Modeling the Hydrological Benefits of Green Roof Systems: Applications and Future Needs

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Water Impact Statement

A range of modelling approaches have been developed to assess green roof performance to manage stormwater. The appropriateness and efficacy of a given model depend on its capabilities and complexity. This comprehensive review of existing tools, including parameterization, evaluation, and identification of key research gaps can facilitate model improvements to critically evaluate green roof implementation for stormwater management.

Modeling the Hydrological Benefits of Green Roof Systems: Applications and Future Needs

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Abstract

Green roof (GR) systems provide a promising stormwater management strategy in highly urbanized areas when limited open space is available. Hydrological modeling can predict the ability of GR to reduce runoff. This paper reviews three popular types of GR models with varying complexities, including water balance models, the U.S. EPA's Stormwater Management Model (SWMM), and Hydrus-1D. Developments and practical application of these models are discussed, by detailing model parameter estimates, performance evaluations and application scopes. These three models are capable of replicating GR outflows. Water-balance models have the smallest number of parameters (≤ 7) to estimate. Hydrus-1D requires substantial parameterization effort for soil hydraulic properties but can simulate unsaturated soil water flow processes. Although SWMM has a large number of parameters (>10), it can simulate water transport through the entire GR profile. In addition, SWMM GR models can be easily incorporated into SWMM's stormwater model framework, so it is widely used to simulate the watershed-scale effects of GR implementations. Four research gaps limiting GR model applications are identified and discussed: drainage mat flow simulations, soil characterization, evapotranspiration estimates, and scale effects of GR. The literature document promising results in GR simulations for rainfall events, however, a critical need remains for long-term monitoring and modeling of full-scale GR systems to allow interpretation of both internal (substrate) and external (meteorological characteristics) system effects on stormwater management.

Key words: green roof, hydrological modeling, stormwater management, green infrastructure

1 Introduction

Urban flooding and water pollution are common in cities. Urbanization increases impervious surfaces, increasing velocity/volume of stormwater runoff and downstream pollutant loads to waterbodies.[1–3] To mitigate potential environmental impacts of stormwater, alternative approaches for stormwater management have been developed. These approaches shifted from traditional practices (sewer systems) to source control methods that detain, store and treat stormwater on-site.[4] Green infrastructure (GI) aims to restore, mimic and maintain natural hydrological conditions by using decentralized nature-based practices[5] and has emerged as one of the most promising and popular stormwater management strategies[6–8].

Green roofs (GR) are vegetated rooftops, a GI approach that can provide green space in developed areas with limited space for ground-level implementation of GI. In addition, their benefits such as esthetics and thermal performance make them popular in highly urbanized areas.[9,10] For example, in 2019, there were 763 projects across North America (approximately 289190 m^2 green roofing).[11] Based on estimates, the areas of installed GRs can retain 0.14 million m^3 of stormwater per year. Although the GR industry is estimated to have grown by 5-15% since 2013, there is still an enormous potential roof area of billions of m^2 for new GRs to be installed at a more rapid rate.

GR often consist of a multi-layered construction: a waterproof membrane, a drainage layer, a filter fabric and a substrate layer (soil and plants), built sequentially upward on the roof deck.[12] Based on the substrate depth, GRs are usually categorized as intensive or extensive: intensive GRs have a soil depth larger than 15 cm while extensive GRs have a medium depth less than 15 cm.[13] Extensive GRs are cheaper and require less maintenance[14], but they may be less efficient, compared to intensive GR in stormwater retention and flow rate attenuation[15]. However, considering the applicability of retrofitting existing rooftops without adding large loads and additional strengthening, the extensive GRs are more widely used.[16–19]

Numerous studies have reported GR can reduce stormwater runoff up to 90% and peak flow rates up to 80% during rainfall events.[20–25] However, the effectiveness of GR to reduce stormwater runoff varies across sites and depends largely on physical properties (substrate depth, roof slopes and vegetation cover)[21,26,27] and local climate characteristics[28]. To promote and guide GR implementation, many models of GR hydrological behavior have been created to evaluate GR intrinsic structural properties and the role of external mereological forcing.[28–30]

GR simulations can be classified in two categories: individual scale simulations and watershed/citywide scale simulations. A large portion of the research focuses on developing models to predict GR on-site hydrological processes. These models varied from simple conceptual models[25,31–33] to complex mechanistic models[34–37]. Their ultimate goals are to develop robust models that can evaluate water transport within GR with varied designs under a range of climatic conditions. However, although studies achieved promising modeling results that replicated GR outflow, uncertainties in model performance remain. For example, Broekhuizen et al. compared the performance of four different models of Urbis, SWMM, Hydrus-1D and Mike SHE to predict GR outflow in Lyon, France and Umeå, Sweden.[37] They found inconsistent predictions of flow rates among models suggesting the four models suffer from inadequacies in representations of GR physical processes. In addition, large-scale simulations are vital tools for better understanding the effects of GR implementation in urban stormwater management. Several studies simulated the effects of different GR retrofiring scenarios on runoff/pipe flow reduction.[38–40] Yet, compared to building scale simulations, research on watershed scale simulations is still less common, because the reliability of GR models is often questioned as a design tool.[41] As a result, efforts are needed to identify model limitations and improve model applicability.

Li and Babcock (2014) conduced an early review that briefly compared 15 case studies of GR modeling, including SWMM and Hydrus-1D, among others.[42] However, given limited modeling applications prior to 2010, this review did not cover the modeling techniques that have become available in recent years. While four more recent reviews have discussed GI modeling applications and future needs, they focused on various other types of GI technologies rather than GRs.[43–46] Different types of GI may require different modeling strategies due to their varied structural designs. For example, a storage zone for exfiltration is commonly used in bioretention systems but is rare in GR systems[45]. None of the previous modeling reviews focused specifically on parameter estimates, evaluation, applications, and gaps in GR modeling. A comprehensive review covering model theoretical developments through practical uses, thus, could provide valuable insights to address the challenges in current applications and future improvements.

Focusing on GR modeling techniques and strategies, literature was reviewed to document currently available knowledge, potential challenges and future research needs in GR modeling. More specifically, this review focused on evaluating widely used free and open-source models or software, including water balance models, SWMM, and Hydrus-1D. The review addressed two specific areas: 1) GR model developments and potential applications; 2) identifying and discussing the key limitations in current GR modeling practices with suggestions for future model improvements.

2 Methods

This review was carried out in the database of Web of Science and ScienceDirect focusing on peer-reviewed primary literature (up to 2022) that aimed to model the hydrological performance of GR. Models built based on full-scale installations as well as pilot-scale experiments were included. To efficiently connect pieces of information most relevant to GR hydrological modeling, the literature search was based on the following keywords: "green roof AND (model or simulation) AND (water balance or hydrology or water or retention) NOT (heat or energy)". The initial exclusion criteria include review papers, non-English publications and duplicates. We then screened the results based on their abstracts and main content to exclude data analyses, field monitoring, or design papers that are irrelevant to modeling. Meanwhile, additional articles were identified by reviewing the cited references of reviewed papers for articles related to hydrological modeling. Ultimately, 76 peer-reviewed papers were considered as relevant studies and included in the literature review. The review is organized into four sections (Section 3 – Section 6). The Section 3 gives an overview of existing GR models and their theoretical developments. In the Section 4, we discuss GR models in practical uses. In the Section 5, we identify potential limitations and challenges for GR model applications. The Section 6 discusses future research needs to improve model applicability.

3 Green roof model development

3.1 Overview of GR models

To physically characterize a GR, it is often simplified as a vertically layered structure with uniform properties within each component (Fig. 1), in which vegetation, soil (substrate), drainage mat and storage can be described separately. GR modeling requires the characterization of the water cycle within these components. The main hydrological processes include rainfall entering soil through infiltration, soil water percolating into drainage mat and water leaving GR by drainage (outflow), evapotranspiration and surface overflow that might occur. Hence, the main research question for GR simulation becomes how to reasonably establish a model incorporating estimates of water budget terms and physical representations of GR structure.

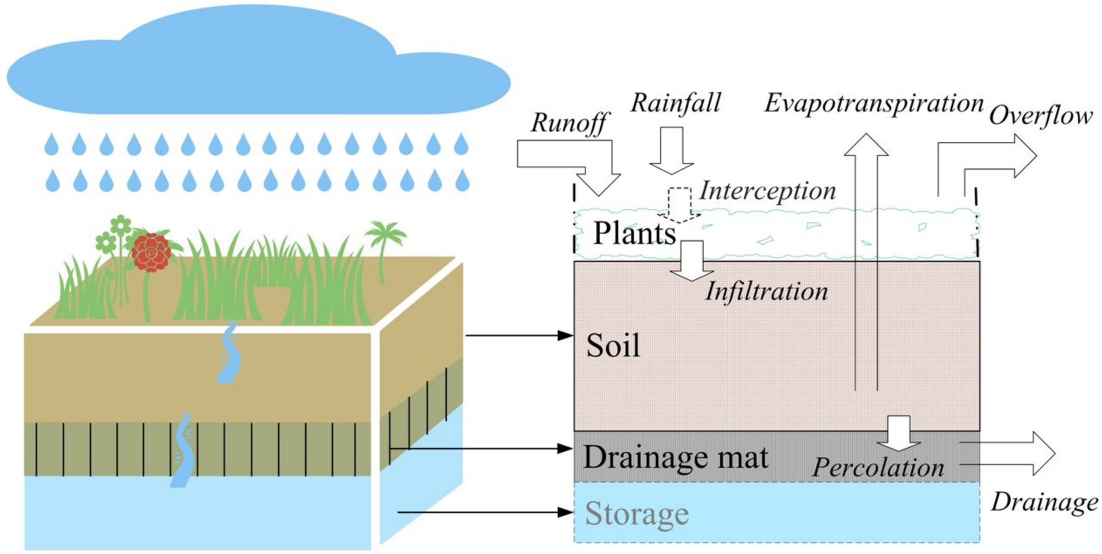

Fig. 1 Components and water fluxes of a simplified GR model. Four layers from top to bottom: vegetation, soil, drainage mat and potential storage units, such as a cistern[32], for water storage and reuse purposes

