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Effects of Substrate Depth and Precipitation Characteristics on Stormwater Retention by Two Green Roofs in Portland OR

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Effects of substrate depth and precipitation characteristics on stormwater retention by two green roofs in Portland OR

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ABSTRACT

Study Region: This study took place in Portland Oregon, a city of over 600,000 residents located in the Willamette Valley in the state of Oregon in the Pacific Northwest region of the United States. Portland experiences a temperate climate with Mediterranean features.
Study Focus: Runoff patterns from two extensive green roofs with substrate depths of 75 and 125 mm, situated on a 5000 square meter retail store, were compared over a one year period. Precipitation, irrigation, and storm water discharge were continuously monitored and the performance of the green roofs for storm water control was investigated in detail.
New Hydrological Insights for the Region: Over the study period, the 125 mm and 75 mm green roofs retained 32.9% and 23.2% of all precipitation by volume, respectively. The hydrologic response of the green roofs during individual storm events was found to depend strongly on the total depth of the storm event as well as the length of the antecedent dry weather period. Differences in performance between the two substrate depths were most pronounced for small storms with long antecedent dry weather periods. Both green roofs showed strong seasonal dependence in storm water retention, with higher percent retention in the relatively dry summer months compared to lower retention in the wetter winter months. These findings have important implications for the effective installation of green roofs for stormwater management in our region. Because of the increased frequency of storm events during the Pacific Northwest winters, it is imperative that efforts to increase storage capacity through increased substrate depth be paired with efforts to ensure rapid removal. If deeper substrates are to be utilized effectively; more research is needed to identify ways to increase evapotranspiration, for example via more informed plant selection, during wet winter months.

1. Introduction

As cities grow and become more densely populated the fraction of the urban surface made up of impervious materials increases (e.g., Carlson and Arthur, 2000; Jia et al., 2002). Among other challenges, such expansion leads to increased stress on storm water management systems, driving interest in innovative solutions to reduce storm water volume and peak flow (U.S. EPA, 2015; Miles and Band, 2015). Green roofs (also known as eco-roofs, living roofs or vegetated roofs) provide numerous benefits, including aesthetic appeal, additional habitat for wildlife, increased energy efficiency of the building, and mitigation of urban heat island effects (Getter and Rowe, 2006; Lundholm, 2006; Sailor and Hagos, 2011; Susca et al., 2011). Green roofs also affect storm water runoff as they are able to temporarily detain some of the incident precipitation. This results in a delay in the timing of peak flow rates into storm water

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systems. Through evaporation from the substrate surface and transpiration from the vegetation, green roofs are also able to reduce runoff. When considering green roofs for storm-water management, reducing total runoff volume and attenuating peak flows are often of greatest concern.

Past studies have shown that green roofs are able to retain storm water, reduce peak flow and increase time-to-peak flow (Villarreal and Bengtsson, 2005; Spolek, 2008; Voyde et al., 2010). Controlling storm water runoff is important to reduce risks of flooding in urban environments. Of the many factors in play when considering the performance of a green roof for storm water control during a storm event, one well-studied yet also debated factor is substrate depth. It would seem intuitive that deeper substrate would be an important factor that should improve storm water performance. However, conflicting evidence has been reported. In a 12-month study of extensive green roofs in New Zealand, Voyde et al. (2010) found no significant difference in performance between 50 mm and 70 mm deep extensive green roofs. In another study from New Zealand, where four green roofs of varying substrate depth were concurrently monitored, runoff reduction was not shown to depend on substrate depth (Fassman-Beck et al., 2013). In a three-year study of five different extensive green roofs in Seattle, WA, Berkompas et al. (2008) reported no relationship between storm water retention and substrate depth for substrate depths ≥ 100 mm.

