Article:

Peng, Z. orcid.org/0000-0003-3918-4479, Garner, B. and Stovin, V. orcid.org/0000-0001-9444-5251 (2022) Two green roof detention models applied in two green roof systems. Journal of Hydrologic Engineering, 27 (2). 04021049. ISSN 1084-0699

https://doi.org/10.1061/(asce)he.1943-5584.0002155

Two Green Roof Detention Models Applied in Two Green Roof Systems

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ABSTRACT

A two-stage physically-based detention model has been developed for green roof systems. Vertical flow in the substrate is represented by the Richards Equation, and horizontal flow in the underlying drainage layer is modeled by the Saint Venant equation. This two-stage physically-based model (2SPB), together with the SWMM green roof LID control model (SWMM-GR), were validated using measured runoff profiles from two contrasting green roof systems: a conventional green roof system; and an innovative system intended to enhance detention. The substrate and drainage layer model parameters were identified from independent physical tests. The 2SPB model provides a reasonable estimation of runoff profiles from a conventional green roof system. However, the model is not capable of representing the flow conditions in the innovative green roof system's detention layer, such that model results were less accurate for this system compared with the conventional green roof system. SWMM-GR model results for the conventional system were less representative of its overall detention performance due to the assumptions inherent in the substrate percolation model.

Keywords: Green Roof, Detention Models, Physically-based Model, SWMM LID Control Model, Validation.

INTRODUCTION

A green roof is a Sustainable Drainage System (SuDS) or Low Impact Development (LID) technology. Studies in different climate contexts worldwide have demonstrated that green roofs have the potential to reduce storm runoff volumes and peak runoff rates (Fassman-Beck et al. 2013; Berghage et al. 2009; Stovin et al. 2012; Villarreal and Bengtsson 2005). Green roofs provide these hydrological benefits through retention (initial losses) and detention (delay) (Kasmin et al. 2010; Voyde et al. 2010a). Retention in green roofs occurs as a result of substrate moisture loss due to evapotranspiration in dry weather periods (Fassman and Simcock 2012; Poë et al. 2015; Stovin et al. 2013; Voyde et al. 2010b). The role played by evapotranspiration in determining green roof retention is now well understood.

Detention refers to rainfall that is temporarily stored in the system before leaving the system as runoff. Current understanding of detention processes is less advanced than retention. While many monitoring studies have reported detention metrics, including peak attenuation and peak delay, such metrics do not directly lead to the development of modeling tools to represent detention in an unmonitored green roof (Stovin et al., 2017).

Although a green roof system consists of different layers, the two main functional components contributing to green roof detention effects are the substrate and drainage layers. Component-specific detention models have been developed to model detention due to these two layers.

The primary function of the green roof substrate is to provide sufficient water storage and drainage capacity. Commercially available substrate mixes generally use crushed brick and/or mineral aggregates as the primary base material; compost, coir and clay may also be added into the substrate in small proportions. The composition of a green roof substrate may vary between mixes.

Models for detention processes in green roof substrates can be divided into two categories, empirical models and physically-based models. An empirical reservoir routing model has been shown to have good capabilities for modelling runoff from green roof substrates (Vesuviano et al. 2014; Yio et al. 2013). However, the parameters in this type of model have no direct link to the measurable substrate properties; they have to be calibrated for specific configurations based on measured data. In contrast, a physically-based model, for which the model parameters can be determined from the substrate's physical properties, has a more generic application (Peng et al. 2019). The most widely-used physically-based model for green roof substrates is the Richards Equation for unsaturated flow (Hilten et al. 2008; Liu and Fassman-Beck 2017, 2018; Palermo et al. 2019; Palla et al. 2009; Peng et al. 2019, 2020). To apply the Richards Equation, the Soil Water Release Curve (SWRC) and the Hydraulic Conductivity Function (HCF) need to be characterized. It has been demonstrated that the Durner model (Durner 1994) provides an accurate estimation of the green roof substrates' SWRC (Liu and Fassman-Beck 2018; Peng et al. 2019, 2020). The HCF is difficult to characterize in the laboratory, and the Mualem model has typically been used to estimate unsaturated hydraulic conductivity from the SWRC. However, Liu and Fassman-Beck (2018) and Peng et al. (2020) have found that this approach does not provide accurate estimations of the HCF for green roof substrates. As a consequence, new HCFs based on measured laboratory data for green roof substrates have been proposed by Peng et al. (2020).

While physically-based modeling to characterize processes within the substrate layer is reasonably well-established, this is not the case for the underlying drainage layer.

A green roof drainage layer may take a variety of forms, including aggregate (gravel), entangled polymeric filaments, geotextiles, shaped plastic modules and foam boards (Vesuviano, 2014). The primary function of this layer is to remove excess water from the system effectively. However, some green roof systems utilize vertically oriented polyester thread fabric for the drainage layer to limit outflow rate and consequently enhance detention (Purple-Roof, 2020).

Empirical models based on reservoir routing have been proposed to characterize the relationships between water depth and runoff rate from different plastic board based green roof drainage layers

(Vesuviano and Stovin, 2013). However, the model parameters are configuration-dependent; intensive characterization experiments are needed to identify relevant parameters. The innovative polyester fabric detention layer only emerged recently, and no published studies to date have attempted to model runoff profiles from this layer.

The Storm Water Management Model (SWMM) is a dynamic rainfall-runoff simulation model that can be used for a single rainfall event or long-term (continuous) simulation of runoff quantity and quality. The LID module in SWMM is intended to simulate and assess the hydrological performance of various SuDS/LID devices. The retention model in SWMM determines evapotranspiration from SuDS controls during dry weather periods, and the detention model simulates the timing and the rate of runoff during storms (Rossman and Huber 2016). The SWMM green roof LID control module represents green roof hydrological performance by tracking water movement through different vertical layers, and the behavior of each layer is represented by an independent model. The detention model in the SWMM green roof LID control module is a simplified physically-based model, and model parameters can be determined based on the components' physical properties.

