Water quantity investigation of simulated green roofs in a tropical climate: influence of vegetation composition

Investigação da quantidade de água de telhados verdes simulados em um clima tropical: influência da composição da vegetação

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ABSTRACT: Green roofs are recognized as a sustainable infrastructure to improve the environmental quality of cities. Among many benefits, green roofs reduce the rate and volume of runoff helping to improve rainwater management. This study investigated the runoff retention capacity of three pilot extensive green roof assemblies with different vegetation (grass, shrub and intercropping of the two plants). Rainwater runoff data were collected for 18 rainfall events that ranged from a minimum of 1.6 mm to a maximum of 157.9 mm. Average precipitation event retention efficiencies were 46.7, 59.7 and 61.6% for intercropped, shrub and grass green roofs, respectively, while the annual runoff retention rates were 43.8, 57.3 and 59.7%. The difference in retention rates for the green roofs with different vegetation was not statistically significant. The rainfall intensity influenced the retention rates, with the highest retentions for small events (<10.0 mm) followed by medium (10.0-24.9 mm). Retention was found to correspond significantly to rainfall depths. On the other hand, regression analysis failed to provide a relationship between retention and antecedent dry weather period (ADWP). The organic soil used as substrate appears to be the deciding factor for rainwater retention.

Keywords: Organic Substrate. Rainwater Management. Runoff Retention. Grass. Shrub.

RESUMO: Telhados verdes são reconhecidos como uma infraestrutura sustentável que melhoram a qualidade ambiental nas cidades. Entre muitos benefícios, os telhados verdes reduzem a taxa e o volume do escoamento superficial, contribuindo no gerenciamento das águas pluviais. Este estudo investigou a capacidade de retenção do escoamento de três conjuntos pilotos de telhados verdes extensivos com diferentes tipos de vegetação (gramínea, arbusto e consórcio entre as duas plantas). Os dados de escoamento de águas pluviais pelos telhados verdes foram coletados em 18 eventos de chuva que variaram de 1,6 mm a 157,9 mm. As eficiências médias de retenção da precipitação foram de 46,7, 59,7 e 61,6% para os telhados verdes consorciados, arbustivos e com gramínea, respectivamente, enquanto as taxas anuais de retenção de escoamento foram de 43,8, 57,3 e 59,7%. Não houve diferença estatística significativa para as taxas de retenção dos telhados verdes com diferentes tipos de vegetações. A intensidade da precipitação influenciou as taxas de retenção, sendo as maiores retenções observadas para eventos fracos (<10,0 mm) seguidas por eventos médios (10,0-24,9 mm). A retenção está diretamente ligada à intensidade do evento chuvoso. Por outro lado, a análise de regressão não forneceu uma relação entre a retenção e o período de tempo seco anterior (PTSA). O solo orgânico usado como substrato parece ser o fator decisivo para a retenção de água da chuva.

Palavras-chave: Substrato Orgânico. Manejo de Águas Pluviais. Retenção do Escoamento. Grama. Arbusto.

1. INTRODUCTION

Many of the environmental impacts of urbanization are a consequence of increase of the impermeable surfaces areas, which excessively raises runoff, erosion and risk of floods. Furthermore, when green areas are replaced by impermeable surfaces, a decrease in canopy interception and transpiration within the city are observed and this leads to increased temperature and decreased air humidity (BERNDTSSON, 2010). As a solution to these problems, green infrastructure approaches based on natural systems have been developed and implemented to improve the environmental quality of cities (TZOULAS *et al.*, 2007).

Green roofs (also called living roofs, vegetated roofs or eco-roofs) are an example of green infrastructure. These green systems strategically integrate vegetation, easily drain soils and provide natural storage into urban landscape, so that rainfall can be treated, stored and evapotranspired to avoid excess rainwater runoff in urban impermeable surfaces (HARPER *et al.*, 2015; BUCKLAND-NICKS *et al.*, 2016; CATALANO *et al.*, 2016; BESIR & CUCE, 2018). Furthermore, other interesting benefits of green roofs also have been reported, as decreased building energy consumption (PARIZOTTO & LAMBERTS, 2011), improved air quality and building aesthetics (YANG *et al.*, 2008), minimized urban heat island effect (FANG, 2008) and reduced noise level (Van RENTERGHEM & BOTTELDOOREN, 2009). Germany, Sweden, USA, Japan and Singapore recognized these benefits and started encouraging or even imposing the use of green roofs in buildings (VIJAYARAGHAVAN & RAJA, 2014). Recently, in Brazil, cities as Porto Alegre, Recife, Rio de Janeiro and São Paulo have approved specific legislation to encourage the application of green roofs.