Perhaps the counter-intuitive relationship between depth and retention can be explained by the known influence of precipitation characteristics on storm water retention by green roofs. Environmental conditions, especially storm frequency, may affect the degree to which additional storage created by increased depth can be accessed. In a study of an 80 mm deep test bed, Stovin (2010) reported that the storm water performance depended most strongly on rainfall amount, rainfall intensity and length of the antecedent dry period. Fassman-Beck et al. (2013) also found runoff reduction during storm events by green roofs to be well-predicted by the size of the storm. Voyde et al. (2010) reported that the antecedent dry period for a storm was the most important factor in predicting rates of storm water retention. The storm water performance (vis-à-vis reducing total runoff) of a green roof has also been found to decrease during wetter seasons and when storm events occur close together (e.g., Voyde et al., 2010; Stovin, 2010). For example, Van Seters et al. (2009) reported that, in comparison to a conventional roof, an extensive green roof in Toronto reduced runoff by 42% in two wet months but reduced runoff by 70–93% during the drier summer months. In their study of three green roofs in New York City, researchers were able to demonstrate a seasonal influence on runoff for storms of 10–40 mm in depth (Carson et al., 2013). Spolek (2008) reported strong seasonal variation in the performance of a green roof in Portland, OR, with runoff reductions of 12% in winter compared with 42% in summer. It should be noted that out of all studies mentioned above, the two conducted in New Zealand (a subtropical climate with an average of 137 wet days spread relatively evenly throughout the year) were the only ones not showing significant seasonal variation in performance. The works discussed here provide evidence that rainfall patterns are an important factor in predicting green roof performance for storm water mitigation.

Substrate depth is a key factor being considered by managers when establishing design criteria, yet the relationship between increasing depth and increased retention is not well understood. Differences in storm event characteristics could explain variation in the substrate depth effect. Additional research on this topic is especially needed in the Pacific Northwest of the U.S. due to its unique climate and dense concentration of green roofs. We compared the performance of green roofs with different substrate depths (75 and 125 mm) across a range of storm scenarios typical of urban Portland, OR, in order to advance our understanding of the interplay between substrate depth and storm characteristics and their effect on green roof performance. Storm water mitigation associated with two green roof installations on the same building in Portland was analyzed over the course of 12 months, and individual storm events were analyzed in detail so that any relationships among substrate depth, runoff, and precipitation patterns could be established.

2. Methodology

2.1. Study site

The present study was conducted on a test roof on a new large retail store in Portland, OR (W 45.52°, N 122.68°). Building construction was completed in late 2013, and installation of the sensors and equipment on the roof was finished in January 2014. The study site included an extensive green roof divided into three equal 1200 m^2 sections of varying substrate depths next to an impermeable 1468 m^2 conventional white membrane roof section. Each roof section was isolated from the others forming unique drainage basins. An additional section of roughly 4000 m^2 conventional white membrane roof was not monitored. One section of green roof had a soil depth of 75 mm, the second had a depth of 125 mm, and the third section featured spatially varying soil substrate depth. Only the uniform depth green roof sections were analyzed in this research.

Fig. 1 shows a schematic of the roof along with locations of the weather stations used to monitor air temperature, rainfall, wind direction, wind speed, solar radiation, and soil conditions. Images of the various roof sections and monitoring stations are shown in Fig. 2.

As illustrated in Fig. 3, the green roof construction included a waterproof membrane, a coarse aggregate foundation layer, surface substrate, and vegetation. The substrate consisted of pumice, compost, and sandy loam (ProGro, Oregon). Vegetation included an assortment of cuttings of nine Sedum plant species (*Sedum spurium, Sedum floriferum Weihenstephaner Gold, Sedum (Phedimus) takesimense, Sedum rupestre Angelina, Sedum divergens, Sedum album micranthemum, Sedum album Athoum, and Sedum sexangulare*) and a seed mixture of 15 additional species (*Lomatium urticulatum, Eriophyllum lanatum, Viola praemorsa, Collinsia grandiflora, Plagiobothyrs nothofulvus, Camassia quamash, Dianthus deltoids, Talinum calycinum, Clarkia* sp., *Penstemon* sp., *Achillea millefolium, Geranium sanguineum, Phlox* sp., *Lewisia* sp., *Erigeron aureus*).

Fig. 1. Layout of the rooftop including the white roof section and the three green roof (GR) sections. The locations of the three weather stations and Air Handling Units (AHU) are marked.

2.2. Instrumentation

Runoff was measured independently from the 75 mm thick green roof, the 125 mm green roof and the conventional roof section using Plasti-Fab extra-large 60-degree trapezoidal flumes recording five-minute averages of flow. Runoff from the third section of green roof featuring varying soil depths was not measured. Rainfall was recorded by a tipping bucket rain gauge located on the conventional roof in increments of 0.254 mm. Rainfall and soil moisture content measurements were recorded at a sampling rate of 5 min and averaged over 15 min.

