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Analyses of the Effectiveness of Different Media Depths and Plant Treatments on Green Roof Rainfall Retention Capability under Various Rainfall Patterns

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Abstract: Green roofs have been used to reduce rainfall runoff by altering hydrological processes through plant interception and retention as well as detention within the green roof system. Green roof media depth, substrate type, plant type and density, regional climatic conditions, rainfall patterns, and roof slope all impact runoff retention. To better understand the impacts of media depth (10, 15, and 20 cm), plant (planted and non-planted), and rainfall pattern (low, medium, and high) on rainfall retention, we analyzed data collected between September 2005 and June 2008 from 24 green roof models (61 cm × 61 cm) for growing and non-growing seasons. Our results showed that a planted green roof has greater rainfall retention capability than a non-planted green roof for all media depths. Interestingly, a non-planted green roof system with a 10 cm media depth retained greater rainfall than a planted green roof during both growing and non-growing periods. Retention capability decreased with increasing rainfall amounts for both planted and non-planted green roofs and seasons (growing and non-growing). The 15 cm media depth green roof retained significantly greater rainfall depth than the 20 cm models during medium (0.64 to 2.54 cm) and high (>2.54 cm) rainfall events for the growing season but not during the non-growing season. The study provides insight into the interactive effects of media depth, rainfall amount, plant presence, and seasons on green roof performance. The results will be helpful for designing economical and effective green roof systems.

Keywords: green roof; media depth; rainfall retention; rainfall amount; growing and non-growing seasons; planted and non-planted green roof

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1. Introduction

Land development and urbanization disturb stable vegetated landscapes and increase impervious areas, which in turn increases the runoff concentrations of pollutants such as oil, sediment, grease, and other chemicals that are washed from impervious surfaces into nearby waterbodies [1–3]. Increased pollutant concentrations in runoff can also reduce the aesthetic value and public use of the receiving waterbodies. Urban impervious surfaces impede stormwater infiltration into the subsurface and groundwater, which results in larger stormwater runoff volumes, limited natural pollutant removal and neutralization processing via soil infiltration, and an increased risk of flooding [1,4–6].

According to the United States Environmental Protection Agency (EPA), a typical city block generates more than five times as much runoff as a forested watershed of the same size [7]. In addition, large urban stormwater runoff volumes and related water quality problems have become a growing concern for many municipalities in recent years. Higher runoff volumes due to imperviousness may cause problems with the hydraulic efficiency of old sewer systems [8,9] and cause combined sewer system overflows, which result in additional environmental harm. Some of the impacts of high stormwater runoff could be reduced through urban planning and good drainage practices.

As roofs account for a large portion of urban impervious surface cover, establishing vegetated roofs, otherwise known as green roof systems, is a potential strategy to recover lost green space, reduce urban stormwater runoff volume, and improve urban stormwater quality. Green roofs, which typically consist of plants in a specially designed growth media with a barrier to prevent plant roots from penetrating the roof membrane, can be used to reduce peak runoff flow [10–12] and increase stormwater retention [1,13]. Green roofs reduce the generation of runoff by altering hydrological processes through plant interception, evapotranspiration, infiltration, and detention within the green roof system [14,15]. They also provide better regulation of building temperatures, a reduced heat island effect, increased sound insulation, and improved longevity of the roof membrane and fire resistance [2,16–18].

Extensive and intensive are two common types of green roof systems based on the depth of the growth media [2,13,19]. Intensive green roofs typically have a variety of plants with deep substrates and the appearance of a conventional ground-level garden or park. Intensive green roofs can also augment living and recreational spaces in densely populated urban areas. They require substantial investments in plant care and convey a higher expectation of aesthetic value than extensive green roofs. Extensive green roofs typically have shallower growth media substrates of 20 cm or less, require less maintenance, are cheaper to construct and maintain, and are generally more strictly functional in purpose and accessibility than intensive green roofs [16,20].

The rainfall retention capacity of green roofs is driven by many variables, but most studies analyze the individual effects of variables [13,14,21]. Low-growing or mat-forming plants do not intercept as much rain as taller plants because of the smaller surface area exposed [14,15,22]. A study in Sweden showed that a green roof can retain about 50% of annual runoff due to evapotranspiration [23,24]. Plant root structure also influences the retention capacity of green roofs because it may affect the water retention capacity of the growth media [25]. The selection of plant species is vital to green roof establishment in any climate, especially in the volatile weather of the US Midwest region. Sedums are often used due to their drought tolerance and ability to store water [5,24,26]. Sedums are also tolerant of extreme temperature conditions, wind, and sun exposure [26].

