Assessing the runoff retention of extensive green roofs using runoff coefficients and curve numbers and the impacts of substrate moisture

Wen Liu, Qi Feng, Weiping Chen and Wei Wei

ABSTRACT

In this study, rainfall-runoff data of four green roofs with varying structural configurations under dry and wet substrates were analyzed to acquire the effective estimation for Runoff Coefficient (C_v) and Curve Number (CN) parameters. Results showed that for the dry and wet substrates, averaged runoff retention of vegetated green roofs varied from 34.7 to 48.5% and from 14.7 to 30.6%, that for bare green roofs was 64.9 and 35.1%, respectively. For dry and wet substrates, mean C_v of vegetated green roofs was 0.58 and 0.75, respectively. For vegetated green roofs under the wet substrate, average CN values ranged from 96 to 98, meanwhile for dry substrate, average CN varied from 93 to 97. For bare green roof, average CN was 93 for dry substrate and 97 for wet substrate. Predicted runoff using the SCS-CN method exhibited a good linear fit with the observed runoff of green roofs. A significantly positive relationship was found between initial substrate moisture and runoff coefficient as well as CNs. The drier initial substrate moisture conditions corresponded to the lower runoff coefficient and curve numbers. These results would facilitate the proper use of estimated C_v and CN values of green roofs for urban stormwater management in a semi-arid region.

Key words | curve number, green roof, runoff coefficient, stormwater management, substrate moisture

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HIGHLIGHTS

- The bare substrate was able to retain more stormwater runoff than the vegetated green roofs.
- The mean runoff coefficient of green roofs was 0.58 and 0.75 for dry and wet substrate respectively.
- Averaged CN values ranged from 96 to 98 for wet substrate and from 93 to 97 for dry substrate.
- Predicted runoff depths using SCS-CN model showed a good linear fit with the observed runoffs.
- The drier initial substrate moisture corresponding to the lower runoff coefficient and CN values.

INTRODUCTION

The increase in impervious surfaces as a result of urbanization has resulted in significant hydrological effects (Choi & Deal 2008; Bell *et al.* 2016). The changes disrupt the urban hydrological cycle and increase the amount of stormwater runoff, leading to the risk of local flooding in cities (Pauleit *et al.* 2005; Zölch *et al.* 2017). Climate change is also causing an increase in rainfall intensity, exacerbating the frequency of urban flooding (Rosenberg *et al.* 2010; Hanak & Lund 2012). To counter this, a number of urban

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stormwater management strategies, such as green infrastructure and other low impact development practices, have been proposed and implemented in recent years (Carter & Jackson 2007; Roy & Shuster 2009). Green infrastructure employs principles such as preserving and recreating natural landscape features, and implementing some on-site facilities that work with nature to reduce the stormwater runoff from sources (Ahiablame et al. 2012; Benedict & McMahon 2012). However, land for green infrastructure construction is usually very limited in urban centers (Berndtsson 2010). As green roofs avoid this problem, they have been widely accepted as one of the best solutions to manage urban stormwater (Bianchini & Hewage 2012). Green roofs are normally classified as either extensive or intensive based on the substrate layer thickness. Extensive green roofs are typically 15 cm thick or less and feature short rooting, drought resistant plants (Carson et al. 2013). Generally, extensive green roofs are implemented more frequently because they are lighter, cheaper and require less maintenance than intensive systems (FLL 2002; Berndtsson 2010). The growth substrate and vegetation retains stormwater runoff and delays the peak flow, thus reducing the likelihood of local flooding (Lamera et al. 2014; Versini et al. 2015).

Many previous studies have investigated the ability of green roofs to retain and detain stormwater runoff. Mentens et al. (2006) reported that extensive green roofs showed runoff reduction was 27–81% of annual precipitation. The hydrologic performance of green roofs is affected by the climate, rainfall intensity, prior-rain substrate moisture and on the green roof characteristics, including the composition and depth of substrate, vegetation species and rooftop slope (Berndtsson 2010; Palla et al. 2012; Berardi et al. 2014). The substrate material and its depth contributed notably more to green roofs' stormwater retention than vegetation and slope factors (Liu et al. 2019). The physical properties of a substrate, particularly the maximum water holding capacity, govern its runoff retention performance (Miller 2003).

