Journal of Hydrology (2008) **358**, 288–293

available at www.sciencedirect.com

ScienceDirect

journal homepage: www.elsevier.com/locate/jhydrol

Modeling stormwater runoff from green roofs with HYDRUS-1D

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Received 20 January 2008; received in revised form 28 May 2008; accepted 9 June 2008

KEYWORDS
Green roof;
Best management practice;
Design storm;
Stormwater;
Runoff;
Hydrograph

Summary A study was conducted on the effectiveness of green roofs to mitigate stormwater using computer simulation. In this study, the stormwater performance was simulated for a modular block green roof using a packaged soil moisture simulation, HYDRUS-1D, with simulation results verified by study site data. Simulations were run using HYDRUS-1D for 24-h design storms to determine peak flow, retention and detention time for runoff. Storm data collected as part of a green roof study in Athens, Georgia, USA were used to validate HYDRUS-simulated runoff. The study site consisted of a 37 m^2 (400 ft^2) modular block green roof containing engineered soil and vegetation including several *Sedum* species. The study revealed that rainfall depth per storm strongly influences the performance of green roofs for stormwater mitigation, providing complete retention of small storms (<2.54 cm) and detention for larger storms, assuming the measured average moisture content (~10%) as the antecedent condition.

Introduction

Stormwater in the US is an issue of major concern. As urbanization increases the imperviousness of watersheds, the stormwater volume reaching municipal storm sewers, and eventually streams, has increased dramatically. More runoff strains stormwater systems that must operate beyond design capacity. Stormwater also threatens the health of water resources by carrying pollutants from roads, parking lots, and rooftops to local waterways. Traditionally,

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doi:10.1016/j.jhydrol.2008.06.010

Nomenclature

CR	capillary rise (mm)	RO	surface runoff (mm)
DP	deep percolation (mm)	R_a	extraterrestrial radiation (mm)
ET	evapotranspiration (mm)	T_{ave}	average temperature (°C)
ET_O	potential evapotranspiration (mm)	T_{min}	minimum temperature (°C)
I	irrigation (mm)	T_{max}	maximum temperature (°C)
P	precipitation (mm)	ΔSF	change in subsurface flow (mm)
RR	roof runoff (mm)	ΔSW	change in soil water content (mm)

high-energy stormwater flow has been diverted to storm sewers and stream channels as quickly as possible leading to flash flooding and degradation of aquatic systems' geomorphology via stream channelization and bank erosion (Booth and Jackson, 1997; Carter and Rasmussen, 2005; Paul and Meyer, 2001). Such streambed alterations often make the physical environment less suitable for native stream flora and fauna (Booth and Jackson, 1997). As urbanization encroaches upon more aquatic systems, the need to mitigate runoff is increasing.

Although many varieties of stormwater best management practices, or BMPs, have been suggested and implemented in order to reduce the ill effects of runoff, green roofing may be of particular use in ultra-urban areas where land area is unavailable for other BMP such as retention ponds, grassed swales, constructed wetlands, and where defined infrastructure makes it difficult to construct underground BMPs such as inline storage devices. Green roofs mitigate runoff as growth media and plant roots absorb precipitation, and in effect, provide rainfall retention. A study by Jarrett et al. (2006) modeled green roof runoff using the last 28 years of rainfall data, and showed that an extensive green roof would retain 45—55% of annual rainfall volume. However, several studies (Carter and Rasmussen, 2005; Moran et al., 2005; Teemusk and Mander, 2007) show that retention depends strongly on the quantity of rainfall per storm event. Carter and Rasmussen (2005) observed that for an extensive green roof site, retention decreases from 90% for a 1.3 cm (0.5 in.) storm to 39% for a 5.4 cm (2.12 in.) storm. Teemusk and Mander (2007) observed 85.7% retention for a 0.21 cm storm while for larger storms, green roofs provide little retention. Both studies observed that once a green roof's field capacity is reached during a rain event, all rainfall exits as outflow from the green roof soil column, and the hydrograph subsequently mimics that of an impervious roof. For rainfall events producing rain at depths greater than the retention capacity of soil, green roofs provide detention in which rainfall is absorbed temporarily and released slowly thereby avoiding the storm surge normally associated with impervious rooftops during rainfall events.