Typically, the construction of green roofs involves multiple layers of materials, including a drainage material, a filter to prevent the loss of soil particles, a soil substrate and vegetation. Depending on the type of construction of the roof, green roofs are categorized in three main categories: extensive, intensive and semi-intensive. An extensive green roof is constructed with a substrate that is less than 15 cm deep and suitable for large rooftops (HASHEMI *et al.*, 2015). Because of shallow media layer, extensive green roofs are planted or sown with grasses, herbs, succulents, and mosses and require low maintenance. Intensive green roofs consist of a more than 20 cm thick substrate and are designed as gardens, supporting bigger plants such as trees and bushes, and require weeding, fertilizing, and watering (BERNDTSSON *et al.*, 2009). Semi-intensive green roofs show intermediate characteristics.

Several studies on the hydrological properties of green roofs have shown a range of average rainwater retention efficiencies (Table 1). The prominent differences observed between extensive green roofs retention values can be attributed to the slope of the green roof (CATALANO *et al.*, 2016), the type and depth of the substrate used (LEE *et al.*, 2015; BUCKLAND-NICKS *et al.*, 2016), green roof design (VANUYTRECHT *et al.*, 2014), characteristics of rain events (intensity and duration) (VOLDER & DVORAK, 2014; ZHANG *et al.*, 2015), weather conditions, climate and season (BERNDTSSON, 2010; WONG & JIM, 2015). In addition to these factors, vegetation composition also has an important influence on green roof hydrological performance. According to Dunnett *et al.* (2008), vegetation can influence through interception and evaporation of rainfall by vegetation canopy and plant surfaces, through uptake and storage of water in plant tissues, and through transpiration of water from the plant back to the atmosphere.

The studies mentioned above have demonstrated that green roof runoff reductions are understandably variable mainly due to the countless possibilities to construct a green roof. This fact highlights the importance of continuous research on quantifying runoff from green roofs. In the present study, the runoff retention by three pilot-scale green roof assemblies with different vegetation (grass, shrub and intercropping of the two plants), constructed and operated on a real roof in an urban setting, was assessed. Moreover, predictive relationships between rainfall characteristics (rainfall depth, rainfall duration, antecedent dry weather period (ADWP)) and green roof retention were also established.

Table 1 - Retention efficiencies (%) reported in various studies on extensive green roofs

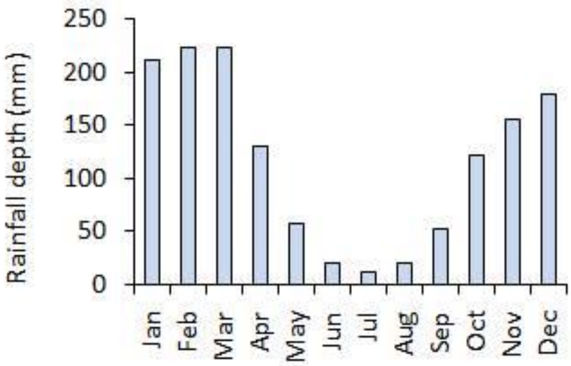
Reference	Retention efficiency observed (%)	Location
Voyde *et al.* (2010)	82.0	Auckland, New Zealand
Getter *et al.* (2007)	80.2	Detroit, USA
Volder & Dvorak (2014)	78.0	College Station, USA
Zhang *et al.* (2015)	77.2	Chongqing, China
Nawaz *et al.* (2015)	66.0	Leeds, England
Villarreal & Bengtsson (2005)	45.7 36.5 23.3	Lund, Sweden
Carson *et al.* (2013)	36.0 47.0 61.0	New York, USA
Lee *et al.* (2015)	27.1 50.3	Seoul, South Korea
Harper *et al.* (2015)	60.0	Missouri, USA
Stovin *et al.* (2012)	42.7	Sheffield, United Kingdom
Gregoire & Clausen (2011)	41.6	Storrs, USA
Beck *et al.* (2011)	17.8 21.1	Portland, USA
Spolek (2008)	12.0 17.0 25.0	Portland, USA
Beecham & Razzaghmanesh (2015)	79.6 78.1 63.7 65.1	Adelaide, Australia
Razzaghmanesh & Beecham (2014)	74.0	Adelaide, Australia