While research has investigated the effectiveness of green roofs in terms of runoff retention and peak flow reduction, these reported results are of limited practical value (Alfredo et al. 2009). In practice, stormwater drainage designers frequently need to calculate runoff volumes and peak flow rates to satisfy permitting applications. For many cities, the local rules suggest applying the less sophisticated methods such as the Rational Method and Curve Number (CN) (Soulis et al. 2009; Soulis & Valiantzas 2012) to estimate the runoff quantity for water resources planning and management (Soulis et al. 2017). Earlier research has therefore sought to establish empirical relationships for green roof runoff based on the CN or Runoff Coefficient (C_v) methods (Moran et al. 2005; Carter & Rasmussen 2006; Getter et al. 2007; Alfredo et al. 2009; Fassman-Beck et al. 2016). Soulis et al. (2017) obtained CN values of 30 extensive green roofs ranging from 88 to 95.5. Fassman-Beck et al. (2016) analyzed the rainfall and runoff volume of 21 green roofs and calculated the mean CN value as 84 for larger rainfall events. Alfredo et al. (2009) calibrated CN was 92 to laboratory-derived hydrographs using the Storm Water Management Model (SWMM). Carter & Jackson (2007) also used the SCS infiltration method to simulate green roof with a CN value of 86. Getter et al. (2007) derived CN values for studied green roofs were 84, 87, 89, and 90 for 2, 7, 15, and 25% slope gradient, respectively. Moran et al. (2005) calculated the averaged runoff coefficient as 0.5 for the 10 rainfall events with rainfall greater than 38 mm. Some designers adopt hydrological models that do not explicitly represent green roof features within their modelling elements, while the involved runoff coefficients and curve numbers mainly related to the prior-rain substrate moisture condition (i.e., wet or dry substrate) which was rarely considered (Loiola et al. 2019). Moreover, the CN values for green roofs reported in the literature vary considerably in different climatic regions (Fassman-Beck et al. 2016). Consequently, there is a gap in the literature regarding the effects of substrate moisture on the accurate estimation of runoff coefficient and curve numbers of green roofs in a semi-arid region.

In the present study, four runoff plots of extensive green roofs with three substrate material compositions, substrate depths (5, 10 and 15 cm), and different vegetation covers (Radix Ophiopogonis, Sedum Spectabile and Iris), as well as a bare substrate without any vegetation, were designed. Rainfall-runoff processes from these green roofs under differing starting substrate moisture content were investigated by imposing a simulated design storm. The SCS model was calibrated using the experimental rainfall-runoff data and CN values of green roofs were estimated. The influences of initial substrate moisture on runoff coefficient and CN values of green roofs were statistically analyzed.

MATERIALS AND METHODS

Experimental setup

Four scale-based runoff plots of extensive green roofs were constructed by 2 mm thick stainless steel platforms with internal dimensions of 100 cm wide × 100 cm long × 15–25 cm height (Figure 1(a)). The assembled constitution of a green roof from top to bottom is a vegetation layer, followed by growing substrate, filter fabric and drainage layers. The last layer was an additional waterproof layer, comprising a waterproof roll paved onto the bottom of the platform. The drainage layer was a 25 mm thick drainage board with a high impact polystyrene dimple sheet. A non-woven geotextile fabric was bonded to the upper surface of the drainage composite as the filter layer. The substrate and plants were padded on top of the non-woven geotextile. The outflow openings were installed in the middle of the drainage layer of the runoff plots and were connected by pipes with a diameter of 25 mm. A runoff plot of conventional roof paved with a 5-cm thick cement surface to the same dimensions as the green roofs was constructed (Figure 1(b)). A marked steel V-flume was created at the outlet of the conventional roof for facilitating runoff collection. These runoff plots were placed on a metal base of 0.5 m height at the testing ground at the Dingxi Institute of Soil and Water Conservation in Gansu province, China (35°34′45.88″N, 104°38′5.67″E). This region is located in a semiarid climatic zone and the mean annual precipitation is 421 mm (Wei *et al.* 2009).

Four green roofs were designed with different structural factors are shown in Table 1 and Figure 2. Three mixture types of lightweight materials were selected as the growing substrate based on roof greening material available in China (BLS 2005) and FLL guidelines (FLL 2002). Three substrate materials compositions were chosen in the present study. The details of the mixture volume ratios of substrate materials are shown in Table 1. The rural soil was taken from the local cropland, which is the infertile clay soil. Three plant species (Radix Ophiopogonis (*Ophiopogon japonicas* (*Linn. f.*) *Ker-Gawl.*), Iris (*Iris tectorum Maxim*), Sedum Spectabile