2.3. Irrigation and leakage on test site

The irrigation schedule for both green roofs was controlled by a Hydropoint controller which used local weather conditions to estimate evapotranspiration and soil moisture content. The green roofs were irrigated daily from April 14, 2014 to October 8, 2014 during the test period (February 1, 2014 to January 31, 2015). The Hydropoint system was set to water according to evaporative demand (as estimated by the irrigation control system using data from the weather station). The irrigation was assumed to have been distributed evenly between both green roof sections. Since both roofs were irrigated with the same amounts and at the same times, we are still able to test for the treatment effect of depth under these conditions. There was no evidence of runoff from either roof being caused solely by irrigation (i.e. all runoff was recorded during or following rain events) at any point during the study period, with one exception in June 2014. During this time there was a leak in the irrigation system which intermittently caused large amounts of water to be poured onto the roof between June 9, 2014 and June 28, 2014. The largest value for irrigation during this time was recorded on June 17 and was equivalent to 42.1 mm of precipitation being added to each roof. Due to its location, evidence of this leak was only seen in the runoff from the 75 mm green roof and the conventional white roof. The artificial runoff coming from the leakage made analysis of four distinct June rain events impossible, but was determined to be inconsequential for the rain event on June 22, 2014. Outside of this leak, irrigation values were recorded as daily total volumes and had an average daily value of 14.0 m^3, which is equivalent to 2.9 mm of precipitation being added to the green roof.

We were able to capture runoff for every storm from both sections, with the exception of two events. Runoff measurements from the 75 mm roof were unavailable for a 62.1 mm storm event on October 21 and a 13.7 mm storm on December 10. For the sake of statistical analysis and consistency, only events in which complete runoff data from both the 75 mm and 125 mm roofs was available are included in the comparison between substrate depths.

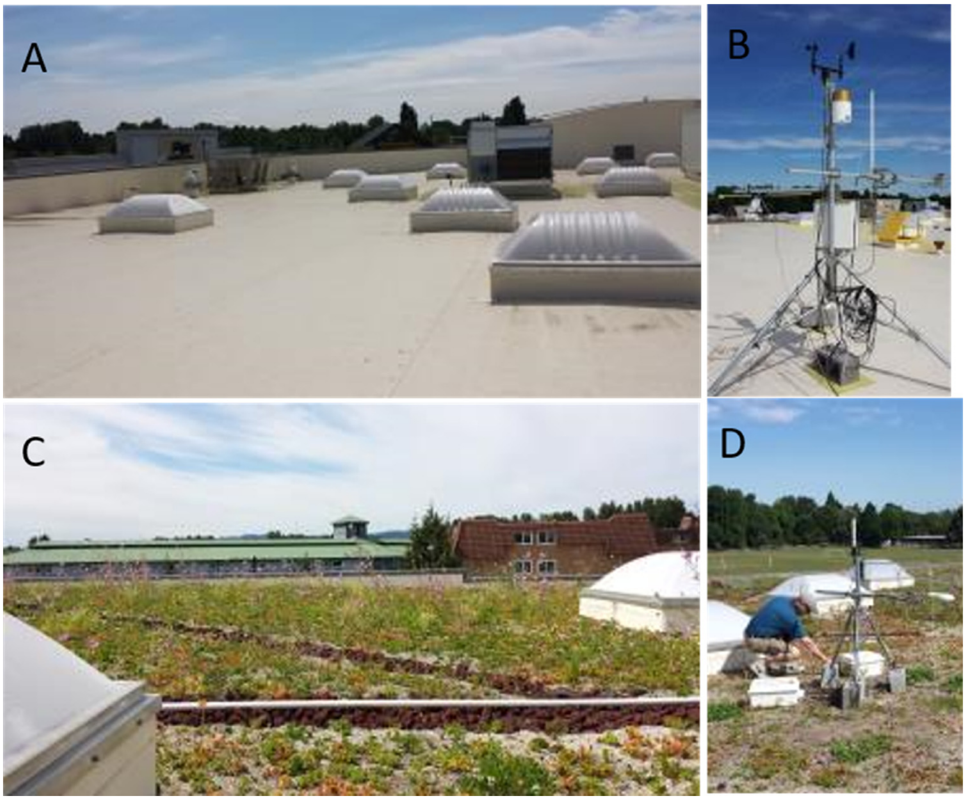

Fig. 2. Images of the white roof (A) and corresponding weather station (B) as well as the green roof (C) and associated environmental monitoring equipment (D).

