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An improvement in drainage flow equation of EPA SWMM green roof module

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ABSTRACT

Green roofs are among the important green infrastructures which decrease the negative impacts of urbanization. In this study, the green roof modeling capability of U.S. Environmental Protection Agency Storm Water Management Model (EPA SWMM) is evaluated and the modeling methods used in EPA SWMM, which need improvements, are determined. In particular, the drainage flow, which is originally calculated with Manning's equation in SWMM, is improved by introducing the drainage mat void thickness and adapting a new value for the exponential coefficient of depth in the equation. In addition, the capability of the percolation equation is further investigated, i.e., the value of the coefficient of the exponential function of soil moisture content that considers the percolation through the soil layer is determined for different substrates using the existing unsaturated hydraulic conductivity and soil moisture content data from steady-state tests. A comparison of the improved equation of drainage flow results with the existing experimental data shows that the improved equation represents the drainage flow more accurately than the one used in EPA SWMM.

Key words: drainage flow, EPA SWMM, green roof, hydrologic model, low impact development

HIGHLIGHTS

- Green roof modeling capability of EPA SWMM is investigated.
- An improved drainage flow equation for the green roof is obtained.
- Decay constant HCO in the percolation equation is determined for different green roof substrates.

GRAPHICAL ABSTRACT

Improved Green Roof Modeling

Surface Runoff Eq.

$$q_1 = \frac{c}{n_1}\sqrt{S_1}(W_1/A_1)\phi_1(d_1 - D_1)^{5/3}$$

Infiltration Eq.

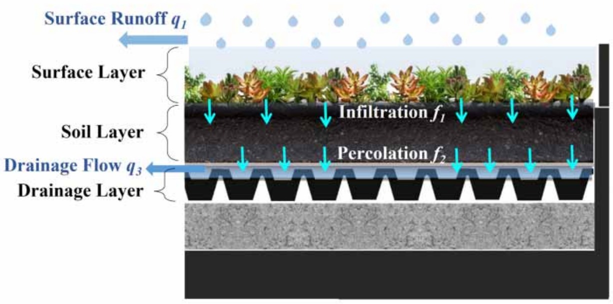
$$f_1 = K_{2S}\left(1 + \frac{(\phi_2 - \theta_{20})(d_1 + \psi_2)}{F}\right)$$

Percolation Eq.

$$f_2 = K_{2S}\exp(-HCO(\phi_2 - \theta_2))$$

Improved Drainage Flow Eq.

$$q_3 = \frac{1}{n_3} s^{\frac{1}{2}} \frac{1}{L} \emptyset_3 (d_3 - Ds_3)^2$$



INTRODUCTION

Rapid urbanization is a major threat to the environment (Hibbs & Sharp 2012). Among the most severe adverse effects of urbanization are the high ratio of impervious surfaces, and wash-off of accumulated pollutants on buildings, roadways, and parking lots into the streams (Grimm *et al.* 2008). The said conditions result in an increase in stormwater runoff which generally leads to an increase in severe flood events. High flood peaks and low flood peak lag times are observed in urbanized regions (Hibbs & Sharp 2012). Thus, the development of innovative stormwater management techniques is necessary to mitigate these problems. Low impact development (LID) best management practice (BMP) is an emerging stormwater management method which relies on various planning tools and control practices to preserve the natural hydrologic functions of the site (Prince George County 1999; Eckart *et al.* 2017). Examples of LID types are green roofs, rain gardens, bioretention cells, swales, permeable pavements and infiltration trenches (Eckart *et al.* 2017).

Green roofs are one of the most common types of LID which consist of three main layers: drainage layer, soil layer for growing plants (substrate) and surface layer for vegetation. There are two major types of green roof drainage layers: (1) drainage mats, which are made of high-strength plastic materials and contain cells for water storage, and (2) drainage granular materials, which have large pores for water storage (Vijayaraghavan 2016). The soil layer directly influences the plant growth and performance of green roofs. The soil used as a growth media for green roofs is different from natural soils and there is a gap in the literature on the standard agronomic properties of such mixtures (Rossman & Huber 2016a). For the vegetation layer, the plant type should be selected based on the local climatic conditions, nutrient content, and the impact of the plant on the ecosystems (Vijayaraghavan 2016). The type and thickness of the soil layer, the type and storage capacity of the drainage layer, vegetation type and coverage, rain event and time of previous dry period, and slope of green roof are the effective parameters on green roof performance (Vijayaraghavan 2016).

Green roofs sustain stormwater management by retention of rainfall, which allows for evapotranspiration (ET) of rainwater in the long run and no contribution to runoff or drainage flow, and detention of runoff, which allows for the temporary storage of rainfall as it passes through the roof layers (De-Ville *et al.* 2018). Green roof performance has been evaluated in various studies (Stovin *et al.* 2012; Carson *et al.* 2013; Johannessen *et al.* 2018; Palermo *et al.* 2019; Sims *et al.* 2019). Some of these studies focus on the behavior of green roof layers and identify features that can increase the performance of the green roof (Vesuviano & Stovin 2013; Hill *et al.* 2017; Bollman *et al.* 2019; Peng *et al.* 2019; Cristiano *et al.* 2020; Ekşi *et al.* 2020).