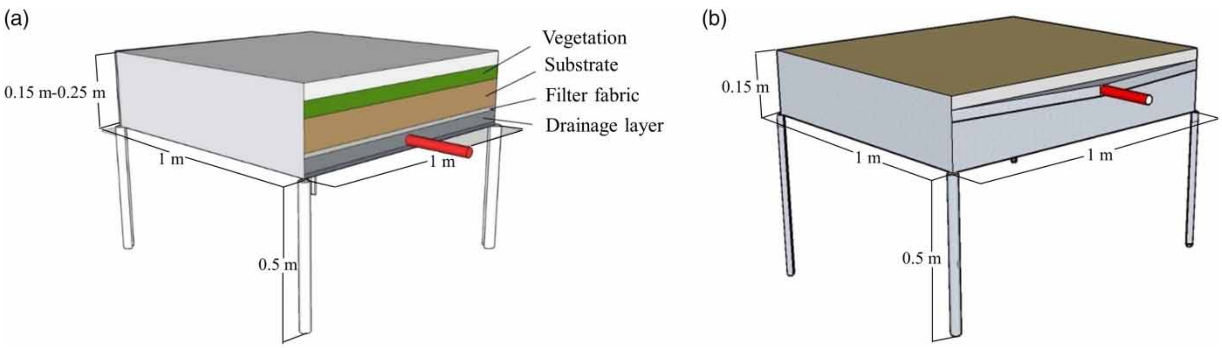

Figure 1 | Design schematic of scale-based runoff plot for: (a) green roof, and (b) conventional roof.

Table 1 | Structural characteristics of extensive green roofs

Green roofs	Substrate materials compositions (mixture volume ratio)	Substrate depth (cm)	Vegetation
GR-5	S1 (rural soil: peat soil was 1:1)	5	Radix Ophiopogonis
GI-10	S2 (rural soil: peat soil: pine needle: perlite was 1:1:1:1)	10	Iris
GS-15	S3 (rural soil: peat soil: perlite: vermiculite was 2.5:5:2:0.5)	15	Sedum Spectabile
BG-5	S1 (rural soil: peat soil was 1:1)	5	None

Figure 2 | Runoff plots of green roofs in the field experiment. (*Note*: The letters a, b, c and d represent green roof GR-5, GI-10, GS-15 and BG-5, respectively).

(*Hylotelephium erythrostictum* (*Miq.*)), that have high resistance abilities to drought stress conditions and have been widely incorporated in local landscapes, were selected. The green roof GR-5 was assembled with the substrate S1 of 5-cm depth, and vegetation layer was planted with Radix Ophiopogonis. The green roof GI-10 was assembled with the substrate S2 of 10-cm depth, and the vegetation planted with Iris. The green roof GS-15 was assembled with the substrate S3, substrate depth of 15 cm, and the vegetation planted with Sedum Spectabile. A bare green roof BG-5 (i.e. with no vegetation) was also considered as a control sample compared with the vegetated green roof GR-5.

Figure 3 | Field rainfall simulation experiments.

Rainfall simulation experiments

Rainfall simulation experiments were conducted on windless days from July to September in 2018. A Norton ladder-type artificial rainfall simulator was set to 3.5 m above the studied runoff plots (Figure 3). In this study, veejet 80100 nozzles with 41 kPa water pressure were applied in the spraying systems to generate a constant rainfall intensity. The median volume of rain-drop size obtained by this simulator was 2.2 mm, and the uniformity coefficient of rainfall reached more than 0.8.

The simulated rainfall intensity was designed based on the local storm formulation (Ji *et al.* 2002), which was expressed as:

$$i = \frac{6.86(1 + 1.33\lg N)}{(t + 12.70)^{0.83}} \quad (1)$$

where i represents the rainfall intensity (mm/min); N represents the recurrence period (year); t represents the rainfall duration (minutes). According to the significant runoff generation process observed in a preliminary experiment, a three-year return period and 60 minutes duration was selected, and the rainfall intensity was close to 0.32 mm/min. Six repetitions of simulated rainfall events were conducted for each runoff plot. In this study, the actual rainfall input depth was monitored by a standard tipping bucket rain gauge (Onset HOBO 0.2 mm Rainfall Smart Sensor, S-RGB), which was positioned adjacent to the experimental runoff plots.

The runoff outflow from the green roofs was collected in a plastic container below the runoff plot by means of a pipe at its downstream end. The plastic container was placed on a fixed base with a pressure transducer that aimed to continuously monitor the weight. The runoff volume in the collection container was converted by means of a precise calibration relationship. The weight of the discharge container was continuously measured by an industrial-grade pressure transducer weighing load cell with an accuracy of ±50 mL (Bengbu Sensor System Engineering Company, JLBU, Bengbu, China). The per-second measurement readings were subsequently averaged to produce 1-minute readings logged into a data logger (Campbell Scientific, CR300, USA). The 5TE sensor (Decagon Devices, 5TE, USA) was inserted horizontally into the mid-depth of the substrate to monitor the moisture content of the substrate layer during simulated rainfall events. In addition, using the above method, a monitoring experiment of substrate moisture in natural rainfall events was also performed with 5TE sensors during July 25–August 25, 2018, before the simulated rainfall experiments. In the field experiments, 5TE sensors were specifically calibrated for the utilized substrate according to the methodology described by Kargas et al. (2013). During the study period, substrate moisture was recorded at 1 min time intervals. In addition, the wet substrate simulation was always on the day after a dry simulation had been conducted. For dry simulation, it was 3 days after the wet substrate simulation.