2. MATERIALS AND METHODS

2.1 Study site

The study site was located in Federal University of Mato Grosso (FUMT), Cuiabá city, Mato Grosso State, which is located at Midwest region of Brazil. Local climate, as well as in most of Brazil, is tropical. According to rainfall data from 1989 to 2015, obtained from Mestre Bombled meteorological station located approximately 100 m from the site of the experiments, the mean annual precipitation at Cuiabá was 1405.3 mm. However, a strong seasonality in the precipitation regime was observed with a rainy season (October to April) and a dry season (May to September) (Figure 1). The rainiest months were January, February and March.

Figure 1 - Average monthly rainfall in Cuiabá, Brazil (1989-2015)



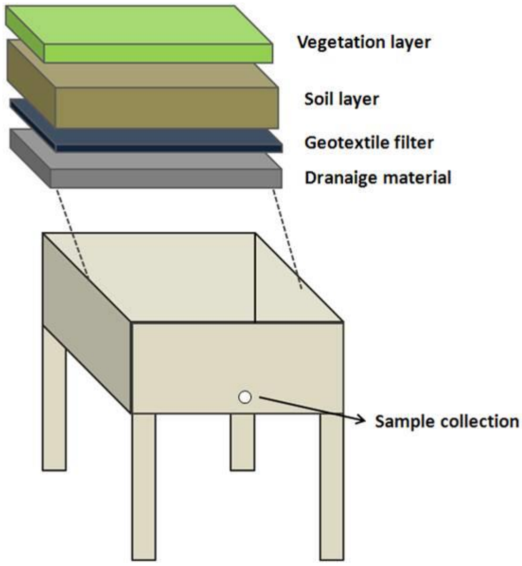
Source: Mestre Bombled meteorological station

2.2 Experimental designs

Extensive green roof experimental modules were assembled using plastic trays (0.4 m wide x 0.6 m long) with the same principle as full-scale vegetated roofs. All modules were placed on a 4° slope to simulate common roof design. The standard green roof module consisted of drainage layer, filter layer, soil substrate, and vegetation (Figure 2). Each one also had a 25 mm diameter drain hole that directed all runoff into a capture container. The drainage layer was 5 cm thick of expanded clay. The filter layers were in form of a geotextile (membrane material, grammage = 200 g/m^2), which prevented small particle from being washed from the substrate layer to the drainage layer. The soil substrate was composed of a mixture of 90% commercial organic soil and 10% vermiculite. *Zoysia japonica* (grass) and *Ixora coccinea* (shrub) were select for the study because they are abundantly used as ornamental plants in gardens of Cuiabá, which indicates that they are adapted to the climatic conditions. Two trays were planted with twelve plugs of *Ixora coccinea* (4 rows x 3 columns) each, equidistantly spaced among themselves and the tray edges. The plugs were of uniform size (approximate height 7 cm). In other two trays, *Zoysia japonica* were planted as a continuous mat over the entire soil surface. The same procedures were used to plant two green roof modules with both plants. Thus, there were six green roof modules in this study, consisting of two of each of the three roof types. For the purpose of adaptation, artificial watering was provided every three days. Field experiments started after three months of plant adaptation. The green roof modules were arranged in an alternating sequence on the roof of the Faculty of Architecture, Engineering and Technology (15°36'29,27"S and 56° 3'52,80"W). They were positioned 1.4 m above the school building roof. The modules were completely free of shading.

The quantity of runoff from each green roof modules was measured using a beaker with graduation scale (± 5 ml). The monitoring took place over a period of three months (January-March 2015). In this period, 42 rainfall events were recorded. However, rainfall events less 1.5 mm and that did not produced runoff were excluded from event-based analysis.

Figure 2 - Layout of green roof module



2.3 Data analysis

Runoff retention rates from green roof modules were calculated by equations 1 and 2 (Zhang *et al.*, 2015):

$$Retetion\ Rate(\%) = \frac{RV - R}{RV} \text{ x } 100 \quad (1)$$

$$RV = P \text{ x } A \quad (2)$$

where RV is the rainfall volume actually received by the green roof (L); R is the runoff depth of the green roof (L); P is precipitation (mm); A is the area of the green roof (m^2).

