Rainwater retention capacity of green roofs in subtropical monsoonal climatic regions: a case study of Taiwan

C. F. Fang
Department of Landscape Architecture,
National Chin-Yi University of Technology, R.O.C.

Abstract

This study investigates how roof substrate and vegetation affect rainwater retention. The investigated parameters are lightweight substrate ratio, substrate depth, precipitation and vegetation type. A planting box was placed on the roof of a building to simulate a green roof. Scheduled artificial rainfall was used to test the rainwater retention capacity of various substrates, substrate depths and plant types. The experimental results indicate that precipitation, substrate depth, substrate ratio and vegetation type affect the rainwater retention capacity of green roofs. The rainwater retention rate is inversely proportional to precipitation intensity; that is, about 87–100% of rainwater is retained for light rain, 62–84% for moderate rain and only 26–33% for heavy rain. Different plants have different abilities to retain rainwater. In this study, *Dianella ensifolia* cv. 'Silvery Stripe' and *Schefflera arboricola* have the best water retention rates of 37–100%. Of the total amount of rainwater retained, the substrate accounts for 77–98% and vegetation accounts for 2–23%. In the sub-tropical region, the green roof water retention rate is roughly 30% of the total storm precipitation (100 mm). Thus, using a green roof is an effective strategy for managing urban stormwater.
Keywords: lightweight substrate, precipitation, rainwater retention, substrate depth, substrate ratio.

1 Introduction

As water cannot penetrate paved surfaces, rainwater cannot percolate into the ground, leading to significant surface runoff that can increase river erosion and

WIT Transactions on Ecology and the Environment, Vol 138, © 2010 WIT Press
www.witpress.com, ISSN 1743-3541 (on-line)
doi:10.2495/DN100211

cause flooding. However, if urban roof tops were transformed into green roofs, municipal surface runoffs can be effectively reduced [6].

Green roofs can retain about 60–100% of rainwater [1, 4, 6, 7, 13]. Kolb [4] showed that 45% of rainfall can be recycled by green roofs. Additionally, green roofs can delay the runoff by about 95 min to 4 hours. The primary factors affecting the water retention capacity of green roofs include substrate depth [6, 7], precipitation [6] and vegetation [14]. Most studies of the water-retention capability of green roofs are conducted in Germany, Sweden and the US, nations located in temperate zones.

Annual precipitation in Taiwan, which is located in a sub-tropical zone, is as high as 2400 mm. Every year, 3–4 typhoons bring massive amounts of precipitation (500–1400 mm) within a short period. The climate in Taiwan is markedly different from the temperate climate; thus, green roof research results for temperate zones cannot be applied to Taiwan. If studies address the climate, substrates and vegetation in Taiwan, experimental results for green roof rainwater retention rainwater will be valuable references when developing policies to manage urban stormwater.

This study examines the effectiveness of green roof substrates and vegetation on rainwater retention in sub-tropical Taiwan. Substrate mixing ratio, substrate depth, precipitation and vegetation are the parameters investigated. Boxes containing substrate and vegetation were placed on a rooftop; a known quantity of water was administered to simulate precipitation for determining the rainwater retention capacity of the planting box. The experimental results will be a reference for managing stormwater surface runoff.

2 Methods

2.1 Rooftop planting box

A plastic planting box, 60 cm (L) × 48 cm (W) × 16 cm (H), had drain holes drilled in its bottom surface. Starting at the bottom, the box contained a drainage and water-retention layer, non-woven material, lightweight substrate and vegetation (Figures 1, 2).

2.2 Substrates ratio

Lightweight substrates are used to reduce the weight load on a roof. Three lightweight substrates, *i.e.*, perlite, vermiculite and peat moss, are mixed at a 1:1:1 volume ratio. This mixture is then blended with sandy soil to form the following final substrates: 60% lightweight substrate; 80% lightweight substrate; and 100% lightweight substrate.

The 60% lightweight substrate contains 60% lightweight substrate and 40% sandy soil with a 20:20:20:40 volume ratio of perlite, vermiculite, peat moss and sandy soil, respectively.

The 80% lightweight substrate contains 80% lightweight substrate and 20% sandy soil with a 26.7:26.7:26.7:20 volume ratio of perlite, vermiculite, peat moss and sandy soil, respectively.