Many factors affect the ability of green roofs to mitigate urban runoff including evaporation and transpiration potential, antecedent moisture conditions, rainfall intensity, and soil hydraulic properties. In order to model green roof performance prior to installation, estimates for these parameters are essential. Extensive green roof systems are designed to optimize the parameters affecting runoff through the use engineered soil material. When choosing green roof soil media, designers must balance factors such as water holding capacity, weight, and hydraulic conductivity, while still providing the required nutrients and moisture to harbor the hardy, drought tolerant plants (usually sedums) that also aid in abstracting and holding moisture. However, myriad variations in green roof systems are available to consumers.

For the engineered soil media in this particular study, no published studies have evaluated the hydraulic properties. The growth media consisted of an engineered soil mix containing 80% expanded slate and 20% organic matter (worm castings). Hilten (2005) assessed the hydraulic properties including wilting point and field capacity moisture content for the growth media used in the green roof system outlined in the current study, and parameters found in that study will be used here. While stormwater runoff is easily measured onsite using rain gauges or cisterns, models are needed to predict runoff from alternate sites using estimates for rainfall, soil moisture, and evapotranspiration in addition to soil hydraulic properties.

The main objective of the study was to evaluate the stormwater performance of a modular block green roof system for individual storms. To achieve this end, a runoff model using HYDRUS-1D (Šimůnek et al., 2005), a soil moisture transport simulation, was developed. The model was devised to predict green roof performance based on input variables measured at the study site. The model was then utilized to simulate runoff for individual storms with rainfall intensity inputs based on Soil Conservation Service (SCS, 1992) design storms.

Methods

Field study site and measurements

The study site consisted of one hundred square aluminum green roof blocks[3] with each block having dimensions, $60 \times 60 \times 10$ cm. The total area for the green roof system was 37 m^2. The blocks were laid on a zero-slope built-up roof above a utility room on the University of Georgia's campus. The 37 m^2 area was roughly U-shaped with x-dimension of 12.3 m and y-dimension of 4.9 m. The individual blocks have three 1.0 cm diameter drains along each side approximately 1.0 cm above the base of the block. Each block was filled with engineered soil (80% expanded slate, 20% organic matter) to a depth of approximately 10 cm. Ten soil core samples were taken in random locations over

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[3] The green roof system was donated to the University of Georgia by Green Roof Blocks, a subsidiary of St. Louis Metalwork's Company.

the green roof surface to determine soil bulk density on a dry basis. Density was found to be 0.865 g/cm^3. Each green roof block was vegetated with one of five species of sedum, a low-lying succulent stonecrop that use crassulacean acid metabolism (CAM) to limit plant water loss. Sedum species used included, *spp. reflexum*, *sexangulare*, *immegrauch*, *spurium*, and *album*.

In situ measurements were collected from January to August of 2005. Automated dataloggers collected micro-meteorological parameters including relative humidity (15 and 110 cm above surface), air temperature (15 and 110 cm), windspeed (120 cm), and radiation (net, solar, and photosynthetically-active), and soil parameters including soil temperature (0.0, 4.5, and 9 cm below surface), volumetric moisture content by time domain reflectometry (TDR), and heat flux.

Runoff volume was collected at an adjacent site where identical modular green roof blocks were mounted atop bins fitted with pressure transducers that sampled water depth every two minutes starting at the onset of a storm event using an automated datalogger (Campbell Scientific model CR23X micrologger) (Prowell, 2006).

Soil hydraulic properties

In Hilten (2005), the engineered green roof soil was analyzed during a laboratory experiment to evaluate the hydraulic characteristic for the soil using pressurized Tempe cells. The method determines volumetric moisture content of a soil versus pressure head. Applied pressures at 0.033 and 1.5 MPa correspond to the soil's field capacity and wilting point moisture content, respectively, which are input parameters required by HYDRUS. These were found to be 0.11 and 0.08 m^3 m^{-3} (volume of water per volume of soil), respectively, for the engineered green roof media. Residual moisture content was estimated at 0.03 m^3 m^{-3} Using these values for field capacity and wilting point, along with soil density and sand, silt, and clay fractions, HYDRUS could then be used to predict runoff for the soil.

Moisture fluxes and water balance in the green roof system

Generally, moisture enters or leaves the system from the soil surface, through plant stomata or through the green roof block drains. Once moisture leaves the green roof blocks' drains, it can be considered runoff, which must be contained and routed just as if no green roof installation were present. A goal of the study was to determine if runoff from the modular block green roof was significantly less than that from a conventional, impervious roof type. For the impervious roof, all rainfall was assumed to become runoff (1 cm rainfall = 1 cm of runoff).

