Influences of Four Extensive Green Roof Design Variables on Stormwater Hydrology

Jenny Hill[1]; Jennifer Drake, Ph.D., M.ASCE[2]; Brent Sleep, Ph.D., M.ASCE[3]; and Liat Margolis[4]

Abstract: This study assesses the relative influence of four independent variables on green roof hydrological performance under rainstorm conditions. Twenty-four extensive green roofs representing all combinations of the following four design factors were used: native meadow species versus *Sedum*; mineral-based versus biologically derived planting medium; 10-cm versus 15-cm depth; and irrigation provided daily, sensor controlled, or not at all. From events covering the period May–October in 2013 and 2014, mean values were determined for the seasonal volumetric runoff coefficient ($C_{vol} = 0.4$), peak runoff coefficient ($C_{peak} = 0.12$), and U.S. Natural Resources Conservation Service (NRCS) curve number (CN = 94). Irrigation had the largest overall impact: daily irrigation increased C_{vol} to 0.5 compared to 0.3 for systems with sensor-controlled or no irrigation. The biologically derived planting medium, composed of a high proportion of aged wood compost, made a significant improvement, maintaining C_{vol} of 0.3 compared to 0.4 for the mineral-based product in the modules without irrigation. A similar pattern was found in the NRCS curve numbers. **DOI: 10.1061/(ASCE)HE.1943-5584.0001534.**

Introduction

Research on the hydrology of green roofs has established that a combination of lightweight planting media and environmentally resilient vegetation on building roofs can improve the rainwater runoff characteristics from buildings compared to traditional non-permeable alternatives (Czemiel Berndtsson 2010; Lundholm et al. 2010; Nagase and Dunnett 2011; Van Seters et al. 2009). In urbanized environments in which there is limited space for decentralized stormwater control on the ground, green roofs can provide a valuable contribution to catchment hydrology (Carter and Jackson 2007). In many cities, the desire to increase building integrated vegetation for stormwater control may require many retrofit installations with limited loading capacities on existing buildings. Of the rooftop systems available, extensive green roofs are thinnest (up to 15 cm), usually the most lightweight, and the cheapest and are therefore most likely to be deployed in retrofit scenarios (Oberndorfer 2007).

Extensive green roofs are typically constructed from a number of layers, as shown in Fig. 1. From the rooftop up, the first hydraulically significant component is a drainage and retention layer, which reduces or eliminates pooling of water on the waterproof roof membrane and ensures that the root zone is not saturated for extended periods. A common format for the drainage and retention layer is a preformed rigid polymer sheet or board with regularly placed drainage holes such that depressions in the sheet form small reservoirs of water held away from the underlying roof. A geotextile is usually employed on top of the drainage board to keep the drainage board depressions free from excess particulate matter. Above that, the next substantial component is a lightweight engineered (usually soilless) porous planting medium. A large number of materials have been trialed and blended for planting media with varying degrees of success in terms of stormwater control or vegetation survival (Farrell et al. 2012; Fassman and Simcock 2012; Molineux et al. 2009; Ouldboukhitine et al. 2012; Steinfeld and Del Porto 2008).

The development of green roof planting media is influenced by the nursery industry, where soilless materials with high organic matter content are common. The German Landscape Research, Development, and Construction Society (FLL) advocates for a much lower proportion of organic material (<6.5%) in green roof planting mixtures (FLL 2008). This recommendation reflects concerns that organic matter can contribute to excess nutrient leaching (Berndtsson et al. 2006; Gregoire and Clausen 2011; Harper et al. 2015; Toland 2010), although the net impact of this on a mixed land-use watershed has not been assessed. Two distinct schools of thought about the role of organic matter in green roof media remain (Hill et al. 2016). Those in favor of following the FLL guidelines state that biologically derived materials will biodegrade and lose porosity, and they have reduced drainage and remain waterlogged to the detriment of the vegetation (Fassman and Simcock 2012; Rowe et al. 2006). Those who prefer to specify high-organic-matter planting media containing a higher proportion of compost or other biologically derived materials believe that these claims about reduced performance are unsupported and unjustified (Buist and Friedrich 2008). In a local study, no significant trends in the water-holding capacity or structural integrity of high-organic-matter planting media were observed in green roofs up to 18 years old (Hill et al. 2016).