The differences in runoff retention rates from the three green roof modules were evaluated using the nonparametric Kruskal-Wallis test (at 5% significance level), as the data failed to meet the assumption of normality and homogeneity of variances, even after data transformations. Regression analysis were also undertaken to develop predictive relationships between rainfall characteristics (rainfall depth, rainfall duration, ADWP) and green roof retention. The correlation strength was indicated by the coefficient of determination (R^2).

2.4 Annual runoff retention rates

The rainfall data from 1989 to 2015, representative of the site where green roofs were installed, and the results of the green roofs runoff retention were statistically analyzed at different rainfall intensities to calculate the annual runoff retention rates for the green roof modules (Table 3).

3. RESULTS AND DISCUSSION

3.1 Rainfall retention

In the eighteen rainfall events quantified during the study period, precipitation ranged from 1.6 to 157.9 mm, and were included in the analysis, with a variety of different characteristics (Table 2). On the *I. coccinea* green roof the rainfall retention rate ranged from 8.5 to 100%, with an average retention rate of 59.7%, while on the *Z. japonica* green roof the retention rate ranged from 34.5 to 100%, with an average of 61.6%. On the intercropped green roof the rainfall retention rate ranged from 4.7 to 100%, with an average retention rate of 46.7%.

Table 2 - Precipitation data and hydrological characteristics of green roofs

Rainfall events	Precipitation (mm)	Runoff (mm)			Retention rate (%)		
		I. coccinea (shrub)	*Z. japonica* (grass)	Intercropping	*I. coccinea* (shrub)	*Z. japonica* (grass)	Intercropping
14/01/2015	21.6	3.13	9.38	1.25	85.5	56.6	94.2
26/01/2015	5.0	0.00	0.00	0.00	100.0	100.0	100.0
02/02/2015	18.9	11.63	8.88	17.50	38.4	53.0	7.3
11/02/2015	66.8	20.25	12.13	28.00	69.7	81.8	58.1
16/02/2015	15.4	0.44	2.75	1.25	97.2	82.1	91.9
18/02/2015	44.7	21.19	22.31	31.06	52.6	50.1	30.5
20/02/2015	157.9	141.00	103.38	141.88	10.7	34.5	10.1
21/02/2015	30.8	28.13	19.25	29.13	8.5	37.4	5.3
23/02/2015	24.5	12.88	11.63	19.00	47.4	52.6	22.4
27/02/2015	37.0	19.13	17.75	32.00	48.3	52.0	13.5
02/03/2015	9.4	0.70	1.13	1.00	92.5	88.0	89.3
03/03/2015	2.8	0.00	0.19	0.19	100.0	93.3	93.3
13/03/2015	1.6	0.14	0.50	0.69	91.2	68.0	56.0
18/03/2015	39.5	8.50	10.00	12.25	78.5	74.7	69.0
24/03/2015	53.4	20.25	26.13	33.63	62.1	51.1	37.0
26/03/2015	59.0	41.06	27.25	43.25	30.4	53.8	26.7
27/03/2015	6.8	4.25	4.25	4.69	37.0	37.0	30.6
30/03/2015	32.2	24.13	18.25	30.69	25.0	43.3	4.7

The results from our tests fall within the range reported in the literature. The average retentions of 59.7 and 61.6% for shrub and grass green roofs were higher than the average of 50.9% obtained in fifteen studies with extensive green roofs presented in Table 1, while the average retention for intercropped green roof (46.7%) was lower. Nevertheless, direct comparisons with other studies are limited given the large number of unique variables that influence the retention efficiency, including vegetation, slope, ADWP, climate and green roof media composition (NAWAZ *et al.*, 2015).