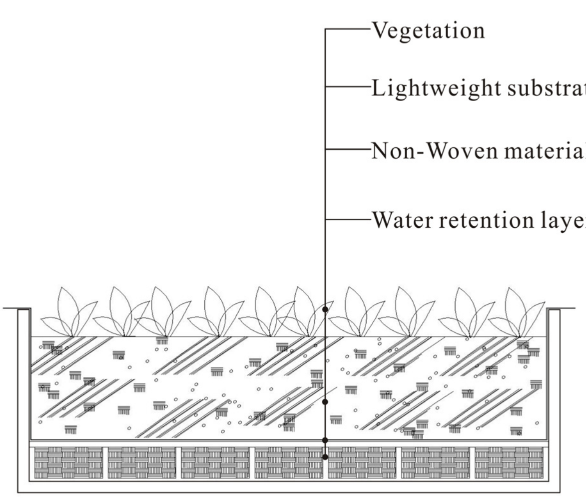

Figure 1: Schematic diagram showing a cross-section of the green roof.

Figure 2: The experiment on rainwater retention capacity.

The 100% lightweight substrate contains 100% lightweight substrate with a 33.3:33.3:33.3 volume ratio of perlite, vermiculite and peat moss, respectively.

Additionally, the influence of substrate depth on rain retention is studied using substrate depths of 5cm, 10 cm and 15 cm.

2.3 Water sprinkling rates

According to Taiwan's Central Weather Bureau, 10 mm of precipitation is considered light rain, 30 mm is considered moderate rain and 100 mm is considered heavy rain. These precipitation amounts are converted based on planting box area into water sprinkling amounts of 2880 cc, 7000 cc and 28800 cc to simulate light rain, moderate rain and heavy rain, respectively.

2.4 Rain retention capacity

Water is sprinkled at 50 cm above the planting box for 30 min. The watered box is then undisturbed for 1 day; the quantity of water collected in the collection box is recorded as drained water. The rainwater retention capacity is the difference between the amount of water sprinkled and that drained. The water retention ratio is the water retention capacity divided by precipitation. The experiment is conducted on the roof of an administrative building on the campus of National Chin-Yi University of Technology, central Taiwan.

2.5 Experimental type

The experiment was carried out in two phases. The objective of the first phase is to study the influence of substrate ratio, substrate depth and precipitation on rainwater retention capacity. The objective of the second phase is to examine the influence of various vegetation types on rainwater retention capacity.

2.5.1 Experiment I

The parameters evaluated in this experiment are substrate ratios (60%, 80% and 100% lightweight substrate), substrate depths (5, 10 and 15 cm) and precipitation

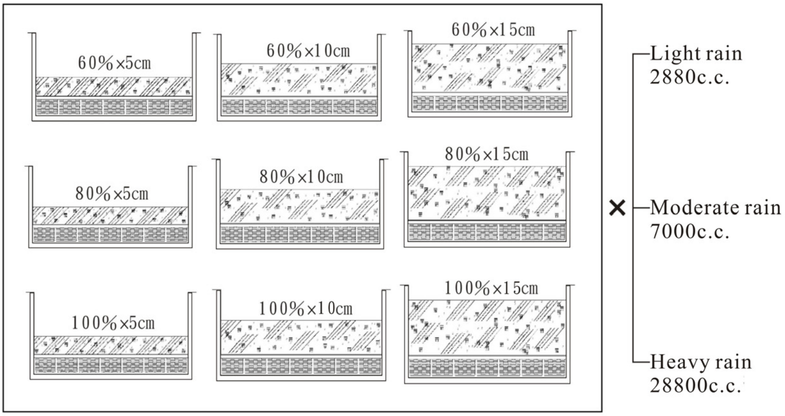

Figure 3: Schematic diagram of planting boxes with various substrate depths and lightweight substrate.

intensities (light, moderate and heavy rain) for a total of 27 combinations. Each combination is repeated 8 times; the average of 8 datasets is used. The experiment was carried out during April–October 2009. Figure 3 shows experimental parameter combinations. All substrates are cured and dried naturally 1 week prior to use in the experiment.

2.5.2 Experiment II

Five vegetations types, *Schefflera arboricola*, *Belamcanda chinensis*, *Wedelia trilobata*, *Dianella ensifolia* cv. 'Silvery Stripe,' and *Zoysia* spp., are planted in 80% lightweight substrate at a depth of 15 cm under simulated light, moderate and heavy rain. Each condition is repeated 8 times and the average is used in evaluation. All substrates and vegetation are cured and dried naturally 1 week prior to use in the experiment.

