Insights into green roof modeling using SWMM LID controls for detention-based designs

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Abstract

Rainfall–runoff responses were observed in a laboratory environment using a rainfall simulator and a 7.43 m\textsuperscript{2} green roof cassette equipped with weighing lysimeters. SWMM LID controls were developed for various green roof profile configurations based on the physical properties of the composite materials. Unknown parameters affecting the drainage layer were adjusted in calibration. The cassette was modeled both as a typical Green Roof LID control using Manning’s equation at the drainage layer and a Bioretention LID control using an orifice equation in the drainage layer. Key parameters from a sensitivity analysis that were not directly measured were Manning’s roughness of the drainage layer, the drainage coefficient at the orifice, and the conductivity slope (HCO). The hydraulics of roof drains were considered by varying the width of the drain outlet from 0.25 m–1.22 m. During calibration and validation of multiple events, SWMM modeling resulted in a good fit compared to observed results (Nash–Sutcliffe model efficiency coefficient values of 0.70–0.89). Key limitations of SWMM green roof modeling are discussed with suggested improvements for future consideration.

1 Introduction

1.1 Background

Urbanization and intensifying municipal stormwater regulations have led to green roofs being used for onsite stormwater management, promoting safer waterways through pollution and flood control. In traditional designs, most hydrologic benefits are realized as retention in the green roof’s component profile. Cipolla et al. (2016) summarized 19 studies that monitored this retention performance and showed performance could range between 11% and 74%, varying by location, depth of substrate, monitoring period and roof area. Relying on retention alone can be troublesome, however, given variable performance due to antecedent conditions and rainfall patterns. By incorporating detention-based practices, green roofs can better manage peak flows in the most critical events (Shafique et al. 2016; Pelorosso et al. 2021; NYC DEP 2013). Rooftop stormwater detention has historically not been encouraged due to concerns for reliable drainage and rooftop integrity. However, more modern designs are now incorporating various detention methods to improve the performance and help meet permitting requirements. The most popular type of these detention-based green roofs is colloquially termed a blue-green roof. Many variations exist, but blue-green roofs generally consist of vegetation within green roof media on top of a storage layer with flow rates controlled by an orifice.

1.2 The purple roof concept to provide stormwater detention

A variation of the blue-green approach is the purple roof concept (Figure 1) which adds a restrictive fabric mat at the base of the storage layer comprised of densely spaced polyester threads (a friction layer). Additional storage can be achieved using a honeycomb shaped array of vertically oriented tubes. These two components provide resistance to drainage throughout the entirety of the profile as opposed to other blue-green roof designs that are constrained only at an orifice restriction. This article focuses primarily on the purple roof concept; however, the discussions are applicable more broadly to detention-based green roof design in general. A comparison of different green roof profiles is shown in Figure 2 (note that needled mineral wool is shown, exemplifying a common variation of having a highly absorbent layer between the media and the storage layer for additional retention).

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Figure 1  Typical layers of the purple roof concept are a vegetated sedum mat, engineered soil media, needled mineral wool, honeycomb storage reservoir and a polyester friction layer.

Figure 2  Four common green roof approaches.

1.3 Overview of hydraulic–hydrologic modeling goals

Being able to accurately determine the performance of detention-based green roof techniques is important both for their design and permitting. One way to accomplish this is with hydrologic–hydraulic modeling. One popular model is the USEPA Stormwater Management Model (SWMM), which allows for green roofs to be modeled as either standalone systems or as part of a comprehensive site stormwater management plan. By incorporating the physical characteristics of a green roof profile, performance can be quantified for both individual design storms and continuous simulations relative to baseline scenarios or other alternatives. Further, SWMM is widely recognized through the United States both academically and regulatorily as an acceptable methodology for design and permitting. Despite its prevalence however, a best practice for modeling detention-based green roof systems is unclear when reading the SWMM guidance manual. As such, this article seeks to provide a general review of SWMM green roof modeling theory to establish a baseline for discussion, outline the development and calibration of a detention-based Green Roof SWMM LID control using observed laboratory results, and give insights into the limitations and future improvements for SWMM green roof modeling.