Rational method and the runoff coefficient

The rational method has been classically applied in micro-drainage design. The peak hydrograph flow L (L/min) calculated as:

$$L = C_v \times i \times A \tag{2}$$

where C_v is an empirical dimensionless coefficient called the runoff coefficient; i is the design rainfall intensity associated with a definite duration and return period (mm/min); A is the drainage area (m^2).

The runoff coefficient C_v is calculated by the following equation:

$$C_v = \frac{R}{DP} \tag{3}$$

where R is the total runoff depth from the green roof units after a rain simulation (mm); DP is the rainfall depth induced through rainfall simulation (mm).

Determination of CN values

The SCS-CN method was determined by a combination of land use and hydrologic soil group, and it was developed from observed rainfall-runoff data by the Department of Agriculture, Soil Conservation Service of the United States and it is widely used for estimating runoff (USDA 1985). The SCS-CN method is based on a water balance hypothesis whereby the ratio of actual retention in a watershed to the potential maximum retention is equal to the ratio of actual direct runoff to the potential maximum runoff (Chin 2017). Direct surface runoff from the SCS-CN method is expressed by:

$$Q = \begin{cases} (P - I_a)^2/(P - I_a + S), & P \geq I_a \\ 0, & P < I_a \end{cases} \tag{4}$$

$$S = \frac{25400}{CN} - 254 \tag{5}$$

$$I_a = \lambda \times S \tag{6}$$

where Q is the runoff depth (mm); P is the rainfall depth (mm); I_a is the initial abstraction of the rainfall (mm); and S is the potential maximum water storage capacity (mm). The initial abstraction coefficient λ is constant, and usually defined as 0.2 (Singh et al. 2013), and CN is a dimensionless parameter, ranging from 0 to 100. The potential maximum water storage capacity S and CN was back-calculated as shown in the following equations respectively:

$$S = 5[P + 2Q - (4Q^2 + 5PQ)^{1/2}] \tag{7}$$

$$CN = \frac{25400}{254 + S} \tag{8}$$

RESULTS AND DISCUSSION

Runoff retention and detention performances of green roofs

Table 2 presents the runoff retention performance of green roofs for both wet and dry substrate conditions. The moisture content of dry substrate ranged from 29.9 to 35.7%, and the wet substrate moisture was varied from 38.7 to 43.3%. The runoff retention percentages were lower in the wet substrate for either vegetated or bare green roofs. For dry substrate, the bare green roof BG-5 achieved a mean runoff retention of up to 64.9%, and the average runoff retention varied from 34.7 to 48.5% for vegetated green roofs. Under the wet substrate, the average runoff retention of the vegetated green roofs ranged from 14.7 to 30.6%, and the mean runoff retention for bare green roof BG-5 was 35.1%. Compared with the average time to runoff of the conventional roof (3 minutes), the mean runoff detention of green roofs for the dry substrate was 12–20 minutes, and 8–18 minutes for the wet substrate. The bare green roof BG-5 was able to retain more stormwater than the vegetated green roofs under dry and wet substrate. The results are aligned with the green roof monitoring studies that indicate that green roofs have a greater ability to retain rainwater under drier conditions (Berndtsson 2010). This was also consistent with the observations of substrate moisture conditions, as the substrate moisture content of the vegetated green roofs was always higher than the bare green roof. Berretta *et al.* (2014) and Poë *et al.* (2015) have also investigated significant differences in evapotranspiration and substrate moisture losses between the vegetated and bare green roofs. As vegetated green roofs lose less water, they tend to retain less rainwater and are not efficient in runoff retention, especially for wet substrate.