Existing GR models varied from simple conceptual models to complex mechanistic models, depending on model complexity and the level of detail required to run simulations.[14,47] A conceptual model keeps the physical basis of GR but requires little structural detail, such as a water balance model. Mechanistic models use finite difference equations to model soil water movement. These models often relate to solving Richard's equations (partial differential equations to describe water moving through unsaturated soil) or simplified infiltration equations (often assume saturation). For example, two free software packages, SWMS_2D and hydrus-1D[48–50], apply Richard's equations to numerically derive soil water movement under unsaturated conditions, with model parameters based on specific soil textures[51,52]. Solving Richard's equations usually requires a high level of computational cost. As an alternative, simplified physically based infiltration equations are utilized by modelers. For example, She and Pang (2010) used the Green-Ampt infiltration method to simulate GR and successfully replicated the outflow from a GR in Portland, Oregon.[53] This method was also used in the popular industry standard US EPA's Storm Water Management Model (SWMM) to simulate infiltration.[54]

The sections below discuss the theoretical developments of popular GR models and simulations of major hydrological processes within GR. The discussions focus on GR models with physical basis that can be easily interpreted. Therefore, empirical models are not included, because they are built based on empirical rainfall-runoff relationships and may not be directly applicable in GR forecasting contexts, for example the Curve Number method[25,31,37,55]. In addition, in recent years, data-driven methods such as machine learning techniques have been investigated[56]. Yet, data-driven methods will not be discussed either, because field data scarcity is a common issue that managers and developers face to train and test models. Other software packages, such as MUSICX[57], have previously been considered for green roof modeling, but as these are not as widely used and either require licenses for use or are not open source, they will not be discussed. A summary of all the reviewed GR models can be found in **Error! Reference source not found.** and **Error! Reference source not found.** (Supporting Information, SI).

Three models were selected to be discussed in detail: water-balance models, SWMM and Hydrus-1D. The complexity of the three models varied from describing conceptual hydrological processes to solving complex partial differential equations. These models focus on one-dimensional vertical flow simulations. Because GR substrate is thin compared to roof surface flow length, water travels more quickly through the substrate vertically than laterally across it.[58] Descriptions of the models' capabilities to simulate hydrological processes within GR are discussed below.

3.2 Modeling soil water transport

Stormwater control mostly relates to the mechanical process of water movement (infiltration) within GR substrate.[30,56,59] Simulation of soil water transport, thus, is the key to building GR models. In the next subsections, we discuss the simulations of soil water transport processes in different models.

3.2.1 Water balance model

A water balance model uses simplified descriptions of water fluxes based on water balance to account for all sources and fluxes of water through the GR[19,29]. Simulations can vary from minutes to daily timesteps[19,32]. The processes can be described by a finite difference (eq. 1).

$$\frac{ds}{dt} = P + I - ET - q - q_s - L \quad \text{eq. 1}$$

Where the $\frac{ds}{dt}$ represents the water storage (s) per unit time (t), P is precipitation, I is irrigation, ET is evapotranspiration, q is drainage (outflow), q_s is surface runoff, L is vegetation interception; the irrigation and surface runoff terms are often assumed to be negligible.

Soil water flow is generated when soil water exceeds the maximum water storage capacity in the GR substrate.[60–62] This capacity can be estimated as the soil depth multiplied by the difference between the soil field capacity and the permanent wilting point.[19,60,63] The flow condition can also be written in the format of soil moisture content exceeding the field capacity.[29,61] Therefore, the outflow from beneath of the substrate can be directly derived based on measured or estimated water budgets of P, ET and s, described as eq. 2, where P_t is rainfall rate at the current time step t, s_{fc} is the soil water storage capacity and s_{t-1} is water storage at the previous time step.

$$q = \begin{cases} P_t + s_{t-1} - s_{fc} - ET_{t-1}, \ s_{t-1} > s_{fc} \\ 0, s_{t-1} < s_{fc} \end{cases} \quad \text{eq. 2}$$

However, this method ignores the dynamics of soil water transport (hydraulic conductivity) related to water potentials. That is, all the water will drain away within one time step if no governing equations on moisture transport was introduced, when $s_{t-1} > s_{fc}$. Therefore, to enable predictions of water storage in the substrate, modelers utilize linear or non-linear (exponential) lumped reservoirs to describe q based on s, by incorporating two parameters that approximately represent the ease of water movement[32,63–66]. The process can be described by eq. 3, where k_1, k_2, φ_1 and $\varphi_2$are fitting parameters, and h is the surface ponding head. A linear reservoir model corresponds to φ and k equal 1.

$$q = \begin{cases} k_1 \cdot (s_{t-1} - s_{fc})^{\varphi_1} + k_2 \cdot h^{\varphi_2}, s_{t-1} > s_{fc} \\ 0, s_{t-1} < s_{fc} \end{cases} \quad \text{eq. 3}$$

3.2.2 SWMM

SWMM is a dynamic rainfall-runoff model primarily used for urban water quantity and quality simulations. It allows simulation of interactions among precipitation, urban sewer systems, land surface, groundwater and GI.[67] Simulations of GR in SWMM have been developed in several phases. Before the low impact deign (LID) modules were released, GR simulations were built solely based on SWMM hydrological and hydraulic packages. Alfredo, Montalto, and Goldstein (2010) developed two strategies based on storage node and the Curve Number method, respectively, to simulate the GR runoff.[68] Even though the two approaches could replicate actual roof discharges, their performance mainly depended on model calibration and lacked structural representation of GR. With demands for generalizable GI simulations, the LID modules were released in SWMM 5.0.19 (2010), including modules of bioretention cells, pervious pavers and infiltration trenches. These modules were built based on process-based continuous equations to describe water transport within each GR layer (Fig. 1.[54] The GR module was added to SWMM 5.1, in which the storage layer was replaced by a drainage mat to simulate GR underdrains. Because SWMM can easily combine GR models into its stormwater model framework, it has become a powerful and popular tool to understand city-level hydrological benefits of GR.[36,40,50,69–71]

GR simulations can be achieved by SWMM GR module or SWMM bioretention module. The infiltration (f, eq. 4) is modeled using Green-Ampt equation[72] in the two modules.

$$f = K_s\left(1 + \frac{(\phi - \theta_i)(d + \psi)}{F}\right) \quad \text{eq. 4}$$

Where K_s is the saturated hydraulic conductivity, ϕ is the soil porosity, θ_i is initial soil water content, d is the ponded water depth on the surface, ψ is the soil suction head at the wetting front, F is the accumulated infiltration volume during the rainfall event.

3.2.3 Hydrus-1D

Hydrus is a public domain Windows-based software that can simulate the movement of water, heat, and solute in variably saturated media. Two- and three-dimensional versions of also exist, but one-dimensional version of Hydrus-1D is more widely used in GR simulations. The governing equation in Hydrus-1D is the one-dimensional form of Richard's equation[73] (eq. 5):

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z}\left[K(\theta) \cdot \left(\frac{\partial h}{\partial z} + 1\right)\right] \quad \text{eq. 5}$$

Where θ is the volumetric water content, $K(\theta)$ is the unsaturated hydraulic conductivity as a function of θ, z is the vertical coordinate, t is time and h is the hydraulic head.

The unsaturated soil hydraulic properties can be simulated with several analytical models in Hydrus-1D, in which the van Genuchten-Mualem method[74] is widely used to obtain the soil water retention curve and hydraulic conductivity function. The Van-Genuchten relationships can be written as:

$$\theta(h) = \begin{cases} \theta_s & h \geq 0; \\ \theta_r + \frac{\theta_s - \theta_r}{[1 + (\alpha h)^n]^m} & h < 0 \end{cases} \quad \text{eq. 6}$$

$$\theta_e = \frac{\theta - \theta_r}{\theta_s - \theta_r} \quad \text{eq. 7}$$

$$K(\theta) = K_s \sqrt[\lambda]{S_e}\left[1 - \left(1 - S_e^{1/m}\right)^m\right]^2 \quad \text{eq. 8}$$

Where θ_s and θ_r are the saturated and residual water content; K_s is the saturated hydraulic conductivity, θ_e is the effective saturation; $\alpha, n, m\left(1 - {}^{1}/_{n}\right)$ and λ (often assumed to be 0.5[15,35,50,75]) are fitting parameters of the soil water retention curve.

3.3 Water-leaving simulations

Water leaves GR through surface runoff, drainage mat flow and evapotranspiration. However, compared to simulating infiltration, these processes are not universal modeling considerations. Water-leaving simulations are model-specific. Therefore, in this section, we discuss the common modeling strategies to simulate drainage mat flow and evapotranspiration.

3.3.1 Drainage mat flow

Among the three models, only SWMM provides the capability to physically simulate bottom drainage. The water balance model may simulate drainage by adding a cascade reservoir model. In the SWMM modules, water percolates from the substrate into the drainage mat (f_p, eq. 9), described with Darcy's Law. Drainage mat flow is then simulated by using Manning's equations (q_1, eq. 10); while, in bioretention module, it is simulated with an empirical power law (q_2, eq. 11).[40,76–79]

$$f_p = K_s e^{HCO(\phi - \theta_t)} \quad \text{eq. 9}$$

Where HCO is a decay constant that describes hydraulic conductivity as a function of soil moisture content; $\theta_t$is soil moisture content at time t.

$$q_1 = \frac{W}{An_2}\sqrt{S}\phi_2(d_2)^{\frac{5}{3}} \quad \text{eq. 10}$$

$$q_2 = C_{3D}(d_3)^{\eta_{3D}} \quad \text{eq. 11}$$

Where n_1 and n_2 are the Manning 's roughness for drainage mat, W is the width of the green roof, A is the area of the roof, d_2 is the depth of water in the drainage mat, S is the roof slope, ϕ_2 is the void ratio of drainage mat, C_{3D} is the underdrain discharge coefficient, $d_3$is hydraulic head, η_{3D} is underdrain discharge exponent. It should be noted that d_3 is not limited to the total depth of storage unit, which can also be added by surface ponding.