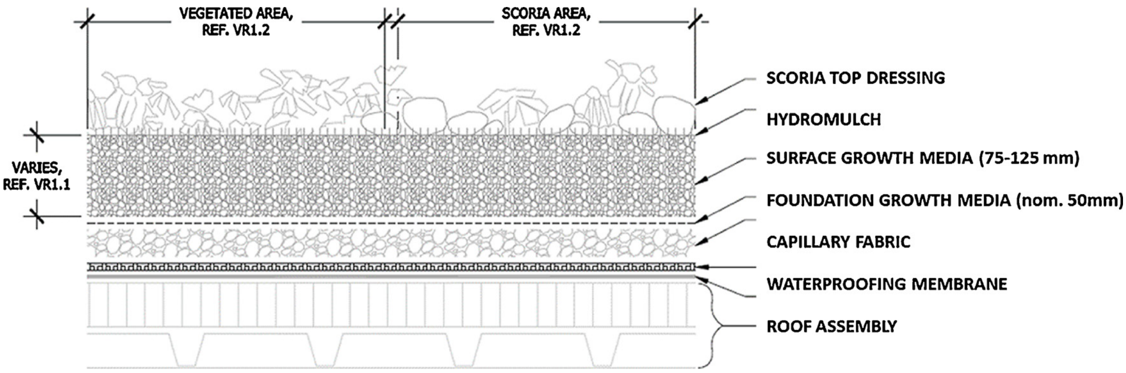

Fig. 3. Layer by layer construction of the extensive green roofs.

2.4. Statistical analysis

In order to test for substrate treatment effects on runoff while also accounting for storm size as a co-variate with runoff, ANCOVA analysis compared the slopes of storm size/runoff relationships for the two substrate size categories (proc glm, SAS version 9.2, SAS Institute, Cary, NC). This assumes a linear relationship between rainfall and runoff; we confirmed this using the Shapiro-Wilks test for the normality of the regression residuals. Because storm size was not normally distributed in our study, we further compared the average percent retention within different storm size categories using paired t-tests.

3. Results

Continuous rainfall and runoff measurements were taken for 12 full months beginning February 1, 2014 and ending January 31, 2015. Analysis of the entire year of data (omitting all storms and time periods with incomplete data) is presented below.

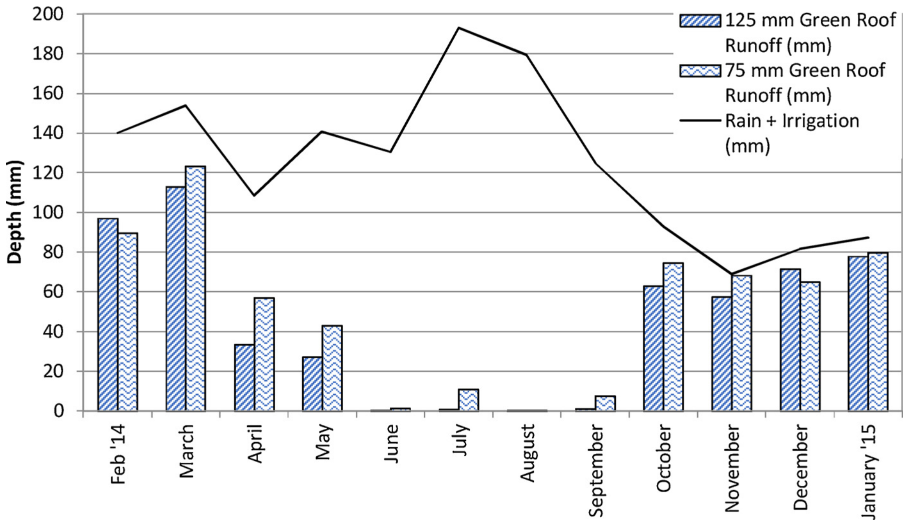

Fig. 4. Precipitation plus irrigation and runoff totals broken down by month for both green roofs. The depth scale is the same for inputs and outputs.