Runoff processes of green roofs

Representative runoff processes of green roofs at 1 minute time intervals are illustrated in Figure 4. For each green roof, the runoff flow rate exhibited a logistic function to the increasing trend where the initial runoff was low, and this increased slowly for the first 1–10 minutes due to rainwater infiltration of the substrate layer. As rainfall continued to input, the runoff flow rate increased quickly. After 50 minutes (except BG-5), the runoff increased slowly then attained a steady state as the substrate water in the green roof appeared to saturate. This is mainly attributable to the fact that after the substrate was saturated, the rainfall is likely to be transferred as the runoff, and thus the runoff rate is in accord with the rainfall intensity. It is noteworthy that the logistic curves of accumulated runoff processes indicated that the studied substrates became saturated during or after the rainfall events, and revealed that runoff generation of the studied green roofs was dominated by the mechanism of saturation-excess runoff. Similarly, Yang *et al.* (2015) concluded that due to the high conductivity of substrate materials that are padded in extensive green roofs, saturation-excess runoff is the dominant mechanism of green roofs. Figure 4 shows that the GS-15 has the fastest runoff rate and highest runoff depth among the four green roofs due to the thin substrate depth. The GI-10 has the lower runoff rate but the runoff depth approaches the GS-15 when the substrate was saturated. The bare green roof BG-5 had the lowest runoff flow rate among the four green roofs and indicated the highest runoff retention.

Table 2 | Mean values of rainfall, runoff and retention performances under dry and wet substrate

	GR-5		GI-10		GS-15		BG-5	
Indicators	**Dry**	**Wet**	**Dry**	**Wet**	**Dry**	**Wet**	**Dry**	**Wet**
Rainfall depth (mm)	20.2	21.8	19.5	19.4	19.8	21.2	17.4	19.4
Runoff depth (mm)	13.2	18.6	11.4	13.8	10.2	14.7	6.1	12.6
Runoff retention (%)	34.7	14.7	41.5	28.9	48.5	30.6	64.9	35.1
Runoff detention (minutes)	19	10	12	9	20	18	20	8

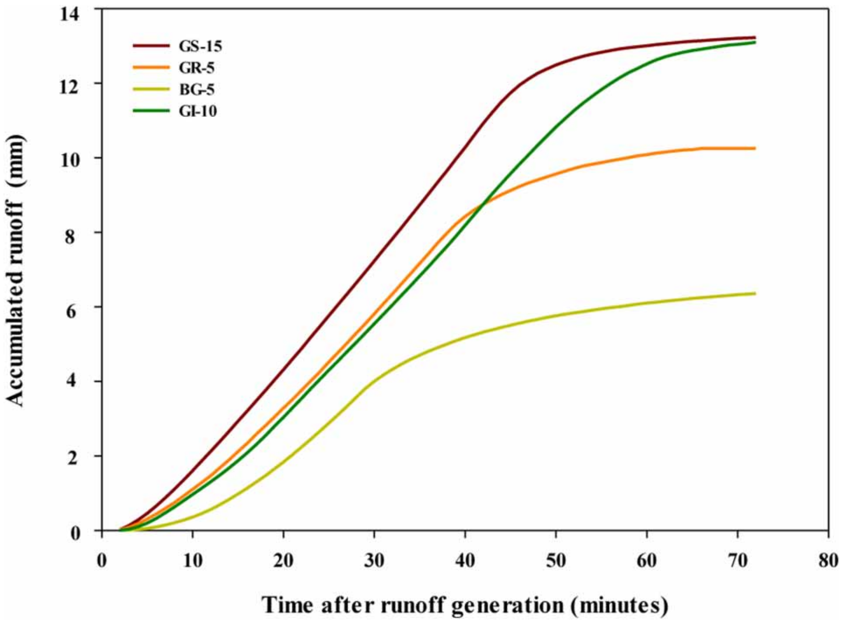

Figure 4 | Accumulated runoff processes of green roofs.

Therefore, these runoff processes are consistent with their runoff retention values.

Runoff coefficient (C_v) values

The derived average C_v values for green roofs under the dry and wet substrate are presented in Table 3. The values of C_v for vegetated green roof ranged from 0.52 (GS-15, dry substrate) to 0.85 (GR-5, wet substrate). As expected, these values are consistent with their runoff retention data. For dry and wet substrates, the mean C_v values of vegetated green roofs were 0.58 and 0.75, respectively. The averaged C_v value of bare green roof BG-5 was 0.35 and 0.65, under dry and wet substrate respectively. For comparison, the averaged C_v value of the conventional roof was 0.94 in the present study, indicating that the bare green roof was more efficient for stormwater runoff retention. Furthermore, it was observed in field experiments that the substrate surfaces of all green roofs were nearly fully covered by vegetation, thus the foliage could protect the substrate surfaces from radiation. Consequently, the vegetated green roofs were always kept in wetter conditions than the bare substrate. These C_v values are compatible with Locatelli *et al.* (2014) and Mentens *et al.* (2006) who obtained values for green roofs ranging from 0.40 to 0.71. Moreover, Fassman-Beck *et al.* (2016) reviewed that a reasonable variability of the C_v values are related to green roof characteristics and climate zones.