The choice of vegetation has also received much attention because it is the most immediately visible and contributes cobenefits such as aesthetic appeal and habitat for biodiversity and urban ecosystem support. A significant body of green roof work has focused on the survival of plants, with fewer studies assessing the

[1]School of Civil Engineering, Univ. of Toronto, 35 St George St., Toronto, ON, Canada M5S 1A4 (corresponding author). ORCID: http://orcid.org/0000-0002-0346-8624. E-mail: j.hill@mail.utoronto.ca

[2]School of Civil Engineering, Univ. of Toronto, 35 St George St., Toronto, ON, Canada M5S 1A4. E-mail: jenn.drake@utoronto.ca

[3]School of Civil Engineering, Univ. of Toronto, 35 St George St., Toronto, ON, Canada M5S 1A4. E-mail: sleep@ecf.utoronto.ca

[4]John H. Daniels Faculty of Architecture, Landscape, and Design, Univ. of Toronto, 230 College St., Toronto, ON, Canada M5S 1A4. E-mail: liat.margolis@daniels.utoronto.ca

Note. This manuscript was submitted on April 1, 2016; approved on February 3, 2017; published online on April 19, 2017. Discussion period open until September 19, 2017; separate discussions must be submitted for individual papers. This paper is part of the ***Journal of Hydrologic Engineering***, © ASCE, ISSN 1084-0699.

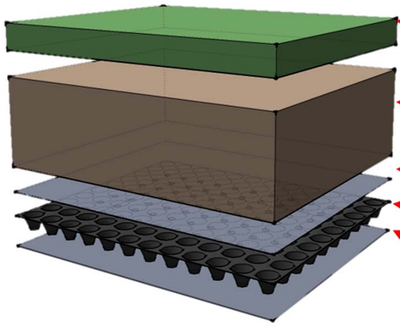

Fig. 1. Typical layering of a built-up extensive green roof system illustrating the drainage layer, geotextile, soilless planting medium, and vegetation layers

hydrological impacts. Some research finds that plants play an important role in hydrology (Berghage et al. 2007; Bousselot et al. 2011; Lundholm et al. 2010), whereas others have not discerned any significant impact (Nardini et al. 2012; VanWoert et al. 2005). Discrepancies exist among the findings of these various studies, owing to the confounding regional climates, microclimates, and species studied. The use of supplementary irrigation is common to support vegetation growth (Rowe et al. 2014) and to optimize evapotranspiration for urban heat island reduction (Van Mechelen et al. 2015), although its sustained use is not recommended (Breuning 2013).

To support the growing application of extensive green roofs as effective tools in stormwater management strategies, it is important to have accurate values for commonly used hydrologic parameters. In this study, aggregated volumetric runoff coefficients (C_{vol}) have been determined for both monthly and whole-season periods, and for individual event calculations, U.S. Natural Resources Conservation Service (NRCS) curve numbers (CNs) have been calculated. For peak flow calculations using the rational method, peak flow runoff coefficients (C_{peak}) were derived using paired peak flow and peak storm intensity data (Young et al. 2009). Many previous studies have reported observations and derivations of these hydrological characteristics for green roofs (Czemiel Berndtsson 2010); these parameters are presumed dependent on the climatic conditions under which they are measured (Fassman-Beck et al. 2015).

This study is designed to provide useful engineering information regarding extensive green roofs pertinent to a humid continental climate (Dfa/Dfb) region (Kottek et al. 2006). The analyses are constrained to the period encompassing May through October, during which all precipitation was received as rain. Within this context, the primary objective is to determine appropriate values for common coefficients and hydrologic parameters, including the volumetric runoff coefficient (C_{vol}), NRCS CN, and peak runoff coefficient (C_{peak}). This study also assesses the robustness of each of these parameters with changes in vegetation selection, planting medium type and depth, and irrigation, and determines the preferred design options to improve stormwater management.