The U.S. Environmental Protection Agency Stormwater Management Model (EPA SWMM) is one of the most widely used software for green roof hydrology simulations. SWMM simulates the flow over and through the green roof layers and calculates the surface runoff, the flow between the layers, i.e., infiltration and percolation, and drainage flow. In recent years, different studies have evaluated the hydrological performance of green roofs using SWMM's green roof module (Abualfaraj *et al.* 2018; Palla *et al.* 2018; Hamouz & Muthanna 2019). Krebs *et al.* (2016) evaluated the runoff simulation ability of SWMM from monitored small-scale green roof test beds under Nordic climate conditions. Peng *et al.* (2017) modeled an extensive green roof test bed using SWMM under both annual time series for predicting long-term volumetric retention and significant rainfall events for predicting detention. Liu & Chui (2019) evaluated the effects of the hydraulic conductivity and thickness of the growing medium on the hydrological performance of the green roof under various rainfall conditions using SWMM. Johannessen *et al.* (2019) investigated the performance of SWMM for several roofs with varying roof buildups, sizes, slopes, and climates.

Most studies evaluated the overall green roof modeling performance of SWMM. However, few studies focused on the improvement of equations used in green roof modeling. Some studies suggested improvements in the calculation of ET in SWMM (Krebs *et al.* 2016; Peng *et al.* 2017; Palla *et al.* 2018). Peng *et al.* (2017) highlighted the need for robust models for soil layer and drainage layer modeling of green roofs. In this study, the green roof modeling capability of SWMM is investigated by exploring the details of each flow modeling component and improvements are suggested. The SWMM version 5.1 is employed in the analyses of this study. The answers to two questions are sought for: (i) what are the appropriate values of the decay constant HCO in the percolation equation for different green roof substrates?; (ii) how can Manning's equation be adopted by SWMM for the calculation of drainage flow through green roof be improved? For this purpose, Manning's equation used for drainage flow calculation in the green roof module is improved by introducing the drainage mat void thickness and adapting a new value for the exponential coefficient of depth. Finally, the SWMM model results and results of the improved equation are compared with the existing experimental data.

METHODOLOGY

SWMM green roof module

The EPA Storm Water Management Model (SWMM) is one of the best-known and most widely used urban runoff quantity and quality models (Rossman & Huber 2016a). SWMM can model many LID practices using a unit process-based representation of their behavior. The green roof type of LID is modeled using a set of coupled one-dimensional ordinary differential equations (Equations (1)–(3)). Each equation describes the change in water content in a particular layer over time. The fluxes in these equations are functions of the current water content in the various layers. As shown in Figure 1, three layers are defined for green roof modeling in SWMM. The infiltration of surface water into the soil layer, f_1, is modeled with the Green-Ampt equation (Equation (4)). The rate of percolation of water through the soil layer into the drainage layer f_2 is modeled using Darcy's Law (Equation (5)). The runoff rate over the surface layer q_1 and the drainage mat flow rate q_3 are computed using Manning's equation (Equations (6) and (7)). ET of water from each layer is computed with the user-supplied time series of daily potential ET rates that are used in SWMM's runoff module. The continuity equations are solved numerically at each time step to convert the inflow hydrograph, which reaches the Green Roof LID unit, into hydrographs of surface runoff over the green roof, and drain flow.

$$\phi_1 \frac{\partial \mathrm{d}_1}{\partial t} = i - e_1 - f_1 - q_1 \tag{1}$$

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

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

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

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

$$q_1 = \frac{c}{n_1}\sqrt{S_1}(W_1/A_1)\phi_1(d_1 - D_1)^{5/3} \tag{6}$$

$$q_3 = \frac{c}{n_3}\sqrt{S_1}(W_1/A_1)\phi_3(d_3)^{5/3} \tag{7}$$

In these equations, i is the rainfall intensity falling directly on the surface layer; e_1 is the surface ET rate; e_2 is the soil layer ET rate; e_3 is the drainage layer ET rate; ϕ_1 is the void fraction of any surface volume (i.e., the fraction of freeboard above the surface not filled with vegetation); d_1 is the depth of water stored on the surface (L); D_2 is the thickness of the soil layer (L);

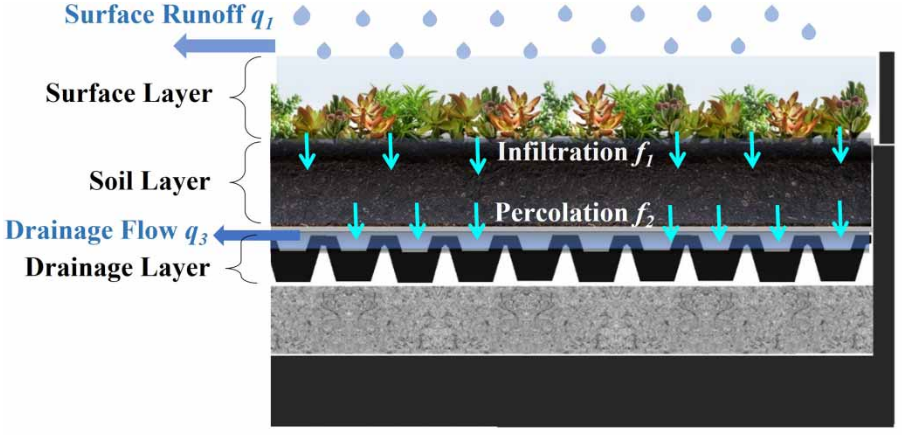


Figure 1 | Green roof modeling principle of EPA SWMM.

