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

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Supporting information

Table S1 General comparison of the main characteristics of GR models (Y: required to specify; N: not required; D: depends on simulations; E: enables; conceptual models are marked in bold and mechanistic models are marked in italics)

Model type	Number of studies	Initial condition	Boundary condition	Grid mesh	Soil characteristic parameterization	Water content simulation	Computational demand
SCS curve number	6	N	N	N	N	N	Low
Green-Ampt	1	Y	N	N	Y	E	Moderate
Machine learning	1	Y	N	N	N	E	High
SWMS_2D	2	Y	Y	Y	Y	E	High
Richard's equation	4	Y	Y	Y	Y	E	High
Water balance	21	Y	N	N	Y	E	Low
Reservoir	10	Y	N	N	Y	E	Low
Hydrus-1D	14	Y	Y	Y	Y	E	High
SWMM	22	Y	N	N	Y	E	Moderate
Other models	11	Y	D	D	D	D	D

Table S2 Summary of the reviewed GR literature

Title	Summary	Model	Scale (cm)	Substrate composition	Performance	Year
Observed and Modeled Performances of Prototype Green Roof Test Plots Subjected to Simulated Low- and High-Intensity Precipitations in a Laboratory Experiment	GR hydrological performance was related to the substrate depth. The curve number method underpredicted roof discharge compared to the storage node approach in SWMM simulations.	SWMM	Lab-scale; 122 x 61 (2.5, 6.3, 10.1 cm); 2% slope		Standard error	2010
Modelling of green roofs' hydrologic performance using EPA's SWMM	The authors found specifying the initial soil moisture content was very important to achieve a successful simulation.	SWMM	Lab-scale; 240 x 120 (35 cm); 7.7% slope		NSE	2013
Assessment of the hydrological impacts of green roof: From building scale to basin scale	GR hydrological benefits were more pronounced at the roof scale than at the basin scale.	SWMM	Full-scale and basin scale; 7 x 5 m (3 or 15 cm); Flat roof	Lapillus, peat and green compost (organic part represents 3.4% in mass of the substrate)	NSE	2015
A long-term hydrological modelling of an extensive green roof by means of SWMM	The hydrological performance of GR was influenced by the definition of rainfall events, green roof scale, and initial soil moisture content.	SWMM	Lab-scale; 5.15 m x 11.30 m (10 cm); slope of 0.5%		NSE	2016
Simulation of green roof test bed runoff	SWMM GR module was capable of simulating GR hydrological performance but was more accurate for high-intensity	SWMM	Lab-scale; 1 × 2 m 10cm;	Crushed brick (85%), compost (5%), peat (5%)	Volume error (VE); NSE	2016

	rainfall events. ET had significant influence on continuous simulations.		Slope of 8%	and crushed bark (5%)		
Green roof benefits for reducing flood risk at the catchment scale	Initial soil water content influenced GR modeling results.	SWMM	Basin-scale; Design purpose of area of 100 m^2			2016
Assessing methods for predicting green roof rainfall capture: A comparison between full-scale observations and four hydrologic models	The CN and GRE method were more accurate to replicate observed flow. SWMM tended to overpredict runoff.	SWMM; CN; HELP; CRE	Full-scale; 310 m^2 and 390 m^2; (32 mm and 100 mm)		NSE	2015
Independent Validation of the SWMM Green Roof Module	SWMM module did not consider ET reduction due to reduced soil moisture.	SWMM	Lab-scale; 3m × 1m (8 cm); slope of 2.6%	Crushed brick and fines	NSE	2017
Monitoring and Modeling the Long-Term Rainfall-Runoff Response of the Jacob K. Javits Center Green Roof	The depth of the substrate had high impacts on water retention.	SWMM	Full-scale; 186 m^2; (2.54 cm)	Composted plant materials and lightweight porous aggregate		2018
Sensitivity of Model-Based Water Balance to Low Impact Development Parameters	Soil thickness, porosity, conductivity slope, and field capacity impacted GR runoff volume.	SWMM				2018
Assessing the significance of evapotranspiration in green roof modeling by SWMM	Model performance can be improved with consideration of ET.	SWMM			NSE	2018
Assessing the Hydrologic Performance of a Green	SWMM may underestimate runoff due to an overestimate of actual ET.	SWMM	Basin-scale		-	2018