3.3.2 Evapotranspiration

During event simulations, evapotranspiration (ET) is often neglected, because the ET rates are often assumed to be much smaller than precipitation.[47] However, ET is an important water budget term for long-term GR simulations, because it is the only way for GR to recover its retention capacity.[80] ET is difficult to directly measure, so it is often estimated based on two widely used methods: the Hargreaves method[81] (e.g., SWMM) (eq. 12) and the FAO-56 Penman Monteith method[82] (eq. 13), also known as potential ET and reference ET, respectively. Potential ET is a temperature-based estimate, while reference ET takes short grass as reference and includes meteorological data as an input to estimate ET.[16,83,84] ET is divided, in Hydrus-1D, into evaporation and transpiration separately. Because none of the reviewed literature used Hydrus-1D to simulate ET, we do not discuss more detail.

$$\text{Potential } ET = 0.0023 \cdot (0.48 \cdot R_a) \cdot (T_{mean} + 17.8) \cdot (T_{max} - T_{min})^{0.5} \quad \text{eq. 12}$$

$$\text{Reference } ET = \frac{0.408 \cdot (R_n - G) + \gamma \cdot \frac{900}{273 + T_{mean}} \cdot \mu_2 \cdot (e_s - e_a)}{\Delta + \gamma \cdot (1 + 0.34 \cdot \mu_2)} \quad \text{eq. 13}$$

In these equations R_a is the daily total extraterrestrial radiation, T_{mean} is daily mean air temperature, T_{max} is daily maximum temperature, T_{min} is daily minimum temperature, R_n is net radiation at the crop surface, G is soil heat flux density, e_s is saturation vapor pressure, e_a is actual vapor pressure, γ is the psychometric constant, μ_2 is daily average wind speed and Δ is slope of the vapor pressure curve.

4 Model practice

Building GR models requires data collection and parameter estimation. Calibrations were then often needed to adjust initial parameter estimates to improve model accuracy, by comparing predicted and measured outflow. This section discusses these model routines in practical applications. At the end of the section, we summarize model characteristics, capabilities, and potential applications (Table 3).

4.1 Model boundary conditions

Model boundary conditions include initial condition, upper boundary condition and lower boundary condition. The initial boundary condition is required for all the three models, which is often specified as the assumed or measured initial soil moisture content. Because Hydrus-1D numerically solves the partial differential equations, the upper and boundary conditions must be specified before running hydrus-1D simulations. The upper boundary is often assumed as a soil-atmosphere interface, with the surface flux equal to the rainfall input P.[47,75] For lower boundaries, the free drainage condition and seepage condition are most commonly used in literature. The free drainage condition assumes the pressure head gradient is zero, corresponds to gravity flow; that is $\frac{\partial h}{\partial z}_{z=-L} = 0$.[18,50,73,85] The seepage boundary assumes that the flux remains zero as long as the boundary is unsaturated and the pressure head is set to zero once it is saturated[14,47], which means the outflow equals either to 0 or K_s.

4.2 Model parameterization

Common data used in GR modeling include rainfall, outflow, GR structural data and meteorological data (Table 1. Precipitation is the most important input for hydrological models, which is generally measured by rain gauge and is usually accessible to the public. Outflow is the output of GR models and its measurements are usually used to calibrate the models. However, outflow data may not be available for many modelers. Given limited funding, full-scale (building-scale) GRs may not exist in many cities. In addition, enabling outflow measurements in full-scale GRs often requires a systematic design prior to GR construction. For example, outflow from a GR in New York, USA was measured using Parshall flumes equipped with pressure transducers.[86] Another used a custom-designed weir device to measure outflow.[87] In-pipe flow meters were installed to measure a GR's outflow in the city of Bologna, Italy.[79] Moreover, different outflow measurement methods have their own associated uncertainties, which also need to be accounted for when using them to evaluate or calibrate models. To solve this issue, substantial research effort has used pilot-scale experiments to mimic GR full-scale implementations, using the measured experimental outflow to build models.[16,18,52,85]

To parameterize soil hydraulic properties, Hydrus-1D requires derivation of both a soil water retention curve and a hydraulic conductivity function (eq. 6 – eq. 8). These parameters can be derived from laboratory experiments such as with a pressure plate extractor[16,18,75], estimated using empirical functions[50], or via inverse solutions based on flow observations[88,89]. Hydrus-1D also can be parameterized with estimates based on soil texture. However, the estimates in Hydrus-1D are limited to the abiotic soil texture classes based on percentiles of sand, silt and clay. Thus, these estimates may not be very useful in simulations, because GR substrate often includes organic matter to reduce substrate weight, increase porosity, and decrease bulk density characteristics[47,84]. In addition, GR substrate, particularly for extensive GRs, often comprises of coarse and granular lightweight materials to reduce loading on the building roofs, which can differ substantially from the textures of natural soil. [90,91] Further other additives, such as biochar, can be used to increase GR retention capacity[85]. SWMM uses the Green-Ampt infiltration equation to simulate infiltration. Therefore, no experiments are needed to derive soil water retention curve and hydraulic conductivity function. Instead, a few soil physical parameters are specified, such as the saturated hydraulic conductivity and porosity.

Table 1 Common data used for GR models

Data type	Objective	Common source	Model required	Data acquisition
Precipitation	Input	Rain gauge	Conceptual model/ mechanistic model	Easy
Temperature	ET estimates	Weather station	Continuous simulations	Easy
Solar radiation				
Vapor pressure				
Atmospheric pressure				
Outflow	Calibration/validation	Flow meter	Conceptual model/ mechanistic model	Difficult in full-scale measurements
Soil data	Parameterization of soil hydraulic properties	Lab experiments	Mechanistic model	Easy (water balance) Moderate (SWMM) Difficult (Hydrus-1D)
Roof dimensions	Model configuration	Field measurements	Conceptual model/ mechanistic model	Easy

Model parameterization depends on model structure complexity; a more complex model requires a larger number of parameters (Table 2. Some literature values and model recommended values are listed in the Table 2. The values of the soil hydraulic parameters for soil water retention curve and hydraulic conductivity function depend on specific soil textures. Accurate estimates are mainly derived through experimental measurements[18,52], so we did not summarize literature values for these in Table 2. Similarly, fitting values for water balance-based reservoir models were not included. Literature values are mainly related to SWMM model parameterization. Obviously, parameter values recommended by SWMM may differ from values used in literature for specific simulations. For example, the saturated hydraulic conductivity values found in the literature (ranging between 2 – 1183 mm/hr) are substantially smaller than the values recommended by SWMM (1016 – 4064 mm/hr) (Table 2), which may suggest the permeability of engineered soils used in GR is deviated from natural soils.

Because model parameters may not be precisely estimated or directly measured, calibration is an important procedure to adjust parameter values. Calibration methods may include Bayesian algorithms[37], optimization techniques[69,92,93], or two-step calibration procedures[41,94]. Prior to calibrating a model, parameter sensitivity analysis is a useful tool to understand the influence of parameters on model outputs and prioritize model parameters in model calibration. Common methods used to identify parameter sensitivity include one-factor-at-a-time[93,94], Bayesian uncertainty[37,95] and global sensitivity analyses[96].

In reviewing parameter sensitivity analyses, we focused on the SWMM model, because it has a large number of parameters and the simplification of flow routing makes some parameters difficult/impossible to measure (such as parameters for the drainage mat). As various methods were used to evaluate parameter sensitivity, it is impossible to compare sensitivity indices across studies. Instead, we summarized the influential parameters identified by ten studies that conducted SWMM parameter sensitivity analysis[34,37,50,69,78,86,92–94,96]. More specifically, we listed and counted the number of occurrences of the influential parameters identified in parameter sensitivity analysis (Table 2). For example, the substrate properties, such as porosity and field capacity, were identified 8 and 6 times, respectively, out of the 10 studies, and drainage mat properties, such as roughness (5 times), also have substantial effects on the outflow predictions.

Table 2 Model parameters and associated parameter sensitivities (Blanks in the table means no available information or specific values; Y: required to specify; Sensitivity frequency* calculated as the counts of parameters identified as influential parameters by studies conducted parameter sensitivity analysis)

Parameters	SWMM BRC module	SWMM GR module	Richard's equation/ Hydrus-1D	Lumped Reservoir model	Default values (referring GR module)	Literature values	Sensitivity frequency *
Surface roughness	*Y*					0.01 – 0.2	
Berm height (mm)	*Y*	*Y*			0 – 76.2	3 – 30	2
Surface void fraction	*Y*	*Y*			0.8 – 1.0	0.8 – 0.9	1
Slope (%)		*Y*				0.5 – 8	
Soil thickness (mm)	*Y*	*Y*	*Y*	*Y*	50.8 – 152.4	32 – 135	4
Porosity	*Y*	*Y*	*Y*	*Y*	0.45 – 0.6	0.39 – 0.7	8
Field capacity	*Y*	*Y*		*Y*	0.3 – 0.5	0.17 – 0.44	6
Wilting point	*Y*	*Y*			0.05 – 0.2	0.01 – 0.22	2
Initial moisture content	*Y*	*Y*	*Y*	*Y*			
Saturated hydraulic conductivity (mm/hr)	*Y*	*Y*	*Y*		1016 – 4064	2 – 1183	4
Wetting front suction head (mm)	*Y*	*Y*			50.8 – 101.6	6 – 100	1
Decay constant	*Y*	*Y*			30 – 55	5 – 50	6
Storage layer (drainage mat) thickness (mm)	*Y*	*Y*			12.7 – 50.8	3.8 – 76.2	2
Storage void (drainage	*Y*	*Y*			0.2 – 0.4	0.01 – 0.98	2

mat) fraction							
Drainage mat roughness	Y				0.01 – 0.03	0.01 – 0.4	5
Drain coefficient (mm/h)		Y				2.1 – 8.4	
Drain exponent		Y				0.5 – 2.1	
Soil residual water contents			Y				
Saturated water content			Y				
α (fitting parameter)			Y				
n (fitting parameter)			Y				
λ (fitting parameter)			Y				
k (fitting parameter)				Y			
φ (fitting parameter)				Y			
Total number of parameters	14	15	9	7			

Even though the initial soil moisture is considered as the initial condition rather than as a parameter, it has significant effects on event-based simulations[76,77,79,94] It reflects the degree to substrate initially filled with water.[76] In general, the lower initial soil moisture, the smaller the runoff volume and peak rate and the longer the peak delay will be[15,69]. In addition, soil water percolation is often assumed to be triggered when the soil moisture content exceeds filed capacity[33,54,97]. An initial water content at field capacity can lead to instant drainage flow even at the beginning of an event[78,94]. Therefore, the initial soil moisture should be carefully specified in simulations. The initial moisture content can be specified by using moisture sensor[33,69,97] or assumed by modelers[87].