Methods

The experimental site, the green roof innovation testing Laboratory (GRIT Lab) is located on the fifth-story roof of the historic John H. Daniels building, situated in the center of the downtown St. George campus of the University of Toronto. The lab has 24 individual green roof modules, each with a 2.86-m^2 drainage area (2.36 × 1.21 m) and each constructed with a 2% slope. The modules are suspended 0.8 m above the roof deck to accommodate instruments and maintenance requirements (Margolis 2013). This study assesses four design variables using a spatially randomized full factorial ($2^3 \times 3$) design: vegetation type, planting medium type, and media depth were considered at two levels, whereas irrigation provision was tested at three levels.

Table 1. Physical Data for GRIT Lab Planting Media according to Manufacturer's ASTM 2399 Reports (Data from Bioroof Systems 2011a, b)

Material property	Mineral	Biological
Dry density ($\mathrm{g/cm^3}$)	>0.8	0.58
Saturated density ($\mathrm{g/cm^3}$)	1.28	1.1
Maximum water holding capacity	45%	>60%
Saturated hydraulic conductivity (cm/s)	>0.02	>0.01
Organic matter (%)	<9%	>70%

Two types of vegetation were considered, a *Sedum* blend initially containing 23 cultivars preestablished onto mats, and a meadow mix of 19 species including grasses and forbs. Both the meadow seeding and the *Sedum* mats were installed in 2011. Further details regarding the plant communities and their growth performance in previous years have been published (MacIvor et al. 2013). The two types of planting media were selected as representative of the extremes in local commercial use: the first type is a mineral-based medium that comprises a large proportion of lightweight expanded aggregates and crushed brick and has low organic-matter content in concordance with FLL (2008) recommendations; the second type is a biologically derived medium containing a matured, screened, pine bark compost with <5% additional components. The manufacturer's specification for each product is presented in Table 1. Each of these two materials was tested at 10- and 15-cm construction depths.

Irrigation was provided to the modules via drip lines, with 300-mm spacing of the emitters. The daily modules received irrigation every morning, thereby allowing a high level of saturation to be maintained in the media throughout the months of application. The sensor-controlled modules each had a custom-adapted, fluid-filled tensiometer (TG, Irrometer, Riverside, California) installed at half height within the planting medium. These were set to open the irrigation valve for media moisture tension < -25 kPa; irrigation was only received by sensor modules if the valve was open because of dryness of the media. Both irrigation programs produced excess discharge water when applied. In 2013, the irrigation system was deployed between the first week of May and the last week of October, and in 2014, this was reduced to include the months of June and September only.

Precipitation was measured on site using a tipping bucket rain gauge (TE525M, Texas Electronics, Dallad, Texas), whereas parameters used for the automated calculation of reference evapotranspiration were measured using an adjacent weather station (Allen et al. 2005) consisting of a wind monitor (05103, RM Young, Traverse City, Michigan), pyranometer (CMP 11, Kipp & Zonen, Delft, The Netherlands), and relative humidity and temperature probe (HMP45C, Campbell Scientific, Edmonton, Alberta, Canada). Planting media moisture content was recorded (5TE, Decagon Devices, Pullman, Washington) after recalibration for the dielectric properties of each of the two planting media types (Hill et al. 2015). Discharged water from each module was measured using a rain gauge (TB6, Hydrological Services, Liverpool, New South Wales, Australia). These rain gauges were adapted to handle the higher flows experienced, using customized 3D printed funnels (Hill et al. 2015). The data logger controlling all of the sensors recorded at a five-minute resolution. On 12 occasions between August 2014 and August 2015, identical open vessels were placed adjacent to each green roof module, and single storm event rainfall depths were collected. These were used for spatial assessment of the rainfall distribution across the laboratory roof. Spatial autocorrelation of rainfall patterns across the GRIT Lab was assessed using Local Moran's I values generated using *GeoDa*. A storm was considered to be any rainfall event of ≥0.2 mm of rainfall preceded and followed by a minimum of 1 hour without measurable precipitation. The distribution of rainstorm depths (x, in mm) for each summer period were fitted to a single parameter exponential function using *Easyfit*:

$$f(x) = \zeta e^{(-\zeta x)} \quad (1)$$

Irrigation supply and resulting discharge were not included in water balance calculations. Instead, irrigation provision was included as a categorical variable with possible values of none, sensor controlled, or daily; therefore, the aggregated (monthly and seasonal) volumetric runoff coefficients (C_{vol}) were calculated as the sum the total discharge depth of the individual event discharge volumes (Q, in mm) as a proportion of the sum of the event total precipitation depth (P, in mm):