Growth media depth also affects the ability of a green roof to retain stormwater. Evaporation from green roofs of 5 and 12 cm ranged from 60 to 79% of the annual rainfall in Germany [27]. A study in Michigan, USA, examined three media depths (2.5 cm, 4 cm, and 6 cm) at different roof slopes. The results showed that the combination of reduced slope and deeper media increased rainfall retention up to a maximum of 87% with a 4 cm depth at a 2% slope [21]. Other factors such as regional climatic conditions, green roof substrate, and roof slope and design affect the process of water loss, especially by evapotranspiration [14,15,18,19,23,26–28]. Furthermore, stormwater retention depends on local weather conditions, such as atmospheric temperature, previous drought periods and rainfall patterns, rainfall duration, and intensity [29]. The ability of vegetation to retain rainwater decreases with increasing rainfall amounts, intensity, and duration. In general, green roofs retain more water during climate conditions characterized by sporadic rainfall events [2]. Therefore, retention may be higher in areas with a temperate climate than in areas with a tropical climate [23,27,30].

Although the rainfall retention capacity of green roofs is driven by many variables and their interactions [31], most studies are focused on the individual effects of variables [13,14,26]. As green roofs are incorporated more frequently in building designs worldwide and awareness of the benefits of green roofs increases among policymakers and the public, more research is needed on both individual factors affecting the performance of green roofs as stormwater runoff reduction systems as well as the interaction of those factors to maximize their potential. Assessment of the efficacy of green roofs in runoff reduction is especially important in areas such as the US Midwest region, where the climate varies considerably, with rainy months followed by short- or long-term droughts and extreme temperatures [32]. In particular, data to evaluate the effectiveness of green roofs in retaining stormwater runoff at different growth media depths, plant treatments, rainfall amounts, and their interaction effects for different seasons (growing and non-growing seasons) are limited. The main goal of this study is to evaluate the effects of (i) growth media depth and plant presence on rainfall retention and (ii) individual and interaction effects of rainfall amount, growth media depth, and plant presence on rainfall retention.

2. Materials and Methods

2.1. Green Roof Models

Twenty-four green roof models were arranged on four tables in a completely randomized design with eight replications of 10 cm, 15 cm, and 20 cm of growth media at the Southern Illinois University Edwardsville (SIUE) Environmental Sciences field site. Two 12 cm glass rain gauges were also installed at the study site to collect rainfall data throughout the study period. Each of the 24 green roof models was a 61 cm × 61 cm block wooden frame with a wafer board substrate and an attached EPDM (ethylene propylene diene monomer) roofing membrane [33,34]. The green roof model had a sheet metal edging to retain growth media and a covered gutter connected to a drainage spout attached to the model. The drainage spout was then connected to a stormwater runoff collection container via a hose. Excess water after the green roof growth media was saturated was channeled through the gutter system to the collection container through the hose [33,34].

The "blended" components of the growth media are critical to the study and to understand some of the principles of the lightweight aggregate-based growth media used in green roof systems. The growing media in each green roof model consisted of 80% arkalite (Bussen Quarries, St. Louis, MO, USA; 6–9 mm expanded clay aggregate) and 20% composted pine bark (River City Landscape, Sauget, IL, USA). Each growth media depth had four replicates planted with *Sedum hybridum "immergrauch"* plugs and four replicates left unvegetated (Figure 1).

Figure 1. Green roof models at SIUE Environmental Sciences field site [33].

The sedums were irrigated manually for the first two weeks of the study as needed and monitored over 10 weeks. At the end of the 10 weeks, more than 30% of each planted green roof system was covered with plant foliage [33,34]. The green roof systems were then used to evaluate the impact of rainfall and plant and media depth on green roof performance in reducing runoff over the study period between September 2005 and June 2008.

2.2. Data Collection and Analyses

Rainfall runoff from each model green roof was collected after each precipitation event within the study period and weighed with a Mettler Toledo SB 32000 (Mettler-Toledo, LLC, Columbus, OH, USA) field balance (maximum weight capacity of 32,100 g). The on-site rain gauge provided the amount of rainfall, which was recorded after every rain event. Each collection system was disconnected from its respective green roof model prior to weighing, and the collection system was reassembled or attached to its respective green roof after weighing. The tare weight of the collection system was subtracted from the total weight of the collection system containing runoff to estimate direct runoff.