While model parameters input into the SWMM green roof LID control module could/should be determined from laboratory analysis, in practice, all model validation work published to date has relied upon calibration of at least some of the key physical parameters. It has been demonstrated that the SWMM green roof LID control model can be used successfully to represent the hydrological performance of a green roof in response to individual rainfall events using calibrated parameters (Burszta-Adamiak and Mrowiec 2013; Johannessen et al. 2019; Palla and Gnecco 2015; Peng and Stovin 2017). However, the performance of individual layer models within the SWMM detention model has not been validated in detail, either for conventional systems or for systems incorporating the innovative detention layer. It is therefore interesting to understand how the simplified physically-based models employed in SWMM perform when compared with more complete physically-based models. For the substrate layer, the comparison may be made with the Richards equation-based models described above. However, for the drainage layer, a new physically-based model will need to be formulated.

The objectives of this study are to: (1) develop a physically-based detention model for green roof drainage layers; (2) identify suitable model parameter values for the drainage layer components for both the new model and the SWMM green roof LID control detention model; and (3) validate the physically-based and the SWMM green roof LID control detention models using two different complete green roof systems.

MATERIALS AND METHODS

Green roof systems

Two laboratory green roof systems (conventional and innovative) were used in this study. Both green roof systems reproduced the complete full-scale vertical profile of the green roof, such that any vertical detention processes (primarily those occurring in the substrate layer) are reproduced exactly at full scale. The length of the system drainage layers in both cases is typical of the full drainage length of a domestic pitched roof. Both laboratory systems were narrow (~ 1 m) compared with a typical pitched roof, which implies that some lateral flow processes will be ignored. However, it is reasonable to assume these will be relatively minor, if not absent. Compared with in-situ monitoring programmes, laboratory studies offer three distinct benefits for model development: the quantity and precision of instrumentation that is possible; the opportunity to focus on individual components in isolation; and the repeatable control of the imposed rainfall.

Conventional green roof system

The conventional green roof system refers to a system in compliance with FLL guidance (a guideline for green roof planning, construction and maintenance, FLL 2008). It consists of 100 mm deep Marie Curie Substrate, a ZinCo Systemfilter SF particle filter sheet, a 25 mm ZinCo Floradrain FD 25 drainage layer, and a fibrous ZinCo SSM 45 protection mat (Fig. 1(a)). The width of the tested system is 1 m, and the length is 5 m. The system was placed on a base with a slope of 2%. A full description of the conventional green roof system can be found in Vesuviano et al. (2014).

Fig. 1

Innovative green roof system

The innovative green roof system refers to a system developed by Green Roof Diagnostics. One embodiment of this green roof system consists of 20 mm sedum vegetation, 50 mm Moerings Mix #9 Substrate, 50 mm needled mineral wool, 50 mm honeycomb detention reservoir and 5 mm detention layer (Fig. 1(b)). The Moerings Mix #9 Substrate was developed and blended to be representative of a green roof substrate for the eastern USA. The tested system is 6.1 m long, 1.1 m wide, and it was placed on a base of 2% slope. The intention of this innovative system is to maximize retention and detention capacity by adding extra storage and detention layers to the system. The mineral wool is a needled lightweight mineral fiber layer. In the innovative green roof system, the mineral wool creates significant micropore spaces for water to be stored against gravity and increases plant-available water for longer periods of time after rainfall compared with an aggregate substrate. The primary hydrological function of the mineral wool is to increase retention at the beginning of rainfall events. During storms, once rainfall exceeds the maximum water retention capacity of the mineral wool, it conducts water without any significant detention effects. The honeycomb detention reservoir is a panel of small diameter (10 mm in this study), vertically oriented, solid-wall tubes. In the innovative green roof system, the honeycomb holds water inside the array of tubes, thereby preventing horizontal flow and increasing the storage capacity of the system. The detention layer at the bottom of the system is a flexible layer comprising vertically oriented polyester threads between two knitted layers of tightly woven polyester fabric. The detention layer increases detention performance by reducing the outflow rate, thus allowing water to backfill into the overlying honeycomb.

Laboratory detention tests

For both roof systems, two types of detention test were undertaken in the laboratory. Tests were undertaken on drainage layer components in isolation to identify the component-specific parameter values to be used in the two alternative models. Subsequently, tests were undertaken with the two complete systems to provide validation data for the two complete models. For the conventional green roof system, the laboratory data presented here was previously reported in Vesuviano (2014), Vesuviano et al. (2014) and Vesuviano and Stovin (2013) and is available through The University of Sheffield's Online Research Data (ORDA) service (Peng et al., (2021)). The tests on the innovative system were all conducted by Green Roof Diagnostics in 2018-2020 specifically for the present paper.

In all cases, tests were run with systems that could be considered to be at field capacity, such that no initial losses (retention) would occur, and the data collected reflects detention processes only. In practice, this was achieved by wetting and then draining the systems until drainage substantially ceased prior to commencing the detention tests, such that the volume of rainfall applied during testing would result in approximately the same volume of runoff.

Conventional green roof system

A rainfall simulator, consisting of dripper networks and a water supply system, was placed over the conventional green roof test bed to apply the design storms. A collection barrel with a pressure transducer installed was placed at the downstream end of the test bed to collect runoff from the system. Detention tests with the 25 mm ZinCo Floradrain FD 25 drainage layer in isolation were conducted at five inflow rates (0.1, 0.3, 0.6, 1.2 and 2.0 mm/minute), two roof slopes (2% and 17.6%), and two drainage lengths (2 m and 5 m). These inflow rates are equivalent to the intensities associated with one-hour 1 in 1, 5, 50 and 500 year and 30-minute 1 in 500 years Sheffield rainfall depths respectively (NERC 1975). Each configuration was tested with three replications, and rainfall-runoff data were recorded at 1-second time-steps throughout the tests. Inflow duration (between 5 and 11 minutes) for individual tests was selected to allow the drainage layer to reach an equilibrium state, where inflow equals outflow rate, before the end of the rainfall. A full description of the drainage layer test program can be found in Vesuviano and Stovin (2013).