1.4 Brief overview of green roof SWMM modeling

Stormwater runoff in SWMM is modeled as a nonlinear reservoir using subcatchments to designate perviousness, depression storage and other overland flow properties. Using time-series rainfall as an input, the subcatchments generate runoff which is routed to a hydraulic network of junctions and conduits. Modeling of green roofs and other forms of green infrastructure can be accomplished using the LID Control Editor which assumes a two-dimensional (2D) cross section of the green roof applied to either the entire subcatchment or a portion of it. In Figure 3, the Green Roof LID control cross section is shown. Rainfall enters the green roof profile and infiltrates down into the soil layer. Porosity, field capacity and wilting point dictate the retention capacity of the medium where it eventually percolates to the storage or drainage layer. Runoff from the drainage layer is modeled using Manning’s equation under the influence of the subcatchment hydraulic width (Figure 4). Evaporation is typically ignored during modeling of an individual storm but would be important for a continuous analysis of multiple storm events to account for moisture conditions antecedent to each event.

Figure 3  LID control cross section used in SWMM with physical processes shown (Rossman and Huber 2016).
In the SWMM Green Roof LID control, drainage is governed by Manning's equation:

$$Q_3 = \frac{1}{n} \sqrt{\frac{W}{A_{LID}}} \phi(d_j)^3$$  \hspace{1cm} (1)

where:
- $Q_3$ = drainage layer outflow,
- $n$ = drainage layer roughness,
- $S$ = slope of green roof,
- $W$ = total length along edge of the roof where runoff is collected,
- $A_{LID}$ = area of the LID control,
- $d_j$ = hydraulic head seen by drainage layer, and
- $\phi$ = drainage layer void fraction.

The subscript 3 denotes that flow is occurring in the third layer of the profile (the drainage layer).

As an alternative to the Green Roof LID control, green roofs can be modeled using the SWMM Bioretention LID control in which drainage is assumed to be from an outlet control (typically an orifice) and represented by the power function:

$$Q_3 = C_{so} A_{so} h_3^n$$ \hspace{1cm} (2)

where:
- $Q_3$ = underdrain outflow,
- $C_{so}$ = underdrain discharge coefficient,
- $A_{so}$ = area of the LID control,
- $h_3$ = hydraulic head seen by underdrain, and
- $n$ = underdrain discharge exponent.

If an orifice is assumed for drainage, then $n_{so} = 0.5$ and the following equation can be used to deduce $C_{so}$ based on a simple orifice equation, assuming SI units (Rossman and Huber 2016):

$$C_{so} = 504257 \frac{C_{office} A_{office}}{A_{LID}}$$ \hspace{1cm} (3)

where:
- $C_{office}$ = the traditional coefficient of discharge used in the orifice equation (typically written $C_o$), and
- $A_{office}$ = the cross-sectional area of the outlet (or orifice).

This equation allows the coefficient used in the LID control to be based on both the physical properties of the orifice and the area of the LID control. More detail and further explanation of the
2 Methods

2.1 Methods overview

In order to understand the accuracy and nuances associated with modeling detention-based green roofs in SWMM, models were developed, and results compared to laboratory observations. The rainfall–runoff responses of various types of green roof configurations were observed using the Green Roof Diagnostics (GRD) laboratory, generated using a rainfall simulator positioned above a 7.43 m² green roof cassette equipped with high precision weighing lysimeters to measure drainage, sheet flow and absorbed water (Figures 5–9).

![Figure 5](image1.png)

**Figure 5** View of the GRD rainfall simulator with green roof cassette. The external hydraulically controlled window is open for viewing purposes but is closed during test administration.

![Figure 6](image2.png)

**Figure 6** Elevation view of rain simulator.

An overhead array of irrigation spray heads dispenses water from the rain reservoir onto the cassette. Nozzles were chosen because they are readily available and demonstrated reliably consistent water distribution. The nozzles were designed to oscillate to create semi-random drop sizes and drop distribution, more similar to natural rainfall than misters or static nozzles. Runoff from the bottom of the cassette drains into a drainage reservoir and separately metered surface runoff is collected in a sheet flow reservoir. The rain reservoir, sheet flow reservoir, and drainage reservoir each rest on a dedicated industrial scale weighing lysimeter (WL in Figures 6 and 7) calibrated to 0.2 kg. The cassette rests on a pair of weighing lysimeters (WL) which work in tandem and which are also calibrated to 0.2 kg.

![Figure 7](image3.png)

**Figure 7** Exploded plan of rain simulator; the letters P (profile), D (drainage collection) and S (sheet flow collection) are the same as in Figure 6.

