.22 in/d, respectively, well within the ranges recommended by literature. The resulting NSE coefficient for this combination is 0.926, which is considered a very good fit. Figure 3(c) shows the comparison of observed and simulated runoff volume using the calibrated parameter values.

Adjusting field capacity and wilting point caused similar increases or decreases in simulated runoff volume for all events, whereas the change in output caused by adjusting the evaporation rate depends on the duration of each event. In particular, evapotranspiration has resulted in the minimization of overestimations and underestimations. This proves the importance of evapotranspiration as a runoff reduction process of green roofs, and thus a necessary part of green roof modeling.

After the above calibration, the model was then validated using another data set. Figure 4 shows the comparison of observed and simulated runoff volumes in validation considering evapotranspiration. The resulting NSE was 0.951, retaining the very good fit attained from calibration, and substantiating that the parameters were calibrated appropriately for the green roof site.

CONCLUSIONS

The results of the sensitivity analysis have shown that considering evapotranspiration influences the results of the event-based simulations. In the calibration procedure, when evapotranspiration was not considered, the simulated values failed to achieve a good fit with the observed values. However, when evapotranspiration was considered, the simulated values achieved a very good fit with the observed values. The very good rating of the simulation considering evapotranspiration was maintained in the validation procedure. In this study, a constant evaporation rate was used in order to represent the effect of evapotranspiration due to a lack of data, and to simplify the process. The model performed well despite this simplification. These results underscore the importance of considering evapotranspiration in green roof modeling; they should not be disregarded as evapotranspiration is the only process aside from draining by which water can exit the green roof system. Furthermore, the results have also proved SWMM 5.1 to be an effective rainfall-runoff model for green roofs, given proper utilization.

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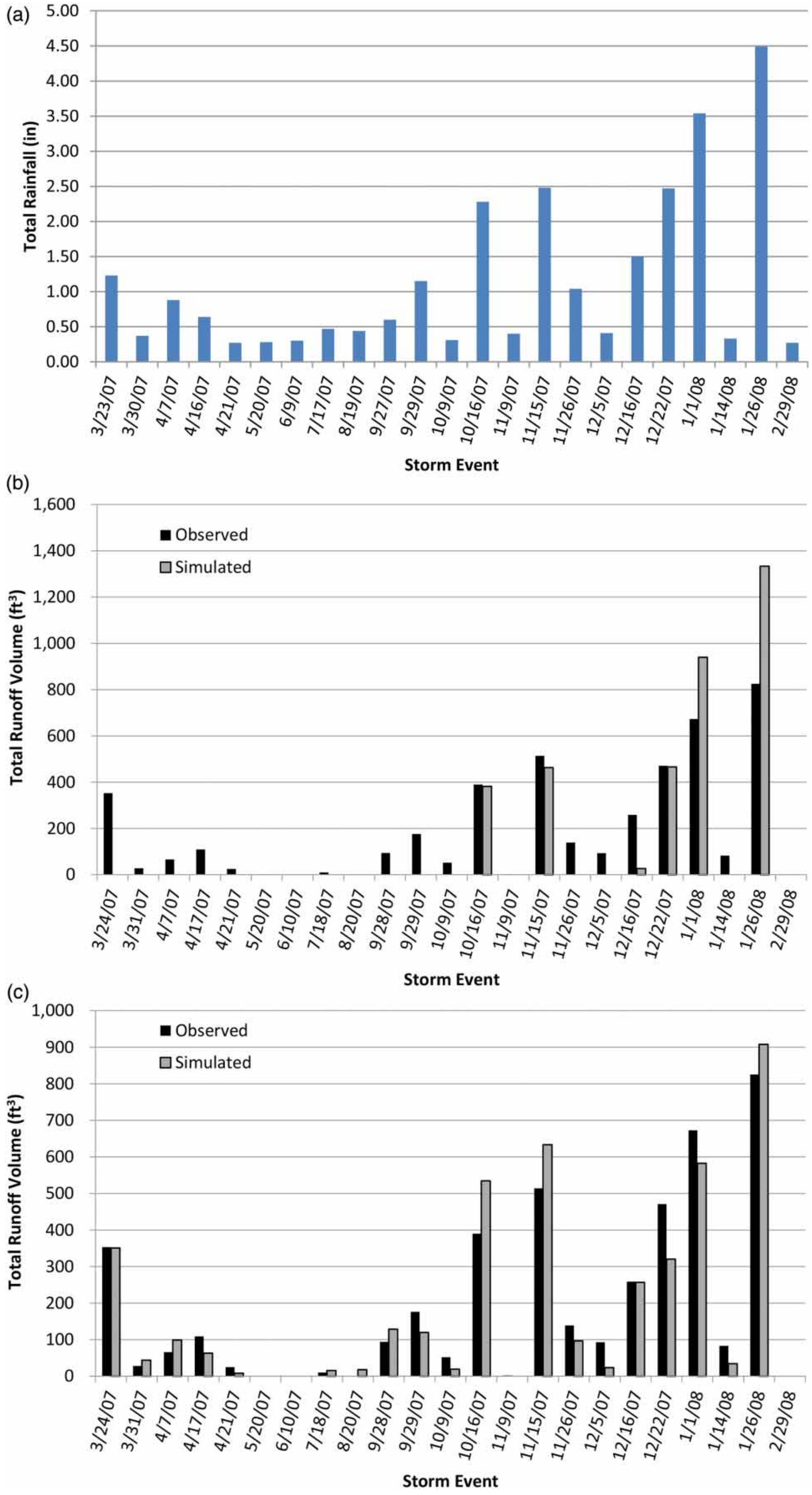

Figure 3 | (a) Total rainfall variation for 23 events used for calibration procedure. (b) Comparison of observed and optimal simulated total runoff volume in the calibration procedure without consideration of evapotranspiration. (c) Comparison of observed and optimal simulated total runoff volume in the calibration procedure considering evapotranspiration.