Detention tests with the complete conventional green roof system were conducted at a length of 5 m and a width of 1 m at a 2% slope. Five 60-minutes design storms were applied to the system with three replications. Three of the storms were constant intensity events at 0.3 mm/minute, 0.6 mm/minute and 1.2 mm/minute. The other two were time-dependent storms equivalent to 1-in-10 year and 1-in-100 year 75% profile peakedness summer storm profiles for Sheffield, UK. The total rainfall depths of 21.94 mm and 44.81 mm were discretized into 15 4-minute steps to generate the two time-varying rainfall profiles (NERC 1975). Sixteen hours of drainage time was allowed after each rainfall test to allow all the runoff resulting from one test to be captured without allowing significant evaporation to take place. Runoff data were collected at 1-minute time steps. A full description of the test program can be found in Vesuviano et al. (2014).

Innovative green roof system

Detention tests with the innovative detention layer and the complete innovative green roof system were conducted by Green Roof Diagnostics, LLC (Culpeper, Virginia, USA). Fig. 2 shows the set up for the detention tests. The water supply reservoir was placed on a scale (0.2 kg sensitivity) above the test bed to monitor the volume of water applied. Simulated rainfall was distributed evenly from above using a pressurized spray network. Two reservoirs downstream of the test bed were each placed on scales (0.2 kg sensitivity) to collect surface runoff (if any) and bottom runoff. As there is a possibility that rainfall landed on the ground, the weight of the test bed was continuously recorded to determine the actual rainfall landed on the surface of the test bed. The rollers beneath the test bed were used to pull the test bed into place. The detention tests were conducted with three constant rainfall intensities (approximately 0.17 mm/min, 0.78 mm/min and 1.9 mm/min) for 15 minutes. The rainfall intensities are representative of local (Southeastern USA) low, medium and high rainfall intensities. However, it should be noted that the purpose of using various rainfall intensities is to identify model parameters that are independent of rainfall intensities. In this context, absolute values of rainfall depth or intensity are not critical. All tests were conducted along the full length of the test bed (6.1 m) at a 2% slope. Three replications were conducted for each rainfall intensity, and data were recorded at a 1-minute time step.

Fig.2

Detention models

Two detention models were considered in this study, a newly-proposed two-stage physically-based detention model (2SPB) for green roof systems and the modeling approach used in SWMM 5.1's Green Roof LID Control (SWMM-GR). The proposed 2SPB model represents detention in the substrate using the Richards Equation and in the drainage layer by the Saint Venant Equation.

Two-stage physically-based model (2SPB) – Substrate layer

It is assumed that rain falls evenly on the surface of a green roof system, and the vertical hydraulic gradient dominates the flow in the substrate. The 1D vertical Richards Equation (Eq. 1) was used to represent the flow in the substrate. Previous research has demonstrated that the Durner model (Durner 1994) provides the best representation of the Soil Water Release Curve (SWRC) for green roof substrates (Liu and Fassman-Beck 2018; Peng et al. 2019, 2020), and a three-segment curve provides the best estimation of a green roof substrate Hydraulic Conductivity Function (HCF) (Peng et al. 2020). Therefore, the Durner model (Eq. 2) and the three-segment curve (Eqs. 3-5) were used in this study for the substrate used in the conventional green roof system. However, as the HCF for the substrate used in the innovative green roof system has not been experimentally determined, the conventional approach of Durner-Mualem (Eqs. 6-8) was used to estimate the HCF for this substrate. Following the approach described in Peng et al. (2020), a constant head (equivalent to the suction head at field capacity) boundary condition was used for the lower boundary, a time-varying flux condition (equivalent to the rainfall input) was assigned for the upper boundary condition, and a constant hydraulic head was set for the initial conditions.

$$\frac{\partial\theta}{\partial t} = \frac{\partial}{\partial Z_G}\left[K(h)\left(\frac{\partial h}{\partial Z_G} - 1\right)\right] \quad (1)$$

$$S_e = \frac{\theta-\theta_r}{\theta_s-\theta_r} = w[1 + \left(\alpha_1 h\right)^{n_1}]^{-m_1} + (1 - w)[1 + \left(\alpha_2 h\right)^{n_2}]^{-m_2} \quad (2)$$

$$if \quad \theta_1 < \theta \leq \theta_s; \qquad K(\theta) = 10^{\beta_1\cdot\theta+\gamma_1} \quad (3)$$

$$if \quad \theta_2 < \theta \leq \theta_1; \qquad K(\theta) = 10^{\beta_2\cdot\theta+\gamma_2} \quad (4)$$

$$if \quad \theta < \theta_2; \qquad K(\theta) = 10^{\beta_3\cdot\theta+\gamma_3} \quad (5)$$

$$S_{e_1} = [1 + \left(\alpha_1 h\right)^{n_1}]^{-m_1} \quad (6)$$

$$S_{e_2} = [1 + \left(\alpha_2 h\right)^{n_2}]^{-m_2} \quad (7)$$

$$K\left(S_e\right) = K_s\left(wS_{e_1} + (1 - w)S_{e_2}\right)^{0.5} \times \frac{w\alpha_1\{1-\left(1-S_{e_1}^{\frac{1}{m_1}}\right)^{m_1} + (1-w)\alpha_2\left[1-\left(1-S_{e_2}^{\frac{1}{m_2}}\right)^{m_2}\right]\}^2}{\left(w\alpha_1+(1-w)\alpha_2\right)^2} \quad (8)$$

where θ is moisture content (v/v), $K(h)$ is hydraulic conductivity (cm/min) at suction head h (cm), Z_G (cm) is the elevation of the point relative to the reference level (the bottom of the substrate layer), S_e is the relative saturation (-), θ is moisture content (v/v), θ_r is residual moisture content (v/v), θ_s is saturated moisture content (v/v), w, α_1, n_1, m_1, α_2, n_2, m_2 are empirical parameters, K_S is saturated hydraulic conductivity (cm/min), $K(\theta)$ is the unsaturated hydraulic conductivity (cm/min) at θ, θ_1, θ_2 are the two intercepts (v/v) on the HCF, β_1, γ_1, β_2, γ_2, β_3 and γ_3 are empirical parameters.