![Figure 8](image4.png)

**Figure 8** Section of typical cassette drain end.

The runoff from the bottom of the profile flows through the drainage layer into the drainage collection lysimeter. Runoff from the surface of the profile, if any, is conveyed via tubing to the sheet flow collection lysimeter.

![Figure 9](image5.png)

**Figure 9** Another view of the green roof cassette (unvegetated); note the multiple pairs of sheet flow tube connections, most of which are capped shut. This configuration allows for adjustment of the sheet flow invert elevation.
Monitoring green roof installations in rooftop environments presents numerous obstacles to high precision measurements such as moisture content, drainage rate and separate metering of drainage versus sheet flow. The GRD lab presents an opportunity to rapidly test and measure various rainfall patterns, antecedent moisture initial conditions, and green roof profiles in a highly controlled environment with high precision instrumentation. SWMM models and LID controls were developed and calibrated for the lab setup then validated against a number of conditions to better understand the simulation dynamics and model robustness.

2.2 Testing protocols

Layers for the purple roof concept in this analysis, shown above in Figure 1, were (from top to bottom):

1. Prevegetated sedum mat. Testing specimens used a prevegetated sedum mat grown by Sempergreen, USA with a nominal media thickness of 20 mm (Moerings 2021). All mats used in test specimens were Grade A (approximately 95% vegetative cover with lush, healthy plants).
2. Engineered soil media (full ASTM E2399 and ASTM F1632 measurements are available upon request).
3. Needleed mineral wool: Knauf Insulation Urbanscape D130 (Knauf Insulation 2018); all test specimens used either one or two layers of material with 25 mm thickness.
4. Storage reservoir: a rigid polypropylene product consisting of 10 mm diameter tubes, of varying sheet thicknesses (Green Roof Specialty Products 2021).
5. Friction layer: a polyester product comprised of 1800 vertical threads per square inch, manufactured for Green Roof Specialty Products (Green Roof Specialty Products 2021).

The friction layer rests directly on an impervious layer, such as the roof membrane or rigid insulation. All test specimens rest on the detention layer directly on the floor of a painted steel cassette.

We now present an outline of the key aspects of the GRD laboratory setup and core protocols.

GRD utilizes custom proprietary software, StormWatch, to facilitate data entry, data collection and data analysis. StormWatch saves all primary research data in a PostgreSQL database (Green Roof Diagnostics 2021). Each component is entered into StormWatch, including dry weight, saturated weight, and field capacity weight, using third party ASTM E2397-2399 test data whenever possible. Lightweight component weights are obtained via a Smart Weigh digital kitchen and postal scale with 1 g precision, and component samples >15 kg are weighed by a Cambridge Model 660 Floor Scale with 0.1 kg precision (Campbell Scientific Inc. 2021).

Each prototypical profile is assembled to full depth for a 1 ft² (0.09 m²) area and entered into StormWatch before building a full scale test specimen with that profile. Profiles are weighed before any simulated rainfall, in a saturated condition and at field capacity, using the following procedure:

1. Saturation: each cassette is flood-tested by blocking the drainage outlet and creating ponding on the profile surface with high intensity simulated rainfall. The cassette is then allowed to drain, denoting when ponding (<0.125 in., 3 mm) is no longer present. This is taken as the saturation point.
2. Field capacity: the cassette is drained from the saturation point. Field capacity is identified once drainage has substantially slowed (<0.5 kg/min) for at least 10 min.

Test specimens are built as a 48 in. × 236 in. (1219 mm × 6 m; width × length) cassette. Cassettes are constructed of 0.125 in. (3 mm) sheet steel with solid walls. Runoff occurs at one end of the cassette to simulate a maximum distance to drain of 6 m. Cassettes are weighed continuously via a pair of Weigh-Tronix DLS4848-10 floor scales, connected via a stainless steel junction box and calibrated to 0.2 kg precision (Avery Weigh-Tronix 2021).

During construction of each test specimen (cassette), each component layer is weighed individually to account for the actual mass of each material installed. Cassettes are constructed in an attempt to replicate standard construction tolerances, including commonly expected compaction, overlaps of layers and jointing of layers that require cutting.