$$C_{\mathrm{vol}} = \frac{\sum Q}{\sum P} \quad (2)$$

To assess the event-based stormwater retention and theoretical storage capacity of the modules, NRCS CNs were generated for the months of May to October in 2013 and 2014. The benefit of using curve numbers in this research is that this allows aggregation of the precipitation and discharge volume of many storm events and reduces one dimension of the data to permit statistical comparisons between the multivariate designs. Calculations were performed on natural data, i.e., data for which the precipitation (P, in mm) and discharge depths (Q, in mm) were retained in event pairs (ASCE/EWRI Curve Number Hydrology Task Committee 2009). Observations of Q and P were fit to Eq. (3) using a least-squares method to solve for storage (S) bounded within limits ($1 \leq S \leq 100$):

$$Q = \frac{(P - 0.2S)^2}{(P + 0.8S)} \quad (3)$$

Storage values were transformed to curve numbers using the metric version of the NRCS curve number as follows:

$$\mathrm{CN} = \frac{25400}{(S + 254)} \quad (4)$$

Further analysis of individual events included an assessment of the relative impact of antecedent moisture conditions on the overall discharge volumes. The individual event volumetric coefficient was calculated for all modules and all rainstorm events. These values were then classified according to the antecedent volumetric water content (VWC) of the medium at event onset. The upper limit of the range considered was 0.35 v/v because of the porosity and free-draining characteristic of the mineral-based medium, whereas VWC > 0.55 v/v was recorded in some modules containing biological media. To enable comparisons, break points were set at 0.15 and 0.25, which created three classes of similar size within each medium type. The mean individual event volumetric coefficient per class per module was then calculated, and these numbers were further aggregated by grouping according to the independent variables.

Peak runoff coefficients (C_{peak}) for each event were determined by rearrangement of the Rational method equation because determination of peak flow remains the most common application of a runoff coefficient; peak flow rates (Q_p) were divided by the product of rainfall intensity (i) and catchment area (A) as follows:

$$C_{\mathrm{peak}} = \frac{Q_p}{iA} \quad (5)$$

Comparisons between group means of the independent variables were made using ANOVA statistics, using *NCSS*. In these cases, significance was ascribed at a 95% confidence interval (i.e., $p < 0.05$). Where multiple factors were implicated in observed variations, regression trees were generated using *Orange Data Mining*. The algorithm performs a stepwise regression, identifying the greatest significant separation of group means at each node. Termination of a branch occurs when no significant factor exists for the remaining data set.

Results and Discussion

Toronto is in southern Ontario, Canada, and enjoys a relatively temperate climate owing to the moderating effect of Lake Ontario to the south. During the study period, weather conditions were typical for the region (Environment Canada 2013), although 2013 was a wetter year than 2014. Monthly values for precipitation depth and reference evapotranspiration are presented in Fig. 2. There was one exception within the duration of the experiment: a storm exceeding the 100-year return period storm occurred on July 8, 2013 (Di Gironimo et al. 2013). This event delivered more than 80 mm in a few hours, overtopping the tipping bucket gauges so that neither the hydrograph characteristics nor the total volume discharged from the modules was recorded. From the beginning of May to the end of October 2013, data were collected from 96 individual storm events, with a total precipitation depth of 561 mm. In the following summer, observations were made on 80 storm events, with a total depth of 314 mm. The ζ parameter, which describes the exponential distribution of rainfall depths [Eq. (1)], was 0.19 in summer 2013 and 0.26 in summer 2014. This indicates not only that 2014 had less rainfall but that a greater proportion of the rainfall arrived in lower-volume events.

Spatial autocorrelation was performed on the manual rain depth data gathered after 12 rainfall events between August 2014 and August 2015. Moran's I test results can range between 1 and −1, where higher values indicate more clustered data and low or negative values indicate an even distribution of the parameter across space. The Moran's I data had a mean of 0.07 and a standard deviation of 0.11. This overall value, close to zero, indicates that the rainfall depth was randomly distributed across the experimental area and was not influenced by the roof shape or aspect.