Roof Retrofitting Scenario for a Small Urban Catchment						
Hydrological modelling of green and grey roofs in cold climate with the SWMM model	SWMM model can predict GR runoff but was less performed in winter seasons. Model parameters may be site-specific and inconsistent with recommended values.	SWMM	Full-scale; 8 × 11 m (20 cm); slope of 2%		NSE; VE	2019
The transferability of SWMM model parameters between green roofs with similar build-up	Parameter transferability was poor even with same roof configurations. Parameters were more site and climate specific.	SWMM	Pilot-scale and Full-scale: 8 – 100 m^2 (3 – 10 cm) Slope of 2% – 27%		NSE; VE	2019
Assessment of a green roof practice using the coupled SWMM and HYDRUS models	SWMM predictions were sensitive to field capacity and porosity. SWMM could be less accurate in soil moisture predictions than Hydrus-1D.	SWMM; Hydrus-1D	Pilot-scale; 4 × 4 m (20 cm)		RMSE; MAE; NSE	2020
Modelling runoff reduction through implementation of green and grey roofs in urban catchments using PCSWMM	Implementation of GR on 11% of the roof area can substantially reduce maximum flows.	SWMM			NSE; VE; R^2	2020
Comparing simulations of green roof hydrological processes by SWMM and HYDRUS-1D	SWMM predictions were sensitive to the roughness of drainage mat and may overpredict peak flow rates compared to Hydrus-1D.	SWMM; Hydrus-1D	Pilot-scale; 0.5 x 0.5 m (13.5cm); Slope of 0%		NSE	2020
Impact of rainfall properties on the performance of	GR model performance was impacted by rainfall event characteristics.	SWMM; Nash model;	Pilot-scale; 1 x 2.5m (15cm);		NSE; RMSE; MSE	2020

hydrological models for green roofs simulation		Hydrus-1D	slope of 1%			
A continuous simulation approach to quantify the climate condition effect on the hydrologic performance of green roofs	The study highlighted the importance of ET to GR continuous simulations. Reduction in runoff and peak flow was related to rainfall characteristics.	SWMM	Basin-scale			2019
Performance comparison of green roof hydrological models for full-scale field sites	Model performance was related to the event characteristics.	SWMM; Hydrus-1D; Mike SHE; Urbis	Full-scale; 280 m^2 (Vary from 4 and 14 cm); 2469 m^2; (Vary from 4.2 and 8 cm)		NSE; VE	2021
Robust Vegetation Parameterization for Green Roofs in the EPA Stormwater Management Model (SWMM)	ET estimation based on Penman–Monteith equation outperformed the Hargreaves equation.	SWMM	Pilot-scale; 2 × 2 m (3.3 cm); Slope of 2%			2021
Insights into green roof modeling using SWMM LID controls for detention-based designs	Model performance was affected by the parametrization of drainage mat.	SWMM	Pilot-scale; 7.43 m^2 (5 cm); Slopes of 0% and 2% respectively		NSE	2022
Moisture content behaviour in extensive green roofs during dry periods: The influence of vegetation and substrate	ET was influenced by soil water availability and climate conditions. Commonly used ET models tended to overestimate ET.	Water balance	Pilot-scale; 3 x 1m (8 cm); Slope of 2.6%	1. Crushed bricks and pumice (ZincolitPlus), enriched with		2014

characteristics				organic matter; 2. 80% LECA, 10% loam and 10% compost by volume		
Parameterizing a Water-Balance Model for Predicting Stormwater Runoff from Green Roofs	Crop coefficients varied across different vegetation species and seasons. Using adjusted ET, a water balance-based model can predict runoff.	Water balance	Pilot-scale; 1.31 m^2			2016
Internal fluctuations in green roof substrate moisture content during storm events: Monitored data and model simulations	Richard equation solutions were sensitive to the lower boundary condition and hydraulic conductivity function.	Lumped reservoir model; Richard's equation	Pilot-scale; 3 m × 1 m (8 cm); slope of 1.5°; sedum			2019
Modeling stormwater runoff from green roofs with HYDRUS-1D	Hydrus-1D could overestimate GR runoff.	Hydrus-1D	Pilot-scale; 60 x 60 cm (10cm); Slope of 0			2008
Compared performance of a conceptual and a mechanistic hydrologic models of a green roof	Hydrus-1D showed high accuracy in runoff predictions.	Hydrus-1D; Lumped reservoir model	Full-scale; 350 m^2 (20 cm)			2012
Saturation-excess and infiltration-excess runoff on green roofs	GR runoff primarily come from substrate saturation rather than the rainfall intensity exceeding infiltration capacity.	Hydrus-1D	Full-scale; 120 m^2 (15 cm); Slope of 3°			2015