During construction of each test specimen (cassette) and profile, all nonsoil materials are assumed to be dry (i.e. near absolute dryness). Nonsoil materials include manufactured drainage layers, mineral wool, fabrics, metals and plastics. Engineered soil media is known to contain some moisture, so the dry mass of soil materials is calculated as follows:

1. The dry unit weight of a given specimen (typically in dry lb/ft³ or kg/m³) is obtained from weighing an oven dried specimen, typically from a third party ASTM-certified laboratory, compacted according to ASTM E-2399.
2. The field unit weight is obtained for the soil at current moisture content by compacting the soil within a 1 ft³ (0.03 m³) box until reaching the point of refusal under 150 lb (68 kg) pressure.
3. The difference between field unit weight per unit and dry unit weight per unit is current moisture unit weight. Current moisture weight of soil materials causes all profiles and cassettes to be assembled at slightly higher than dry weight. The weight of the cassette at the time of assembly minus the current moisture weight of the cassette is assumed to be the dry weight of the cassette.
4. Current moisture level of pre-grown sedum mats is ascertained similarly except using 1 ft³ (0.09 m³) specimens rather than 1 ft³ (0.3 m³) specimens.

Following initial construction of each cassette, no significant mass of material is added to or subtracted from the cassette. (e.g. a few grams of nutrient may be added once annually, and weeds are occasionally removed from the cassette). Therefore, all changes in weight after initial construction are attributed to changes in water volume.

Drainage (runoff from the bottom of the profile) and sheet flow (runoff from the top of the profile) are separately metered via collection in stainless steel reservoirs, which are continuously weighed via Campbell Model 660 Floor Scales, calibrated to 0.2 kg precision (Cambridge Scale Works 2021).

Simulated rainfall is produced via an array of TeeJet QJ363C Nozzle Body (TeeJet Technologies 2021) and a variety of TeeJet spray nozzles mounted above the cassette. Operating pressure and temperature within the irrigation system are continuously monitored. The rain simulator can produce synthetic rain events ranging from 10 mm/h to >150 mm/h.

Simulated rain events are calibrated before being used in tests. During each test and during each calibration, actual rainfall delivered is measured to account for the increase in weight of the three areas that receive rainfall (the cassette, the drainage reservoir and sheet flow reservoir). Calibrated rain events are compared with actual simulated rain delivered during tests as a quality control measure. The rain simulator is capable of consistently delivering rainfall within 3% of the total volume of calibrated events.

Overhead spray nozzles oscillate to simulate natural atmospheric conditions, and spray nozzles overspray the sides of the cassette to minimize specimen-size bias (to minimize potential edge bias). Overspray (water dispensed by the irrigation system that does not land on the cassette), is separately measured during calibration and test runs. The rain simulator is capable of testing cassettes at slopes ranging from 0% to 2.5%. Slope adjustment is made after each calibration and test run.

A standard battery of tests performed on a cassette is ascertained similarly except using 1 ft³ (0.09 m³) specimens rather than 1 ft³ (0.3 m³) specimens. Calibration and test runs. The rain simulator is capable of consistently delivering rainfall within 3% of the total volume of calibrated events.

Within the laboratory specimen, the as-built thickness of these combined layers is 81 mm. This factors in compression of both layers, particularly in the mineral wool layer. A ~20%–25% compression factor was assumed based on research that recommends long term stable densities for moderately trafficked green roofs (Garner and Furbish 2015). The porosities and infiltration rates of the soil and mineral wool were determined using third party verification from Turf and Soil Diagnostics, LLC (Turf and Soil...
Diagnostics 2019) using ASTM E2397 (ASTM International 2019) and ASTM E2399 (ASTM International 2015). The porosity of the soil layer in the LID control is assumed to be a weighted average of the soil and mineral wool. The infiltration rate was taken to be that for the least permeable layer, the soil, 881 mm/h (not the mean of both combined rates). The thickness of the drainage layer was the depth of the incompressible 50 mm honeycomb plus the 5 mm fabric mat. Slopes of 0% and 2% were used in the lab configuration. Field capacity was determined by multiple lab observations of the soil moisture content at which runoff occurs. Unknown parameters such as vegetative volume, surface roughness, wilting point and suction head were estimated using the SWMM Reference Manual (Rossman and Huber 2016).