Two-stage physically-based model (2SPB) – Drainage layer

The flow conditions in the green roof drainage layer can be considered as water flowing over the surface of the drainage layer (Fig. 3(a)), therefore the 1D gradually varied unsteady flow Saint Venant equation may be applied. The mass balance form of the equation is given in Eq. 9 (Chow 1959).

$$\frac{\partial h_s}{\partial t} + \frac{\partial h_s U_s}{\partial x} = R(\mathrm{x,t}) \tag{9}$$

where h_s is the unit storage of water, U_s is the depth-averaged flow velocity, t is time, x is the distance coordinate and R(x,t) is the rate of recharge. In the case of a green roof drainage layer, recharge represents the outflow from the overlying substrate layer calculated from the simulated suction head (Eq. 1) and Eq. 10.

$$R(t) = K(h)\left(\frac{\partial h}{\partial Z_G} - 1\right) \tag{10}$$

Fig.3

The velocity term U_s in the Saint Venant equation may be estimated by Manning's equation (Eq. 11).

$$U_s = \frac{h_s^{2/3}}{n}\sqrt{s_f} \tag{11}$$

where n is Manning's coefficient and s_f is the friction slope (Eq. 12).

$$s_f = -\frac{\partial(h_s + z)}{\partial x} \tag{12}$$

where z is the surface elevation.

Under the assumption that the water depth gradient is much smaller than the surface elevation gradient, Eq. 13 is obtained, and Eq. 9 can be written as Eq. 14.

$$U_s = -\frac{h_s^{2/3}}{n\sqrt{s}}\frac{\partial(h_s + z)}{\partial x} \tag{13}$$

$$\frac{\partial h_s}{\partial t} = \frac{\partial h_s}{\partial x}\left[\frac{h_s^{\frac{2}{3}}}{n\sqrt{s}}\left(\frac{\partial h_s}{\partial x} - s\right)\right] + R(x,t) \tag{14}$$

where s is the mean local slope.

Fig. 3(a) shows the longitudinal section of a green roof drainage layer laid on a base with a slope. L is the length of the drainage layer, and θ is the slope angle. The drainage layer receives recharge (inflow) from the upper layers and discharges the water at $x = L \cos cos\, \theta$. In this sloped system, water is added along the length of the layer and accumulates at the outlet. The left boundary was treated as a constant head boundary (Eq. 15), and the right boundary was treated as a free drainage condition (Eq. 16).

$$h_s(t, x = 0) = 0 \tag{15}$$

$$\frac{\partial h_s(x = L\cos cos\, \theta)}{\partial x} = 0 \tag{16}$$

At the beginning of the rainfall, the initial water level in the drainage layer is assumed to be zero. Therefore, Eq. 17 represents the initial conditions for the model.

$$h(t = 0,\ x) = 0 \tag{17}$$

The change in water levels in the drainage layer is due to recharge; the runoff from the layer can be calculated from the difference between recharge and storage (Eqs. 18 and 19).

$$v(x, t) = R - [h_s(x, t) - h_s(x, t - 1)] \tag{18}$$

$$Runoff(t) = \left(\sum_{1}^{L/dx} v(x, t)\right)/[L/dx] \tag{19}$$

where $v(x, t)$ is the velocity distribution (mm/min), R is the recharge (mm/min), $Runoff(t)$ is the runoff from the layer (mm/min), and dx is the spatial step (mm).

MATLAB code for the physically-based model is available through The University of Sheffield's Online Research Data (ORDA) service (Peng et al., (2021)).

SWMM green roof LID control model (SWMM-GR)

In SWMM, a green roof is represented by three horizontal layers (Fig. 3(b)). During a rainfall event (assuming no evapotranspiration), the surface layer receives direct rainfall and infiltrates to the soil layer or generates surface runoff if ponding occurs (Eq. 20). The soil layer receives infiltration from the surface layer and loses water through percolation (Eq. 21). The drainage layer receives percolation from the soil layer, and rainfall exits the system as runoff (Eq. 22).

Within the SWMM-GR model, different models are used to represent the flow in each layer. Manning's equation for uniform flow (Eq. 23) is used to model surface runoff; the Green-Ampt model (Eq. 24) is used to model infiltration of surface water into the soil layer; percolation in the soil layer is modeled using Darcy's Law for steady-state flows (Eq. 25), and runoff from the drainage layer is modeled using Manning's equation for uniform flow (Eq. 26). The conditions of the layer limit the flux within and between layers. The flux from the surface layer to the soil layer is limited by the amount of empty pore space in the soil and the volume removed by drainage (Eq. 27). Soil percolation rate is limited by the drainable water plus the water added to the soil layer (Eq. 28). Soil percolation rate is also limited by available storage in the drainage layer and the amount of water removed from the drainage layer (Eq. 29). Runoff rate from the drainage layer is limited by the amount of water that can be stored plus any inflow from the soil layer (Eq. 30). It should be noted that a coefficient of 0.6017 is used in Eqs 22 and 25 to convert empirical units to SI units.

$$\emptyset_1 \frac{\partial d_1}{\partial t} = i - f_1 - q_1 \tag{20}$$

$$D_2 \frac{\partial \theta_3}{\partial t} = f_1 - f_2 \tag{21}$$

$$\emptyset_3 \frac{\partial d_3}{\partial t} = f_2 - q_3 \tag{22}$$

$$q_1 = \frac{0.6017}{n_s}\sqrt{S_1}(W_1/A_1)\emptyset_1(d_1 - D_1)^{\frac{5}{3}} \tag{23}$$

$$f_1 = K_s(1 + \frac{\left(\emptyset_2 - \theta_3\right)\left(d_1 + \varphi_1\right)}{F}) \tag{24}$$

$$f_2 = \{0, \qquad \theta_3 < \theta_{FC} K_s \exp exp\left(- HCO\left(\emptyset_2 - \theta_3\right)\right), \qquad \theta_3 \geq \theta_{FC} \tag{25}$$

$$q_3 = \frac{0.6017}{n_3}\sqrt{S_1}(W_1/A_1)\emptyset_3(d_3)^{\frac{5}{3}} \tag{26}$$