3.1. Precipitation and irrigation during test period and seasonal performance

There was a total of 807.6 mm of measured precipitation on the test site during the study period. The precipitation varied strongly with the season; 70% of the yearly runoff occurred in the six months from Nov-Apr. For the purpose of this study a rain event was defined as any event with greater than 0.50 mm precipitation and with a dry period of least six hours before and after any measurable precipitation (Voyde et al., 2010). Runoff events had an average size of 9.8 mm but a median value of 5.2 mm indicating that most runoff events were relatively small with some outlying large storms. Runoff for individual storm events was calculated as all runoff discharged from the green roof beginning with the first measurable precipitation and continuing until the start of the next rain event. This method of calculating runoff ensures that the sum of runoff from all storm events will be equal to the total annual runoff, and also accounts for all runoff due to each individual storm. There were 82 rain events with complete runoff data from both roofs available; runoff and precipitation from events with incomplete data are not included. Aggregate monthly statistics of precipitation and runoff are summarized in Fig. 4. The solid line reflects the combination of irrigation and rain, which peaks in the summer months, but results in virtually no runoff due to the controlled rates of application of irrigation. The peak runoff occurs in the month of March. Over the course of the entire study the 125 mm green roof retained 32.9% of all rainfall and the 75 mm green roof retained 23.2%. However, there was actually greater runoff from the 125 mm green roof during the months of February and December—an effect that is not readily explained from the available data.

Table 1 presents summary statistics for discrete precipitation events for the 75 mm and 125 mm green roofs. The performance of the green roofs was considered as a percentage of rain retained each season. The 12-month study period was broken down into four seasons of three months each in order to gain a better understanding of the climatic effects on the performance of the roof. The performance of both the 75 mm and 125 mm showed a strong seasonal dependence with high retention values in the summer months and low retention in the winter months.

3.2. Performance during storm events of different size and antecedent moisture conditions

The capacity of a green roof to retain storm water depends on several parameters that can be controlled (i.e. substrate depth, slope, substrate, vegetation) and on some that cannot be controlled, namely the size and frequency of precipitation events.

Table 1
Summary performance metrics of the 75 mm and 125 mm green roof by season. The abbreviation ADWP refers to the Antecedent Dry Weather Period.

	Number of Events	Total Precipitation (mm)	Median Event Size (mm)	75 mm Green Roof Retention (%)	125 mm Green Roof Retention (%)	Median ADWP (hrs)
Winter (Dec-Feb)	30	308.9	3.1	24.1	20.2	29.1
Spring (Mar-May)	23[a]	293.1	9.1	23.8	40.8	52.8
Summer (Jun-Aug)	4	23.1	4.6	48.8	96.6	328.1
Fall (Sep-Nov)	25[a]	182.6	3.0	17.7	33.5	40.6
Annual	82	807.7	5.2	23.2	32.9	49.1

[a] indicates statistically significant difference (t-test) in mean precipitation retained for each size category.

Table 2
Summary statistics of both green roofs broken down by size of precipitation event.

Size of Event (mm)	p-value	# of Events	Total Rainfall (mm)	125 mm Total Precipitation Retained (mm) [% retained]	75 mm Total Precipitation Retained (mm) [% retained]
< 5	0.61	40	79.5	39.9 [*50.1*]	33.4 [*42.0*]
5–10[a]	0.013	16	119.9	68.4 [*57.0*]	39.4 [*32.8*]
10–15	0.095	9	116.1	45.3 [*39.0*]	23.5 [*20.19*]
15–25	0.17	9	186.4	59.0 [*31.7*]	39.7 [*21.29*]
25–35	0.29	3	91.9	25.3 [*26.5*]	17.7 [*19.28*]
35–50	0.43	5	213.6	28.3 [*13.2*]	33.9 [*15.9*]

[a] indicates statistically significant difference (t-test) in mean precipitation retained foreach size category.

3.2.1. Effect of size of rain event

Table 2 breaks down the performance of both green roofs by the size of individual precipitation events. Both roofs show significantly better performance for small storms. Retention during storm events was calculated as the runoff during the storm and extending six hours after the end of measurable precipitation for each event. No overall effect of depth on mm retained was found to be significant (t-test, p = 0.28). Further tests were run, including only storms within defined ranges of depth (same depth ranges as in Table 2). Storms between 5 and 10 mm in depth were the only range to show a statistically significant effect of depth (t-test, p = 0.03).

Fig. 5 shows the runoff for each individual storm event plotted against the size of the rain event. A linear relationship is seen for both substrate depths, the slope of the linear best fit for the 125 mm green roof was lower than that of the 75 mm green roof, suggesting that it was able to retain more storm water during events. An ANCOVA analysis of runoff and precipitation data showed when the influence of storm size on runoff was factored out; as using the type III sum of squares results, there was no significant effect of substrate depth on runoff (p = 0.17).