Wilting point in SWMM is the least amount of water that can exist in the layer, and soil moisture content cannot go below this value (typical values 0.05–0.1 according to the SWMM Reference Manual). To avoid having wilting point as a calibration parameter, a typical value was used. Manning’s roughness at the drainage layer and the drain coefficient were determined through model calibration. The drain exponent was assumed to be 0.5 to model the drainage as an orifice. Conductivity slope (HCO) was also determined through model calibration. HCO is an exponent that affects the percolation rate from the soil layer to the drainage layer. HCO is defined in the SWMM Reference Manual as a decay constant derived from moisture retention curve data that describes how conductivity decreases with decreasing moisture content. Typical values given in the SWMM Reference Manual are 30–55, although lower values have been reported (Saxton and Rawls 2006). HCO could also be determined for soil based on its percentage sand and clay but this method was not used due to the unknown variable of the mineral wool.

A full list of the modeling parameters and their values and sources is provided in Table 1 below.

### 2.4 Model calibration

After starting the profile at an unsaturated antecedent moisture condition, six consecutive rainfall patterns were applied to the profile with increasing intensity over a 5 h duration. This sequence of medium-intensity to high intensity rainfall was chosen to allow the profile to approach field capacity during the first events, then demonstrate a rainfall–runoff response along with detention performance during the later events. The rainfall–runoff response was observed and compared to modeled results by total volume, peak flow rate and the Nash–Sutcliffe model efficiency coefficient (NSE). Runoff was taken as the sum of drainage and sheet flow. To set the initial moisture in the model, additional rainfall was applied in the model before the actual rainfall. Initial moisture was determined based on the starting weight of the profile minus the known dry weight. Section 2.2 presented information regarding determination of initial moisture content. A sensitivity analysis on all the terms in the LID control was performed to demonstrate the importance of each variable on the analysis using the SRTC calibration tool in PC SWMM. Parameters were varied one at a time between a high of 2x the value a low of 0.5x the value.

### 2.5 Validation

After calibrating the parameters to the 50+50+50×10 profile in the GRD lab, a second 70+25+10×10 profile was modeled against observed data to validate the calibration. Only the physical parameters were altered in this validation, including the soil thickness, porosity, field capacity and drainage layer depth. The calibrated Manning’s roughness, drain coefficient and HCO were kept the same as the calibration. Two other tests from the 50+50+50×10 profile were also analyzed to further validate the model. Finally, a third profile, 70+50+50×10, was modeled against observed results, with the cassette set to 0% slope to demonstrate a limitation of Manning’s equation in the Green Roof LID control.

### 2.6 Modeling roof drain hydraulics using green roof width and bioretention discharge coefficients

To better understand ways of using the existing toolset of SWMM LID controls to model the hydraulics of roof drains, the outlet of the lab setup was altered by restricting the width of the drainage opening from 1.22 m to 0.61 m, 0.25 m and 0.05 m. In the Green Roof LID control, the width was adjusted in the LID Usage Editor using these values. In the Bioretention LID control, the varied orifice area was used to adjust $C_m$ in Equation 3 above. Rainfall–runoff responses were modeled using consecutive rainfall events and compared to observed results.

### 3 Results

The results of this analysis are discussed from four perspectives: calibrated model results as compared with observed green roof cassette data; sensitivity analysis of key modeling terms; assessment of model robustness through a number of validation events altering the green roof profile, antecedent conditions, applied rainfall and slope; and analysis of the effect of rooftop drain hydraulics comparing the Green Roof and Bioretention SWMM LID controls.

#### 3.1 Calibration results

Observed rainfall–runoff responses are compared to Green Roof and Bioretention SWMM LID controls noting the peak flow, total runoff volume and NSE (Figure 10). Both LID controls show a period of retention during the first two events, with runoff occurring at the third rainfall event. The Bioretention LID control overpredicts the first runoff event. Both LID controls overpredict total volume and peak flows during the large rainfall; however, NSE values were high (0.88 and 0.81) in both instances.
Table 1  SWMM modeling parameters for both Green Roof and Bioretention LID controls.