Considering data acquisition and parameter estimation, several things emerge from the reviewed literature:

(1) Outflow measurements are often unavailable, because 1) an existing built GR is the prerequisite to measure in-site outflow; and 2) the setup of outflow measurement is complex. Many GR models, thus, were built using experimental data.
(2) little data are needed to parameterize soil hydraulic properties for water-balance models, but the routing parameters requires calibration.
(3) SWMM has the largest number of parameters to specify (>10), but it can explicitly simulate flow through the entire vertical profile. Parameter values can be easily found from literature or assumed.
(4) Soil parameters in Hydrus-1D often require large efforts of laboratory measurements or model calibrations.

4.3 Model potential application

(1) Model evaluation

To evaluate model performance, several metrics have been used in the literature. Among these evaluations, Nash-Sutcliffe efficiency is widely used (NSE, eq. 14), which measures the goodness of fit between model predictions and observations (closer to 1, better simulations)[98]. To define acceptable model performance, several studies suggest a threshold of NSE > 0.5[41,70,78]. Although comparing NSE values across models constructed at different sites (Fig. 2) may not be a good way to compare model performance because of their varying climate conditions and input data, a naïve comparison can still show some aspects of the ability of a model to replicate measured outflow. Based on Fig. 2, all three models can generate good predictions of GR outflow. For the majority of all events (90%), the NSE is > 0.5. SWMM seems to show greater variability in predictions with a larger portion (28%) of events with NSE < 0.5 than the other two models. Furthermore, NSE evaluations for SWMM present a degree of correlation to event depths, with NSE values more likely to be > 0.5 when larger events are simulated (depths > 20 mm).

$$NSE = 1 - \frac{\sum_{i=1}^{n}(Q_{o,i} - Q_{s,i})^2}{\sum_{i=1}^{n}(Q_{o,i} - \overline{Q_O})^2} \quad \text{eq. 14}$$

Where $Q_{o,i}$ and $Q_{s,i}$ are the observed and simulated flow discharge values, respectively; $\overline{Q_O}$ is the observed mean flow.

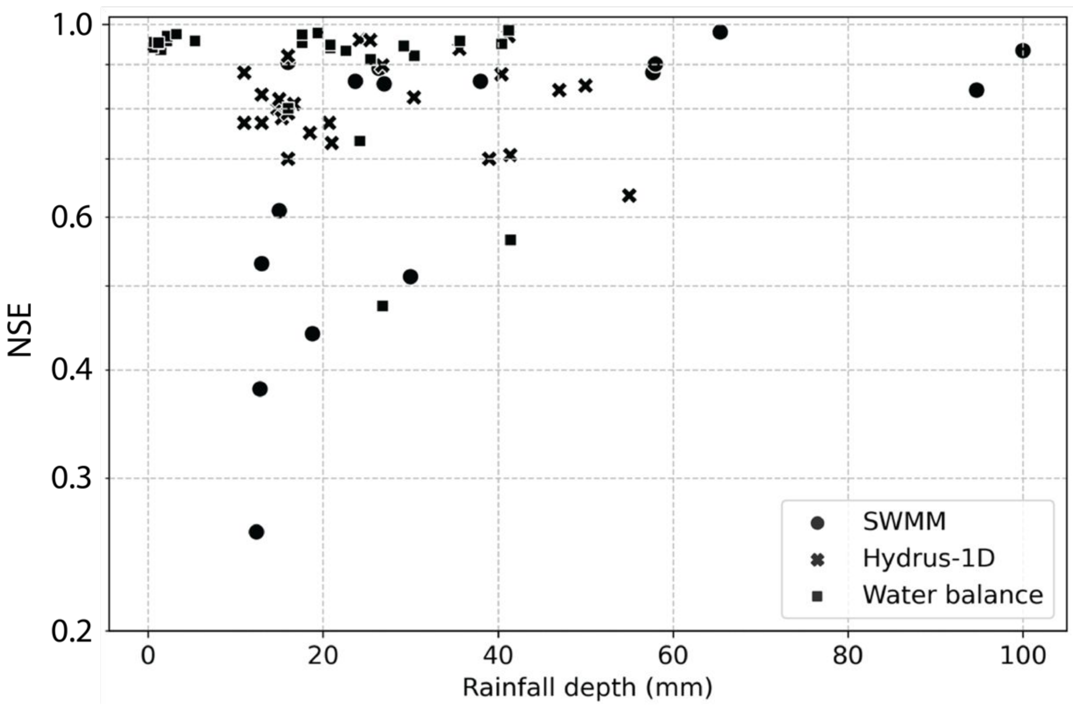

Fig. 2 Comparison of NSE and rainfall depth (mm) in GR outflow event-based simulations based on the reviewed studies evaluating model performance.[14,34,47,70,93]

Two model evaluation strategies are often considered. The first strategy is selecting rainfall events observed at the same site, which is a commonly used method[18,35,36,47]. In general, so-called validated models perform more poorly than calibrated models, because calibration involves optimizing model performance by finding the parameter values that lead to best-fit outputs[18,34–36,78,92,94]. The second strategy is cross-validation, in which models are tested among different sites and climate forcings[41,56,58]. This strategy is becoming increasingly popular, because it is important for GR planning that the model can predict the performance of new implementations when data are unavailable. Nevertheless, the transferred model often fails to predict GR outflow at different sites[56,58]. The reasons for this failure are associated with the uncertainties in model physical characterization and parameterization, which will be discussed in more detail in Section 5.

(2) Model applications

One goal of GR modeling is characterization of GR performance under various designs and climate forcings. Although the three models can replicate GR outflow, Hydrus-1D can simulate unsaturated flow processes based on water retention curve and hydraulic conductivity function, which are essential to clarify soil hydraulic properties. Therefore, Hydrus-1D can be used to experimentally simulate the effects on substrate compositions on GR detention.[52,91] For example, Huang et al. (2020) explored the effects of biochar addition on soil hydraulic properties.[88] They found biochar-amendments increased the retention capacity and detention capacity but decreased saturated hydraulic conductivity because of the rough surface of biochar. That said, large data demands on model parameterization and high computational costs may limit Hydrus-1D applications to situations where soil hydraulic properties are vital to render.

Another goal of GR modeling is to explore the watershed/citywide effects of GR implementation scenarios on stormwater reduction. GR models are commonly integrated into watershed hydrological models.[37,40,70,99] Thus, a simple model that can be easily built and incorporated into watershed models will provide more modeling flexibility. In these cases, many current large-scale simulations rely on the use of SWMM.[37,40,69,70] Using SWMM 1) model parameters can be easily found or calibrated; 2) SWMM GR module and bioretention modules have full capacity to physically simulate the entire water circle with GR; 3) GR simulations can be easily incorporated into SWMM stormwater model network.

The three GR models have specific strengths and shortcomings, so model selections and applications depend on available data and research question. If monitored outflow data are available to calibrate GR model, the water balance model is a good option, because it can generate accurate simulation results (Fig. 2) with low computational demands[29,33,63,100]. However, conceptual models such as the lumped reservoir model may have more uncertainties in flow predictions relative to mechanistic models because their simple model structures cannot reflect soil water transport dynamics.[37] Further, without explicit parametrization of soil properties, the water-balance model is often case-specific.[63] In contrast, SWMM and Hydrus-1D both explicitly parameterize soil water transport processes, which can better interpret soil water transport processes. Benefits from numerically solving Richard's equation, Hydrus-1D is capable to be used to explore soil hydraulic properties. However, considering the ease of data collection and parameter estimation, SWMM could be more applicable than Hydrus-1D, since parameter values can be gathered from the literature. A summary of the potential model practical uses is shown in Table 3.

Table 3 The main characteristics and capabilities of GR models

Model types	Characteristics	Capabilities	Potential applications
Water balance	*Type*: conceptual model *Development*: water fluxes based on water balance and often combined with lumped reservoir models. *Computational cost*: low	Water storage; Infiltration; Drainage flow; ET	Outflow simulations
SWMM	*Type*: mechanistic model *Development*: Green-Amp infiltration equation, Manning' equation and empirical power law *Computational cost*: moderate	Water storage; Infiltration; Drainage flow; ET	Outflow simulations; Full vertical profile flow simulations; Large-scale simulations;
Hydrus-1D	*Type*: mechanistic model *Development*: Richard's equation *Computational cost*: high	Water storage; Infiltration; ET	Outflow simulations; Understanding substrate hydraulics

5 Limitations and challenges for GR model applications

Although the reviewed studies contributed to GR model development, some critical issues may continue to limit model applications. For example, model parameter transferability is very low among different models at same sites or the same models at different sites[37,40,41,86]. Discrepancies in the calibrated model parameters raise concerns about the accuracy and reliability of GR models as a design tool. Therefore, identifying the limitations of existing models is important for improving future models. In this section, four key challenges in GR model development are identified, including modeling drainage mat flow, characterization of soil hydraulic properties, ET estimates and scale effects on GR simulations.