For any soil, moisture fluxes occur by several means evident in the following soil water balance equation, which evaluates fluxes by depth equivalent (volume of moisture divided by flux surface area):

$$I - \mathrm{ET} + P - \mathrm{RO} - \mathrm{DP} + \mathrm{CR} \pm \Delta\mathrm{SF} \pm \Delta\mathrm{SW} = 0 \qquad (1)$$

where, *I* is irrigation, ET is evapotranspiration, *P* is precipitation, RO is surface runoff, DP is deep percolation, CR is capillary rise, ΔSF is change subsurface flow, and ΔSW is change is soil water content. Variables are measured in depth equivalent (millimeters or centimeters).

In utilizing the water balance equation (Eq. (1)) for a green roof system, several simplifications could be made to the formula due to the nature of the green roof system. First, no irrigation (*I*) was applied throughout the duration of the study due the hardy, drought tolerant vegetation. Soil moisture content never reached the calculated saturation moisture content during the study period (January–August, 2005) during which time rainfall was 44% higher than the 30-year normal rainfall (NCDC, 2000). Saturation was not observed most likely due to high hydraulic conductivity evident in engineered green roof soil. The lack of saturation indicated that surface runoff (RO) from Eq. (1) was nonexistent. Capillary rise (CR) was impossible as there is no accessible water table in the modular green roof containers, and subsurface flow (ΔSF) was considered zero (again due to soil column containment). Finally, deep percolation (DP) was considered to be the flow leaving the drains in the aluminum green roof blocks. Once the quantity DP exits the blocks' drains, it is conveyed in the conventional manner to roof drains and then to a municipal stormwater system. DP is hence referred to as roof runoff (RR). Accounting for this alteration and removing unused variables, the soil water balance simplifies to

$$\mathrm{ET} = P - \mathrm{RR} \pm \Delta\mathrm{SW} \qquad (2)$$

The variables, precipitation (*P*) and change in soil water content (ΔSW), were measured directly at the study site using automated sampling equipment. Roof runoff (RR), previously called deep percolation, was measured concurrently at an adjacent site in a parallel ongoing study (Prowell, 2006).

From this simple water balance, ET could easily be computed. Due to the difficulty measuring small changes soil water content, longer intervals (7+ days) are suggested to obtain accurate evapotranspiration values using Eq. (2) (Allen et al., 1998). For this study, the model will be validated based on measured runoff, while simulated evapotranspiration will be verified by water balance-derived ET over one full study month to reconcile the longer time period suggested for measuring changes in soil moisture content.

For modeling purposes, an estimate for potential evapotranspiration was also required. Although the HYDRUS authors' recommend using the Penman–Monteith combination equation (Penman, 1948; Monteith, 1965; Allen et al., 1998) for estimating potential evapotranspiration, ET$_\mathrm{O}$, a prior study at the same green roof site (Hilten, 2005) showed that ET$_\mathrm{O}$ calculated using the simpler Hargreaves and Samani (1985) method was not statistically different from water balance-derived ET. Thus, the simpler method outlined by Hargreaves' was used in order to obtain ET$_\mathrm{O}$ as an input variable for HYDRUS simulations. The grass reference surface assumed in both estimation methods can be described as

> ''A hypothetical reference crop with an assumed crop height of 0.12 m, a fixed surface resistance of 70 s m^{-1} and an albedo of 0.23''(Allen et al., 1998).

Hargreaves' method requires only a few weather parameter inputs, including average (T_{ave}), minimum (T_{min}), and maximum (T_{max}) temperature and extraterrestrial radiation (R_a) for ET calculations. The Hargreaves' equation follows:

$$\text{ET}_0 = 0.023^{\times} R_a (T_{\text{ave}} + 17.8)(T_{\text{max}} - T_{\text{min}})^{0.5} \tag{3}$$

Modeling with HYDRUS

The version of HYDRUS referred to in this paper is HYDRUS-1D, version 4.04 (Šimůnek et al., 2005). Using the Richards' equation for variably-saturated water and convection—dispersion type equations, HYDRUS-1D numerically solves heat and moisture transport for a given soil (Šimůnek et al., 2005). Using the combined heat and moisture transport program, HYDRUS, the study system was simulated based on measured or estimated parameters.