3 Experimental results

3.1 Precipitation and substrate

The rainwater retention capacity was relatively low under light rain and relatively high under heavy rain (Figure 4), indicating that the substrate rainwater retention capacity is proportional to precipitation; water retention during heavy rain is almost triple that during light rain. However, when the ratio of water retention to total precipitation is considered, the substrate can retain 87–100% of total precipitation for light rain, 62–84% for moderate rain and only 26–33% for heavy rain. The 60% lightweight substrate has the best rainwater retention capacity, followed by 80% lightweight substrate (Figure 4).

Table 1: The ANOVA of rain water retention from precipitation, substrate ration and substrate depth.

Source	S	df	MS	F	Sig.
Precipitation	1.1E+09	2	5.6E+08	889.741	.000***
Substrate ration	1.3E+07	2	6259934	9.891	.000***
Substrate depth	2.1E+07	2	1.0E+07	16.378	.000***
Precipitation* Substrate ration	5322755	4	1330689	2.103	.082
Precipitation* Substrate depth	9387963	4	2346991	3.708	.006**
Substrate ration* Substrate depth	3369769	4	842442	1.331	.260
Precipitation* Substrate ration* Substrate depth	5703501	8	712938	1.126	.347
Residual	1.2E+08	189	632902		
Total	7.4E+09	216			

*R^2 = .908; ** $P \leq 0.01$; *** $P \leq 0.001$.

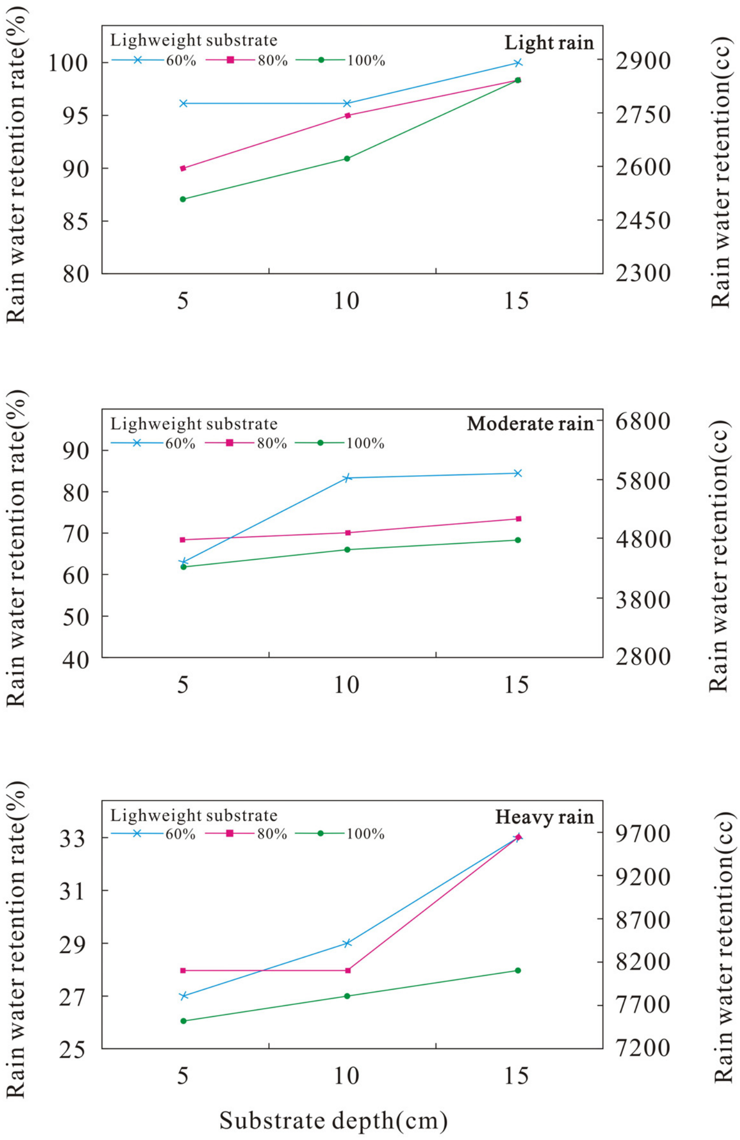

Figure 4: The rainwater retention capacity for various substrates under 10 mm of precipitation for light rain, 30 mm for moderate rain and 100 mm for heavy rain.