|                         | Value | Unit | Comment                                                                 |
|-------------------------|-------|------|-------------------------------------------------------------------------|
| **Purple roof LID control in SWMM (green roof)** |       |      |                                                                         |
| Surface                 |       |      |                                                                         |
| Berm height             | 5     | mm   | Height of lab cassette flashing.                                       |
| Vegetation volume       | 0.1   | fraction | From the SWMM Reference Manual (Rossman and Huber 2016); this is the volume of the surface layer occupied by vegetation. |
| Surface roughness (Manning's n) | 0.2 | | Between grass short and dense.                                         |
| Surface slope           | 2     | %    | Slope of green roof lab configuration.                                  |
| **Soil**                |       |      |                                                                         |
| Thickness               | 81    | mm   | Assumes soil plus sedum mat and mineral wool, factoring in compression. |
| Porosity                | 0.69  | fraction | From ASTM E2399 test.                                                   |
| Field capacity          | 0.35  | fraction | ASTEM E2399 for the media tested indicates a maximum retention of 53% per volume, but actual field capacity is typically observed as lower than the ASTM E2399 value. This 0.35 value was determined as the moisture capacity at which drainage substantially ceased after the profile was subjected to simulated or organic rain events (see point 3b in the lab protocol above). |
| Wilting point           | 0.05  | fraction | Assuming low from the SWMM Reference Manual (Rossman and Huber 2016). |
| Conductivity            | 881   | mm/h | Saturated conductivity from ASTM E2399.                                 |
| Conductivity slope      | 55    |       | Calibrated parameter.                                                  |
| Suction head            | 51    | mm   | Assuming low from the SWMM Reference Manual (Rossman and Huber 2016); this is used for unsaturated Green-Ampt which will not come into play due to high infiltration rates of soil. |
| **Drainage mat**        |       |      |                                                                         |
| Thickness               | 51    | mm   | Depth of honeycomb layer plus drainage layer.                          |
| Void fraction           | 0.98  |       | Assumed void space of honeycomb.                                       |
| Roughness (Manning's n) | 0.4   |       | Calibrated parameter made high to restrict flow through the detention layer. |
| **Purple roof LID control in SWMM (bioretention)** |       |      |                                                                         |
| Surface                 |       |      |                                                                         |
| Berm height             | 5     | mm   | Height of lab cassette flashing.                                       |
| Vegetation volume       | 0.1   | fraction | From the SWMM Reference Manual (Rossman and Huber 2016); this is the volume of the surface layer occupied by vegetation. |
| Surface roughness (Manning's n) | 0.2 | | Between grass short and dense.                                         |
| Surface slope           | 2     | %    | Slope of green roof lab configuration.                                  |
| **Soil**                |       |      |                                                                         |
| Thickness               | 81    | mm   | Assumes soil plus sedum mat and mineral wool, factoring in compression. |
| Porosity                | 0.69  | fraction | From ASTM E2399 test.                                                   |
| Field capacity          | 0.35  | fraction | ASTEM E2399 for the media tested indicates a maximum retention of 53% per volume, but actual field capacity is typically observed as lower than the ASTM E2399 value. This 0.35 value was determined as the moisture capacity at which drainage substantially ceased after the profile was subjected to simulated or organic rain events (see point 3b in the lab protocol above). |
| Wilting point           | 0.05  | fraction | Assuming low from the SWMM Reference Manual (Rossman and Huber 2016). |
| Conductivity            | 881   | mm/h | Saturated conductivity from ASTM E2399.                                 |
| Conductivity slope      | 20    |       | Calibrated parameter.                                                  |
| Suction head            | 51    | mm   | Assuming low from the SWMM Reference Manual (Rossman and Huber 2016); this is used for unsaturated Green-Ampt which will not come into play due to high infiltration rates of soil. |
| **Storage Layer**       |       |      |                                                                         |
| Thickness               | 51    | mm   | Depth of honeycomb layer.                                              |
| Void ratio (voids/solids)* | 0.98   | | Assumed void space of the honeycomb plus the drainage layer.            |
| Seepage rate            | 0     | mm/h | This assumes no water will seep into the roof.                         |
| Clogging factor         | 0     |       | This assumes that infiltration performance will remain constant overtime and will not be clogged by fine particles. |
| **Underdrain**          |       |      |                                                                         |
| Drain coefficient       | 8.4   | mm/h | The drain coefficient is determined through calibration and is a function of the area of the green roof and the size of the drain edge. This results in an orifice coefficient of 0.1 suggesting a highly restricted orifice. |
| Drain exponent          | 0.5   |       | This assumes that the drain edge is acting like an orifice.              |
| Drain offset height     | 0     | mm   | The drain edge is level to the roof with no offset.                    |
| Open level              | 0     | mm   | There is no variation in the drain based on height.                    |
| Closed level            | 0     | mm   | There is no variation in the drain based on height.                    |
| Control curve           |       |      | No control curve used.                                                 |

* Note that void ratio is not porosity, a potential point of confusion in modeling high porosity systems. This limitation was not sensitive to the model but worth noting for future modeling efforts. (OpenSWMM 2014; 2015).
3.2 Sensitivity analysis: total runoff and peak flow

The most significant differences between the parameters of the two LID control modules are in Manning’s roughness and hydraulic width within the Green Roof LID control module and the drain coefficient and drain exponent within the Bioretention LID control.