Past studies have shown that, generally, the retention capacity of a green roof decreases with increased total rainfall [21,30,35]. The rainfall amount was categorized to facilitate retention data analysis as follows:

- Rainfall amount I (low): total rainfall amount < 0.64 cm (0.25 inch)
- Rainfall amount II (medium): total rainfall amount 0.64 to 2.54 cm (0.25–1 inch)
- Rainfall amount III (high): total rainfall amount > 2.54 cm (1 inch)

The study period was split into growing (1 April to 31 September) and non-growing (1 October to 31 March) seasons. Data analysis of each substrate media depth (10, 15, and 20 cm) was performed to examine if deeper media in a vegetated green roof system provides an increased reduction in runoff quantity for both growing and non-growing seasons. The amount of rainfall retained by each green roof model was estimated by the difference between the rainfall and the runoff amount for each green roof. Additional analyses were conducted to examine the seasonal effect on retention. The green roof retention data collected in this study were analyzed using the R software package [36] to determine the differences in runoff retention at different growth media depths and seasons, considering various rainfall amounts.

2.2.1. Plant Treatment

We analyzed the rainfall retention capacity of planted and non-planted green roofs (plant treatment) for different growth media depths (i.e., 10, 15, and 20 cm) under high, medium, and low rainfall categories. The percentage of rainfall retention was calculated based on average rainfall retention divided by the average rainfall. A one-way analysis of variance (ANOVA) and a pair-wise Tukey honestly significant difference (HSD) test at an alpha (α) level of 0.05 were used to evaluate differences in rainfall retention capacity between planted and non-planted green roofs [37]. We used full/combined (i.e., growing and non-growing season data combined), growing season only, and non-growing season datasets for the analysis. Table 1 shows all analyses, tests, and datasets used to quantify the effect of different growth media depths and plant treatments on rainfall retention.

2.2.2. Media Depth

The green roof growth media depth was expected to influence the amount of rainfall retained in a similar manner on both the planted and non-planted green roof systems. Therefore, only the planted green roof systems were further analyzed to quantify the effects of growth media depth on rainfall retention. The effects of growth media depth on rainfall retention for growing and non-growing seasons were evaluated for different rainfall amounts using ANOVA and a pair-wise Tukey honestly significant difference (HSD) test at an alpha (α) level of 0.05 [37] (Table 1). Furthermore, variabilities of retention in different growth media depths were analyzed based on the coefficient of variation (CV).

Table 1. Different analysis to analyze effects of media depths and plant treatment in rainfall retention.

Analysis	**Green Roof**	**Media Depth (cm)**			**Rainfall Amount**			**Data**
				Plant Treatment Effect				
Plant vs. Non-plant (ANOVA, Tukey HSD)	P and NP							* Full/combined
Plant vs. Non-plant (ANOVA, Tukey HSD)	P and NP							Growing season
Plant vs. Non-plant (ANOVA, Tukey HSD)	P and NP							Non-growing season
Plant vs. Non-plant (Tukey HSD)	P and NP	10	15	20				* Full/combined
Plant vs. Non-plant (Tukey HSD)	P and NP	10	15	20	Low	Medium	High	Growing season
				Media depth effect				
10 vs. 15 vs. 20 (Tukey HSD, ANOVA)	P	10	15	20	Low	Medium	High	Growing and non-growing
				Individual and interaction effect				
** Media depth and plant treatment (ANCOVA)	P	10	15	20	Low	Medium	High	Growing and non-growing
** Rainfall amount and plant treatment (ANCOVA)	P	10	15	20	Low	Medium	High	Growing and non-growing
** Media depth and rainfall amount (ANCOVA)	P	10	15	20	Low	Medium	High	Growing and non-growing

* Full/combined: Data (without separation into growing and non-growing season) from September 2005 to June 2008. Growing season: Data during 1 April to 31 September; Non-growing season: Data during 1 October to 31 March. Rainfall amount- Low: less than 0.64 cm (0.25 inch); Medium: between 0.64 to 2.54 cm (0.25–1 inch); High: greater than 2.54 cm (1 inch). ** Individual and interaction effects; P: Planted; NP: Non-planted.

2.2.3. Individual and Interaction Effects

An analysis of covariance (ANCOVA) was used to determine the individual and interaction effects of growth media depth, rainfall amount, and green roof treatment on rainfall retention by the green roofs for growing and non-growing seasons [38,39]. An interaction between two predictor variables means that the effect of one variable on the response depends on the value of the second variable [31]. Therefore, the response variable is influenced by the interaction effects of the two predictor variables. The ANCOVA test was performed using growing and non-growing season data. For each ANCOVA dataset, linear regression models were created with retention as the response (independent) variable and media depth, rainfall amount, and green roof treatment (planted or non-planted) as the predictor (dependent) variables.