θ_2 is the soil layer moisture content; d_3 is the depth of water in the drainage mat (L) and ϕ_3 is the void fraction of the storage layer (void volume/total volume). K_{2s} is the soil's saturated hydraulic conductivity (L/T); ϕ_2 is the porosity (void volume/total volume) of the soil layer; ψ_2 is the suction head at the infiltration wetting front formed in the soil (L); and F is the cumulative infiltration volume per unit area over a storm event (L). HCO is a decay constant derived from moisture retention curve data; θ_{FC} is the soil's field capacity (FC) moisture content, n_1 is the surface roughness coefficient; S_1 is the surface slope; W_1 is the total length along edge of the roof where runoff is collected (L); D_1 is the surface depression storage depth (L); A_1 is the roof surface area (L^2); c is a conversion factor between SI and English units. The unit of the length dimension is meter for SI system and feet for English system and the unit of the time dimension is second.

SWMM green roof percolation equation

SWMM assumes that the percolation rate is equal to the unsaturated hydraulic conductivity which changes as a function of moisture content and is given as follows:

$$K(\theta) = K_s\, e^{-HCO(\emptyset-\theta)} \tag{8}$$

where K_S is the saturated hydraulic conductivity, θ is the moisture content, ϕ is the porosity and HCO is the decay constant which can be estimated from soil test data. Thus, the percolation rate expression is as follows (Rossman & Huber 2016b):

$$f_2 = K_s\, e^{-HCO(\emptyset-\theta)} \tag{9}$$

If the moisture content θ is less than or equal to FC $\theta_{FC,}$ then the percolation rate becomes zero. The coefficient HCO characterizes the exponential decrease in hydraulic conductivity with decreasing moisture content. In order to estimate HCO for a given soil accurately, measured data of hydraulic conductivity K as a function of soil moisture content θ should be used. HCO values for some soil classes such as sand, sandy loam, and silty loam are available in the literature, but these values may not work well for green roof substrates since soil used as growth media for green roofs is different from natural soils and there is a limited amount of information on the standard agronomic properties of such mixtures (Rossman & Huber 2016a).

Improvement of SWMM green roof drainage flow equation

SWMM models the drainage flow using Manning's equation (Equation (7)) and this equation does not take the storage capacity of the drainage mat into account. However, the said storage capacity may have an important effect on the drainage flow and thus should be considered. Therefore, as the first step of the improvement, the storage capacity of the drainage mat is represented by introducing the drainage mat void thickness D_{s3} into Manning's equation. As the second step of the improvement, a new value for the exponential coefficient of depth is sought. This coefficient takes the value of 5/3 in the original Manning's equation. However, the drainage flow is not well represented for green roofs with this value (Peng *et al.* 2017). In order to carry out these improvements, the experimental data by Vesuviano (2014) is employed. The new value of the exponential coefficient was determined by using the nonlinear curve fitting algorithm embedded in Matlab and named as lsqcurvefit, which solves data-fitting problems in the least-squares sense. The best fit of the calculated drainage flow to the measured drainage flow is satisfied with the value of 2 for the exponential coefficient. Moreover, there is no need for a conversion factor between SI and English units in the improved equation anymore as the fundamental quantity of length to the power one is obtained on the right-hand side of the equation.

The following improved equation is finally obtained as follows:

$$q_3 = \frac{1}{n_3}\, s^{\frac{1}{2}}\, \frac{1}{L}\, \emptyset_3 (d_3 - Ds_3\,)^2 \tag{10}$$

where q_3 is the drainage flow rate (L/s), L is the drainage length of the layers (L), S is the surface slope (L/L), ϕ_3 is the void fraction of the drainage mat, d_3 is the depth of water in the drainage mat (L), n_3 is the roughness coefficient for the mat.

The improved equation (Equation (10)) is obtained by employing the experimental data of the experiments conducted using independent drainage mats without part of a green roof. In the next section, the improved equation is incorporated into the entire green roof system.

Improvement of green roof model

In this part of the study, the improved equation for drainage flow calculation is incorporated into the whole green roof model. For this purpose, the continuity equation (Equation (3)) is solved for drainage layer water depth d_3 and entered as input into the improved equation (Equation (10)) to solve for drainage rate q_3 at each time step. The calculated drainage rate q_3 is used in the next time step to calculate water depth d_3. In these calculations, the drainage layer ET rate e_3 is assumed as zero and the percolation rate f_2 values calculated by SWMM are used. Figure 2 shows the schematic of the improved green roof model.

Two different green roofs used in the existing experimental studies are modeled with SWMM and with the improved method. Then, the drainage flow calculated with SWMM, the drainage flow calculated with the improved equation and the measured drainage flow are compared.