5.1 Uncertainties in drainage mat flow

The drainage mat (bottom layer) temporarily stores and gradually drains excess water from the system to enhance detention (Fig. 3).[78] **Fig. 3**Current GR studies mainly focus on extensive GRs, with a depth of substrate less than 15 cm, in which the substrate void volume can be quickly filled, resulting in a fast drainage response.[34] Parameterization of the drainage mat, therefore, plays a significant role in successful replication of observed outflow in extensive GR.[34,41,67,76,78,92] However, the detention of a drainage mat is rarely understood and physically simulated. Most GR models, such as hydrus-1D and water-balance models, lack the ability to simulate drainage mat flow. Those models that did not include drainage mat simulations often used conceptual reservoir models to simulate the effects of drainage mat on water detention.[97] Palla, Gnecco, and Lanza (2012) connected two linear reservoirs to simulate water moving through the substrate and drainage mat respectively, in which the second layer (assumed as a drainage mat) took the output from the first layer (assumed as the soil medium) as input to simulate the drainage.[47] Vesuviano, Sonnenwald, and Stovin (2014) modelled GR by connecting two nonlinear reservoirs in series, which inflow to the drainage layer being equal to the outflow from the substrate.[65] However, the lumped model aims to replicate the drainage flow but lacks physical interpretations on the associated routing parameters for the drainage mat, which cannot link back to the model to physically interpret the effects of shape or material of drainage mat on GR outflow.

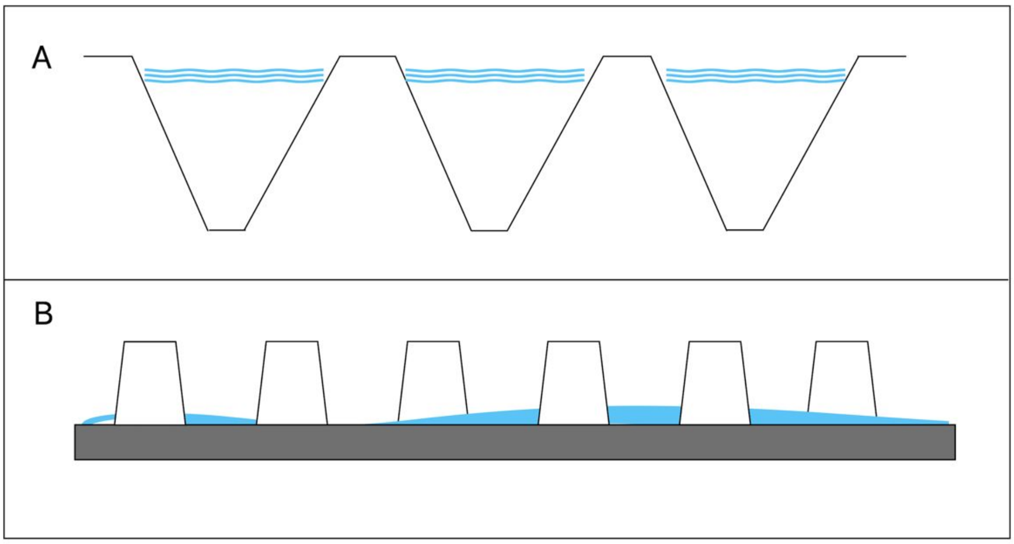

Fig. 3 Schematic examples of drainage mat with temporary storage (A) and without

temporary storage (B)

Of the reviewed models, only the SWMM model explicitly incorporates drainage mat flow simulations in the GR and bioretention cell modules. Regardless of the routing assumptions in the two SWMM modules, the main physical difference between them is the roof slope characterization. The SWMM GR module utilizes Manning's equation, in which the roof slope can be explicitly parameterized. However, when a flat roof is simulated with the slope set to zero, the assumption of uniform open channel flow based on Manning's equation is violated, corresponding to instantaneous runoff.[54,78] In contrast, a drainage layer in the bioretention module is modeled with an empirical power law (assuming a slope of 0), which can be interpreted as an orifice equation.[76] Jeffers et al. (2022) evaluated the effectiveness of the two modules to simulate GR outflow with different slopes and they found the bioretention cell module is more accurate to replicate flow in flat roof simulations.[78] However, they did not deduce an optimal module to parameterize and simulate the drainage mat flow.

5.2 Representation of soil characteristics

Parameterization of soil characteristics is crucial to precisely model water movement in the GR substrate.[87,92–94,96,101] In many cases, the simple conceptual model only obtains a robust representation of the hydraulic behavior of GR and does not derive an accurate representation of soil physics. Therefore, compared to the mechanistic model, fitted parameters of the conceptual model cannot be transferred to models built at different sites.[63]

In mechanistic model applications, calibrated values of soil parameters are often used to estimate soil hydraulic characteristics when soil experiments are unavailable.[14,15,35,47,75] However, sometimes model calibration is only based on the goodness of fit of outflow simulations and the calibrated parameters do not necessarily correspond to the actual soil properties.[37,41,93,94] Broekhuizen et al. (2021) compared four models – SWMM, Hydrus-1D, Mike-SHE and Urbis – and found low consistency of soil parameter values across models after calibration, which raises questions about the generalizability of soil parameterization on model applications.[37] Jeffers et al. (2022) found the calibrated hydraulic conductivity slopes (equivalent to the decay constant in eq. 9) were different between SWMM modules, with values of 20 and 51, respectively, for the bioretention cell module and GR module.[78] As a result, a non-representative set of soil parameters with low transferability inevitably led to unreliable modelling results when the model was applied to different sites and scales.[40,86,102]

Further, the substrate properties are influenced by vegetation[14,75,97], resulting in field substrate characteristics that may not match the results from laboratory soil tests[102]. Johannessen et al. (2019) found laboratory measured porosity was higher than calibrated porosity[41], possibly due to cracks generated by vegetation roots development[85]. They also found the wilting points were lower in lab measurements. This may be due to the wilting point being plant-specific — for example, drought-tolerant vegetation planted in GR can resist wilting, which leads to higher retention capacity than bare soil[87]. In a SWMM simulation, Hamouz and Muthanna (2019) used laboratory measured porosity and hydraulic conductivity to simulate GR outflow, but could not successfully replicate the outflow.[93]

Last, soil hydraulic properties may change over time due to substrate aging and changes in soil water condition. An experiment conducted by Bouzouidja et al. (2018) that monitored the aging of substrate suggested the saturated water content decreased by 4% and the saturated hydraulic conductivity increased by 22%, after three years exposure of substrate.[39] Starry et al. (2016)

found the substrate field capacity was related to antecedent soil water conditions in the substrate.[33] Sims et al. (2019) assigned different values to field capacity (with 0.215 for the wet periods and 0.193 for drier period) and achieved good predictions even without model calibration.[103]

5.3 Evapotranspiration estimates

Unlike other GI techniques with deeper soil that rely on infiltration as the primary water retention mechanism, GR retains water within the shallow substrate and then recovers its retention capacity via ET over dry weather days. Therefore, the water retention performance of GR is positively related to soil water storage capacity and ET[104].

In the literature, potential ET (Hargreaves method) and reference ET (FAO-56 Penman Monteith method) are mostly used to estimate ET, but many studies found these two approaches may not appropriately estimate actual ET because actual ET is not only influenced by climate conditions but also by vegetation type and soil moisture content.[16,40,70,79,80,87,92,94,96] Poë, Stovin, and Berretta (2015) found a declining ET occurred when the soil moisture availability was reduced and an increased ET (by 17% in spring and 23% in summer) in substrate with addition of vegetation compared to bare soil.[105] Similar findings were observed by Harper et al. (2015) that when the plants were dormant over winter, variation of ET between the planted and unplanted substrate trays was small.[8] However, potential ET and reference ET models do not include parameters to capture the effects of vegetation and soil water availability.

To capture the influence of soil moisture on ET estimates, in a simple manner, monthly soil recovery patterns were used to modify the estimated ET[41,79]. However, one drawback of this modification is it requires calibration and thus does not necessarily indicate the actual soil water availability.[41] As a result, more complex modifications were explored to explicitly account for the influence of soil water availability, for example modifications based on the dry period duration[36,94] or soil moisture time series[16,71,86].

To capture the influences of vegetation type on ET, the reference ET is multiplied by a crop coefficient to account for the physiological influence of different types of vegetation on ET [16,33,92]. However, this approach was initially developed for agricultural applications and the crop coefficients are not well-defined for green roof species and often unavailable to be used for GR modeling or design[33]. In GR literature, common plants can be classified as C_3 plants and Crassulacean Acid Metabolism (CAM) vegetation. C_3 plants are characterized by C_3 metabolisms, in which the CO_2 is fixed into a compound with three carbon atoms.[106] C_3 plants, including lawn grasses and herbs, usually have a high water demand and show high ET rates but these plants can require irrigation in drought areas.[106] CAM vegetation, such as *Sedum* species, can absorb CO_2 in the night and usually do not require irrigation, and have relatively low ET rates.[92,107] Cristiano et al. (2020) found that high water demand species such as C_3 plants could have higher ET rates with a crop coefficient > 1, which results in a higher retention capacity due to its higher probability to have low antecedent soil moisture at the beginning of rainfall events.[106] Based on the literature, crop coefficients were summarized in Table 4. The crop coefficients are seasonal and species-specific, and high water-demand species can have crop coefficients lager than 1. However, there are still limited data reported on crop coefficients for GR plant species. Therefore, more studies are needed to investigate crop coefficients for different species and provide reference values for GR modeling and design.

Table 4 Summary of different crop coefficients used in GR modeling

Study	Locations	Plant species	Crop coefficients
Sherrard and Jacobs (2012)[19]	New Hampshire, US	Sedum species	0.53
Berretta, Poë, and Stovin (2014)[16]	Sheffield, UK	Sedum species	0.65 – 1.36, substrate specific
Cristiano et al. (2020)[106]	Cagliari, Italy	Several American Agave plants	0.5
Starry et al. (2016)[33]	Maryland, US	Sedum species	0.21 – 0.71, species and seasonal specific
Locatelli et al. (2014)[63]	Copenhagen and Odense, Denmark	Sedum species	0.89–0.95
Szota et al. (2017)[107]	Melbourne, Australia,	High water use plants	1.16 – 1.67, species specific
Szota et al. (2017)[107]	Melbourne, Australia,	Low water use plants	0.59 – 0.97, species specific

5.4 Scale effects on GR simulations

Many GR simulations depend on data measured from pilot-scale experiments, because pilot-scale GR can be easily accessed and monitored[108]. For example, drainage in pilot-scale GR can be easily observed by installing rain barrels under the test beds to measure water level[63,68,92]. However, because pilot-scale GR is often built on elevated test beds above the roof base[76,92,95,103], it suffers from the exposure to additional heat at the bottom which can lead to higher soil water loss[79,109]. In contrast, the full-scale GR is installed directly on the rooftop and can contain non-vegetated areas[77,86], so the combined total flow of bottom drainage and overland flow eventually discharges into the local sewer [40,79,86], even though the surface flow may contribute a small portion to the total flow[35]. Drainage monitoring in full-scale GR is complex and depends on the presence and design of roof drains.[86] Possible monitoring strategies include use of flow meters or water level sensors installed in either GR drainage channels[48,86] or downspouts[79].