Fig. 6 shows the residuals associated with these aforementioned regressions. After fewer than 8 outliers were removed, Shapiro-Wilks testing confirmed normality of these residuals (W = 0.98, p = 0.69, α = 0.05).

3.2.2. Antecedent dry weather period and storm water retention

The retention for individual events showed a strong dependence on both the length of the antecedent dry weather period and the size of the event. It was found that when storm events fall closely together in time the performance of both roofs suffered.. Figs. 7 and 8 demonstrate the effect of Antecedent Dry Weather Period (ADWP) on retention. The storm depicted in Fig. 7 occurred after a period of seven days without precipitation and featured 10.7 mm of precipitation over 19.5 h. The difference in performance between substrate depths was substantial in this storm. Fig. 8 is a hydrograph of a 36.3 mm storm event in March which occurred after an antecedent dry period of only 38 h. Runoff from both roofs is nearly identical throughout the event, with the 125 mm roof retaining 5.4 mm and the 75 mm roof retaining 4.8 mm of precipitation. The poor performance of both roofs in this storm was found to be

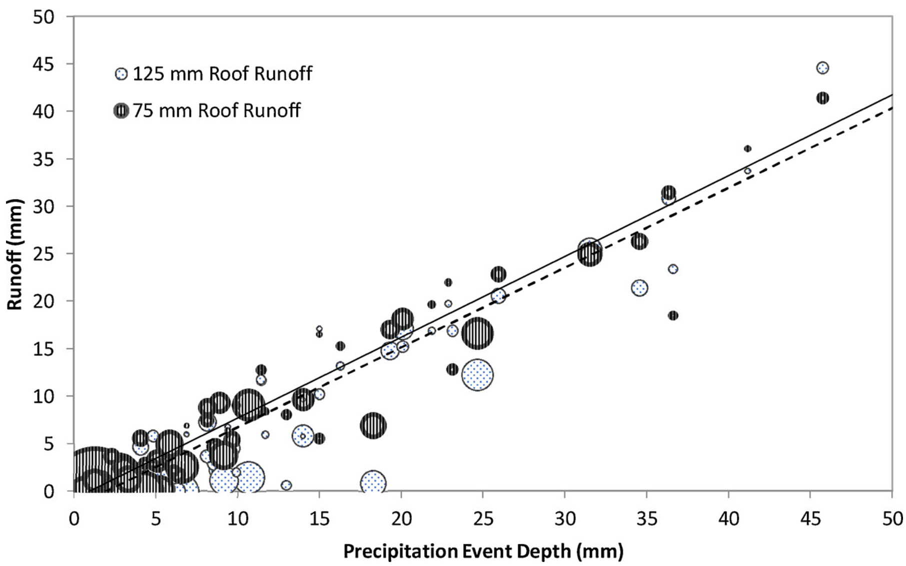

Fig. 5. Runoff from both green roofs as a function of depth of the precipitation event. Sizes of circles are proportional the length of the antecedent dry weather period. Lines shown are linear fits to the data for the 75 mm (solid) and 125 mm roof (dashed). Equations for linear fits were found to be r = 0.852d-0.828 for the 75 mm roof and r = 0.8412d-1.627 for 125 mm roof (where d is precipitation event depth and r is runoff in mm).

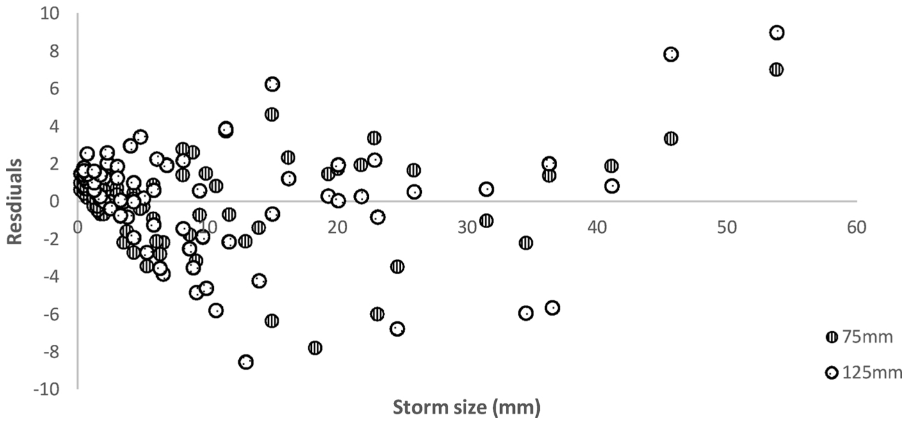

Fig. 6. Residual plot associated with ANCOVA analysis on data from all storms presented in Fig. 5.