Curve number (CN) values

Average CN values under the dry and wet substrate for green roofs are presented in Table 4. For vegetated green roofs under the wet substrate, the average CN values ranged from 96 to 98, while for dry substrate, the mean CNs varied from 93 to 97. For bare green roof BG-5, the

Table 3 | Average values of runoff coefficients for dry and wet substrate

C_v values	GR-5	GI-10	GS-15	BG-5
Dry	0.65	0.58	0.52	0.35
Wet	0.85	0.71	0.69	0.65

Table 4 | Mean CN values of green roofs for dry and wet substrate

CN values	GR-5	GI-10	GS-15	BG-5
Dry	97	94	93	93
Wet	98	98	96	97

average value for CNs was 93 for dry substrate and 97 for wet substrate. Moreover, the results showed that for wet substrate, the bare green roof would be more efficient for the purpose of minimising stormwater runoff. As a comparison, the averaged CN value for a conventional roof was 99 in this study. As discussed before, the results were consistent with the substrate moisture content and associated with their rainwater storage capacity. Similarly, Hill *et al.* (2017) reported that the mean CN of 10–15 cm depth green roofs was 94. Stovin *et al.* (2013) showed the green roof of 50 mm depth presents the highest CN of 96. However, Carter & Rasmussen (2006) derived a CN of 86 for a green roof with 7.62 cm of substrate depth. However, these derived CN values of studied green roofs were relatively higher in the simulated rainfall events. This can be attributed to the relatively higher rainfall depths simulated in this study. The reported CN values for green roofs vary considerably in different climatic regions, which were also associated with different experimental setups (Fassman-Beck *et al.* 2016). Therefore, runoff retention capacity of a green roof depends on substrate moisture at the onset of a rainfall event, which in turn depends on the substrate's water storage capacity (Fassman & Simcock 2011; Wadzuk *et al.* 2013).

As shown in Figure 5, the predicted runoff depths exhibited a significant linear relationship with the observed runoff depths (r (24) = 1.003, $R^2 = 0.69$, $p < 0.001$). The predicted versus measured runoff depths of green roofs in all the simulated rainfall events were very close to the 1:1 line, which confirms the acceptability of the SCS-CN model predictions. Further, the obtained results proved that the prediction performance was adequate. In practice, the water storage capacity will be a key hydrologic characteristic of green roofs for assessing runoff retention effectiveness (Stovin *et al.* 2013).

Influences of substrate moisture on C_v and CN values

The fluctuation of substrate moisture content in seven successive natural rainfall events is depicted in Figure 6. It is noted that the substrate almost saturated after rainfall events, then the substrate moisture content dropped considerably faster in the bare substrate BG-5 than vegetated green roofs. Moreover, the reduction rate of substrate moisture content for Radix Ophiopogonis (GR-5) and Iris (GI-10) vegetation was higher compared with Sedum Spectabile (GS-15). In addition, the moisture content of shallow

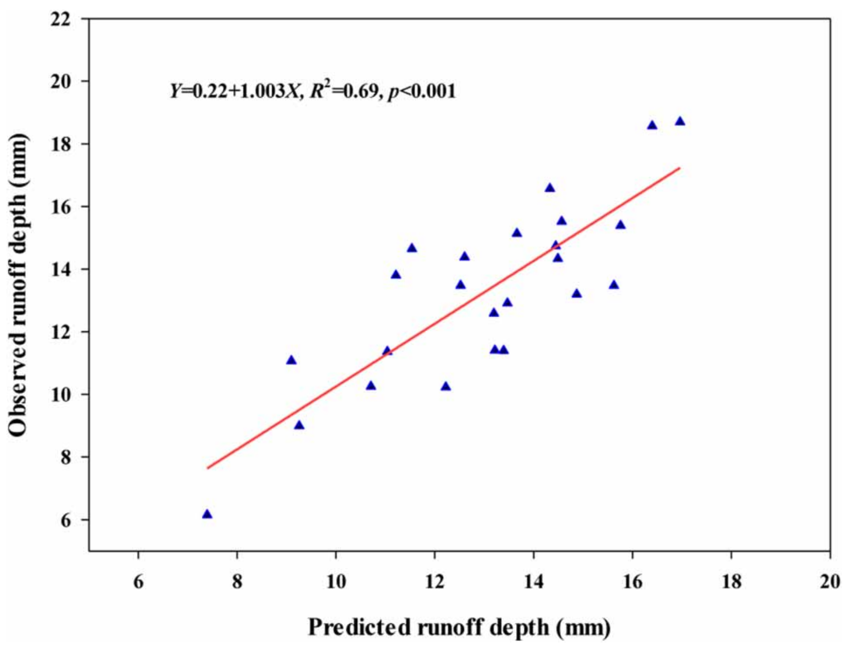

Figure 5 | Scatterplots and the fitted curves for predicted runoff depths plotted against observed runoff depths.