$$f_1 = min[f_1, \left(\emptyset_2 - \theta_s\right)D_2 + f_2] \tag{27}$$

$$f_2 = min[f_2, \left(\theta_3 - \theta_{fc}\right)D_2 + f_1] \tag{28}$$

$$f_2 = \left[f_2, \left(D_3 - d_3\right)\emptyset_3 + q_3\right] \tag{29}$$

$$q_3 = min[q_3, \left(d_3 - D_3\right)\emptyset_3 + f_2] \tag{30}$$

where d_1 (mm) is the depth of water stored on the surface, d_3 (mm) is the depth of water in the storage layer (mm), i is the precipitation rate falling directly on the surface layer (mm/min), q_1 is the surface layer runoff (mm/min), q_3 is the drainage layer outflow rate (mm/min), f_1 is the infiltration rate (mm/min), f_2 is the percolation rate (mm/min), $\emptyset_1$ is the void fraction of surface volume, $\emptyset_2$ is the soil porosity, $\emptyset_3$ is the void fraction of the drainage layer, D_1 is the surface depression storage depth (mm), D_2 is the soil thickness (mm), D_3 is the drainage layer thickness (mm), n_s is the surface roughness coefficient, n_3 is the drainage layer roughness coefficient, S_1 is the system slope (m/m), W_1 is the total length along the edge of the roof where runoff is collected (m), A_1 is the roof surface area (m^2), K_s is the soil saturated hydraulic conductivity (mm/min), θ_3 is the soil moisture content (volume of water/total volume of soil), θ_{FC} is the soil field capacity (v/v), φ_1 is the suction head at the infiltration wetting front formed in the soil (mm), F is the cumulative infiltration volume per unit area over a storm event (mm), and HCO is the soil hydraulic slope, a decay constant derived from the hydraulic conductivity function of the substrate.

Model implementation

Both the 2SPB model and the SWMM-GR model were built in MATLAB R2017b. Numerical solutions for the 2SPB model equations were obtained using the MATLAB *pdepe* function (https://uk.mathworks.com/help/matlab/math/partial-differential-equations.html; Skeel and Berzins 1990). All simulations employed 1-second or 1-minute time-steps depending on the time intervals of measured data (the time step merely specifies where the solution is required; the function selects the time step dynamically). 1 mm vertical spatial steps were used for the Richards Equation (Eq. 1), and 100 mm horizontal spatial steps were used for the Saint Venant equation (Eq. 14). All simulations started from field capacity to exclude retention effects, and the initial storage in the drainage/detention layer at the beginning of simulations was assumed to be zero. However, it should be noted that in the SWMM 5.1 interface, the initial storage in the drainage layer cannot be set independently from the initial saturation in the substrate layer; this limitation was avoided in the bespoke MATLAB tool. Mass balance checks were undertaken to confirm that differences between input rainfall and simulated runoff were always within 2%.

Each layer in the conventional green roof system has its corresponding model in the physically-based and SWMM models. Although the innovative green roof system consists of multiple layers, not every layer in the system provides a significant contribution to detention. The detention impact of mineral wool was neglected in both models. In the 2SPB model, the honeycomb and the detention layer were combined and modeled by the Saint Venant equation (Eq. 14). In the SWMM-GR model, the honeycomb depth was added to the total drainage layer depth, and Eq. 26 was used to model their combined detention effect.

Model parameters Two-stage physically-based model (2SPB)

Table 1 lists the value of parameters used in the 2SPB model for the two green roof systems. The SWRC and HCF for the Marie Curie Substrate were measured in Peng et al. (2020). For the substrate used in the innovative green roof system, the SWRC parameters were based on the Durner model, for which the parameters were fitted to data points measured using the Hanging Column method (test data provided by Green Roof Diagnostics). The HCF for the innovative green roof substrate was estimated based on the Durner-Mualem model. While using an estimated HCF for the substrate introduces uncertainty into the model, the substrate in the innovative green roof system is only 50 mm deep, and it is therefore expected to provide limited detention.

Manning's n values for the drainage layer in the conventional green roof system and the detention layer in the innovative green roof system were determined based on component isolated detention tests. Sonnenwald et al. (2014) demonstrated that R_t^2 (Young et al. 1980) (Eq. 31) provided a robust and generically applicable indicator of model performance for temporally-varying data. Therefore, R_t^2 was used to evaluate the goodness-of-fit of the modeled runoff.

$$R_t^2 = 1 - \frac{\sum_{i=1}^{T}\left(q_o - q_m\right)^2}{\sum_{i=1}^{T}\left(q_o\right)^2} \tag{31}$$

where T is the total number of observed data, q_o is the observed runoff data, q_m is the modeled runoff data.

At the same time, the Nash-Stuliffe Model Efficiency index (E) (Eq. 32) was also used to evaluate the goodness-of-fit of the model results.

$$E = 1 - \frac{\sum_{i=1}^{T}\left(q_o - q_m\right)^2}{\sum_{i=1}^{T}\left(q_o - q_{mean}\right)^2} \tag{32}$$

where q_{mean} is the mean value of observed data. A value of R_t^2 or E equal to one corresponds to a perfect match of modeled data to the observed data.

The Monte-Carlo method was used to identify values of Manning's n corresponding to the maximum observed mean R_t^2 and E values over the complete set of drainage layer isolated detention tests. The same optimal values of Manning's n were identified using R_t^2 or E as the metric for goodness-of-fit.

Table 1

SWMM green roof LID control model (SWMM-GR)

Table 2 lists the values of parameters used in the SWMM model for the two green roof systems. The saturated hydraulic conductivity, porosity and field capacity of the Marie Curie Substrate were determined through the FLL methods (FLL 2008). The hydraulic slope for the Marie Curie Substrate was determined from the measured hydraulic conductivity function data. The saturated hydraulic conductivity, porosity and field capacity for the Moerings Mix #9 Substrate were determined using the ASTM E2399 method (test data provided by Green Roof Diagnostics). The hydraulic slope for the Moerings Mix #9 Substrate was determined based on the characterized particle size distributions using Eq. 33 (Saxton and Rawls 2006).

$$HCO = 0.48 \times \%sand + 0.85 \times \%clay \tag{33}$$

Values for the surface layer parameters for both systems were assumed as suggested in Rossman and Huber (2016) (Table 2). The suction head at the infiltration wetting front for both substrates was assumed to be 50 mm, which is a suggested value for a typical green roof substrate (Rossman and Huber 2016).