Input requirements for HYDRUS included surface moisture fluxes (evapotranspiration and rainfall) and soil properties including field capacity, wilting point, density, and sand, silt, and clay fractions. Field capacity, wilting point and density were measured and found to be 0.11, 0.08, and 865 kg m^{-3}, respectively. Green roof soil texture is difficult to describe based on sand, silt and clay percentages. Here, the texture was chosen to be 100% sand. Though 100% sand texture consistently provides model closure, a better way to describe soil texture is needed for future analyses. The hydraulic model used by HYDRUS follows the hydraulic functions of van Genuchten (1980). HYDRUS uses a neural network prediction (Rosetta Lite version 1.1, (Schaap et al., 2001)) function based on pedotransfer functions (PTF's) to estimate other parameters required by van Genuchten's hydraulic model including residual and saturated moisture content and hydraulic conductivity.

In order to test the accuracy of the simulation, runs were performed and runoff values obtained were compared to actual runoff measured *in situ*. Using Microsoft Excel, analysis of variance, ANOVA, statistical methods were used to determine if simulated runoff values differed significantly from observed runoff. Results of validation are presented below.

Design storm runoff simulation

Upon verifying the accuracy of the HYDRUS model, simulations were run using synthesized transient rainfall hyetographs based on SCS (1992) 24-h design storms for the study site located in Athens, Georgia, USA. The SCS designates 24-h storm hourly fractions from which hourly rainfall for any storm event can be determined. The rainfall intensity exhibited in Athens is best simulated using an SCS Type II storm distribution, though simulations could be run for any location based on SCS storm distributions. For the study, storms with rainfall depths at 1.27, 2.54, 3.81, 5.08, and 7.9 cm were simulated using HYDRUS. Storms were simulated as independent events. Water content at the outset of each individually simulated storm was assumed to be 0.1, the average soil moisture measured at the study site at the outset of storms during the study period. In 2005 at the Athens, GA study site, the average storm event was 1.0 cm while the maximum was 9.4 cm with 106 events occurring including events with trace amounts of rainfall. The simulated depths were chosen to represent the normal range of rainfall depths encountered at the study site. The simulated storm at depth, 7.9 cm, represents the value for a 1-year return interval storm for Athens.

Results and discussion

Evapotranspiration at the study site

In order to verify the accuracy of the HYDRUS model, an estimate for potential evapotranspiration, ET_O, was required. For the study, the Hargreaves' method for predicting reference crop (potential) evapotranspiration, ET_O, was used with required meteorological data collected from the green roof study site. Though the Penman—Monteith equation is recommended, Hilten (2005) showed that when comparing ET calculated monthly for each method, ANOVA revealed no significant difference ($p > 0.05$) between the two methods at significance level, $\alpha = 0.05$.

After inputting potential evapotranspiration estimates, rainfall, and soil hydraulic properties, HYDRUS was used to simulate both runoff and actual evapotranspiration for the study site during June 2005. Runoff measured on site was used to verify the accuracy of the HYDRUS-derived runoff (Fig. 1). It is obvious from Fig. 1 that observed and simulated runoff values are related due to the high R^2 (0.92). Further statistical analysis by ANOVA reveals that simulated and observed values are not statistically different at significance level, $\alpha = 0.01$. However, when observing the plot of residuals shown in Fig. 2, it is evident that as runoff rates increases, the residuals from observed minus simulated values increase, as well. This observation would seem to indicate that the HYDRUS model tends to over-predict runoff. This over-prediction is not significant however as analyzed by a z-test, which shows that the mean from the residuals is not significantly different than zero at $\alpha = 0.01$. In addition, if the clear outlier is removed at (x, y) $(4.5, -1.9)$, the relationship changes to a positive slope with an $R^2 = 0.032$ indicating that the residuals show no relationship with runoff rate. However, visually, there is an indication, though statistically insignificant, that HYDRUS tends to overpredict runoff. This is assumed to be due to the difficulty in describing the texture of green roof soils. For future

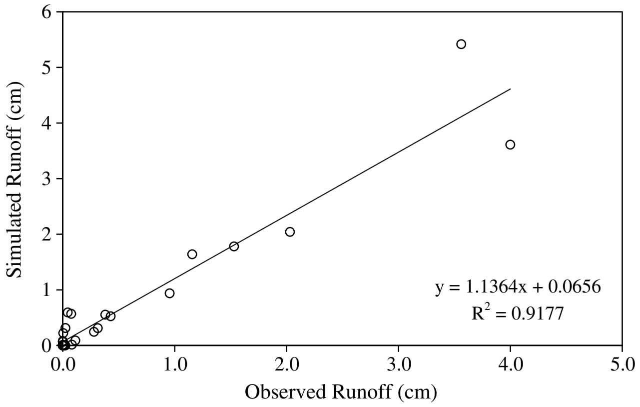

Figure 1 Hydrus-simulated versus observed runoff rate (cm/day) for June, 2005 in Athens, GA.