Available data

Three sets of data available in the literature were used in this study. The first set of data belongs to a study by Peng *et al.* (2020) and consists of measurements of unsaturated hydraulic conductivities with respect to soil moisture content for four representative green roof substrates. The measurements were taken using steady state and transient techniques by using the test column with a height of 540 mm and a diameter of 300 mm. In addition, they determined the substrate characteristics including porosity, maximum water holding capacity (MWHC) and saturated hydraulic conductivity (*Ks*). The tested green roof substrates are Heather with Lavender Substrate (HLS), Sedum Carpet Substrate (SCS), Marie Curie Substrate (MCS) and New Substrate Mix (NSM) substrate. In this study, the steady-state data are employed to obtain HCO values in the percolation equation for different substrates.

The second set of data belongs to a study by Vesuviano (2014) and consists of inflow and drainage flow collected using different types of drainage mats. The experiments were conducted using a rainfall simulator chamber which consists of a channel base with a length of slightly over 5 m and a width of slightly over 1 m. The tested drainage mat types were ZinCo Floradrain FD 25, FD 40 and ZinCo Floraset FS 50. The drainage mat lengths are 2 and 5 m and drainage mat surface slopes are 2 and 18%. ZinCo Floradrain FD 25 and FD 40 drainage layers consist of a thin layer of hard plastic (high density polyethylene) molded into a regular three-dimensional pattern containing cup-like storage receptacles and channels. FS 50 type of drainage mat has deep polystyrene modules with water storage receptacles formed in the upper surface profile (Vesuviano 2014). A collection barrel with a pressure transducer was used for measurements. The momentum of flow entering the barrel resulted in instabilities in the recorded data. In addition, the pressure transducer generates its own noise (Vesuviano 2014). Therefore, some oscillations are observed in the measurements. The roughness coefficient n of high-density polyethylene and expanded polystyrene are given as 0.012 and 0.014, respectively. For all types of drainage mats, void fraction

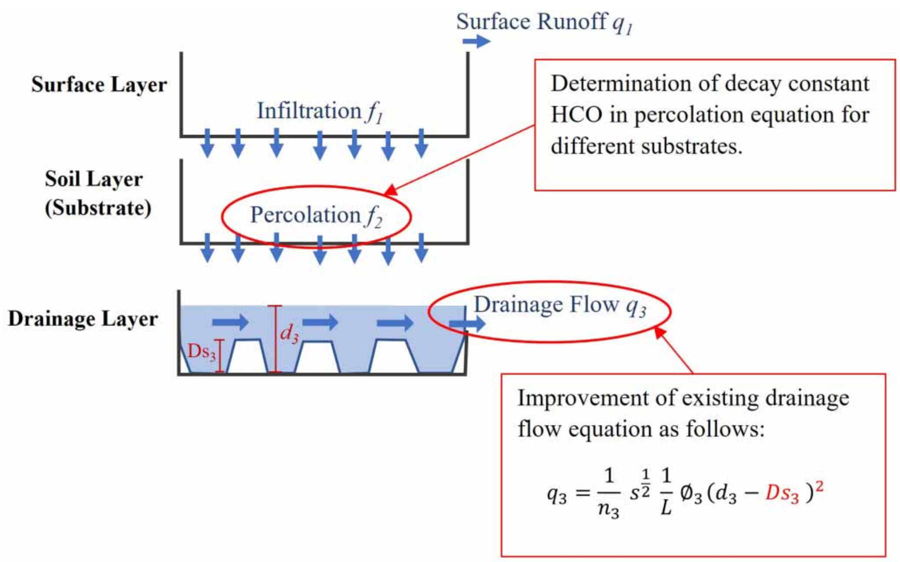


Figure 2 | Schematic of green roof model improvement.

ϕ_3 was 0.5. In this study, the experimental data by Vesuviano (2014) is used for improving the green roof drainage flow equation.

The third set of data belongs to green roof experimental studies done by Sims *et al.* (2019) and Peng *et al.* (2019). Peng *et al.* (2019) conducted experiments using a green roof test bed (Green Roof A) located on a terrace of a building at University of Sheffield, UK, and has dimensions of 3 m × 1 m with 1.5° slope. Sims *et al.* (2019) conducted experiments using a single module drainage unit (Green Roof B) with dimensions of 0.3 m × 0.3 m located on a building at Western University in London, Ontario. The green roofs used in the experimental studies are modeled with SWMM and with the improved model. The data sets consist of rainfall and drainage flow. The effective design parameters, which need to be defined in SWMM, are provided by Peng *et al.* (2019), Peng *et al.* (2020), and De-Ville *et al.* (2018) for Green Roof A and by Sims *et al.* (2019) for Green Roof B. The values of the rest of the parameters, which need to be defined in SWMM, are selected according to the possible range of values provided by SWMM (Table 1).