The species of plants are an important factor affecting retention capacity of green roofs. Plants with developed foliage and root systems, such as grasses, have been shown to be more effective in reducing surface runoff (DUNNETT *et al.* 2008). Nagase and Dunnett (2012) showed that the highest water capture was observed in grasses, followed by forbs and sedum. This is also consistent with previous research of Lundholm *et al.* (2010), which showed that the highest water capture was observed in grasses, followed by tall forbs, creeping forbs and succulents. In our study, however, differences in retention rates between three types of green roofs (grass, shrub and intercropping of the two plants) were not significant (p=0.2908). On the order hand, it is also likely that other factors are decisive in the retention capacity of green roofs. It has been shown that growing media composition (substrate), rather than vegetation type, can determine the water retention capacity (MONTERUSSO *et al.*, 2004). Dunnet *et al.* (2008) found inconsistent results in two experiments to identify the relative contribution of soil and vegetation to runoff values, with bare soils resulting in both the highest and the lowest runoff reduction compared to treatment with plants. These results were debated as a result of the different organic matter content of soils. High organic matter content of substrate increases its water holding capacity, contributing to high retention (SPEAK *et al.* 2013). Buccola & Spolek (2011) found that increased green roof soil depth improved water retention and runoff lagtime, but plant type does not seem to have a significant effect on either discharge quantity. Therefore, plant selection can be based on other factors, such as energy transfer, plant hardiness, and aesthetics. VanWoert *et al.* (2005) also claimed that the effects of vegetation on rainfall retention is minimal relative to the effects of growing media. The substrate used in our study was a commercial organic soil and it is likely that it had more influence in rainfall retention than type and composition of vegetation.

3.2 Regression analysis

A strong relationship between rainfall depth and runoff (p<0.00001, Figure 3) was observed for three types of green roofs. The runoff on green roofs with *Z. japonica* was generally lower than on green roofs with *I. coccinea* and intercropping. This is indicated by regression line slopes of 0.61 on grass green roof and 0.84 and 0.86 on shrub and intercropped green roofs, respectively. Nevertheless, differences in runoff volume between three types of green roofs were not significant (p=0.5512). The relationship between rainfall depth and runoff is also shown in terms of percentage of retention (Figure 4). There was a significant inverse relationship (at 5% significance level) between retention rate and rainfall depth for three green roofs. Numerous studies have reported similar results to this study (SIMMONS *et al.*, 2008; RAZZAGHMANESH & BEECHAM, 2014; NAWAZ *et al.*, 2015; ZHANG *et al.*, 2015).

A negative correlation was also apparent between retention and rainfall duration (Figure 5), although this was not deemed statistically significant for grass (p=0.1000) and intercropped (p=0.1615) green roofs. The scatter plots for retention and ADWP (Figure 6) show a large amount of scattering. Linear and non-linear (exponential, logarithmic and power) regressions were attempted, though they all resulted in poor R^2 and no significance. Low ADWPs often result in low retention; however, a high ADWP does not guarantee high retention due to the finite retention capacity of the roof and the influence of weather conditions, which could increase evaporation rates during the ADWP (STOVIN *et al.*, 2012). Although this study was conducted in summer (January to March), when the highest evaporation rates are expected, this is the rainy period in the study site. During all study period (75 days), 42 rainfall events were recorded and the ADWPs were short, not exceeding five days (results not shown). This may have influenced the large amounts of scattering in regression plots for retention and ADWP. On the order hand, the results imply that green roofs modules can make a significant contribution to the mitigation of rainwater runoff associated with high frequency rainfall events.

Figure 3 - Regression plot of rainfall depth and runoff for (a) *I. coccinea* green roof, (b) *Z. japonica* green roof and (c) consortium green roof

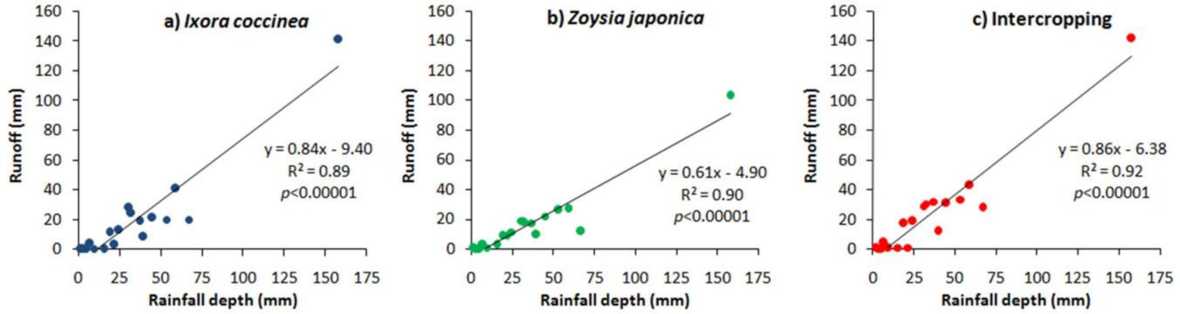


Figure 4 - Regression plot of rainfall depth and retention rate (%) for (a) *I. coccinea* green roof, (b) *Z. japonica* green roof and (c) consortium green roof