3. Results

3.1. Plant Treatment

The planted green roofs retained significantly ($\alpha = 0.05$) more rainfall than the non-planted green roofs based on ANOVA and Tukey HSD for the full/combined dataset from 2005 through 2008 (Figure 2a). Similar trends were observed for growing and non-growing seasons, while the difference was not significant ($\alpha = 0.05$) for the non-growing season (Figure 2a). The differences were 9%, 12%, and 7% for full/combined, growing, and non-growing datasets, respectively. The planted green roofs retained higher rainfall for all growth media depths than the non-planted roofs retained for the growing season (Figure 2b). However, the differences were not significant for any media depths based on the Tukey HSD pair-wise test.

Planted green roofs retained more rainfall than non-planted roofs for growth media depths of 15 and 20 cm for all rainfall amounts (Figure 2c), considering full/combined datasets. However, the trend was reversed for the growth media depth of 10 cm, where the retentions were higher for non-planted roofs (Figure 2c). The differences were not statistically significant ($\alpha = 0.05$) for any growth media depth or rainfall amount based on the Tukey HSD pair-wise test. The percentage of rainfall retention decreased from low to high rainfall amounts at each growth media depth for both planted and non-plated green roofs (Figure 2c). For example, rainfall retention in planted green roofs decreased from 94% (low) to 46% (high) for 15 cm growth media depth considering full/combined datasets (Figure 2c).