The relative effects of the four design factors—irrigation, medium type, medium depth, and vegetation—on the volumetric runoff coefficient were analyzed using a stepwise regression, producing a regression tree (Fig. 3). At each level on the tree, the group mean value and number of contributing modules are presented. The technique then identifies the single factor that provides the greatest difference in group means and classifies the data accordingly. This continues through successive branches until no significant difference in the group means can be elucidated. Technical problems caused the data set to be reduced by one unique combination; because this was a full factorial experimental design, statistical elucidation of all factors remained valid (Walpole 2007). In 2013, a leaking irrigation line resulted in the exclusion of the module containing the 15-cm mineral-based medium with *Sedum* vegetation and daily irrigation. In 2014, the module containing the 15-cm biological medium with *Sedum* vegetation and daily irrigation produced little data, owing to the malfunction of the discharge tipping bucket.

Green roofs that received no or sensor-moderated irrigation each resulted in a group mean C_{vol} of 0.3 and so retained approximately

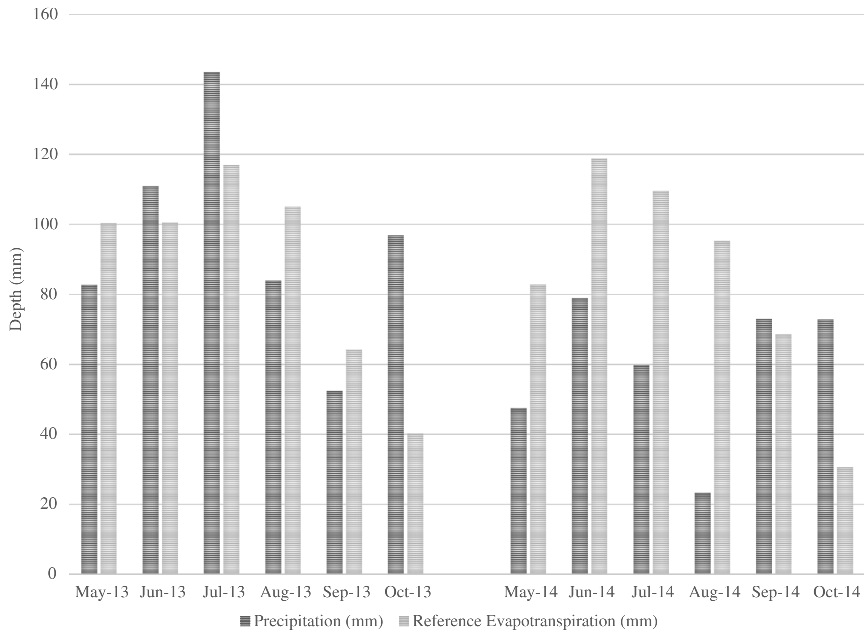

Fig. 2. Weather at the green roof innovations testing laboratory (GRIT Lab), Toronto, during the months of May–October in 2013 and 2014; these are the months within which precipitation falls as rain, resulting in a temporal connection between the storm event and water from the extensive green roof modules

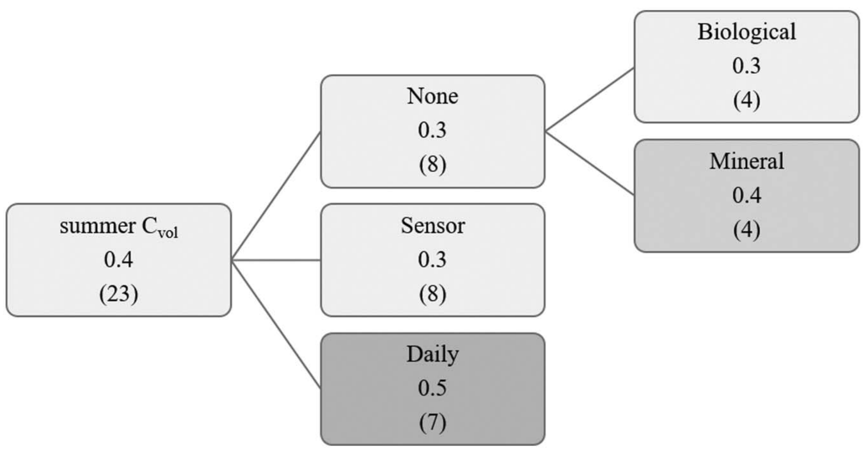

Fig. 3. Regression tree for the net runoff coefficients (C_{vol}) determined on experimental extensive green roof modules during the months of May–October in 2013 and 2014; the primary influence of irrigation programming is supported by the secondary importance of planting medium type only within the group of modules that received no irrigation