The roughness coefficient for the drainage layer used in the conventional green roof system (n_3 = 0.0578) and the detention layer used in the innovative green roof system (n_3 = 0.952) were determined from the component isolated detention tests using the *lsqcurvefit* function in MATLAB. A value of 0.5 was assumed for the drainage layer void fraction for both systems (Table 2).

Table 2

Model validation

Comparisons between model predictions and measured laboratory data are presented in two stages. First, we present the measured and modeled runoff profiles for the drainage layer isolated tests and comment on the ability of the two drainage layer models to reproduce the observed behavior of this single layer in isolation.

Second, we introduce the substrate layer models (and the surface layer model in SWMM) to evaluate the multi-layered models' abilities to reproduce the runoff profiles observed in the two complete systems.

RESULTS

Parameter identification for the conventional drainage layer component

Fig. 4 shows the measured and modeled runoff profiles from the FD-25 drainage layer using the physically-based and the SWMM models. As good consistency was achieved between replicate tests and different rainfall intensities, only one rainfall intensity (0.06 mm/min) for each configuration is presented. As different behaviors for each of the four different configurations (two slopes and two drainage lengths) were observed in the tests, four different values of Manning's n and drainage layer roughness coefficient were identified (Table 3). Manning's n in the 2SPB model and configuration-specific drainage layer roughness coefficient in the SWMM-GR model are based on the mean value that achieved the highest R_t^2 and E for the 15 tests (five rainfall intensities and three replications).

Table 3

With all R_t^2 higher than 0.97 and E higher than 0.98, both models are capable of modeling the runoff from the FD-25 drainage layer. The 2SPB model performs consistently well for all four configurations. Among all the configurations, the SWMM-GR model has the lowest R_t^2 value of 0.984 and lowest E value of 0.969 with the configuration 2% slope 5 m drainage length (this is the configuration used in the complete system experiments). In this case, the 2SPB model slightly overestimated the detention effects in both the rising and falling limbs of runoff profiles, while the SWMM-GR model delayed the time for the system to reach an equilibrium state by 300 seconds. The falling limb of runoff profiles was modeled well by both models for all the cases. It should be noted that the time-step here is 1-second; the difference between the two model results will be minor if a 1-minute time-step is used (e.g. for complete system modeling).

Fig. 4

Parameter identification for the innovative detention layer component

Fig. 5 shows modeled runoff from the innovative detention layer component in response to the three rainfall intensities using the identified values of Manning's n (0.017) and the drainage layer roughness coefficient (0.952). The identified drainage layer roughness coefficient is significantly higher than the typical value for a green roof drainage layer (0.01-0.03) suggested in Rossman and Huber (2016), which indicates high detention potential. As good consistency was achieved between replicate tests, only one test for each rainfall intensity is presented. Significant fluctuations were observed in the measured runoff profile in response to the low rainfall intensity (Fig 5(a)), which are due to the resolution of the weighing scale. Both models were able to simulate the runoff from the detention layer to some extent. At the low rainfall intensity (0.2 mm/min, Fig. 5(a)), the SWMM-GR model provided a better estimation of the runoff profile than the physically-based model, but both models appeared to overestimate detention effects. As the 2SPB model accounts for the effects of horizontal flow, the peak runoff rate was maintained for a prolonged period. Both models perform best in the medium rainfall intensity (1.1 mm/min, Fig 5(b)), with R_t^2 higher than 0.96 and E higher than 0.95. However, the 2SPB model overestimated the peak runoff by 15.2%, and SWMM-GR overestimated the peak by 5.5%. In response to the high rainfall intensity (2.4 mm/min, Fig 5(c)), both models provided similar runoff profiles, and both significantly overestimated the peak.

While Fig. 5 shows the results of using a single parameter value, independent of rainfall intensity, it was observed that the best-fit parameter values for both Manning's n and the drainage layer roughness coefficient increased with rainfall intensity. This suggests that the flow conditions in the innovative detention layer are more complicated than they are in the FD-25 drainage layer, such that a constant value for the parameters may not be sufficient to fully describe the relevant processes.

As the rainfall intensities used in the detention tests with the FD-25 drainage layer and the detention layer are not identical, no direct comparison can be made between their detention performance. However, Stovin et al. (2015) noted that the calibrated parameters in a detention model could be used to characterize the detention performance of a system. Based on the identified Manning's n (0.0012 for the FD-25 drainage layer and 0.017 for the detention layer) and the drainage layer roughness coefficient (0.0578 for the FD-25 drainage layer and 0.952 for the detention layer), both parameters indicate that the innovative detention layer has the potential to provide more significant detention effects than the (conventional) FD-25 drainage layer. This may indicate that the innovative green roof system that contains this detention layer has a better performance in reducing downstream peak flow, delaying the time of peak flow and mitigating the downstream flooding risk than a conventional green roof system that uses the FD-25 drainage layer.

Fig. 5

Complete conventional green roof system

Fig. 6 shows the measured and modeled runoff profiles from the complete conventional green roof system. The parameters used in the models are as listed in Tables 1 and 2. As good consistency was achieved between replicate tests, one test for each design storm is presented in Fig. 6. Both models are capable of generating reasonable runoff profiles from the conventional green roof system, although with a tendency to underestimate the observed detention. However, with consistently higher values of R_t^2 and E the 2SPB model provides better estimations of the runoff profiles than the SWMM-GR model.

In the lowest two constant intensity design storms (0.3 mm/min and 0.6 mm/min, Fig. 6(a) and (b)), the 2SPB model underestimates the detention effects in the rising limb of the runoff profiles. However, the falling limb is modeled well. In the highest constant intensity design storm (1.2 mm/min, Fig. 6(c)), the entire runoff profile is modeled well by the physically-based model, with R_t^2 equal to 0.984 and E equal to 0.976. In the two time-dependent design storms (Fig. 6(d) and (e)), the 2SPB model slightly overestimates the peak runoff, by 4% and 7.8%, respectively.