RESULTS

Determination of HCO values

HCO values in Equation (8) are estimated by fitting a line to the plot of the logarithm of the measured unsaturated hydraulic conductivity K versus soil layer moisture content θ provided by Peng *et al.* (2020). The best-fitting *HCO* value is determined by minimizing the sum of the squared (SSQ) deviations between the measured and calculated unsaturated hydraulic conductivities. Figure 3 shows the fitted line for each substrate with two sets of data. Eventually, *HCO* was determined as 37, 32, 18, and 20 for substrate types of SCS, NSM, HLS, and MCS, respectively. The results obtained here are employed in the drainage flow calculations presented in the next sections.

Improved drainage flow equation

The experimental data provided by Vesuviano (2014) is compared with the drainage flow calculated with Manning's equation and with the drainage flow calculated with improved equation (Figure 4). The results show that the drainage flow calculated with the improved equation is in better agreement with the measured data than the one calculated with the original drainage flow equation used in SWMM, i.e., Manning's equation (Figure 4). In particular, the falling limb of the drainage flow hydrograph calculated by using the improved equation matches with the measured data much better than the one calculated with Manning's equation.

Linear regression was performed between experimental and calculated data for nine experiments. As shown in Table 2, the mean correlation coefficient for Manning's equation changes from 0.33 to 0.891 whereas it takes values of 0.865–0.991 for the improved equation. Thus, there is a significant improvement in the results when calculated with the improved drainage flow equation.

Table 1 | Effective design parameters values used in simulation

Parameter	Green roof A (Peng *et al.* (2019))		Green roof B (Sims *et al.* (2019))	
	Value	Source	Value	Source
Soil layer thickness, mm (D_2)	80	Peng *et al.* (2019)	100	Sims *et al.* (2019)
Porosity (ϕ_2)	0.556	Peng *et al.* (2019)	0.45	Sims *et al.* (2019)
Field capacity (θ_{FC})	0.38	Peng *et al.* (2020)	0.215	Sims *et al.* (2019)
Wilting point (θ_{WP})	0.066	De-Ville *et al.* (2018)	0.01	Sims *et al.* (2019)
Saturated hydraulic conductivity, mm/h (K_{2S})	1608	Peng *et al.* (2020)	607	Sims *et al.* (2019)
Percolation parameter (HCO)	18	Determined	14	SWMM
Drainage layer thickness, mm (D_3)	25	Peng *et al.* (2019)	30	SWMM
Drainage layer void fraction (ϕ_3)	0.5	SWMM	0.65	SWMM
Drainage layer roughness (n_3)	0.1	SWMM	0.1	SWMM

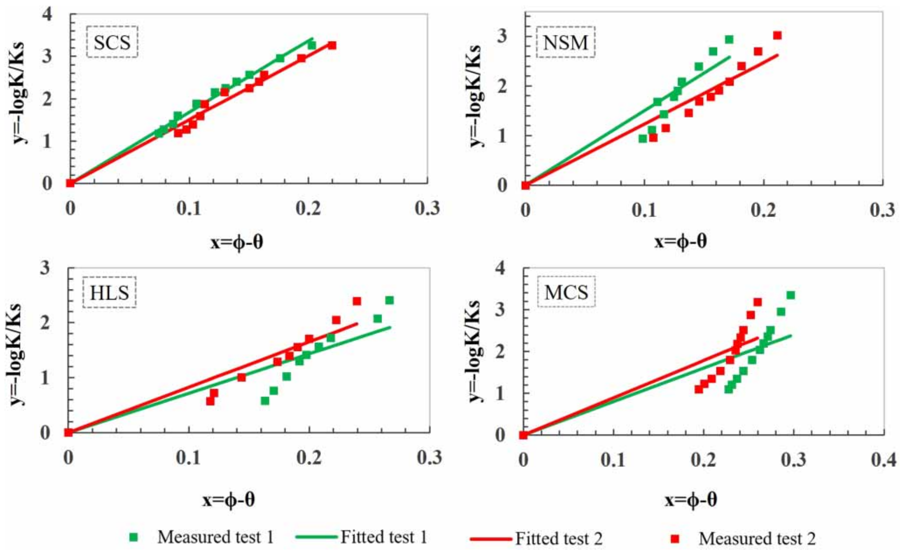


Figure 3 | Determination of HCO values for the four substrates.

Simulation of improved green roof model

The drainage flow data of the experiments conducted by Peng *et al.* (2019) and Sims *et al.* (2019) are compared with the results of green roof model of SWMM and with the improved drainage flow equation. For this purpose, the Green Roof A