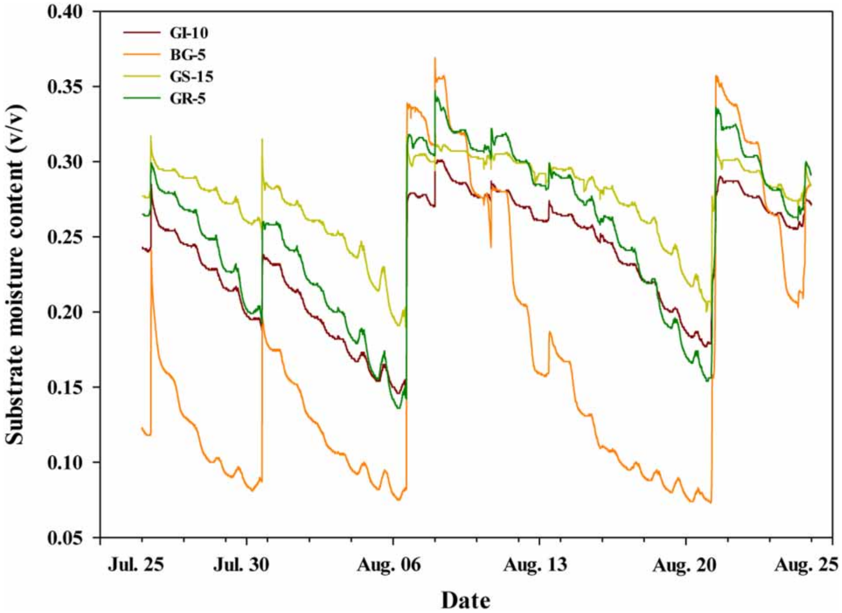

Figure 6 | Variation of substrate moisture content during rainfall events from July 25 to August 25, 2018.

substrate of 5 cm (GR-5) decreased faster compared with the deeper substrate of 10 cm depth (GI-10). Thus, the initial substrate moisture content before the next rainfall event was higher for Sedum Spectabile and the deeper substrate. The behaviors of substrate moisture of green roofs are in accordance with their observed runoff retention during the experimental period.

The initial substrate moisture content of green roofs varied from 29.9 to 43.3% in the field experiments. A significant positive relationship was found between the initial moisture content and runoff coefficient C_v, with r (24) = 0.02, $R^2 = 0.32$, $p < 0.01$ (Figure 7(a)). Similarly, a positive relationship between the initial moisture content and CN values of green roofs was also established, r (24) = 0.16, $R^2 = 0.11$, $p < 0.001$ (Figure 7(b)). Although the data were scattered and the adjusted R^2 was lower than 0.5, the positive trends are significant.

In the present study, differences in CNs between simulated rainfall events are considered to mainly be a function of the initial substrate moisture conditions. The wetter initial

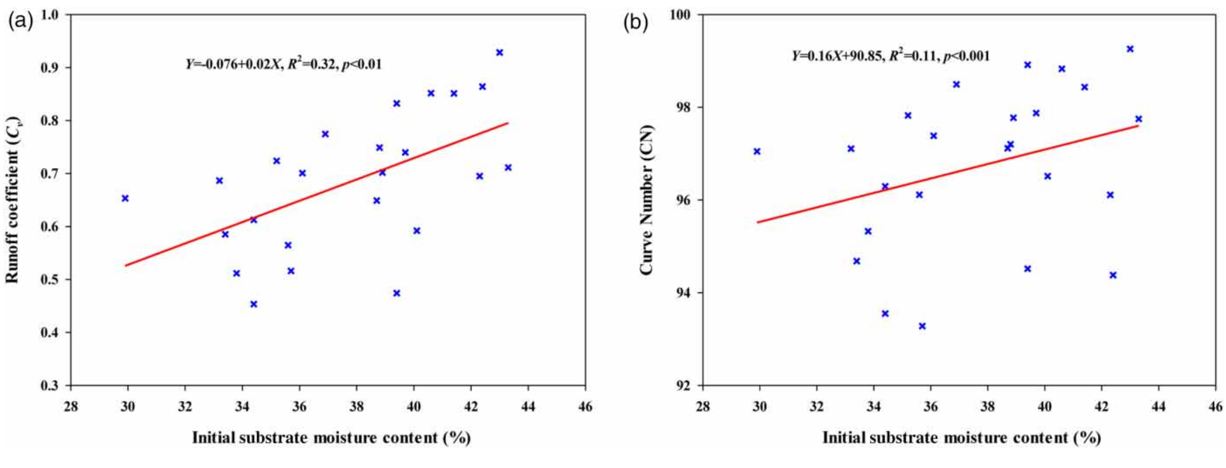

Figure 7 | Correlation analysis of initial substrate moisture with: (a) runoff coefficient, (b) curve number.