The SWMM-GR model underestimates the detention effects of the system in all five design storms, and some numerical stability problems were also observed at high rainfall intensities (Fig. 6 (d) and (e)). In the constant intensity design storms, the time for the system to reach equilibrium was modeled to be between 6 minutes (Fig. 6(c)) and 20 minutes (Fig. 6(a)) earlier than measured. The SWMM-GR model also overestimated the peak runoff rate by 7.3% (Fig. 6(d)) and 20.6% (Fig. 6(e)) in the two time-dependent design storms.

The substrate model and the drainage layer model in the 2SPB model were independently parametrized using component isolated detention tests, and the model performs well when applied to a complete system. This indicates that the proposed model has the potential for generic application to modeling detention in a conventional green roof system. While the drainage layer model in the SWMM-GR model appeared capable of regenerating the runoff from the drainage layer in the drainage layer isolated tests, the SWMM-GR model failed to regenerate the runoff profiles from the complete system accurately. This could be caused by limitations in the way the overlying substrate layers are modeled in SWMM. Further discussion on the SWMM-GR percolation model will be provided in the Discussion section.

Fig. 6

Innovative green roof system

Fig. 7 shows the measured and modeled runoff profiles from the complete innovative green roof system. The parameters used in the models are as listed in Tables 1 and 2. As consistent results were obtained between replicate tests, only one test for each rainfall intensity is presented in Fig. 7. Again, both models provided reasonable estimations of the measured runoff profile (i.e. R_t^2 ranges from 0.7 to 0.9 and E ranges from 0.3 to 0.8). However, in response to the low rainfall intensity (0.17 mm/min, Fig. 7(a)), the 2SPB model delayed the time of peak runoff. This is caused by the consideration of horizontal flow in the model, as it takes time for the water added along the length of the detention layer to flow to the outlet. In the medium rainfall intensity (0.78 mm/min, Fig. 7(b)), the models overestimated the peak runoff by 31.7% (2SPB model) and 22.9% (SWMM-GR model). In the high rainfall intensity (1.9 mm/min, Fig. 7(c)), the 2SPB model overestimated the peak runoff by 61.9%, while the SWMM-GR model overestimated the peak runoff by 51.1% and delayed the time of peak runoff about 2 minutes.

The time to start of runoff was delayed by 3 minutes in the SWMM-GR model in all cases. This is because the SWMM-GR model uses the outflow from the previous time step to calculate the inflow into the lower layer for the current time step. The three models for the three processes in the substrate and the drainage layer therefore resulted in the three-minute delays. The model results for the detention layer isolated tests suggested that a higher value of Manning's n or drainage layer roughness coefficient needs to be used in the high rainfall intensity to fit the measured runoff; this is consistent with the observation that detention is underestimated for the complete system when a universal coefficient value is applied.

Fig. 7

The SWMM-GR model underestimates detention at the start of a runoff event in the conventional green roof system, and both the 2SPB and SWMM-GR models overestimate the peak runoff associated with the innovative detention system. The underestimated detention effects noted above suggest that both models’ performance could be improved by increasing the values of the roughness parameters.

DISCUSSION

Purely physical modeling objectives

One of the authors' goals for this modeling exercise was to develop a physically-based model that can be parametrized from independent laboratory tests of the separate components without the need for any calibration. The work documented in this paper accomplishes much of that goal. For the conventional system, in particular, both model structures are capable of generating good matches to the measured data. The model results presented here can be improved with further system-specific calibration. However, such a calibration exercise defeats the objective of developing a physically-based model that can be parametrized from independent laboratory tests of the separate components.

Recalibration of the roughness parameters (Manning's n or detention layer roughness coefficient) did not fully address the problems highlighted when attempting to model the complete innovative green roof. The model results indicate that flow conditions in the detention layer vary with rainfall intensity, which has not been fully represented by either model. In the following section, we explore possible reasons for the observed discrepancies and highlight opportunities for future work.

Infiltration model

The SWMM-GR model uses the Green-Ampt model (Eq. 24) to represent the water infiltrating from the substrate surface into the deeper substrate. In this model, the infiltration rate is controlled by the head of water ponding on the surface of the substrate. However, as the two substrates used in the two green roof systems are highly permeable (higher than the highest tested rainfall intensity), no water ever ponded on the surface of the substrate, and no detention effects were modeled due to this process. Green roof substrates commonly have a high permeability (e.g. 0.6 mm/min to 70 mm/min (FLL 2008)), which generally prevents surface runoff. As it had been foreseen that the detention effects due to surface infiltration would not be significant, this process was not considered in the physically-based model.

Percolation model

The SWMM-GR model uses a percolation model (Eq. 25) to represent runoff from the substrate. This model assumes the substrate is in a steady-state condition, such that moisture content is uniform throughout the depth of the soil layer. At this condition, flow is driven only by gravity, and the runoff rate from the substrate is equivalent to the unsaturated hydraulic conductivity corresponding to its moisture content (Eq. 25). However, in response to low rainfall intensities, the substrate does not reach steady-state condition instantaneously, and the detention effects due to the vertical moisture content gradient are significant. Therefore, this model is not appropriate to model the response of the substrate to low rainfall intensities. Fig. 8 shows the modeled substrate runoff from the two systems in response to low rainfall intensities. For the conventional green roof system, Fig. 8(a) shows that no detention effects are modeled by SWMM-GR. In contrast, the Richards Equation in the 2SPB model accounts for the non-uniform wetting process, and the detention effects in the substrate are more realistically modeled. The same unrealistic estimation of the substrate runoff profiles was also observed for SWMM-GR in the innovative green roof system in response to the low rainfall intensity (Fig. 8(b)). It should be noted that the substrate in the conventional green roof system is twice as deep as in the innovative green roof system (100 mm versus 50 mm). Therefore, the impact of the substrate model is more significant in the conventional green roof system. The comparisons made between the Richards Equation in the 2SPB model and the percolation model in SWMM-GR indicate that the Richards Equation provides a better representation of the substrate detention effects. However, it is acknowledged here that the use of the Richards equation would significantly increase the computational cost. The substrate outflow and the runoff modeled by the two models for the two systems presented in Fig. 8 indicates that although both the substrate and drainage layer contribute to detention, the detention layer in the innovative green roof system provides more significant detention than the drainage layer in the conventional green roof system, leading to observably improved performance in the complete innovative green roof system.