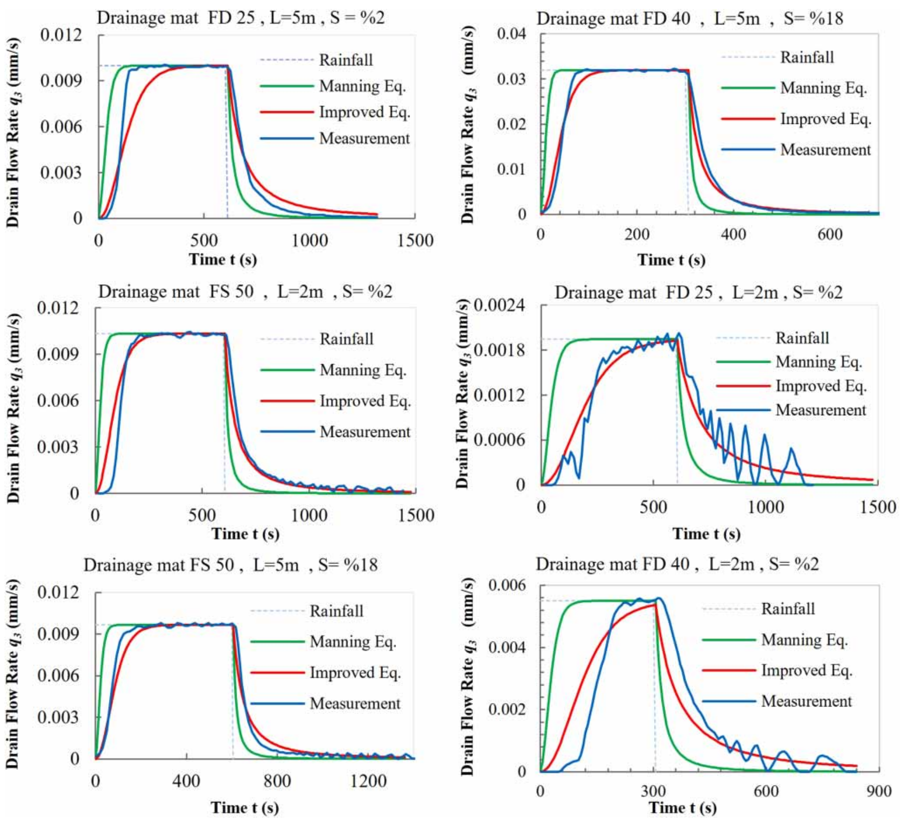


Figure 4 | Comparison of the measured drainage flow with the calculated drainage flows using Manning and the improved equation for different drainage mat types.

Table 2 | The mean correlation coefficient for Manning's equation and the improved equation

Experiment no	R^2 (Manning equation)	R^2 (Improved equation)
Drainage mat FD 25, $L = 2$ m, $S = 18\%$	0.692	0.944
Drainage mat FD 40, $L = 2$ m, $S = 2\%$	0.33	0.865
Drainage mat FD 25, $L = 5$ m, $S = 2\%$	0.818	0.965
Drainage mat FD 40, $L = 5$ m, $S = 18\%$	0.825	0.991
Drainage mat FS 50, $L = 2$ m, $S = 2\%$	0.735	0.964
Drainage mat FD 25, $L = 2$ m, $S = 2\%$	0.42	0.916
Drainage mat FS 50, $L = 5$ m, $S = 18\%$	0.891	0.986
Drainage mat FS 50, $L = 2$ m, $S = 4\%$	0.738	0.959
Drainage mat FS 50, $L = 5$ m, $S = 4\%$	0.73	0.98

used in the experimental studies by Peng *et al.* (2019) and Green Roof B used in the experimental studies by Sims *et al.* (2019) are modeled with SWMM by using the parameters provided in Table 1. Then, the drainage flow calculated with SWMM, the drainage flow calculated with the improved equation and the measured drainage flow are compared.

When the drainage flow calculated with the improved equation, the drainage flow calculated with the SWMM and the measured drainage flow are compared, the results with both calculation methods are in good agreement with the measured data. However, the drainage flow calculated with the improved equation is in better agreement with the measured data (Figures 5 and 6).

Linear regression was performed between experimental and calculated data for seven experiments. As shown in Table 3, the mean correlation coefficient for SWMM changes from 0.29 to 0.874 whereas it takes values of 0.549–0.97 for the improved equation.

DISCUSSION

Assessment of existing percolation equation

The rate of percolation f_2 through the soil layer is modeled using Darcy's Law in SWMM (Rossman & Huber 2016a). In the case of an unsaturated flow, the hydraulic conductivity K is a function of the moisture content θ, and the percolation rate is equal to the unsaturated hydraulic conductivity.

The method that considers K to be an exponential function of θ, gives relatively accurate and reproducible hydraulic conductivity results for steady-state conditions during which the soil surface is ponded with water (Libardi *et al.* 1980). However, this assumption may not be valid for green roof substrate which generally has different agronomic properties from natural soils. Figure 3 presents the results for four different substrates, among which two of them match well. However, the behavior of the rest of the two substrates did not fit to an exponential decrease in hydraulic conductivity with decreasing moisture content. Therefore, there is a need for more experiments using a wider range of green roof substrates to evaluate and improve the used percolation equation.

Assessment of improved drainage flow equation

Manning's equation is originally derived to present flow in prismatic channels which is then adapted to present the drainage flow in green roofs and gives the storage depth-discharge rate relationship as a function of drainage length, roof slope and the roughness coefficient n. Since the shape of drainage mats is like an egg box, the Manning equation cannot represent the flow through drainage mats well in its original form. The value of the exponential coefficient of depth, which is 5/3 in the original Manning's equation and valid for prismatic channels, becomes 2 in the improved equation which is determined by the best fit of the experimental data to the calculated data. In addition, the storage capacity of the drainage mat is represented by introducing the drainage mat void thickness D_s into the improved equation.