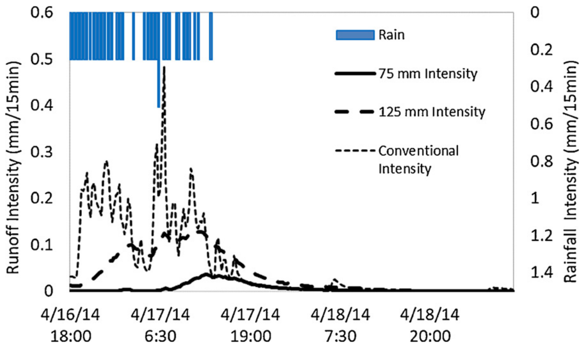

Fig. 7. Hydrograph of a medium-sized April storm event (after a long Antecedent Dry Weather Period) showing a substantial difference in runoff performance between 75 and 125 mm substrate depths. This graph also shows runoff intensity from a conventional white roof.

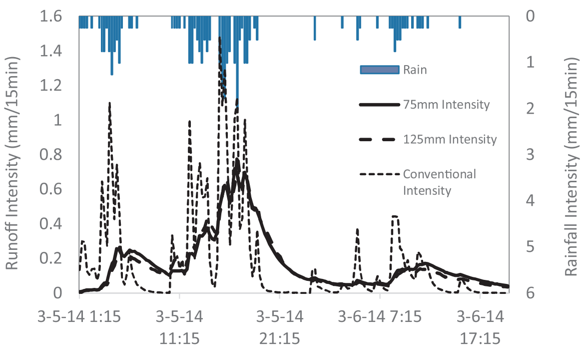

Fig. 8. Hydrograph of medium-sized March storm event (with short Antecedent Dry Weather Period) showing little retention from both 75 and 125 mm substrate depths. This graph also shows runoff intensity from a conventional white roof.

typical of storms with short ADWP. It is clear that the roofs are unable to dry out with these short dry periods in between storms, indicating that the longer the dry period between storms the better the roofs will perform.

4. Discussion

This study found that the storm water runoff performance of side-by-side green roofs of different depths depended strongly on the precipitation patterns (ADWP and size of rain events). The largest differences between the two depths was seen only when the soil was below saturation level before precipitation events and for small rain events (5–10 mm). For storm events measuring between 5–10 mm precipitation, the 125 mm green roof retained significantly more (57%) rainfall compared to 32.8% for the 75 mm green roof. For large storm events (> 35 mm) there was little difference seen between substrate depths where average retention per event was 13.2% and 15.9% for the 125 mm and 75 mm roofs, respectively. More research is needed to understand how the shallower roof slightly outperformed the deeper roof in this storm size category. One explanation might be that large storms could push stored water previously held by gravity into runoff, and deeper substrates presumably have more water in storage. Another explanation might be that the shallow roof heated up more quickly, evaporating water away and creating more storage capacity.

The antecedent dry period was found (Berkompas et al., 2008; Voyde et al., 2010) to be one of the most important parameters in predicting storm water performance. We also have evidence to support this in our study; substrate depth effects on runoff were more pronounced when there was a longer antecedent dry weather period (Figs. 7 and 8). Additional data on substrate moisture content or load cell measurements could be used to compare rates of evapotranspiration in the different substrate depths. However, due to the large size of the roof, we were not able to get readings that we felt would be representative of the different microclimates present.

For both substrate depths, performance in summer months was much higher than winter performance. The poor winter and strong summer performance demonstrated here has been reported in other similar studies of extensive green roofs, specifically in the Pacific Northwest (e.g. Spolek, 2008; Schroll et al., 2011; Berkompas et al., 2008). This is also consistent with the findings of Viola et al. (2017) whose model of green roof performance in different climate showed the worst performance in Mediterranean climates where rainfall and potential evapotranspiration were mismatched.