Modelling green roof stormwater response for different soil depths	GR peak flow reduction was positively correlated to the soil depth and negatively correlated to the initial soil moisture content.	Hydrus-1D				2016
Simulation of green roof runoff under different substrate depths and vegetation covers by coupling a simple conceptual and a physically based hydrological model	The conceptual model performed better than Hydrus-1D in outflow predictions.	Hydrus-1D; Reservoir models	Pilot-scale; 200 x 100 cm (8/16 cm)	Pumice, attapulgite clay, zeolite and grape marc compost at volumetric proportions of 65:15:5:15		2017
Hydrological Performance and Runoff Water Quality of Experimental Green Roofs	Hydrus-1D could overestimate the runoff. Total nitrogen in GR runoff was higher than in the rainwater.	Hydrus-1D	Pilot-scale; 200 x 100 cm (12 cm); Slope of 3°			2018
Experimental study on the hydrological performance of green roofs in the application of novel biochar	Vegetated soil had higher saturated hydraulic conductivity than bare soil. Biochar increased GR retention capacity.	Hydrus-1D	Pilot-scale; Cylinder with diameter of 25 cm (15 cm)	Grinded and sieved through 2 mm		2020
Experimental and numerical investigation on hydrological characteristics of extensive green roofs under the influence of rainstorms	Under the condition of surface ponding, GR water retention was impacted by the cumulative rainfall and the available water storage within GR. Adding a bottom water storage layer increased retention capacity and had larger effects than increasing soil depth.	Hydrus-1D	Pilot-scale; 30 x 30 cm (10 cm)			2022
A Mass Balance Model for Designing Green	A mass balance model was introduced to support design of irrigated GR systems	Water balance				2012

Roof Systems that Incorporate a Cistern for Re-Use	using cisterns to capture and reuse rain waters.					
Vegetated Roof Water-Balance Model: Experimental and Model Results	Experiments based on a weighing lysimeter approach were used to develop, calibrate, and validate a water balance model.	Water balance	Pilot-scale; 1.22 x 0.62m (10 cm); Slope of 0	65% lightweight expandable shale, 15% biosolids, 10% perlite or other lightweight additives, and 10% fines	NSE; MSE; RMSE	2012
Modelling of green roof hydrological performance for urban drainage applications	GR can effectively reduce runoff volume by 18–28% for common events with return periods less than 1 year.	Water balance; Lumped reservoir model	3 x 3 m (4 cm); a slope of 10°; 2 of 20 m^2 (3 cm and 6 cm); slope of 4.3°		Peak error; VE	2014
A modelling study of the event-based retention performance of green roof under the hot-humid tropical climate in Kuching	The GR presented a mean retention rate of 72.5%. It reduced to 12.0% under large events that could cause flash flood.	Water balance				2017
Retention performances of green roofs worldwide at different time scales	The paper assessed the feasibility of GR implementation based on ERA-Interim database.	Water balance				2018
Water retention performance of green roof technology: A comparison of canadian climates	The performance of GR in runoff reduction depended on local climate and vegetation types.	Water balance				2019

Theoretical Framework to Assess Green Roof Performance in Mitigating Urban Flooding as a Potential Nature-Based Solution	The impacts of vegetation types on GR runoff reduction was investigated based on a hypothetical GR.	Water balance	Pilot-scale; 1 m^2; sedum		NSE	2021
Modelling the hydrological responses of green roofs under different substrate designs and rainfall characteristics using a simple water balance model	GR was more effective to capture small rainfall events.	Water balance	Pilot-scale; 1 m^2 (5cm/ 10cm); Slope of 2%, 7%, 12%		NSE; VE	2021
Vegetated roofs for stormwater management at multiple spatial scales	Watershed-scale GR implementation can significantly reduce peak runoff, particularly for small storm events.	CN				2007
Unsaturated 2D modelling of subsurface water flow in the coarse-grained porous matrix of a green roof	A GR model based on SWMS_2D was built and successfully replicated the outflow.	SWMS_2D	Full-scale; 170 m^2 (20 cm); Flat roof	Volcanic material (pumices 25%, lapillus 65%, zeolite 10%) and organic matter (peat and vegetable compost, 16%)		2009
Physically Based Green Roof Model	Soil water would drain through the growing medium when soil moisture varied between field capacity and saturation.	Green-Ampt equation; Water balance	Full-scale; 2,620 ft^2 slope of 2.1%	20% digested fiber, 10% compost, 22% coarse perlite, and 28% sandy loam; The field		2010