Figure 11 shows the results of the sensitivity analysis for peak and total runoff volume for both LID types were porosity and soil thickness, both directly measured physical properties. The hydraulic conductivity slope (HCO) was also a sensitive term and was used as a calibration parameter. Field capacity and soil conductivity are significantly more sensitive parameters within the Bioretention LID control than within the Green Roof LID control; both properties are directly measured. Wilting point is of moderate sensitivity within both LID controls and was taken from the \textit{SWMM Reference Manual} (Rossman and Huber 2016). For peak flow rates, the two most sensitive parameters were porosity and soil thickness. Hydraulic conductivity slope (HCO) was also sensitive for peak flow. Vegetative cover is also known to be a sensitive term in a full scale green roof model but could not be isolated using the lab dataset. This sensitivity analysis relates directly to the model calibration of the lab data and results could vary in a site scale due to the unique condition and design of each site.

Figure 10  Observed and modeled results for the calibrated Green Roof and Bioretention LID controls.

Nonsensitive parameters are listed below the chart but were considered. Negative values mean an increase in that term will result in a decrease in total runoff volume. Manning’s roughness, conductivity slope, wilting point, and the drain coefficient and exponent are the only parameters not physically measured. Note that roughness above pertains to roughness of the drainage layer.

3.3 Validation results

Validation events are shown in Figure 12. The single event tests (761 and 769) began with a nearly saturated profile to better understand detention performance, so little retention is observed.

Model results with multiple rain events can generally be evaluated using NSE (Hossain et al. 2019): Very good, >0.75; Good, 0.65–0.75; Satisfactory, 0.5–0.65; and Unsatisfactory, <0.5. The calibration and validation simulations were very good. In the calibration and validation events, peak flows and total volumes were similar with percent errors of 5%–31% for observed peak flows and 2%–24% for observed total volumes. This suggests that generalizations of the model to other profiles and geometries are possible.

When slope was set to 0%, the results presented in Figure 13 show that bioretention is able to model the observations with an NSE of 0.86. The Green Roof LID control shows much greater peak values resulting in a low NSE of 0.02 despite overpredicting the total volume by <10%. This is the result of a 0% slope in the LID control ignoring Manning’s equation with instantaneous runoff from the soil layer skipping the storage layer entirely.

Figure 11  Ranked parameters in order of sensitivity to peak and total runoff.

Figure 12  Comparison of continuous and single event simulations in SWMM of modeled (both Bioretention and Green Roof LID controls) and observed data for validation; peak flow, total volume and goodness of fit results are shown.
3.4 Effect of outlet width reduction on drainage hydraulics

Rainfall–runoff responses were modeled and compared to observed results for 1.22 m, 0.61 m and 0.25 m width drainage outlets for the 70+50+50×10 profile (Figure 14).

The 0.05 m width was not considered in the analysis, as the limited ability to drain resulted in an overflow of the system and water unaccounted for. The total volume of each sequence, peak flow rate and NSE values are reported (Figure 15). More total rainfall was applied to the larger width drainage outlets to achieve saturated conditions in a faster draining condition.

Based on the NSE values, the method used to determine roof drain hydraulics dynamics in the SWMM LID control was very good for the Bioretention LID control at 1.22 m and 0.61 m. The Green Roof LID control was good for 1.22 m and 0.61 m. Both were satisfactory for 0.25 m. Peak flow rates and total volume differences were greater in the roof drain hydraulics experiments from event to event; however, when taken as a complete sequence, the model to observed percentage error was 2%–17% for total volume (16%–39% for peak flow) for the Bioretention LID control and 3%–9% (7%–29% for peak flow) for the Green Roof LID control with more errors introduced at the smaller widths.
4 Discussion