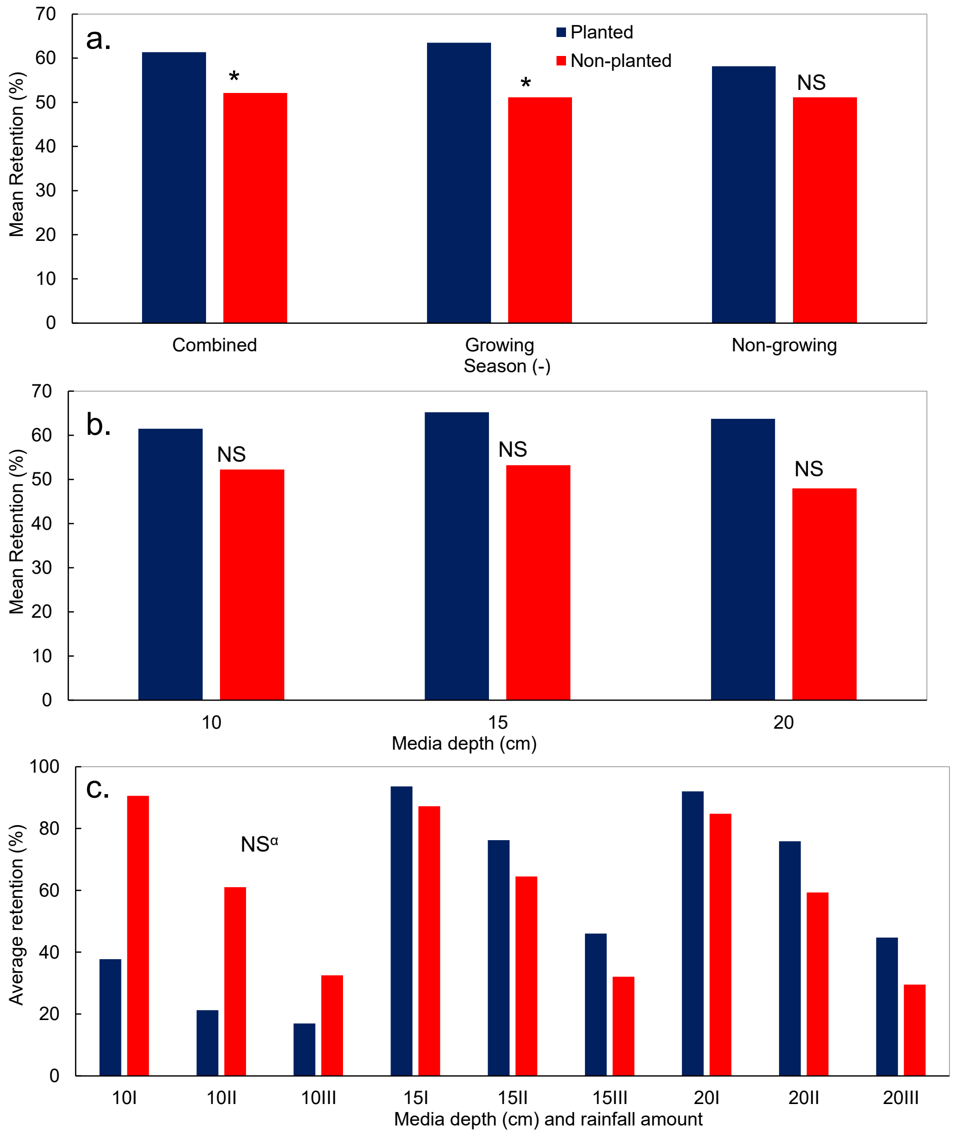

Figure 2. Percentage (%) of average rainfall runoff retention by planted and non-planted green roof systems. * indicates the difference is statistically significant at $\alpha = 0.05$, whereas NS is not statistically significant. (**a**) Considering full/combined, growing and non-growing seasons datasets regardless media depth, and rainfall amount; (**b**) different media depths (10, 15, and 20 cm) in the growing season; and (**c**) Different media depths and rainfall amount considering full/combined datasets. Rainfall amounts I, II, and II represent low, medium, and high rainfall, respectively. NS^{α} indicates the difference is not statistically significant for any media depth or rainfall amount.

3.2. Media Depth

The average rainfall retained increased as the growth media depth and the rainfall amount increased in both growing and non-growing seasons (Figure 3). The average rainfall retained by the 15 cm media depth green roof was greater than the 10 and 20 cm under all rainfall amounts for both the growing and non-growing seasons. The CV, which indicates retention variability in green roofs, increased with media depth for both growing and non-growing seasons (Table 2). For example, CV increased from 0.62 to 0.72 for media depths of 10 cm to 20 cm for the growing season for low rainfall amounts (<2.54 cm).

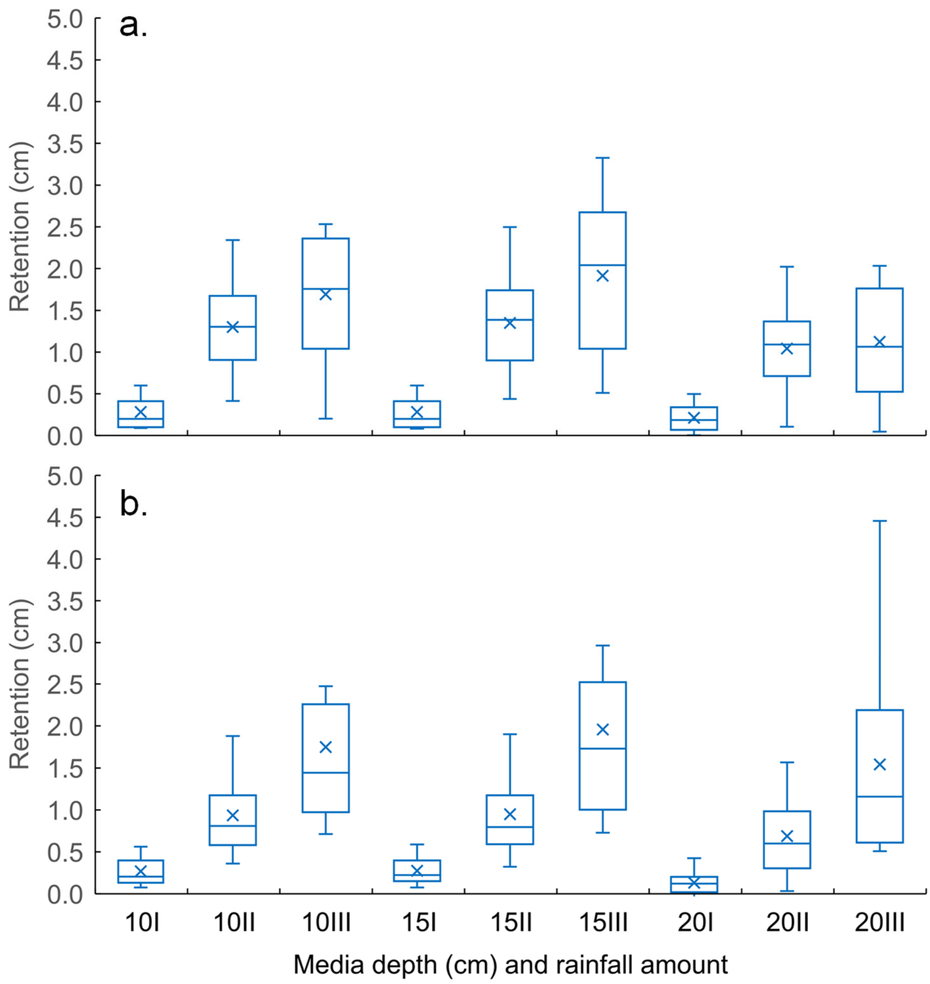

Figure 3. Rainfall retention distribution in planted green roofs at different depths and rainfall categories during (**a**) growing season and (**b**) non-growing season. Rainfall amounts I, II, and II represent low, medium, and high rainfall, respectively. Box plot represents the lowest, highest, first quartile (25th percentile), median (50th percentile), and third quartile (75th percentile) values. The sign "X" represents the mean value.