Researchers and stormwater managers who pursue GR implementations to address stormwater issues need simulations of GR city-level performance to support their decision-making. Considering the differences in runoff routing and monitoring between pilot-scale GR and full-scale GR, it is unclear whether GR models based on pilot-scale experiments are representative of full-scale GR implementations for stormwater management[79]. Further, city-level performance is often simulated by creating roof retrofitting scenarios. These scenarios are defined based on spatial analyses to identify potential roof areas and assume different percentages of grey roof to be replaced with GR [70]. However, the city-level performance of GR could also be influenced by the GR spatial distributions. Versini et al. (2016) identified that the distribution of roofs, locating them upstream or downstream of the catchment, impacted stormwater runoff delay.[62] They also found GR implementations in the upstream of the catchment could better delay runoff. Therefore, modeling city-level performance of GR requires further considerations to define scenarios that render GR designs, intrinsic catchment characteristics, and GR spatial distributions. Finally, in addition to understanding the large-scale effects of GR implementation, investment costs can be a significant concern for the practical application of GR. In the reviewed literature, only three studies[86,106,110] included a cost-effectiveness analysis in their simulations. Their results suggest cost-effective stormwater management using GR should consider attentively the designs (such as soil and plants) and potential implementation locations. Given limited funding, the ability to realize potential benefits through practical uses still needs to be comprehensively evaluated.

6 Future needs

6.1 GR monitoring to improve model validation

GR models need to be validated to improve model predictions in an urban landscape, particularly for models built based on pilot-scale experiments. Considering the possible inconsistent values of soil parameters between measurements and model calibrations, uncertainty and variability among different model types could be reduced with more field monitoring to support understanding of GR performance. Therefore, building more monitoring programs can help improve understanding of the changing/aging effects of soil properties on water transport. Installing sensors, such as moisture sensors, could facilitate monitoring, because they can continuously track soil water conditions and provide insights to detect potential changes in soil hydraulic properties.

6.2 Deriving actual ET for GR systems

Currently, most common ET predictive methods do not properly predict GR ET. GR managers could consider different types of plants under different climate regimes. Pilot-scale studies need to be expanded to derive crop coefficients for various GR plant types to estimate actual ET and inform future GR design. Soil moisture conditions can impact GR ET. Further research is needed to improve ET estimates under water stress conditions and provide reasonable estimates of the soil moisture levels that significantly impact actual ET in GR systems.

6.3 Characterization of GR components

Further studies are needed to characterize the effects of plants, soil, and drainage mat on GR hydrological modeling. The interception GR plants can serve to store and return rainfall to the atmosphere through evaporation. For example, a mean initial abstraction varying from 5 mm to 5.9 mm was reported in a previous GR study.[55] To expand current soil column experiments[52], adding a commercial vegetation mat atop the soil may help to explore the effects of plant interception. Considering the granular difference between GR substrate and natural soil, conventional models describing soil water characteristic curves and hydraulic conductivity functions need to be evaluated with various substrate types by fitting experimental data to improve substrate physical representation and model transferability. Further observations of outflow from full-scale GRs are recommended to determine the impact of GR geometry and drain placement on GR detention.

6.4 City-scale performance evaluation

More holistic GR simulations at the city scale could be very helpful to support decision-making. Current city-scale GR simulations mainly focus on evaluating stormwater runoff reductions. Broader hydrological benefits associated with GR implementations, such as combined sewer overflow reductions, need to be evaluated to provide a better understanding of city-scale GR performance. Moreover, identifying potential GR siting locations in scenario simulations can be influenced by many factors, e.g., roof slopes and building functions. Use of rooftop maps alone can overestimate GR siting potentials. To better identify all potential GR spatial distributions, rigorous land use analysis is needed with consideration of the comprehensive general city plan. Last, to better understand city-level performance of GR, studies on optimization of GR designs and placements incorporating cost and benefit analysis are suggested to provide insights to stormwater managers regarding the incorporation of GR into stormwater management.

7 Conclusion

Existing efforts to model GR can be classified as conceptual models and mechanistic models. Both models can predict GR outflow[14,47]. Compared to mechanistic models, conceptual models are simple and require low computational costs. However, due to lack of physical meaning of the routing parameters, conceptual models are often case-specific[63] and the results usually cannot be generalized. SWMM and Hydrus-1D both explicitly parameterize soil water transport processes. By solving Richard's equation, Hydrus-1D is able to simulate flow through unsaturated soil and, therefore, provide understanding of soil hydraulic properties, but it requires substantial effort to derive soil parameters. SWMM has a large number of parameters to specify (>10), but it has full capacities to simulate flow through the entire GR vertical profile. In addition, SWMM GR models can be easily incorporated into SWMM stormwater model framework, so it is widely used to simulate the large-scale effects of GR implementations. Considering the limitations in model applications, efforts are still needed to improve model accuracy, by better parameterizing drainage mat flow, estimating evapotranspiration, characterizing soil properties and conducting monitoring programs. To promote GR implementation, comprehensive studies are required to illuminate trade-offs between the cost of GR placement/retrofit and the resulting flow reductions.

Conflicts of interest

The authors have no competing interests to declare.

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Authors Contributions

Zhaokai Dong: investigation, reviewed literature, designed review process, wrote manuscript.

Daniel A Bain: edited manuscript, provided guidance on content.

Kimberly A Gray: edited manuscript, provided guidance on content.

Murat Akcakaya: edited manuscript, provided guidance on content.

Carla Ng: funding acquisition, resources, supervision, edited manuscript

Notes and references

1 C. L. Arnold and C. J. Gibbons, Impervious surface coverage: the emergence of a key environmental indicator, *Journal of the American Planning Association*, 1996, **62**, 243–258.
2 T. R. Schueler, L. Fraley-McNeal and K. Cappiella, Is impervious cover still important? Review of recent research, *J. Hydrol. Eng.*, 2009, **14**, 309–315.
3 H. Li, L. J. Sharkey, W. F. Hunt and A. P. Davis, Mitigation of impervious surface hydrology using bioretention in north carolina and maryland, *J. Hydrol. Eng.*, 2009, **14**, 407–415.
4 J. Marsalek, *Urban water cycle processes and interactions*, CRC Press, 2014.
5 L. S. Coffman, R. Goo and R. Frederick, Low-impact development: an Innovative alternative approach to stormwater management, *WRPMD'99 : Preparing for the 21st Century*, 1999, 1–10.
6 J. Zischg, B. Rogers, A. Gunn, W. Rauch and R. Sitzenfrei, Future trajectories of urban drainage systems: A simple exploratory modeling approach for assessing socio-technical transitions, *Science of The Total Environment*, 2019, **651**, 1709–1719.
7 Y. Her, J. Jeong, J. Arnold, L. Gosselink, R. Glick and F. Jaber, A new framework for modeling decentralized low impact developments using Soil and Water Assessment Tool, *Environmental Modelling & Software*, 2017, **96**, 305–322.
8 G. E. Harper, M. A. Limmer, W. E. Showalter and J. G. Burken, Nine-month evaluation of runoff quality and quantity from an experiential green roof in Missouri, USA, *Ecological Engineering*, 2015, **78**, 127–133.
9 Center for Neighborhood Technology (CNT), *The value of green infrastructure, A guide to recognizing its economic, environmental and social benefits*, 2010.
10 L. S. H. Lee and C. Y. Jim, Thermal-cooling performance of subtropical green roof with deep substrate and woodland vegetation, *Ecological Engineering*, 2018, **119**, 8–18.
11 Green Roofs for Healthy Cities, *2019 annual green roof industry survey: executive summary*, 2019.
12 R. Berghage, D. Beattie, A. Jarrett, C. Thurig, F. Razaei and T. O'Connor, *Green roofs for stormwater runoff control*, U.S. Environmental Protection Agency, Washington, DC., 2009.
13 L. Kosareo and R. Ries, Comparative environmental life cycle assessment of green roofs, *Building and Environment*, 2007, **42**, 2606–2613.
14 K. X. Soulis, J. D. Valiantzas, N. Ntoulas, G. Kargas and P. A. Nektarios, Simulation of green roof runoff under different substrate depths and vegetation covers by coupling a simple conceptual and a physically based hydrological model, *Journal of Environmental Management*, 2017, **200**, 434–445.
15 R. Castiglia Feitosa and S. Wilkinson, Modelling green roof stormwater response for different soil depths, *Landscape and Urban Planning*, 2016, **153**, 170–179.
16 C. Berretta, S. Poë and V. Stovin, Reprint of "Moisture content behaviour in extensive green roofs during dry periods: The influence of vegetation and substrate characteristics", *Journal of Hydrology*, 2014, **516**, 37–49.
17 L. Bengtsson, L. Grahn and J. Olsson, Hydrological function of a thin extensive green roof in southern Sweden, *Hydrology Research*, 2005, **36**, 259–268.
18 J. Wang, A. Garg, N. Liu, D. Chen and G. Mei, Experimental and numerical investigation on hydrological characteristics of extensive green roofs under the influence of rainstorms, *Environ Sci Pollut Res*, , DOI:10.1007/s11356-022-19609-w.
19 J. A. Sherrard and J. M. Jacobs, Vegetated roof water-balance model: experimental and model results, *J. Hydrol. Eng.*, 2012, **17**, 858–868.
20 Doug Banting, Hitesh Doshi, James Li, and Paul Missios, *Report on the environmental benefits and costs of green roof technology for the city of toronto*, Ryerson University, 2005.