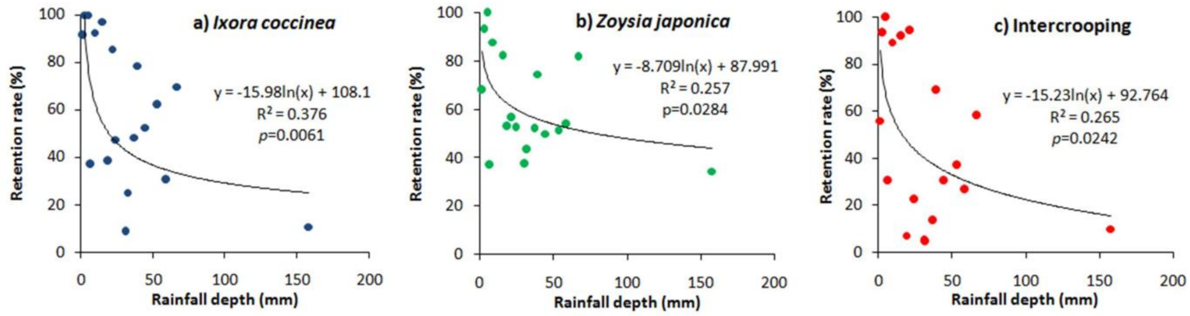


Figure 5 - Regression plot of rainfall duration and retention rate (%) for (a) *I. coccinea* green roof, (b) *Z. japonica* green roof and (c) consortium green roof

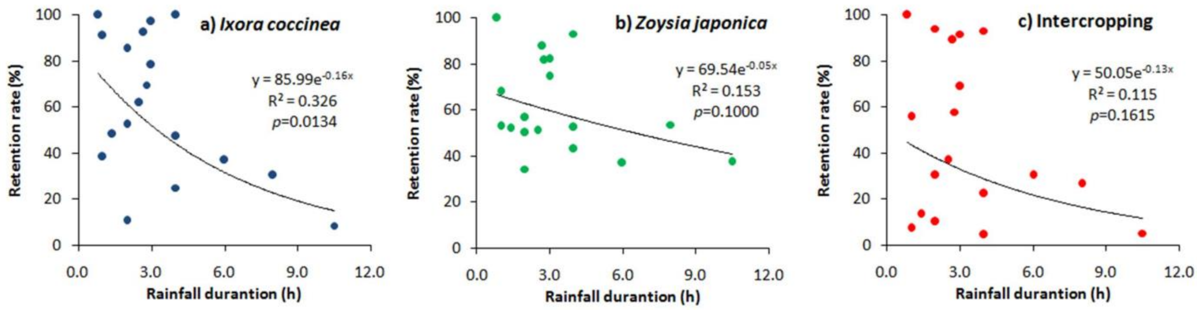
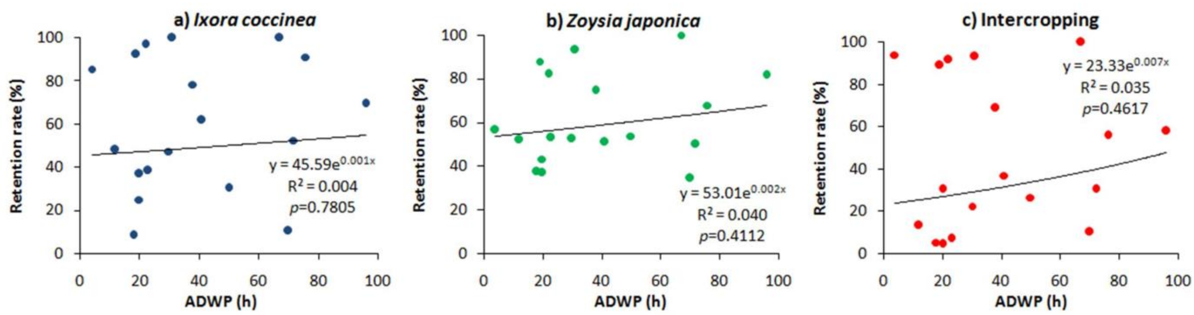