70% of the rainfall. This retention value is comparable to those from previous studies in similar climatic zones, both locally (Liu and Minor 2005; Van Seters et al. 2009) and further afield, including the United States, the United Kingdom, and New Zealand (Hathaway et al. 2008; Moran et al. 2004; Starry 2013; Uhl and Schiedt 2008; VanWoert et al. 2005; Voyde et al. 2010). However, green roof modules that received indiscriminate daily irrigation retained significantly less stormwater and achieved a group mean C_{vol} of 0.5, i.e., half of all the stormwater was discharged and only half was retained. Within the no-irrigation group, the type of planting medium made a significant difference: the biologically derived medium had a group mean C_{vol} of 0.3, and the mineral-based material had a C_{vol} of 0.4. This distinction was not statistically significant in the irrigated groups.

The overall relative insignificance of vegetation and medium depth is supported by findings from previous studies. Two studies assessing both depth and vegetation selection found no significance in either factor (Nardini et al. 2012; VanWoert et al. 2005), whereas others have also reported that increased depth alone makes no significant difference to net stormwater retention (Graceson et al. 2013; Kelly 2008); however, it has been reported that the vegetation makes a large difference in stormwater retention when studied in isolation (Berghage et al. 2009; Bousselot et al. 2011; Lundholm et al. 2010). With a holistic green roof design perspective, this provides some leeway for the depth of planting media to be influenced by loading capacity of the roof and plant selection to accommodate other design priorities such as aesthetics, biodiversity, and shading.

The total amount of water retained each month was calculated to identify any seasonal trends in the effects of each design variable. The group mean C_{vol} across the whole project showed some trends (Fig. 4), with higher values in the fall, when evapotranspiration rates are lower. The relative impact of the irrigation programs is

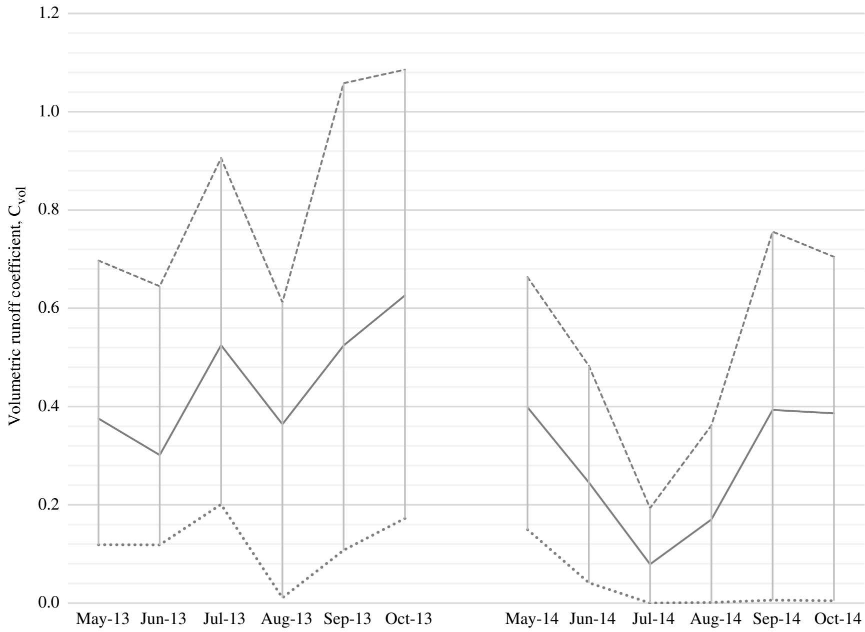

Fig. 4. Monthly mean, maximum, and minimum C_{vol} observed across all of the experimental extensive green roof modules for the months of May–October in 2013 and 2014

also evident in the monthly group mean C_{vol} data (Fig. 5). The impact of irrigation in September and October is attributed to excess saturation of the green roof media as evapotranspiration reduces. The observed difference among the irrigation programs is in keeping with the previous study by Schroll et al. (2011), which concluded that when irrigation is provided at controlled levels, it is detrimental only to the retention of the largest storm events. The biological planting medium retained more water and reduced