substrate conditions decrease water storage potential, resulting in higher CNs. The results are aligned with the general agreement that green roofs have a greater ability to retain stormwater during the drier conditions than the wetter substrate (Berndtsson 2010). The runoff retention ability of a green roof is sensitive to the initial substrate moisture prior to a rainfall event, which is controlled by the plant evapotranspiration process during dry periods (Berretta *et al.* 2014). Hakimdavar *et al.* (2014) concluded that the initial substrate moisture content is a more direct indicator of runoff retention capacity for a green roof than the antecedent dry weather period. Therefore, a better understanding of the behavior of substrate moisture during dry periods will have important implications for urban stormwater management (Stovin *et al.* 2013).

Limitations of the study and future research

As a limitation, the present study did not consider adjusting the initial abstraction ratio in estimation of green roof runoff from the SCS-CN method. The SCS-CN is an empirical model which was originally developed for simulating runoff from natural watersheds. Generally, the initial abstraction ratio is taken as a constant value of 0.2. The standard SCS-CN method (which uses the initial abstraction ratio value of 0.2) has been widely used in describing the empirical relationship of rainfall-runoff for green roof systems (Getter *et al.* 2007; Fassman-Beck *et al.* 2016; Carson *et al.* 2017; Soulis *et al.* 2017; Jahanfar *et al.* 2019; Loiola *et al.* 2019). However, the initial abstraction ratio in the SCS-CN method, which largely depends on the climatic conditions, should be regarded as a regional parameter (Ponce & Hawkins 1996). Several researchers have investigated the impacts of initial abstraction ratio on estimating runoff by using SCS-CN method (Hawkins *et al.* 2002; Mishra *et al.* 2006; Shi *et al.* 2009). Hawkins *et al.* (2002) found that the assumption of constant value is usually high. Shi *et al.* (2009) concluded that the adjusted average initial abstraction ratio of 0.053 was more appropriate for runoff prediction in the Three Gorges Area of China. They also found that the standard initial abstraction ratio in SCS-CN method underestimates large runoff events. Therefore, the selection of a proper initial abstraction ratio is essential and should be prior to the application of the SCS-CN method. Further research is needed to calibrate the initial abstraction ratio by using locally observed data for accurate estimation of green roof runoff from the SCS-CN method.

CONCLUSIONS

In this study, extensive green roofs with dry and wet substrate conditions under simulated intense storms were investigated to obtain their effective estimations for C_v and CN parameters in a semi-arid region, and the acquired parameters used to assess the effects of substrate moisture. The bare green roof was able to retain more rainwater than the three vegetated green roofs, which indicated that bare green roof was more efficient for runoff retention. Because the foliage could protect the substrate surfaces from radiation, the substrate moisture content of the vegetated green roofs was always higher than the bare green roof. The accumulated runoff processes revealed that runoff generation of the studied green roofs was followed by the mechanism of saturation-excess runoff. The mean C_v values of green roofs were 0.58 and 0.75, for dry and wet substrate, respectively. For green roofs under wet substrate, the average CN values ranged from 96 to 98, meanwhile for dry substrate, the mean CN ranged from 93 to 97. Moreover, the results substantiated that the SCS-CN model adequately predicted the total runoff depths of green roofs in all the simulated rainfall events. The drier initial substrate moisture conditions corresponded to lower runoff coefficients and curve numbers. Therefore, the simplified model provides adequate predictions of the runoff depths based on the maximum water storage capacity of the green roofs. Further, this study would facilitate the proper use of the estimated C_v and CN values of green roofs for urban stormwater management in a semi-arid region.

These empirically derived C_v and CN values will assist urban planners and managers in evaluating the potential of green roofs to minimize stormwater runoff generation in urban watersheds. Meanwhile, the results highlight the importance of considering initial substrate moisture conditions for generalizing C_v and CNs to model green roof performance. Therefore, there is a need to quantify the variability of green roof's C_v and CNs based on pre-construction information (e.g. substrate properties, substrate depth and vegetation cover), initial substrate moisture, and rainfall characteristics to improve the accuracy of C_v and CN parameter selection for model application. Further, calibrating the initial abstraction ratio by using locally observed data is also needed to accurately estimate green roof runoff from the SCS-CN method.

DISCLOSURE STATEMENT

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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