Table 2. ANOVA and Tukey HSD test to analyze effects of green roof media depths on rainfall retention for different rainfall amounts and seasons. * indicates statistically significant at $\alpha = 0.05$, whereas NS is statistically not significant. Rainfall amounts I, II, and II represent low, medium, and high rainfall, respectively. Coefficient of variation (CV) is calculated for retention variability for different green roof media depths and rainfall amounts.

Pair	Growing Season (Tukey HSD)			Non-Growing Season (Tukey HSD)		
	I	II	III	I	II	III
10 vs. 15	NS	NS	NS	NS	NS	NS
10 vs. 20	NS	NS	NS	*	NS	NS
15 vs. 20	NS	*	*	*	NS	NS
ANOVA	NS	*	*	*	NS	NS
	Coefficient of variation (CV)					
10	0.62	0.42	0.44	0.54	0.47	0.63
15	0.62	0.44	0.45	0.55	0.48	0.58
20	0.72	0.49	0.62	1.00	0.65	0.71

3.2.1. Growing Season

The average rainfall retention was 0.3, 0.3, and 0.2 cm for growth media depths of 10, 15, and 20 cm, respectively, under low rainfall amounts (<2.54 cm) (Figure 3a). The ANOVA test showed no significant difference at $\alpha = 0.05$ (Table 2). The pair-wise comparison based on the Tukey HSD test did not show statistically significant differences for any media depth pair (i.e., 10 vs. 15 cm, 15 vs. 20 cm, and 10 vs. 20 cm) (Table 2).

The average retention was 1.3, 1.3, and 1.1 cm for growth media depths of 10, 15, and 20 cm, respectively, for medium rainfall amounts (0.64–2.54 cm) (Figure 3a). There were statistically significant differences between the average rainfall retained in different depths at $\alpha = 0.05$ (Figure 3a, Table 2). However, the pair-wise comparison based on the Tukey HSD showed a statistically significant difference only for the growth media depth pair of 15 vs. 20 cm (Table 2).

The average rainfall retention was 1.7, 1.9, and 1.1 cm, respectively, for growth media depths of 10, 15, and 20 cm under high rainfall amounts (>2.54 cm). Similar to the medium rainfall amount, there were statistically significant differences between the average rainfall retained by the different depths at $\alpha = 0.05$ (Figure 3a and Table 2). The pair-wise comparison for media depths based on the Tukey HSD showed a statistically significant difference only for the media depth pair of 15 vs. 20 cm (Table 2).

3.2.2. Non-Growing Season

Similar to the growing season, the average rainfall retention during the non-growing season under the low rainfall amount was 0.3, 0.3, and 0.1 cm for growth media depths of 10, 15, and 20 cm, respectively (Figure 3b). The ANOVA test for differences in rainfall retention between the 10 cm, 15 cm, and 20 cm growth media depths was statistically significant at $\alpha = 0.05$ (Table 2). The pair-wise comparison based on the Tukey HSD showed a statistically significant difference for the media depth pairs of 10 cm vs. 20 cm and 15 cm vs. 20 cm at $\alpha = 0.05$ (Table 2).

The average rainfall retention was 0.9, 0.9, and 0.7 cm, respectively, for growth media depths of 10, 15, and 20 cm under medium rainfall amounts. Based on the ANOVA test, these differences in rainfall retention were not statistically significant at $\alpha = 0.05$ (Figure 3b, Table 2). Similarly, based on pair-wise comparison, none of the pairs (i.e., 10 vs. 15 cm, 15 vs. 20 cm, and 10 vs. 20 cm) was statistically significant (Table 2).

The average rainfall retention depths were 1.7, 2.0, and 1.5 cm, respectively, for growth media depths of 10, 15, and 20 cm under high rainfall amounts. However, the differences between the average rainfall retained were not statistically significant at $\alpha = 0.05$ (Figure 3b, Table 2). In addition, the pair-wise Tukey HSD test showed that the differences in average rainfall retention were not statistically significant for any media depth pair (Table 2).

3.3. Individual and Interaction Effects

3.3.1. Growing Season

The individual influence of growth media depth was not statistically significant for green roofs on rainfall retention capacity at $\alpha = 0.05$ during the growing season (Table 3). However, the individual influence of plant treatment on rainfall retention was statistically significant. Therefore, the growth media depth impacts rainfall retention in a similar manner on both planted and non-planted green roofs. Furthermore, the interaction between growth media depth and plant treatment was not statistically significant for the growing season (Table 3).