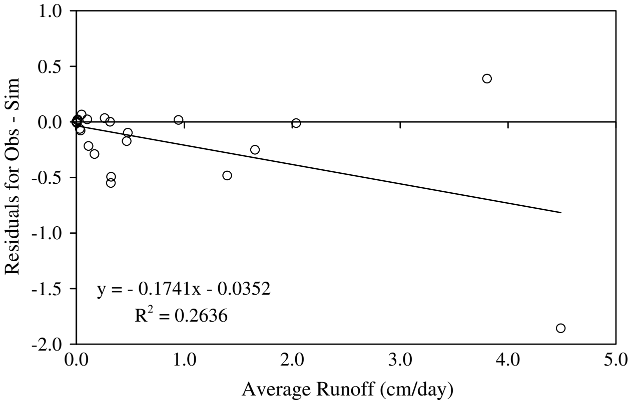

Figure 2 Residuals for observed minus simulated runoff versus the average of observed and simulated.

analyses, a greater number of larger rain events will need to be observed to validate the HYDRUS model's performance for larger storms. During the study period, there were simply not enough large storms (>5 cm) to validate simulated results.

Design storm simulation results

Once simulated runoff values for the study site were verified using site-measured values (Figs. 1 and 2), SCS design storms were simulated for rainfall depths at 1.27, 2.54, 3.81, 5.08, and 7.90 cm, and runoff was modeled using HYDRUS. Fig. 3 shows the hydrographs produced from HYDRUS output and from SCS-synthesized storms. Runoff is represented by the solid (cumulative) and the thick grey (rate) line, and rainfall is shown by the light-dashed (cumulative) and the dark-dashed (rate) line. Results from the 1.27 cm storms are not shown in Fig. 3 since no runoff was produced (100% retention). Rainfall rates and cumulative amounts shown in Fig. 3 are assumed to be equivalent to the rate and cumulative amount of runoff for an impervious roof. For both rate and cumulative amount for all SCS design storms, greenroofs exhibit some level of reduction. The reduction is mainly due to the fact that the green roof blocks are designed with drain holes 1.0 cm above the base creating a reservoir capable of holding 1.0 cm of moisture. Once the reservoir fills with percolating moisture, runoff commences. This fact is evident in each hydrograph as a spike in runoff intensity (thick, grey line) and the initiation of the cumulative runoff curve (solid line).

Table 1 gives peak flow reduction and retention (both in percent) and detention time for each rainfall depth. Retention is calculated as the difference between total rainfall and total runoff. Detention time was calculated as the time required for runoff to effectively end (<0.0001 cm h^{-1}) after the rainfall ceases. As evident from Table 1, the performance of green roofs decreases with increasing rainfall amount. Above some rainfall threshold lying between 3.81 cm (1.5 in.) and 5.08 cm (2 in.), the modular block green roof's hydrograph essentially mimics that of the impervious roof (equated to the rainfall intensity curve). However for overwhelming majority of storms at the study site location, the rainfall depths fall below this threshold. In addition, green roofs exhibit detention for storms of all rainfall amounts as shown in Table 1 by approximately 12-h detention times compared to detention times for an