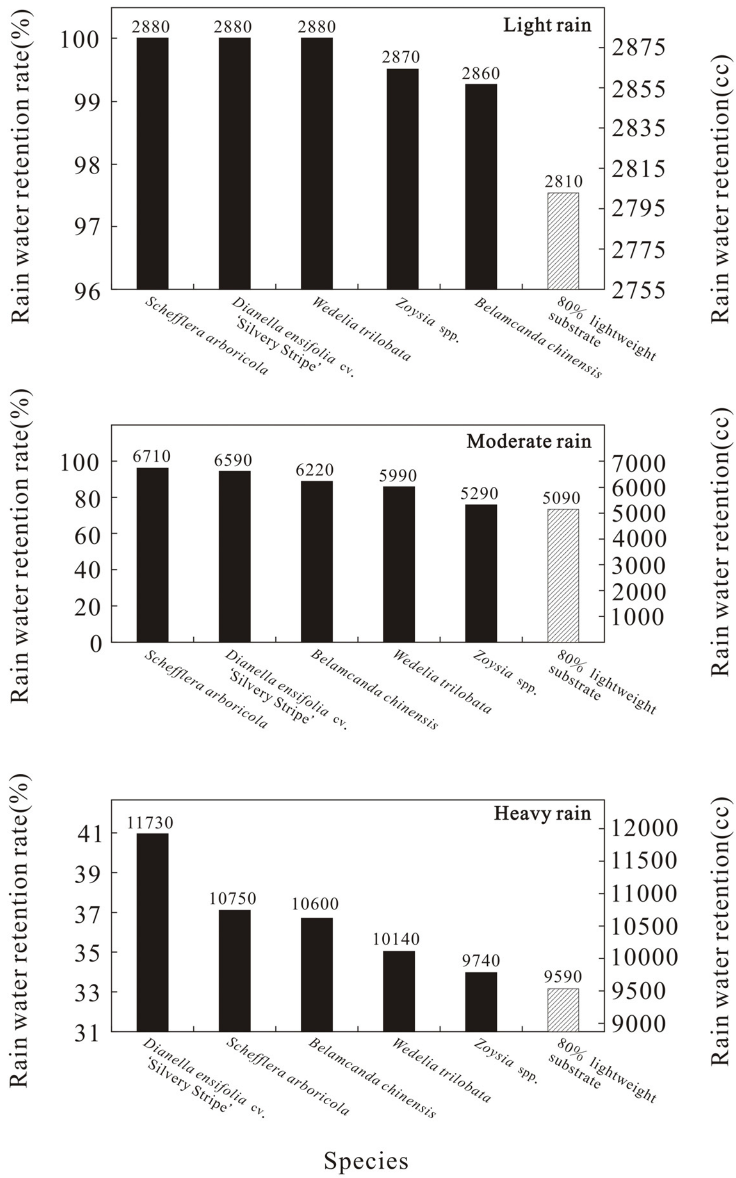

Figure 5: The percentage of rainwater retention for vegetation types (light rain, 10 mm; moderate rain, 30 mm; and heavy rain, 100 mm).

A three factorial ANOVA is applied identify the important factors for rainwater retention by green roofs. The dependent factor is rainwater retention and independent factors are precipitation, substrate depth and substrate ratio. Precipitation, substrate depth and substrate ratio are the significant parameters influencing rainwater retention capacity (Table 1).

3.2 Green roof with different vegetation types

The green roof using a 15-cm-deep layer of 80% lightweight substrate retains 99–100% of rainwater under light rainfall (10 mm), 76–96% of rainwater under moderate rain (30 mm) and 34–41% of rainwater under heavy rain. *Dianella ensifolia* cv. 'Silvery Stripe' and *Schefflera arboricola* retain water best, rainwater and *Zoysia* spp. has the worst rainwater retention rate (Figure 5).

The substrate accounts for 77–98% and the vegetation accounts for 2–23% of total rainwater retained. Hence, the substrate is an extremely important parameter for retaining rainwater.

4 Discussion

Experimental results reveal that heavy precipitation is associated with the highest amount of rainwater retained (Figure 4). However, the water retention rate is lowest for heavy rainwater. This is because precipitation exceeds the total retention capacity, an observation in agreement with that made by Nicholaus *et al*. [8]. Combining the data obtained by Nicholaus *et al*. [8] and that acquired by this study, to discuss the relationship between precipitation and rainwater retention rate of ecological roof (Figure 6). Although the precipitation in the study by Nicholaus *et al*. [8] differs from that in this research, similar negative relationships were found between substrate retention capacity and precipitation. Nicholaus *et al*. [8] reported a rainwater retention of 38.9–99.3%, rainwater whereas that in this study was 26–87% rainwater. The lower rainwater retention rate in Taiwan is likely caused by that fact that temperate regions receive 2–10 mm of per precipitation, whereas sub-tropical Taiwan receives 10–100 mm of per precipitation, exceeding the capacity of soil to retain water.