Fig. 5. Monthly group mean C_{vol} for the four design factors—irrigation, medium, depth, and planting—for the months of May–October in 2013 and 2014

C_{vol} compared to the mineral-based alternative in most months. Also, as shown in Fig. 5, there was no clear overall influence of planting medium depth on the total water discharged, and the influence of the vegetation palette on seasonal C_{vol} was indiscernible compared to the other design factors. It was notable that there are no seasonal trends in C_{vol} between the two types of vegetation. Through the spring time, the coverage and canopy structure of the meadow plants develops quickly and more dramatically than in the *Sedum* (MacIvor et al. 2013). The *Sedum* mix was expected to achieve much lower potential transpiration rates through the summer (Blanusa et al. 2013), which could manifest as higher discharge if the medium was not being dried so swiftly. A mechanism possibly countering higher transpiration rates is canopy capture in the *Sedum* modules. Two of the dominant species found in the *Sedum* mixture during the study period, *S. kamtschaticum* and *S. spurium* (MacIvor et al. 2013), have cuplike leaves and waxy cuticles, foliage characteristics ideal for intercepting rainfall, which would then be available for direct evaporation from the leaf surfaces.

NRCS CNs were calculated for all available modules (R^2 between 0.3 and 0.8) and were also subject to regression tree analysis to determine the most influential factor(s). After two summers, the overall mean curve number across all modules was 94 ($\sigma = 1.8$). This mean curve number is similar to the value of 92 recently calculated from data collected previously in Toronto (Van Seters et al. 2009) and within the 90–96 range determined for extensive green roofs in the Dfa/Dfb region (Fassman-Beck et al. 2015). The provision of daily irrigation had a significant impact on the curve number, resulting in a group mean CN of 96, compared to 93 in the sensor-controlled or zero-irrigation conditions. No other significant consistent influence of design was evident in the data.

Variations in antecedent VWC are accommodated through suggested calibration of the NRCS curve numbers used for modeling design storm events (Mishra 2003). Here, the relationship between individual event volumetric discharge and VWC was assessed using one-way ANOVA. Irrigation was excluded from this analysis because of its direct and causal relationship with the antecedent condition. The effect of increased VWC was significant in the group means across all other design factors, particularly with increased volume being discharged in the 0.25–0.35 v/v range. The most influential design variable was the choice of planting medium, for which the increase in discharge volume from moist mineral-based modules was much greater than in the biologically derived counterparts. The group means C_{vol} for the 0.25–0.35 v/v condition were 0.17 and 0.71 for the biological and mineral media, respectively. This is a highly significant fourfold improvement of the C_{vol} in biological medium compared to the mineral medium, when both are storing a similar amount of water. The additional porosity of the biological medium also permits a greater range of VWC; in Fig. 6, it is shown that the C_{vol} of the biological medium only reaches a similar value once it is similarly saturated (VWC $= 0.45$–0.55). This demonstrates that there is a detrimental effect in using a very free-draining, mineral-based planting medium when irrigation is also being used to continuously boost the VWC.

The highest intensity rainfall was recorded at 1.6 mm/min (8 mm within 5 min) in August 2013. Regression of the paired rainfall intensity and peak flow data over both summers was undertaken for each individual module; R^2 values were low (0.3–0.5) owing to the simplicity of this model and the wide variation of storm characteristics and antecedent conditions encompassed. The resultant mean peak runoff coefficient (C_{peak}) across all combinations was 0.12 ($\sigma = 0.02$). A similar value for C_{peak} (0.11) has been reported previously, after Carpenter and Kaluvakolanu (2011) made observations on 21 storms on an extensive green roof.