				capacity and porosity (calibration): 0.35 and 0.41,		
Storm water infiltration in a monitored green roof for hydrologic restoration	A GR model based on SWMS_2D successfully simulated GR outflow.	SWMS_2D	Full-scale; 170 m^2 (20 cm); Flat roof	Volcanic material (pumices 25%, lapillus 65%, zeolite 10%) and organic matter (peat and vegetable compost, 16%)		2011
Experimental analysis of green roof substrate detention characteristics	GR detention increases with increasing substrate depth and organic content.	Reservoir model	Pilot-scale; Diameter of 36 cm (15 cm)			2013
A two-stage storage routing model for green roof runoff detention	Non-linear reservoir model can be used to predict GR flow.	Reservoir model	Pilot-scale; 1m x 5m (20 cm); slope of 2%	55% crushed brick, 30% pumice, 10% coir, 5% compost		2014
Analytical Probabilistic Model for Evaluating the Hydrologic Performance of Green Roofs	An analytical probabilistic model was developed based on local rainfall characteristics using Poisson distributions.	Probabilistic model				2013
Stochastic Analysis of Hydrologic Operation of Green Roofs	Based on water balance, analytical solutions were derived for a probabilistic GR model for supporting GR design and operations.	Probabilistic model				2016
Toward an operational tool to simulate green	GR can significantly reduce runoff volume and peak flow and the model performance	Multi-Hydro	Pilot-scale; 35 m^2	Lapillus, peat and green	VE	2016

roof hydrological impact at the basin scale: a new version of the distributed rainfall–runoff model Multi-Hydro	was impacted by the rainfall intensities and soil initial saturation.		(3 cm)	compost		
Laboratory Tests of Substrate Physical Properties May Not Represent the Retention Capacity of Green Roof Substrates In Situ	Laboratory-based measures (water holding capacity) significantly overestimated the real rainfall retention in GR.	Mass balance	Pilot-scale; 116 cm × 116 cm (10 cm); Slope of 2◦	80% mineral component and 20% horticultural grade coir		2017
Drainage flux simulation of green roofs under wet conditions	CN method may reproduce the drainage of GR under extreme wetness conditions.	CN	Pilot-scale; 0.77×0.57m (12.0 cm)	volcanic medium; blonde peat and a recycled medium	NSE	2018
Using a Hydrological Model to Simulate the Performance and Estimate the Runoff Coefficient of Green Roofs in Semiarid Climates	IHMORS was able to predict the soil moisture dynamics for tested specimens of 10 cm depth.	Integrated Hydrological Model	Pilot-scale; 25/35 m^2 (5/10/20 cm); Slope of 1◦, 2◦, 5◦	68% sand, 20% silt, 12% clay	MAE	2018
Mechanisms controlling green roof peak flow rate attenuation	When the GR substrate moisture content reached field capacity, peak flow attenuation significantly decreased.	Richard's equation	4 m × 3 m (10 cm)		RMSE	2019
Analysis of potential benefits on flood mitigation of a CAM green roof in Mediterranean urban areas	A GR model was built to simulate the runoff reduction considering two types of vegetation – C3 and CAM. The model showed C3 presented a higher runoff retention capacity than CAM vegetation with frequent irrigation.	Ecohydrological Streamflow Mode; Water balance	Full-scale; 16 m × 3 m (30 cm)	Sandy soil	NSE	2020

Assessing the runoff retention of extensive green roofs using runoff coefficients and curve numbers and the impacts of substrate moisture	Experimental rainfall-runoff data were used to derive CN for four designs of GR. A positive relationship was found between initial moisture and CN.	CN	Pilot-scale; 100 cm × 100 cm (5/10cm)	rural soil, peat soil, pine needle, perlite, vermiculite		2020
The importance of unsaturated hydraulic conductivity measurements for green roof detention modelling	Soil column experiments were conducted to derive hydraulic conductivity function (HCF). A simplified HCF was proposed and provided reasonable HCF estimations.	Richard's equation			RMSE; NSE	2020
On the impact of porous media microstructure on rainfall infiltration of thin homogeneous green roof growth substrates	Larger particle sizes in relation to the substrate thickness may reduce infiltration.	Lattice Boltzmann method				2020
Evaluating different machine learning methods to simulate runoff from extensive green roofs	Well-trained ML models can estimate GR runoff.	Machine learning model; Conceptual model	16 pilot-roofs		RMSE; VE	2021
Unprecedented Retention Capabilities of Extensive Green Roofs—New Design Approaches and an Open-Source Model	Increasing flow length and decreasing slope can reduce GR runoff.	Richards' equation	Pilot-scale; 20 m x 1 m (8 / 10 cm)		RMSE	2021
Effects of initial abstraction ratios in SCS-CN method on runoff prediction of green roofs in a semi-arid region	The initial abstraction ratios in CN method influenced rainfall-runoff simulations.	CN	Pilot-scale; 1 m^2		RMSE; MSE; NSE; Willmott's index (WI)	2021