Better results are obtained with the improved equation without losing the simplicity of the original equation. In particular, the start time of the rising limb, the peak flow arrival time, and the end time of the recession limb of the hydrographs obtained

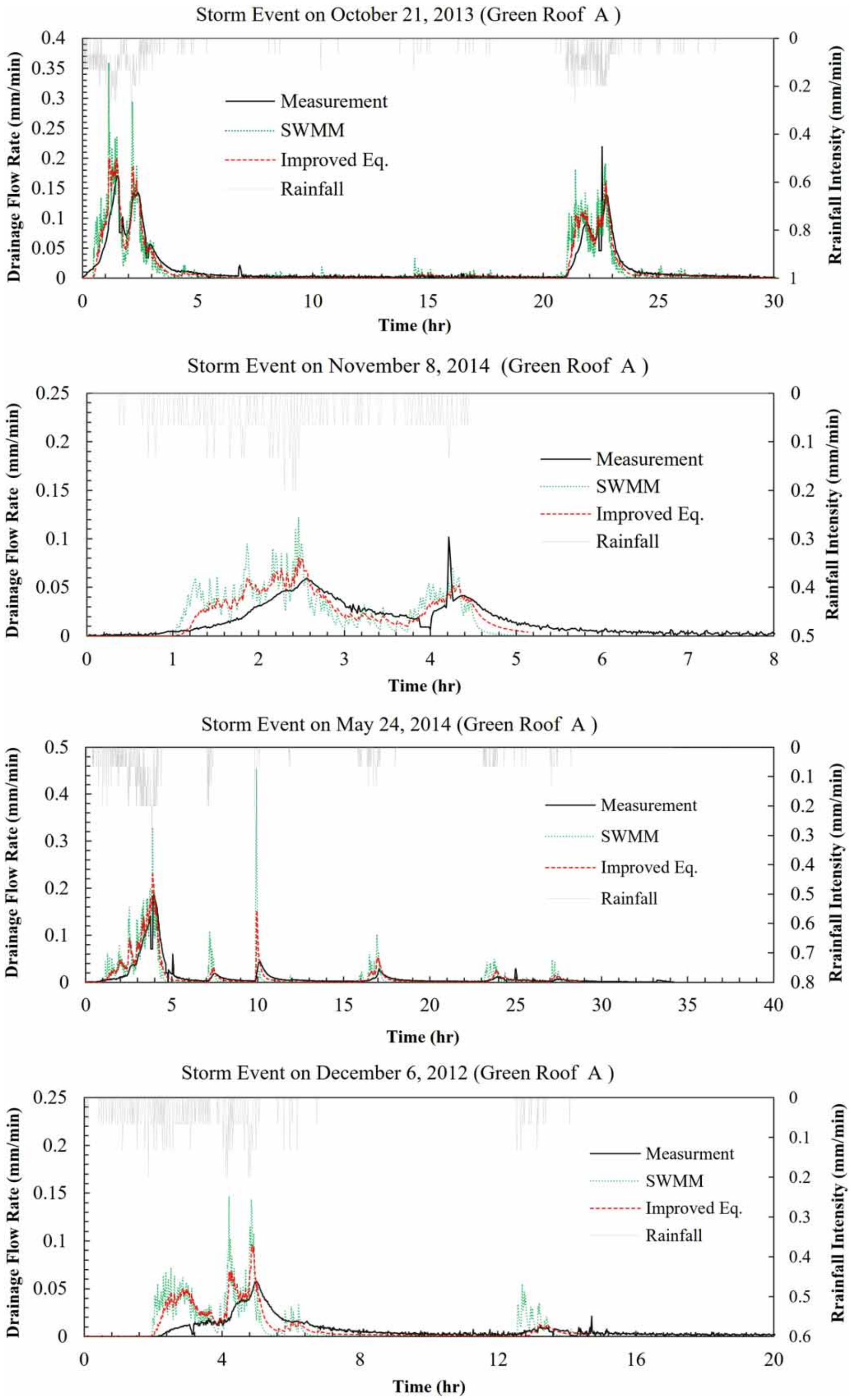


Figure 5 | Comparison of the measured drainage flow with the calculated drainage flows using SWMM and the improved equation for different rainfall events for green roof A.

with the improved equation show a better match with the observations than the hydrographs obtained with the original equation (Figure 4). The start and end time of drainage and the peak drainage rate arrival time play an important role in the detention performance of green roofs and therefore should be determined accurately.