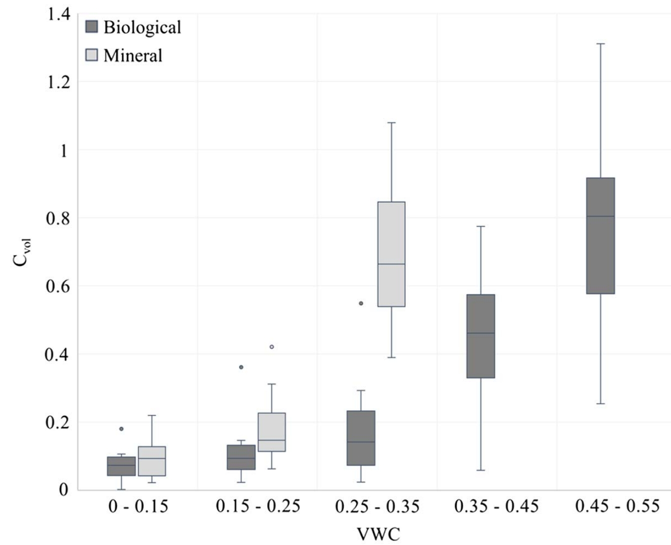

Fig. 6. Box plot of volumetric runoff coefficients over all rainfall events in the months of May–October in 2013 and 2014, grouped according to medium type and antecedent VWC over the range 0–0.55 v/v; the additional storage capacity of the biologically derived medium is evident through the relatively lower discharge resulting from modules with similar antecedent moisture to the mineral alternative

Regression tree analysis did not find any of the four design factors significantly influential on this parameter.

Conclusions

The coefficients determined would be suitable for use in modeling rainstorm responses of extensive green roofs in a Dfa/Dfb climatic region. A mean net summer seasonal rainfall retention of approximately 70%, alternatively described as a volumetric runoff coefficient of 0.3, is consistent with previous reports and reflects the recommendations of local policy (Toronto Water, and Water Infrastructure Management 2006). The relative impact of four simple, easily altered design variables was determined to inform hydrological performance directed design of extensive green roofs. The provision of daily timed irrigation was detrimental to net stormwater retention (down to just 50% seasonal retention), but the use of tensiometer control significantly reduced excess discharge down to that of a system without irrigation. Processing the precipitation and discharge data in event-based pairs yielded a similar pattern: the group mean NRCS curve number of 94 was reduced to 93 in both the sensor-controlled and no-irrigation groups, but raised to 96 for the daily timed irrigation systems. The sensor-controlled responsive irrigation is particularly well indicated when design teams are balancing priorities including the aesthetic and biodiversity benefits of reliable vegetation survival. The biologically derived planting medium, comprising mostly aged wood compost, made a supporting contribution, maintaining a lower C_{vol} compared to the mineral-based in the systems without irrigation. The biologically derived material particularly improved individual event retention in wetter antecedent conditions.

Compared to the irrigation program and type of planting medium, the depth of medium played relatively little role in any of the hydrological characteristics analyzed. Because the 50% variation in planting medium depth, between 10 and 15 cm, played no significant role in the measured performance of the roofs, this design variable remains a discussion point for vegetation planting depth requirements versus roof dead load capacity. The lack of vegetation influence on C_{vol} illustrates that transpiration rates are not the only important factor in the performance of this biotic component. It is suggested that the canopy capture potential of green roof vegetation warrants further investigation with respect to different foliage geometries and cuticle properties.

The peak runoff coefficient (0.12) was not sensitive to the four design variables tested. This indicates a robustness that makes this number suitable for use in modeling any extensive green roofs within the bounds explored here.

Acknowledgments

The authors would like to thank Matthew Perotto and Catherine Yoon for their management of the Green Roof Innovation Testing laboratory (GRIT Lab) at the Daniel's Faculty of Architecture, Landscape, and Design at the University of Toronto. The GRIT Lab benefits from the support of industrial sponsors Bioroof Systems, DH Water Management Services Inc., GroBark, IRC Group, Toro, and Tremco Roofing, and receives grant funding from the City of Toronto Environment Office, Ontario Centers of Excellence, RCI Foundation, the Connaught Fund, and the Landscape Architecture Canada Foundation. This hydrological study has been facilitated by an Industrial Postgraduate Scholarship from the Natural Sciences and Engineering Research Council of Canada (NSERC) and Flynn Canada Ltd.

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