Hydrological Performance of Green Roof Systems: A Numerical Investigation	The SEEP/W model predicted faster and greater peak time and peak discharge values.	SEEP/W Model	Pilot-scale; 2m × 2m (25 cm); Slope of 5°			2021
Green roof performance potential in cold and wet regions	GR annual retention was found to be more sensitive to the changes in crop coefficients than in storage capacities.	ET models; Water balance				2017
Retention performance of green roofs in representative climates worldwide	Substrate depth played a crucial role in determining GR retention performance. GR can reduce runoff into sewer systems at an annual time scale.	Water balance				2017
Towards a generic rainfall-runoff model for green roofs	Thornthwaite ET formula can be used for monthly ET estimation.	Conceptual model	Pilot-scale; 3m x 1m (8 cm); a slope of 1.58		R^2	2010
Nine-month evaluation of runoff quality and quantity from an experiential green roof in Missouri, USA	Plant species and substrate characteristics influenced the hydrological performance of GR.	Water balance	Pilot-scale; 60.8 cm x 60.8 cm			2015
Parameters influencing the regeneration of a green roof's retention capacity via evapotranspiration	Differences in ET were found between vegetated and non-vegetated configurations.	Water balance	Pilot-scale; 23.7 x 23.7 (8 cm)			2015
A Comprehensive Analysis of the Variably Saturated Hydraulic Behavior of a Green Roof in a Mediterranean Climate	Hydrus-3D model provided high accuracy to replicate runoff.	Hydrus-3D	Full-scale; 50 m^2 (8 cm)	Mineral soil with 74% gravel, 22% sand, and 4% silt and clay.	NSE	2016

A modelling study of long term green roof retention performance	Lower soil water holding capacity and ET reduced GR water retention.	Conceptual model				2013
Scale dynamics of extensive green roofs: Quantifying the effect of drainage area and rainfall characteristics on observed and modeled green roof hydrologic performance	Peak reduction increased with increasing drainage area. Hydrus 1-D partially captured the GR hydrological behavior.	Hydrus-1D	Full-scale; 3.2 cm		NSE	2014
Green roof aging: Quantifying the impact of substrate evolution on hydraulic performances at the lab-scale	Hydraulic parameters were obtained based on inverse solution using hydrus-1D software. The substrate saturated water content decreased and saturated hydraulic conductivity increased over time.	Hydrus-1D	Pilot-scale; 14 mm	80% pozzolana and 20% organic matter	NSE; normal Root Mean Square Deviation	2018
The influence of substrate and vegetation configuration on green roof hydrological performance	Vegetated beds presented higher capacity of water retention compared with unvegetated beds.	Conceptual mode	Pilot-scale; 3 m × 1 m (8 cm); a slope of 1.5◦			2015
Runoff reduction from extensive green roofs having different substrate depth and plant cover	Curve number was influenced by both substate depth and plant type.	CN	Pilot-scale; 110 cm x 210 cm (8cm/16cm)	Pumice, attapulgite clay, zeolite and grape marc compost with proportions of 65:15:5:15.	RMSE; determination coefficient	2017
Stormwater management of biochar-amended green roofs: peak flow and hydraulic parameters	Biochar can improve saturated water content but decrease the saturated hydraulic properties.	Hydrus-1D	Pilot-scale; 30 cm in diameter (15cm)	Four substrate types were included.		2020

using combined experimental and numerical investigation						
An experimental and numerical investigation of the mechanism of improving the rainwater retention of green roofs with layered soil	Multi-layered soils can improve GR hydrological performance–an upper layer of higher permeability and a lower layer of lower permeability.	Hydrus-1D	Pilot-scale; 300 mm × 300 mm (10 cm)	Substrate1: rural soil, peat, and river sand with a volume ratio of 1:1:1, substrate S2 with rural soil and peat of 4:1	RMSE	2022