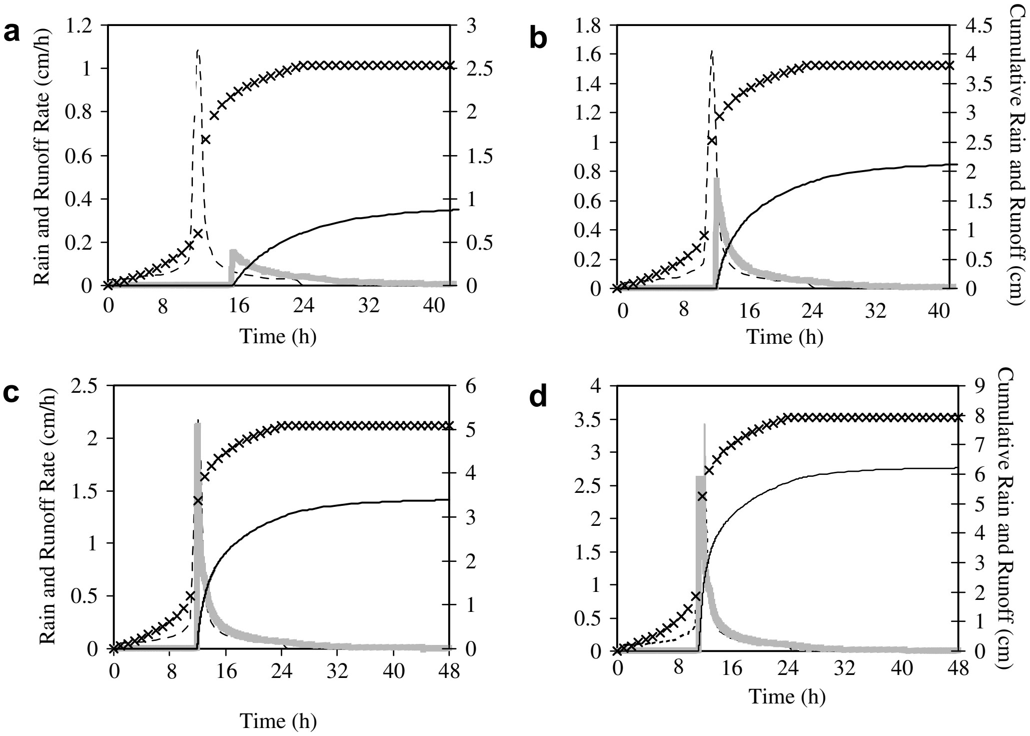

Figure 3 Simulated hydrographs including cumulative runoff (solid line), cumulative rainfall (x-symbols), instantaneous runoff (thick shaded line), and instantaneous rainfall (thin dashed line) for rainfall amounts of (a) 2.54 cm, (b) 3.81 cm, (c) 5.08 cm, and (d) 7.93 cm.

Table 1 Peak flow reduction, retention, and detention time for a green roof BMP compared to an impervious roof

Rainfall amount (cm)	Peak flow reduction (%)	Rainfall retention (%)	Detention time (h)
1.27	100	100	
2.54	86.1	65.6	11
3.81	54.7	44.0	12
5.08	2.82	33.3	13
7.93	0.40	21.6	14

impervious roof (assumed to be zero). Thus for a large majority of storms, the modular block green roof observed in this study will perform well by providing complete retention of rainfall, and provide detention for storms at rainfall quantities up to 7.9 cm.

Conclusions

As stormwater concerns in urban settings have become ubiquitous, green roofs have been introduced as an effective stormwater BMP for reducing runoff from roof surfaces in highly urbanized areas. The adverse impacts of stormwater surge have been widely studied and are undeniable, so finding methods to lessen storm surge is an imperative. In this study, the stormwater performance of a modular block green roof was assessed using a packaged soil moisture simulation, HYDRUS-1D, with simulation results verified by study site data. HYDRUS accurately predicts runoff especially for small rain events. At larger rainfall quantities, HYDRUS appears to over-predict. However, additional large storms need to be observed at the study site to verify the over-prediction.

Simulation results for runoff in terms of peak flow reduction, retention, and detention time were evaluated for the green roof. It was shown that a modular block green roof with growth media depth at 10 cm provides complete retention for storms up to 2.0 cm in depth, while providing detention for storms as large as 7.93 cm when assuming an initial soil moisture content of 0.1. Detention time for storms between 5 and 7.93 cm were approximately 12 h.

Concerning the effectiveness of green roofs to reduce stormwater runoff, simulations showed that green roofs are highly effective for small storms. For larger storms (>2.54 mm), green roofs can act to extend runoff duration thereby reducing surge normally evident with impervious surfaces. The model proposed could easily be adjusted to use SCS design storms for any location by simply changing the storm type to determine how well a green roof sited in another location would perform for individual design storms. Alternately, weather data from any location can be input to the model proposed to determine runoff for any depth modular block green roof using a similar soil media type.

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