Fig. 8

Drainage layer models

The drainage layer model in SWMM-GR assumes that the water level in the drainage layer is constant throughout the length of the layer and that the outflow rate is determined by the water level. In the physically-based model, the water level in the drainage layer is assumed to be spatially varied, and the outflow rate is determined by the horizontal flow. Despite the fact that the 2SPB model is more 'complete' than SWMM-GR, both models provided reasonable predictions of the runoff profiles from the drainage layer in the conventional green roof system, and there is not a strong case to be made that the new model performs better than SWMM-GR. However, both models depend on the correct characterization of a drainage layer roughness coefficient.

For the innovative green roof system, both Manning's n and the drainage layer roughness coefficient for the detention layer showed an increasing trend with rainfall intensity. This may indicate that the actual flow conditions in the detention layer are more complicated than the model assumes. The vertically oriented polyester threads in the detention layer act as obstacles in the flow path. When the rainfall intensity is low, the flow velocity is low, and the flow around the obstacles is more likely to be laminar. Under these conditions, the distance traveled for the water to reach the outlet of the detention layer is short. In contrast, when the rainfall intensity is high, higher flow velocities in the detention layer may lead to more turbulent, chaotic flow with increased travel distance and energy loss. Neither the model equation in the 2SPB model nor SWMM-GR considers the effects of turbulent flow in the detention layer. This limits the accuracy of the runoff estimations for the innovative system.

Transferability of model parameters

A generic green roof detention model should have the characteristic of good parameter transferability. In this study, parameters determined from component isolated characterization tests were used to model the runoff from the complete systems. When the newly-derived drainage layer model and parameters were combined with the independently parametrized physically-based substrate model, this approach (2SPB model) led to reasonable estimates of runoff from a conventional green roof system without the need for further calibration. In the case of the SWMM-GR model, however, the limitations inherent in the SWMM percolation model meant that the full system was not modeled satisfactorily.

For the innovative green roof system, the parameters identified from the detention layer isolated tests for both models provided a reasonable estimation of the runoff profiles from the innovative green roof system in response to the low and medium rainfall intensities. However, both models failed to regenerate the runoff profile in the high rainfall intensity accurately, potentially reflecting more complex flow processes and layer interactions than conventional green roof systems, which neither model is capable of representing.

Uncertainties associated with the physically-based model

When parameterized from independent physical analyses of each layer’s components, the 2SPB model was shown to generate reasonably good estimates of runoff profiles associated with a conventional green roof system (Fig 6). Nonetheless, it was acknowledged that simulations tended to underestimate observed detention effects, particularly on the rising limb of the runoff hydrograph at lower rainfall intensities.

One simplification made in the present model is that the filter sheet between the substrate and the drainage layer is not explicitly modeled. It is possible that this layer also contributes to detention. It is also possible that flow processes in the drainage layer are modified by the presence of the overlying layers. Finally, there are a number of considerations relating to the substrate layer model that contribute further uncertainties. The model assumes 1D – purely vertical – flow in the substrate, and the model is sensitive to the correct characterization of substrate SWRC and HCF. The characteristics observed in independent media tests may not be representative of the specific sub-sample and compaction levels utilized in the detention experiments or field installations. Indeed, the heterogeneity of substrates will, unfortunately, always limit simulation accuracy for green roof systems. Therefore, while further refinements to the 2SPB model may improve its accuracy in theory, in practice, the proposed model probably represents an appropriate balance between model complexity and the uncertainties inherent in this type of system.

CONCLUSIONS

A new physically-based green roof drainage layer model based on the Saint Venant equation has been proposed. When combined with a Richards equation-based 1D substrate detention model, the complete two-layer model regenerates measured runoff profiles from a conventional green roof system with an acceptable level of accuracy. A tendency to underestimate detention was noted, which represents a conservative design tool from a stormwater management perspective.

The SWMM green roof detention model is able to provide an accurate estimation of runoff profiles from the drainage layer. However, the model fails to provide accurate estimations of the runoff from the complete system due to limitations in the method used to model substrate percolation.

The unique configuration of the detention layer in the innovative system led to higher detention potential than a conventional green roof system. This was evidenced by the higher roughness coefficients for both models identified in the component isolated tests. When using the parameters identified from the detention layer isolated tests to regenerate runoff profiles from the complete system, both models significantly overestimated the peak runoff in response to the medium and high rainfall intensities. This finding suggests that neither model has fully captured the flow conditions occurring in the innovative detention layer.

While the performance of both models can be improved via further calibration of the model parameters based directly on full system build-up tests, this defeats the objective of applying physically-based models to explore design opportunities associated with unseen systems made up of different component layers.

Opportunities for further work include improved understanding of how substrate heterogeneity and compaction affect detention performance, more detailed exploration of potential detention effects associated with filter fabric layers, and a deeper understanding of flow conditions in the detention layer of the innovative green roof system.

DATA AVAILABILITY STATEMENT

The experimental data for the conventional green roof system and the code for the physically-based model are available in a repository or online in accordance with funder data retention policies (DOI: 10.15131/shef.data.16583852).

The experimental data from the innovative green roof system was provided by a third party (Green Roof Diagnostics). Direct requests for these materials may be made to the provider as indicated in the Acknowledgements.

ACKNOWLEDGEMENTS

Zhangjie Peng is supported by the University of Sheffield, Faculty of Engineering Doctoral Academy Award. The authors would like to thank Dr Gianni Vesuviano for the detention test data with the FD-25 drainage layer and the conventional green roof system. The authors would also like to thank Derek Hidalgo and Scott Jeffers at Green Roof Diagnostics, for their contributions in obtaining and analyzing the experimental data from the innovative green roof system.

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