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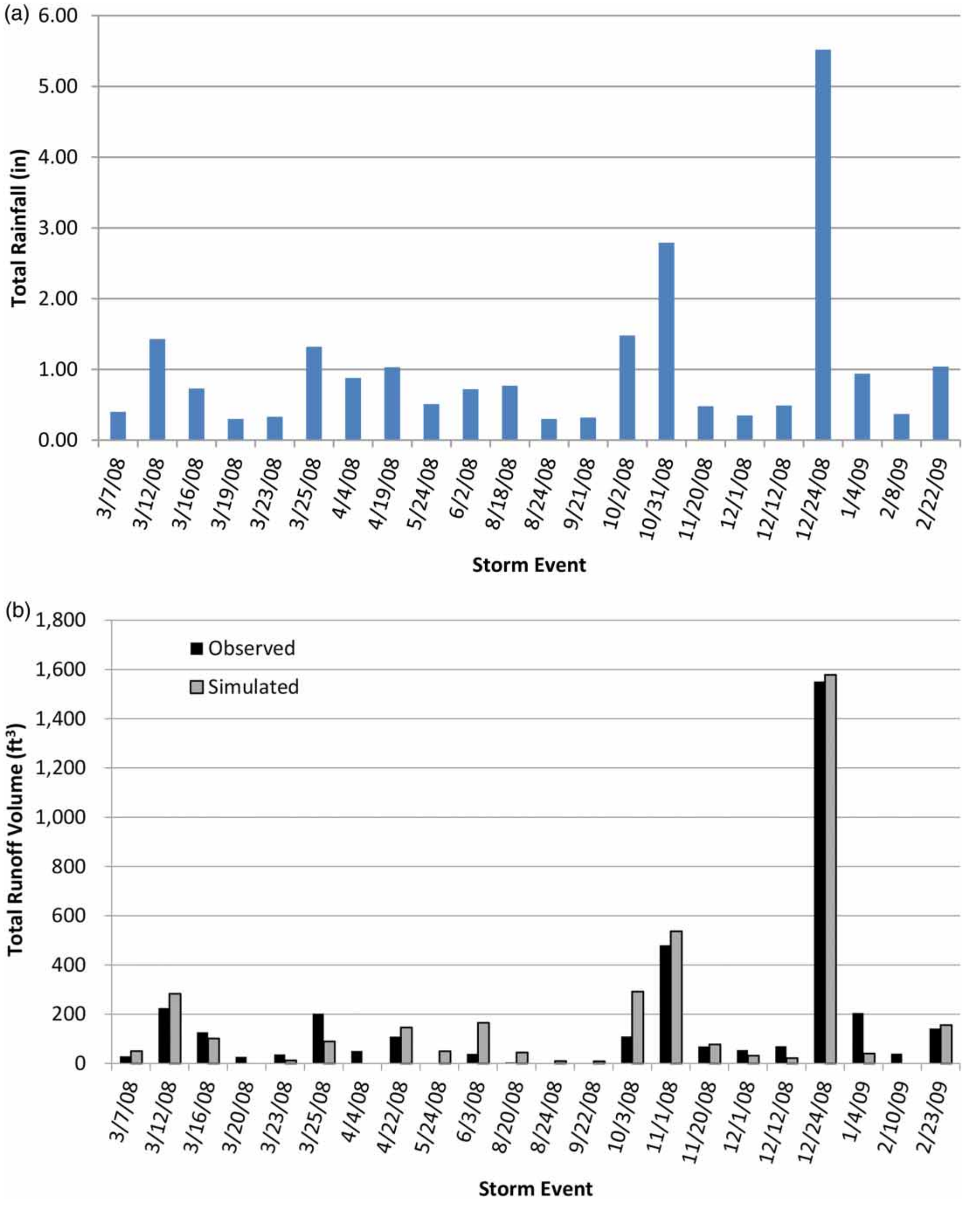

Figure 4 | (a) Total rainfall variation for 22 events used for validation procedure. (b) Comparison of observed and simulated total runoff volume in the validation procedure considering evapotranspiration.

In the future, a more realistic and accurate representation of evapotranspiration will be integrated into the model, either by using time-series evapotranspiration values from monitoring or by estimating evapotranspiration using empirical equations. It will also be beneficial to use more finely tuned data in order to analyze the effect of the evapotranspiration parameter simulating green roof hydrographs and peak flows.

ACKNOWLEDGEMENTS

This research was supported by Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Education (NRF-2015R1D1A1A01057882). This research was also supported by a grant from Korea University.

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First received 9 October 2017; accepted in revised form 6 February 2018. Available online 27 February 2018

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