21 K. L. Getter, D. B. Rowe and J. A. Andresen, Quantifying the effect of slope on extensive green roof stormwater retention, *Ecological Engineering*, 2007, **31**, 225–231.
22 D. Hutchinson, P. Abrams, R. Retzlaff and T. Liptan, *Stormwater monitoring two ecoroofs in portland, Oregon, USA*, 2003.
23 J. Mentens, D. Raes and M. Hermy, Green roofs as a tool for solving the rainwater runoff problem in the urbanized 21st century?, *Landscape and Urban Planning*, 2006, **77**, 217–226.
24 D. J. Bliss, R. D. Neufeld and R. J. Ries, Storm water runoff mitigation using a rreen roof, *Environmental Engineering Science*, 2009, **26**, 407–418.
25 T. Carter and C. R. Jackson, Vegetated roofs for stormwater management at multiple spatial scales, *Landscape and Urban Planning*, 2007, **80**, 84–94.
26 A. C. Moran, W. F. Hunt and J. T. Smith, Green roof hydrologic and water quality performance from two field sites in north carolina, *Managing Watersheds for Human and Natural Impacts*, 2005, 1–12.
27 T. Liptan and R. K. Murase, Watergardens as stormwater infrastructure in Portland, Oregon, *Handbook of water sensitive planning and design*, 2002, 125–154.
28 F. Viola, M. Hellies and R. Deidda, Retention performance of green roofs in representative climates worldwide, *Journal of Hydrology*, 2017, **553**, 763–772.
29 A. Talebi, S. Bagg, B. E. Sleep and D. M. O'Carroll, Water retention performance of green roof technology: A comparison of canadian climates, *Ecological Engineering*, 2019, **126**, 1–15.
30 B. G. Johannessen, H. M. Hanslin and T. M. Muthanna, Green roof performance potential in cold and wet regions, *Ecological Engineering*, 2017, **106**, 436–447.
31 F. Bettella, V. D'Agostino and L. Bortolini, Drainage flux simulation of green roofs under wet conditions, *J Agricult Engineer*, 2018, **49**, 242–252.
32 M. Hardin, M. Wanielista and M. Chopra, A mass balance model for designing green roof systems that incorporate a cistern for re-Use, *Water*, 2012, **4**, 914–931.
33 O. Starry, J. Lea-Cox, A. Ristvey and S. Cohan, Parameterizing a water-balance model for predicting stormwater runoff from green roofs, *J. Hydrol. Eng.*, 2016, **21**, 04016046.
34 X. Haowen, W. Yawen, W. Luping, L. Weilin, Z. Wenqi, Z. Hong, Y. Yichen and L. Jun, Comparing simulations of green roof hydrological processes by SWMM and HYDRUS-1D, *Water Supply*, 2020, **20**, 130–139.
35 W.-Y. Yang, D. Li, T. Sun and G.-H. Ni, Saturation-excess and infiltration-excess runoff on green roofs, *Ecological Engineering*, 2015, **74**, 327–336.
36 A. Palla, I. Gnecco and P. La Barbera, Assessing the hydrologic performance of a green roof retrofitting scenario for a small urban catchment, *Water*, 2018, **10**, 1052.
37 I. Broekhuizen, S. Sandoval, H. Gao, F. Mendez-Rios, G. Leonhardt, J.-L. Bertrand-Krajewski and M. Viklander, Performance comparison of green roof hydrological models for full-scale field sites, *Journal of Hydrology X*, 2021, **12**, 100093.
38 G. Ercolani, E. A. Chiaradia, C. Gandolfi, F. Castelli and D. Masseroni, Evaluating performances of green roofs for stormwater runoff mitigation in a high flood risk urban catchment, *Journal of Hydrology*, 2018, **566**, 830–845.
39 R. Bouzouidja, G. Séré, R. Claverie, S. Ouvrard, L. Nuttens and D. Lacroix, Green roof aging: Quantifying the impact of substrate evolution on hydraulic performances at the lab-scale, *Journal of Hydrology*, 2018, **564**, 416–423.
40 P.-A. Versini, D. Ramier, E. Berthier and B. de Gouvello, Assessment of the hydrological impacts of green roof: From building scale to basin scale, *Journal of Hydrology*, 2015, **524**, 562–575.
41 B. G. Johannessen, V. Hamouz, A. S. Gragne and T. M. Muthanna, The transferability of SWMM model parameters between green roofs with similar build-up, *Journal of Hydrology*, 2019, **569**, 816–828.
42 Yanling Li and Roger W. Babcock Jr, Green roof hydrologic performance and modeling: a review, *Water Science and Technology*, 2014, **69**, 727–738.
43 K. Zhang and T. F. M. Chui, A review on implementing infiltration-based green

infrastructure in shallow groundwater environments: Challenges, approaches, and progress, *Journal of Hydrology*, 2019, **579**, 124089.
44 J. Reu Junqueira, S. Serrao-Neumann and I. White, A systematic review of approaches for modelling current and future impacts of extreme rainfall events using green infrastructure, *Journal of Cleaner Production*, 2021, **290**, 125173.
45 W. A. Lisenbee, J. M. Hathaway, M. J. Burns and T. D. Fletcher, Modeling bioretention stormwater systems: Current models and future research needs, *Environmental Modelling & Software*, 2021, **144**, 105146.
46 C. E. Nika, L. Gusmaroli, M. Ghafourian, N. Atanasova, G. Buttiglieri and E. Katsou, Nature-based solutions as enablers of circularity in water systems: A review on assessment methodologies, tools and indicators, *Water Research*, 2020, **183**, 115988.
47 A. Palla, I. Gnecco and L. G. Lanza, Compared performance of a conceptual and a mechanistic hydrologic models of a green roof, *Hydrol. Process.*, 2012, **26**, 73–84.
48 A. Palla, I. Gnecco and L. G. Lanza, Unsaturated 2D modelling of subsurface water flow in the coarse-grained porous matrix of a green roof, *Journal of Hydrology*, 2009, **379**, 193–204.
49 A. Palla, J. J. Sansalone, I. Gnecco and L. G. Lanza, Storm water infiltration in a monitored green roof for hydrologic restoration, *Water Science and Technology*, 2011, **64**, 766–773.
50 S. Baek, M. Ligaray, Y. Pachepsky, J. A. Chun, K.-S. Yoon, Y. Park and K. H. Cho, Assessment of a green roof practice using the coupled SWMM and HYDRUS models, *Journal of Environmental Management*, 2020, **261**, 109920.
51 K. Förster, D. Westerholt, P. Kraft and G. Lösken, Unprecedented Retention Capabilities of Extensive Green Roofs—New Design Approaches and an Open-Source Model, *Front. Water*, 2021, **3**, 689679.
52 Zhangjie Peng, Colin Smith, and Virginia Stovin, The importance of unsaturated hydraulic conductivity measurements for green roof detention modelling, *Journal of Hydrology*, 2020, **590**, 125273.
53 N. She and J. Pang, Physically based green roof model, *J. Hydrol. Eng.*, 2010, **15**, 458–464.
54 L. A. Rossman and W. C. Huber, *Storm water management model reference manual volume III – water quality*, US EPA Office of Research and Development, Washington, DC:, 2016.
55 W. Liu, Q. Feng, R. Wang and W. Chen, Effects of initial abstraction ratios in SCS-CN method on runoff prediction of green roofs in a semi-arid region, *Urban Forestry & Urban Greening*, 2021, **65**, 127331.
56 E. M. H. Abdalla, V. Pons, V. Stovin, S. De-Ville, E. Fassman-Beck, K. Alfredsen and T. M. Muthanna, Evaluating different machine learning methods to simulate runoff from extensive green roofs, *Hydrol. Earth Syst. Sci.*, 2021, **25**, 5917–5935.
57 C. N. Nguyen, M. A. U. R. Tariq, D. Browne and N. Muttil, Performance evaluation of large-scale green roofs based on qualitative and quantitative runoff modeling using MUSICX, *Water*, 2023, **15**, 549.
58 I. Broekhuizen, S. Sandoval, H. Gao, F. Mendez-Rios, G. Leonhardt, J.-L. Bertrand-Krajewski and M. Viklander, Performance comparison of green roof hydrological models for full-scale field sites, *Journal of Hydrology X*, 2021, **12**, 100093.
59 K. Pettersson, D. Maggiolo, S. Sasic, P. Johansson and A. Sasic-Kalagasidis, On the impact of porous media microstructure on rainfall infiltration of thin homogeneous green roof growth substrates, *Journal of Hydrology*, 2020, **582**, 124286.
60 C. T. Chai, F. J. Putuhena and O. S. Selaman, A modelling study of the event-based retention performance of green roof under the hot-humid tropical climate in Kuching, *Water Science and Technology*, 2017, **76**, 2988–2999.
61 M. Hellies, R. Deidda and F. Viola, Retention performances of green roofs worldwide at different time scales, *Land Degrad Dev*, 2018, **29**, 1940–1952.
62 P.-A. Versini, A. Gires, I. Tchinguirinskaia and D. Schertzer, Toward an operational tool to simulate green roof hydrological impact at the basin scale: a new version of the