The results of this study suggest that SWMM LID controls can model detention-based green roofs if proper best modeling practices are considered. These findings are similar to the findings of other academic research related to traditional green roofs. Peng and Stovin, (2017) monitored and modeled a 3 m² outdoor extensive green roof plot in Sheffield, United Kingdom using SWMM LID Controls and found that using an uncalibrated model (over a year’s worth of events) produced NSE >0.5 for all but two events but noted generally a relatively poor agreement that tended to underpredict peak flows. After calibration, however, the model significantly improved with event NSE reaching up to 0.95. Similarly, Palla and Gnecco (2015), in a 2.5 m² laboratory setup, demonstrated NSEs in the range 0.79-0.91 in 7 simulated rainfall events. On a larger scale, Caron (2014) demonstrated a modeled NSE of 0.91 for predicting runoff in 210 m² and 390 m² extensive green roofs in the Bronx, New York.

In this calibration, the three main non-physically based terms were HCO, Manning’s roughness and the drain coefficient. For HCO, calibrations showed a good fit for higher values in the Green Roof LID control and significantly lower values in the Bioretention LID control. However, due to the uncertainty in the multivariable calibration of the HCO and drainage variables (Manning’s roughness in the Green Roof LID control; drain exponent and drain coefficient in the Bioretention LID control), these calibrated HCO values should not be assumed to represent the actual physical processes. A better calibration would eliminate HCO uncertainty through more rigorous physical lab testing to focus primarily on the drainage properties. One approach is suggested in the SWMM reference manual, based on the research of Saxton and Rawls, that bases the term on the percent soil and percent clay of the layer (Rossman 2016; Saxton and Rawls 2006). It is currently unclear how to factor mineral wool in to this methodology.

A fundamental difference between the two methods (Green Roof and Bioretention LID control) is in the theoretical assumptions introduced. The Green Roof LID control assumes that Manning’s roughness is occurring ubiquitously throughout the profile while the Bioretention LID control assumes that resistance to flow is only occurring at the drainage outfall. In the case of the purple roof concept, resistance to flow is occurring ubiquitously as modeled via the Green Roof LID control. However, the Bioretention LID control provides favorable mechanisms to model roof drain hydraulics, as attempting to restrict flow via a width adjustment to Manning’s equation is constrained and may introduce potential error in very large events that would cause sheet flow to occur (due to the larger implied flow length of the surface). The Bioretention LID control is more advantageous in this regard, being less susceptible to error introduced in sheet flow and its ability to model hydraulic continuity between layers. There was no clear preferred method deduced in this analysis; rather, it demonstrated ways to use either, noting the limitations and theoretical downsides that could be introduced if misapplied to a model.

5 Conclusions

This analysis showed that the SWMM LID control methodology can be applied to detention-based green roof designs if appropriate precautions are taken to account for the limitations of SWMM in its current state. The following recommendations are encouraged when modeling, and we suggest that future releases of SWMM address these concerns more directly:

1. The Bioretention LID control is more appropriate for situations where the depth of water in the drainage layer exceeds the total depth of the drainage layer. The Green Roof LID control should adopt the same hydraulic head logic incorporated in Bioretention to avoid this potential issue.
2. It needs to be possible to directly model the hydraulics of roof drains as they are modeled in non-LID control SWM modeling (such as orifices and weirs).
3. Drainage coefficients and the associated methodology may be counterintuitive to many practicing civil engineers and require extra steps in model development. In the Green Roof LID control, relying on width in Manning’s equations as a surrogate for drain hydraulics is not an ideal workaround and will likely result in overpredicting overland flow during flooding conditions due to an implied larger flow length.
4. Bioretention LID controls are recommended for flat roof modeling because slopes set to 0 in SWMM result in runoff in Manning’s equation becoming instantaneous.
5. It is recommended that the initial moisture variable only affect the soil layer and not the drainage layer in order to properly model antecedent moisture conditions without unusual or counterintuitive workarounds.

In further modeling research, observations from a larger scale outdoor green roof are recommended. This would determine if:

- the LID control calibration is scalable;
- the rooftop hydraulic assumptions were accurate;
- performance is more variable when factoring seasonal effects;
- evapotranspiration plays a significant role compared to traditional green roof design;
- roof geometry and drain placement play a critical role in green roof detention behaviour; and
- vegetation growth and maturity exert a significant effect on the system parameters.

Declaration of competing interests

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