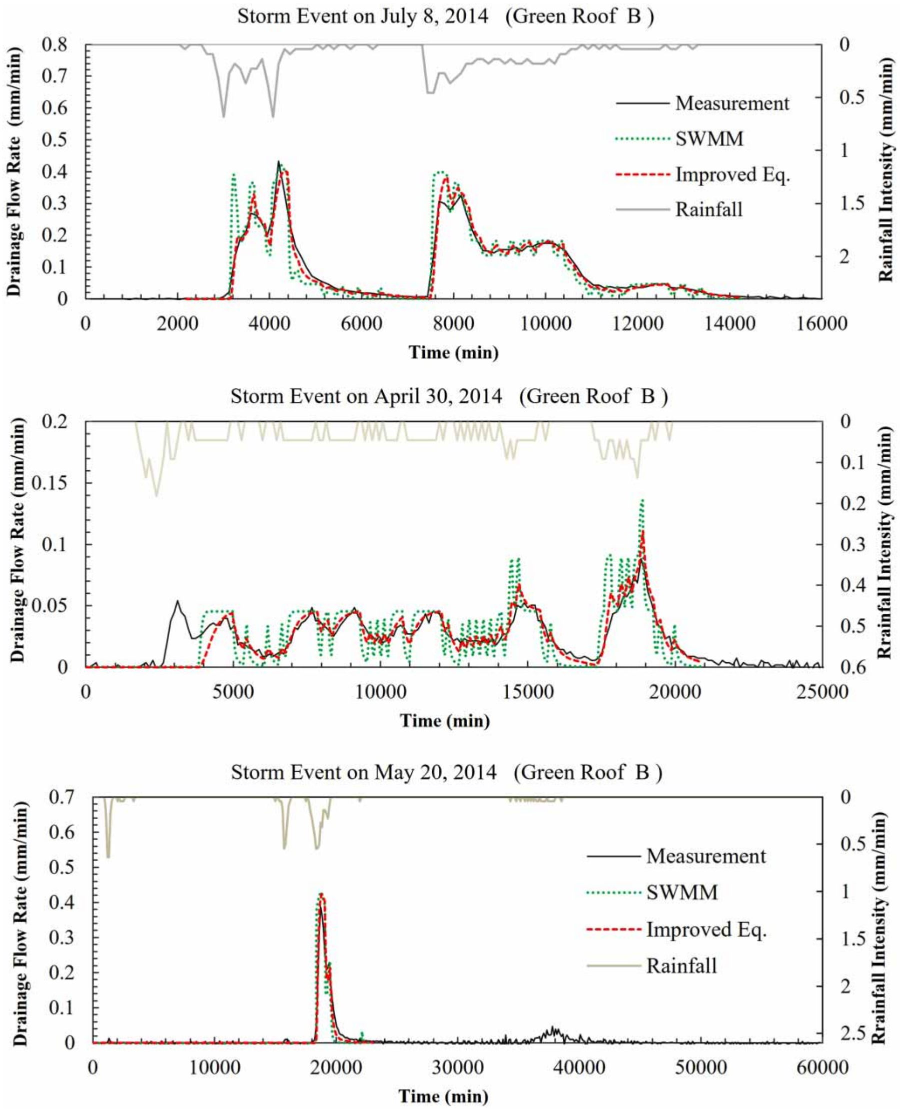


Figure 6 | Comparison of the measured drainage flow with the calculated drainage flows using SWMM and the improved equation for different rainfall events for green roof B.

Table 3 | The mean correlation coefficient for SWMM and the improved equation

	Experiment no	R^2 (SWMM)	R^2 (Improved Eq)
Green Roof A Peng *et al.* (2019)	Storm Event on 21 October 2013	0.756	0.901
	Storm Event on 8 November 2014	0.512	0.763
	Storm Event on 6 December 2012	0.29	0.549
	Storm Event on 24 May 2014	0.496	0.796
Green Roof B Sims *et al.* (2019)	Storm Event on 8 July 2014	0.845	0.97
	Storm Event on 30 April 2014	0.543	0.72
	Storm Event on 20 May 2014	0.874	0.959

Assessment of SWMM green roof model

SWMM green roof model gives acceptable results for the most part of this study. In some cases, the SWMM results cannot catch the rising limb of the hydrograph which may be attributed to inaccurate measurement of initial moisture content. In addition, there are a few outliers in the peak drainage flow values which may be attributed to the inaccurate rainfall measurement in a few time steps. Comparison of the measured hydrographs with the simulated hydrographs shows little difference in first flow and peak flow arrival and recession time and the peaks. These issues have been fixed to some extent with the improved drainage flow equation.

While doing the assessment of SWMM green roof modeling capacity, additional details are noticed: SWMM models green roofs in three layers. However, in some cases, green roofs contain a retention layer as a fourth layer for more water retainment. Such a layer cannot be taken into account in SWMM modeling. Thus, future studies may focus on including a fourth layer in the SWMM green roof model. Moreover, some suggestions were made by Peng *et al.* (2017) aimed at improving SWMM green roof modeling. The ET rate should be calculated by taking the water content in the substrate into account. And, modeling efforts should focus on improving soil layer and drainage layer models (Peng *et al.* 2017).

CONCLUSIONS

In this study, the green roof modeling capacity of EPA SWMM is evaluated. In particular, an improved equation representing the drainage flow is developed. In addition, the green roof percolation model is examined and HCO values for four types of substrates were determined. Experimental data sets obtained in several former studies are employed to determine the HCO values and improve the drainage flow equation. A comparison of the results show that the drainage flow values obtained with the improved drainage flow equation are in better agreement with the experimental findings than the drainage flow obtained with Manning's equation. Furthermore, a comparison of the measured drainage flow with the calculated drainage flow using SWMM and the improved equation for different rainfall events also support this outcome. Additional experiments with a wider range of conditions are needed for further comparison to have a better support for this outcome.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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