distributed rainfall–runoff model Multi-Hydro, *Water Science and Technology*, 2016, **74**, 1845–1854.
63 L. Locatelli, O. Mark, P. S. Mikkelsen, K. Arnbjerg-Nielsen, M. Bergen Jensen and P. J. Binning, Modelling of green roof hydrological performance for urban drainage applications, *Journal of Hydrology*, 2014, **519**, 3237–3248.
64 M. H. N. Yio, V. Stovin, J. Werdin and G. Vesuviano, Experimental analysis of green roof substrate detention characteristics, *Water Science and Technology*, 2013, **68**, 1477–1486.
65 G. Vesuviano, F. Sonnenwald and V. Stovin, A two-stage storage routing model for green roof runoff detention, *Water Science and Technology*, 2014, **69**, 1191–1197.
66 H. Kasmin, V. R. Stovin and E. A. Hathway, Towards a generic rainfall-runoff model for green roofs, *Water Science and Technology*, 2010, **62**, 898–905.
67 L. A. Rossman, *Storm water management model user's manual version 5.1*, US EPA Office of Research and Development, Washington, DC, 2015.
68 K. Alfredo, F. Montalto and A. Goldstein, Observed and modeled performances of prototype green roof test plots subjected to simulated low- and high-intensity precipitations in a laboratory experiment, *J. Hydrol. Eng.*, 2010, **15**, 444–457.
69 D. Masseroni and A. Cislaghi, Green roof benefits for reducing flood risk at the catchment scale, *Environ Earth Sci*, 2016, **75**, 579.
70 V. Hamouz, P. Møller-Pedersen and T. M. Muthanna, Modelling runoff reduction through implementation of green and grey roofs in urban catchments using PCSWMM, *Urban Water Journal*, 2020, **17**, 813–826.
71 A. Palla and I. Gnecco, A continuous simulation approach to quantify the climate condition effect on the hydrologic performance of green roofs, *Urban Water Journal*, 2020, **17**, 609–618.
72 W. Heber Green and G. A. Ampt, Studies on soil phyics, *The Journal of Agricultural Science*, 1911, **4**, 1–24.
73 David Rassam, Jirka Šimůnek, Dirk Mallants, and Martinus Th. van Genuchten, *The HYDRUS-1D software package for simulating the one-dimensional movement of water, heat, and multiple solutes in variably-saturated media: tutorial, version 1.00*, CSIRO Land and Water, Australia, 2018.
74 M. Th. Genuchten and P. J. Wierenga, Mass transfer studies in sorbing porous media I. Analytical solutions, *Soil Sci. Soc. Am. j.*, 1976, **40**, 473–480.
75 G. Pęczkowski, T. Kowalczyk, K. Szawernoga, W. Orzepowski, R. Żmuda and R. Pokładek, Hydrological performance and runoff Water quality of experimental green roofs, *Water*, 2018, **10**, 1185.
76 E. Burszta-Adamiak and M. Mrowiec, Modelling of green roofs' hydrologic performance using EPA's SWMM, *Water Science and Technology*, 2013, **68**, 36–42.
77 M. Mobilia and A. Longobardi, Impact of rainfall properties on the performance of hydrological models for green roofs simulation, *Water Science and Technology*, 2020, **81**, 1375–1387.
78 S. Jeffers, B. Garner, Derek Hidalgo, D. Hidalgo, Dionisi Daoularis, and Oscar Warmerdam, Insights into green roof modeling using SWMM LID controls for detention-based designs, *JWMM*, , DOI:10.14796/JWMM.C484.
79 S. S. Cipolla, M. Maglionico and I. Stojkov, A long-term hydrological modelling of an extensive green roof by means of SWMM, *Ecological Engineering*, 2016, **95**, 876–887.
80 A. Ebrahimian, B. Wadzuk and R. Traver, Evapotranspiration in green stormwater infrastructure systems, *Science of The Total Environment*, 2019, **688**, 797–810.
81 G. H. Hargreaves and Z. A. Samani, Reference crop evapotranspiration from temperature, *Applied Engineering in Agriculture*, 1985, **1**, 96–99.
82 R. G. Allen, L. S. Pereira, D. Raes and M. Smith, Crop evapotranspiration-Guidelines for computing crop water requirements-FAO Irrigation and drainage paper 56, *Fao, Rome*, 1998, **300**, D05109.
83 G. H. Hargreaves and R. G. Allen, History and evaluation of hargreaves evapotranspiration equation, *J. Irrig. Drain Eng.*, 2003, **129**, 53–63.

84 R. N. Hilten, T. M. Lawrence and E. W. Tollner, Modeling stormwater runoff from green roofs with HYDRUS-1D, *Journal of Hydrology*, 2008, **358**, 288–293.
85 S. Huang, A. Garg, G. Mei, D. Huang, R. B. Chandra and S. G. Sadasiv, Experimental study on the hydrological performance of green roofs in the application of novel biochar, *Hydrological Processes*, 2020, **34**, 4512–4525.
86 N. Abualfaraj, J. Cataldo, Y. Elborolosy, D. Fagan, S. Woerdeman, T. Carson and F. Montalto, Monitoring and modeling the long-term rainfall-runoff response of the Jacob K. Javits Center green roof, *Water*, 2018, **10**, 1494.
87 T. Carson, M. Keeley, D. E. Marasco, W. McGillis and P. Culligan, Assessing methods for predicting green roof rainfall capture: A comparison between full-scale observations and four hydrologic models, *Urban Water Journal*, 2015, **14**, 589–603.
88 S. Huang, D. Huang, A. Garg, M. Jiang, G. Mei and S. Pekkat, Stormwater management of biochar-amended green roofs: peak flow and hydraulic parameters using combined experimental and numerical investigation, *Biomass Conv. Bioref.*, , DOI:10.1007/s13399-020-01109-x.
89 J. Wang, A. Garg, S. Huang, Z. Wu, T. Wang and G. Mei, An experimental and numerical investigation of the mechanism of improving the rainwater retention of green roofs with layered soil, *Environ Sci Pollut Res*, 2022, **29**, 10482–10494.
90 Filip Stanić, Yu-Jun Cui, Pierre Delage, Emmanuel De Laure, Pierre-Antoine Versini, Daniel Schertzer, and Ioulia Tchiguirinskaia, A Device for the Simultaneous Determination of the Water Retention Properties and the Hydraulic Conductivity Function of an Unsaturated Coarse Material; Application to a Green-Roof Volcanic Substrate, *Geotechnical Testing Journal*, 2019, **43**, 547–564.
91 J. Hill, B. Sleep, J. Drake and M. Fryer, The effect of intraparticle porosity and interparticle voids on the hydraulic properties of soilless media, *Vadose zone j.*, 2019, **18**, 1–13.
92 R. Iffland, K. Förster, D. Westerholt, M. H. Pesci and G. Lösken, Robust vegetation parameterization for green roofs in the EPA stormwater management model (SWMM), *Hydrology*, 2021, **8**, 12.
93 V. Hamouz and T. M. Muthanna, Hydrological modelling of green and grey roofs in cold climate with the SWMM model, *Journal of Environmental Management*, 2019, **249**, 109350.
94 Z. Peng and V. Stovin, Independent Validation of the SWMM Green Roof Module, *J. Hydrol. Eng.*, 2017, **22**, 04017037.
95 G. Krebs, K. Kuoppamäki, T. Kokkonen and H. Koivusalo, Simulation of green roof test bed runoff: Simulation of Green Roof Test Bed Runoff, *Hydrol. Process.*, 2016, **30**, 250–262.
96 J. Leimgruber, G. Krebs, D. Camhy and D. Muschalla, Sensitivity of model-based water balance to low impact development parameters, *Water*, 2018, **10**, 1838.
97 Z. Peng, C. Smith and V. Stovin, Internal fluctuations in green roof substrate moisture content during storm events: Monitored data and model simulations, *Journal of Hydrology*, 2019, **573**, 872–884.
98 R. H. McCuen, Z. Knight and A. G. Cutter, Evaluation of the Nash–Sutcliffe efficiency index, *J. Hydrol. Eng.*, 2006, **11**, 597–602.
99 B. Barnhart, P. Pettus, J. Halama, R. McKane, P. Mayer, K. Djang, A. Brookes and L. M. Moskal, Modeling the hydrologic effects of watershed-scale green roof implementation in the Pacific Northwest, United States, *Journal of Environmental Management*, 2021, **277**, 111418.
100 A. S. Basu, F. Pilla, S. Sannigrahi, R. Gengembre, A. Guilland and B. Basu, Theoretical framework to assess green roof performance in mitigating urban flooding as a potential nature-nased solution, *Sustainability*, 2021, **13**, 13231.
101 A. G. Limos, K. J. B. Mallari, J. Baek, H. Kim, S. Hong and J. Yoon, Assessing the significance of evapotranspiration in green roof modeling by SWMM, *Journal of Hydroinformatics*, 2018, **20**, 588–596.
102 R. Hakimdavar, P. J. Culligan, M. Finazzi, S. Barontini and R. Ranzi, Scale dynamics of

extensive green roofs: Quantifying the effect of drainage area and rainfall characteristics on observed and modeled green roof hydrologic performance, *Ecological Engineering*, 2014, **73**, 494–508.

103 A. W. Sims, C. E. Robinson, C. C. Smart and D. M. O'Carroll, Mechanisms controlling green roof peak flow rate attenuation, *Journal of Hydrology*, 2019, **577**, 123972.

104 V. Stovin, S. Poë and C. Berretta, A modelling study of long term green roof retention performance, *Journal of Environmental Management*, 2013, **131**, 206–215.

105 S. Poë, V. Stovin and C. Berretta, Parameters influencing the regeneration of a green roof's retention capacity via evapotranspiration, *Journal of Hydrology*, 2015, **523**, 356–367.

106 E. Cristiano, S. Urru, S. Farris, D. Ruggiu, R. Deidda and F. Viola, Analysis of potential benefits on flood mitigation of a CAM green roof in Mediterranean urban areas, *Building and Environment*, 2020, **183**, 107179.

107 C. Szota, C. Farrell, N. S. G. Williams, S. K. Arndt and T. D. Fletcher, Drought-avoiding plants with low water use can achieve high rainfall retention without jeopardising survival on green roofs, *Science of The Total Environment*, 2017, **603–604**, 340–351.

108 J. Herrera, G. Flamant, J. Gironás, S. Vera, C. Bonilla, W. Bustamante and F. Suárez, Using a Hydrological Model to Simulate the Performance and Estimate the Runoff Coefficient of Green Roofs in Semiarid Climates, *Water*, 2018, **10**, 198.

109 G. Brunetti, I.-A. Papagrigoriou and C. Stumpp, Disentangling model complexity in green roof hydrological analysis: A Bayesian perspective, *Water Research*, 2020, **182**, 115973.

110 L. Yao, Z. Wu, Y. Wang, S. Sun, W. Wei and Y. Xu, Does the spatial location of green roofs affects runoff mitigation in small urbanized catchments?, *Journal of Environmental Management*, 2020, **268**, 110707.

111 S. De-Ville, M. Menon, X. Jia, G. Reed and V. Stovin, The impact of green roof ageing on substrate characteristics and hydrological performance, *Journal of Hydrology*, 2017, **547**, 332–344.