Figure 4 shows the linearly proportional relationship between substrate depth and rainwater retention effectiveness. A deep substrate layer has more volume for storing rainwater than a shallow layer rainwater. Nicholaus *et al*. [8] reported that water retention capacity increased as substrate depth increased. Some researchers have considered the substrate depth also influence vegetation growth, drought stress and drought tolerance [2, 7, 8]. Hence, a deep substrate is recommended to enhance vegetation growth and rainwater retention capacity. We suggest that substrate depth should exceed 15 cm for a green roof to be effective in retaining rainwater in sub-tropical regions subject to considerable amounts of precipitation.

Experimental results obtained by this study show that the substrate is more important that the vegetation species to rainwater retention efficiency. Monterusso *et al*. [7] made the same observation. Because water is directly

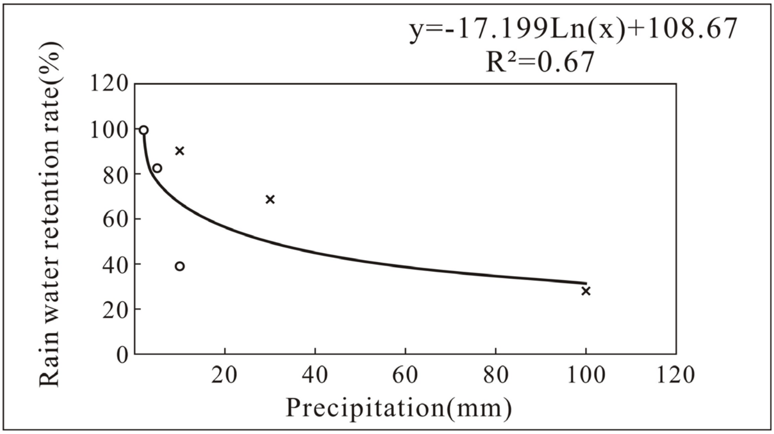

Figure 6: Regression analysis on the relationship between the logarithmic rainwater retention quantity and precipitation. O: Data obtained by Nicholaus *et al.* [8] for a 6-cm-deep substrate without vegetation. X: Data from this study for a 5-cm-deep substrate without vegetation.

retained in the substrate void and vegetation absorbs water through absorption and evaporation, the rate of water retention for vegetation is slower than that for a substrate. Although vegetation is not as effective as substrates in retaining rainwater, vegetation prevents soil loss and solar radiation impacting green roofs [3, 5, 8], provides habitat, reduce the heat by evaporation [9, 11], mitigates air pollution [10] and elevate the amenity [14].

Most studies in temperate regions used <10 mm of precipitation and obtained rainwater retention percentages of 40–100% [7, 12]. In this study water retention capacity for light rain of 10 mm precipitation was also 99.5–100%. Although the rainwater retention rate of a green roof is only 34–41% for heavy rain, this water retention rate is still valuable when managing urban stormwater.

High-intensity rainfall during the monsoon season in sub-tropical regions is a significant challenge for managing municipal stormwater surface runoff. Although green roofs cannot absorb all rainwater, green roofs mitigate the adverse impact of stormwater and, thus, are an effective option for managing municipal stormwater surface runoff. Additionally, green roofs are more cost-effective than other techniques for managing stormwater.

5 Conclusions and recommendations

The effectiveness of using green roofs for retaining rainwater was assessed in this study using substrate ratio, substrate depth, precipitation and vegetation as parameters.

1. Precipitation, substrate depth, substrate ratio and vegetation affect the rainwater retention capacity of a green roof.

2. The rainwater retention capacity of a substrate is proportional to precipitation. However, the rainwater retention rate is inversely proportional to precipitation because substrates have a limited number of voids for storing water. Once the rainwater retention capacity is reached, a substrate cannot retain additional water.
3. Substrate ratio is proportional to rainwater retention efficiency; the 60% lightweight substrate has the highest rainwater retention rate, followed by 80% and 100% lightweight substrates.
4. The green roof with a substrate layer 15 cm deep retained 98–100% of precipitation for light rain, 68–84% for moderate rain and 28–33% for heavy rain. Water retention was 77–98% by the substrate and 2–23% by vegetation. Thus, substrate was the most important factor for rainwater retention and vegetation type was of minor importance.
5. In sub-tropical regions, green roofs can retain 28–33% of rainwater during heavy rain (100 mm). Although all stormwater is not absorbed, green roofs are an effective strategy for managing urban stormwater. Additionally, green roofs are inexpensive to build as they utilize unused rooftops.

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