The effects of rainfall amount and plant treatment on rainfall retention showed a statistically significant difference for the individual variables and interaction between them for the growing season at $\alpha = 0.05$ (Table 3). Since the interaction effect of rainfall amount and plant treatment was statistically significant, retention depended on rainfall amount, regardless of whether or not plants were present.

Table 3. Individual and interaction effects of different variables on rainfall retention for growing and non-growing season. * indicates statistically significant at α = 0.05, whereas NS is statistically not significant.

Variables	Individual Effect			Interaction Effect
	Media Depth	Plant Treatment	Rainfall Amount	
	Growing season			
Media depth and plant treatment	NS	*		NS
Rainfall amount and plant treatment		*	*	*
Media depth and rainfall amount	NS		*	NS
	Non-growing season			
Media depth and plant treatment	NS	NS		NS
Rainfall amount and plant treatment		NS	*	NS
Media depth and rainfall amount	NS		*	NS

Rainfall amount had a statistically significant (at α = 0.05) effect on the retention capability of green roofs during the growing season (Table 3). However, the growth media depth did not influence rainfall retention significantly. Furthermore, the interaction between growth media depth and rainfall amount did not influence rainfall retention statistically. Therefore, rainfall retention will be similar for all green roofs regardless of growth media depth (i.e., 10, 15, and 20 cm).

3.3.2. Non-Growing Season

Individual and interaction of growth media depth and plant treatment did not influence rainfall retention at α = 0.05 during the non-growing season. Therefore, growth media depth or planted or non-planted green roofs do not alter rainfall retention capability (Table 3).

The individual effect of rainfall amount was statistically significant on rainfall retention at α = 0.05 for the non-growing season, whereas there is an opposite effect for plant treatment. This showed that rainfall amount affects the retention capacity of rainfall on a green roof. The interaction of plant treatment and rainfall amount did not have a statistically significant influence on rainfall retention at α = 0.05 in the non-growing season (Table 3).

Similarly, only the individual effect of rainfall amount was statistically significant for rainfall retention of green roofs at α = 0.05, but not for growth media depth. Furthermore, interactions between rainfall amount and media depths were not statistically significant for rainfall retention (Table 3).

4. Discussion

This study examined the effect of green roof growth media depth, plant treatment (planted or non-planted), and rainfall amount on rainfall retention during the growing (1 April to 30 September) and non-growing (1 October to 31 March) seasons over a 3-year period. Overall, there were differences in the average rainfall retained by the green roofs for different rainfall amounts and plant treatments. However, varying the media depth did not result in statistically significant differences in rainfall retention.

4.1. Planted and Non-Planted Green Roof

In general, the planted green roofs retained a statistically significant higher rainfall than the non-planted green roof systems, considering full/combined and growing season datasets for all growth media depths. However, there was no statistically significant difference for the non-growing season. Furthermore, the influence of plant treatment was statistically significant for individual and interaction with different variables (i.e., media depth and rainfall amount), whether it was paired with growth media depth or rainfall amount for both growing and non-growing seasons (Section 3.3 and Table 3). This result is consistent with past studies that have shown that vegetated green roofs have significantly greater rainfall retention compared to bare substrates [19,40] and that sedum-type vegetation planted in green roof systems can transpire moisture up to 40% of a green roof's capacity depending on the size and timing of storm events [5].

Past studies concluded that the depth and type of growth media have much larger impacts on green roof retention capacity than the vegetation type [22,26]. However, vegetation plays an important role in removing water when rainfall exceeds the retention capacity of growth media [41]. Sedums can tolerate a wide range of temperatures, and their storage capacity is influenced by varying temperatures and humidity [25]. The greater rainfall retention observed in the planted green roof systems could be due to a combination of canopy interception, plant water use, and evapotranspiration [18].

Nevertheless, the differences between rainfall retention between various vegetation types and bare-growing media were negligible during the winter (non-growing) season but significant during the summer (growing) season [22,23]. We also observed a similar trend, with rainfall retention greater during the growing season than in the non-growing season (Figure 3). Interestingly, the non-planted green roof retained greater rainfall (%) than the planted roof at the 10 cm media depth, which was opposite of the 15 and 20 cm media depths. The hypothesis is that the bare growth media depth was able to dry faster because the vegetation provided coverage of the growth media, which resulted in less evaporation [22].