From our analysis it is apparent that consistently wet climates (such as the Pacific Northwest winter months) make it difficult for green roofs to retain a large fraction of incoming precipitation. While the average yearly rainfall in Portland is close to the national average, the number of wet days is higher than average resulting in soil moisture values that hover close to saturation levels for extended periods of time. At the same time, the region experiences several months of drought during the warm and dry summer months, with more than half of annual precipitation falling in the months of November through February. The strong dependence of green roof performance on weather conditions and the generally lower temperatures and extended periods of precipitation characteristic of the Pacific Northwest (Schroll et al., 2011) make it apparent that storm water management via green roofs for this region is a complicated task.

It is unlikely that irrigation affected the overall findings of this study that increasing substrate depth did not proportionally reduce annual runoff. This is largely a result of the fact that most of the runoff during the study period (> 70%) occurred during times for which no irrigation was applied. Due to the aforementioned dry summers, irrigation is typical of many green roofs in Portland. However, most of the green roofs documented in the local online database managed by the authors and the City of Portland (https://ecoroofs.research.pdx.edu/), do not report any irrigation information. For the 80 or so sites that do report on irrigation, 75 percent indicate some kind of watering practice. As such, despite the fact that the roofs in our study were irrigated, our findings are still broadly applicable since this practice is typical in our region.

Overall, ANCOVA analysis showed no significant effect of increased substrate depth on runoff that was consistent over the entire range of storms we experienced in our study (Fig. 5). This analysis is useful for identifying effects of greenroof design on runoff that might otherwise be masked by the large effect of storm size on runoff. However, using ANCOVA in this way does require the relationship between rainfall and runoff to be linear. Like others in our region (Schroll et al., 2011) we were able to demonstrate this relationship and carry out this test (Fig. 6). In other locations, where the rainfall/runoff relationship is for example, quadratic (Elliott et al., 2016), the curve may need to be sectioned out or a different test chosen. Future research should explore the effects of even more variable substrate depths on stormwater retention by green roofs, perhaps via modeling, for the Portland region.

The performance of a green roof in mitigating storm water is of greatest importance during storm events when flooding or combined storm water-sewage system overflow is possible. Even though the ANCOVA analysis didn't find a consistently higher rate of retention by the deeper roof, an annual 10% increase in retention from the deeper roof could have meaningful effects on stormwater management in the Portland region if this water storage comes at the right time of year. The benefit of additional substrate depth was shown in the study for the spring and fall months; this could have some effect on combined sewer overflow that could occur during late fall and early spring, but little effect was noted for winter storms when the risk of CSO would be greatest.

It should be further noted that these findings are based on measurements from irrigated green roofs planted in an herbaceous/succulent mix subject to the weather and precipitation of Portland Oregon. Future work should explore different design combinations that might increase retention in the Pacific Northwest. Especially given that this was a new roof constructed in 2014, it may even be possible that once the plants become more established that the depth effect on overall retention will increase. Through the process of evapotranspiration, for example, these plants may reduce the length of ADWP necessary to produce this desired retention. Variable substrate depth could allow for an increased plant palette (Thuring et al., 2010) as well as measures of plant growth such as coverage and root density (Durhman and Rowe, 2007; Getter and Rowe, 2009; Lu et al., 2015). A strong interaction between substrate depth and planting type was observed for 120 and 200 mm deep green roofs in Italy (Nardini et al., 2011).

5. Conclusions

By studying annual precipitation patterns, including frequency and magnitude of storm events, in various climates, better decisions can be made in regard to storm water management practices. In order for a deeper green roof to perform better than a shallow one, the soil must be dry enough so that its capacity to hold water is higher than the shallow roof. In conclusion, our findings suggest that when Portland's annual weather patterns and storm characteristics are taken into account, increasing green roof substrate depth by 50 mm may result in a 10% increase in annual retention. However, we also found that the effect of increased substrate depth was only statistically significant for 5–10 mm storms, accounting for only a third of the annual precipitation total. Future studies involving a larger range of substrate depths might reveal more substantial effects. We advise managers to consider whether the timing of the retention that results from added substrate depth is relevant to storm water management challenges. Thus, when designing a green roof system for storm water retention, it is imperative that efforts to increase storage capacity through increased substrate depth be paired with efforts to ensure rapid removal. If deeper substrates are to be utilized effectively; more research is needed to identify ways to increase evapotranspiration, for example via more informed plant selection, during wet winter months.

Conflict of interest

None.

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