The amount of rainwater retained by the planted green roof systems in this study varied by season under the same rainfall amount, suggesting the effect of seasonal changes on green roof retention capacity. More rainfall was retained during the growing season than the non-growing season under rainfall amounts greater than 0.25 inches (medium and high rainfall), which is consistent with other studies [14,30]. Furthermore, vegetation had no significant influence on water retention during the winter rainy (non-growing) season compared to growth medium-only and vegetated roofs, whereas, vegetated green roofs retained significantly greater rainfall compared to growth medium-only roofs during the summer (growing) months in a study [14].

The resulting differences in green roof retention during the growing and non-growing seasons may partially be due to the effect of temperature differences during each season. For Southern Illinois, the non-growing season (October through March) has low to moderate temperatures compared to moderate to high temperatures during the growing season (April through September). The highest temperatures typically occur in the summer months of June, July, and August, with the average high temperature being near 32 degrees Celsius. Given the increased temperatures during the growing season, the evapotranspiration rate of the planted green roofs is greater than during the cool and humid non-growing season. A greater substrate capacity is created in the planted green roof systems on hot and dry days to facilitate rainfall retention by the green roofs compared to cool and humid days [30].

4.2. Media Depth

In general, growth media depth was not the major variable that impacted rainfall retention capacity in this study (Section 3.2, Tables 2 and 3). The planted green roofs with a larger substrate depth were expected to store more rainfall. As expected, the results for 15 cm green roof models showed an increase in rainfall retention over the 10 cm media depth (Figure 3). The retained rainfall in the growth media evaporates, is transpired, and is used by the plants, which explains the runoff volume reduction using green roofs [2,30]. Under dry initial soil conditions, rainfall can be both retained and detained, whereas only detention is possible for initially wet conditions [23]. The observed variability of rainfall retention in this study and other green roof research indicates the necessity of more research and long-term monitoring locally [2,22].

However, the models with 20 cm growth media depth retained statistically significantly reduced amounts of rainfall compared to the green roof with 15 cm growth media depth for medium and high rainfall amounts in the growing season (Figure 3), which is consistent with [21]. Furthermore, rainfall retentions were not statistically significantly different for any growth media depth pairs for medium and high rainfall amounts during the non-growing season (Table 2). This observation is due to the deeper growth media remaining saturated from previous rainfall events longer than in the shallower depths. A past study concluded that deeper substrate thickness did not dry faster [26]. A greater proportion of water is available in the media layer; therefore, when additional rainfall occurs, there is less rainfall retention [21,35].

4.3. Study Application

Our study results are consistent with previous studies that show the rainfall retention in a green roof varies based on season, rainfall amount, plant treatment, and growth media depth due to potential evapotranspiration and antecedent moisture conditions [14,21]. This is an important finding of the study because the result not only showed how growth media depth affects green roof retention capacity but also demonstrates the potential financial cost of implementing a green roof. While this study showed that increasing media depth past 15 cm does not increase retention, media depth plays other important roles, for example, protecting plants from freezing injury, improving their growth performance, and improving the roof's drought tolerance [15,26].

In order for green roofs to thrive in any climate, research is necessary to determine which growth media depth provides the greatest rainfall retention for different rainfall amounts during growing and non-growing seasons and the best-growing environment for the vegetative layer. Due to the variability in climate conditions across the geographic region and the influence of the timing and intensity of rainfall events and the effects of growth media depth on the retention capacity of green roofs, it is important to research green roof performance both regionally and locally.

5. Conclusions

This study provided insight into the individual and interactive effects of growth media depth, rainfall amount, plant presence, and season on green roof performance. Planted green roof models retained greater rainfall than non-planted green roofs considering data for the growing (12%), non-growing (7%), and full/combined seasons (9%). The rainwater retained by green roofs with 10 cm, 15 cm, and 20 cm growth media depths decreased with increasing rainfall amounts for both planted and non-planted models and seasons. However, a planted green roof with a 15 cm growth media depth retained the greatest percentage (46%) and absolute average rainfall depth (1.97 cm) considering both growing and non-growing seasons for high rainfall events (>2.54 cm). There were no statistically significant differences in rainfall retention performance by different growth media depth green roofs at $\alpha = 0.05$, but it depends on the rainfall amount and plant treatment. During low rainfall events (<0.64 cm), retention was not statistically different between various growth media depths in planted green roof models in the growing season. However, during medium (0.64 to 2.54 cm) and high (>2.54 cm) rainfall events, the 15 cm growth media depth green roof models retained significantly greater rainwater than green roofs with a 20 cm growth media depth for the growing season but not for the non-growing season. Additional studies are necessary to optimize retention capacity and balance retention capacity versus other benefits and uses of green roofs (e.g., aesthetics). Therefore, to optimize the retention capacity and economical design of green roofs, research should be focused on growth media depth, plant water use, rainfall density and distribution, and regional climate.

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