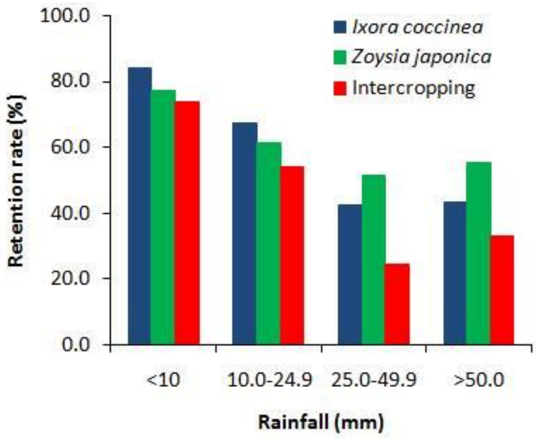
Figure 6 - Regression plot of ADWP and retention rate (%) for (a) *I. coccinea* green roof, (b) *Z. japonica* green roof and (c) consortium green roof



3.3 Influence of rainfall intensity in retention on green roofs

The influence of rainfall intensity in green roof retention is shown in Figure 7. Rainfall events were classified according to Zhang *et al.* (2015) in small rainfall (<10.0 mm), medium rainfall (10.0-24.9 mm), large rainfall (25.0-49.9 mm) and storm (>50.0 mm). The events selected for analysis were composed of 5 small, 4 medium, 5 large and 4 storms. There was an inverse relationship between the depths of rainfall and the percentage of that rainfall that was retained; for small rainfall events, 73.8-84.2% was retained in three green roofs; for medium events, 54.0-67.1% was retained; for large events, 24.6-51.5% was retained; and for storms, 33.0-55.3% was retained. These results were similar to those obtained by Villarreal and Bengtsson (2005), Getter *et al.* (2007) and Zhang *et al.* (2015), who found that an inverse relationship existed between the depth of rainfall and capacity of retention by green roofs. These results can be explained based on finite storage capacity of green roofs. A lager rainfall event produces a greater proportion of runoff, when compared to a smaller event (GETTER *et al.*, 2007). Likewise, a green roof will retain a greater proportion of rainfall from a smaller event. So the finite storage capacity of a green roof notably restricts its ability to retain rainwater from larger events (STOVIN *et al.*, 2013). The data of rainfall intensity x type of green roof were also statistically analyzed (at 5% significance level), but no significant results were observed.

Figure 7 - Relationship between rainfall intensity and retention rate by green roofs



3.4 Annual green roof runoff retention

Annual runoff retention volume and the annual retention rates by the green roofs with *I. coccinea*, *Z. japonica* and intercropping reached, respectively, 805.8 mm and 57.3%, 838.8 mm and 59.7% and 615.7 mm and 43.8% (Table 3). These values are within the range reported in two meta-analysis studies, which reported that extensive green roofs showed annual runoff reduction of 27-81% (MENTENS *et al.*, 2006) and 16-87% (SPOLEK, 2008) of annual precipitation. The cumulative retention demonstrates that the green roof can significantly contribute to the total volume of rainwater that might otherwise impact upon watercourses. However, it is critical to have a fuller understanding of the roof's ability to retain and detain flows from larger extreme events, which are more likely to contribute to significant catchment flooding (STOVIN *et al.*, 2012).

Table 3 - Data summary for the mean annual rainfall types, rainfall days (RD), precipitation (P) and green roofs runoff retention rates between 1989 and 2015

Rainfall type	RD* (days/year)	P** (mm)	Annual runoff retention (%)			Annual runoff retention (mm)		
			I. coccinea (shrub)	*Z. japonica* (grass)	Intercropping	*I. coccinea* (shrub)	*Z. japonica* (grass)	Intercropping
<10.0	72	243.0	84.2	77.3	73.8	204.6	187.8	179.3
10-24.9	27	425.0	67.1	61.1	54.0	285.2	259.7	229.5
25.0-49.9	12	433.0	42.6	51.5	24.6	184.5	223.0	106.5
>50	4	304.3	43.2	55.3	33.0	131.5	168.3	100.4
Total	115	1405.3	57.3	59.7	43.8	805.8	838.8	615.7

* Average annual rainfall days considering the period 1989 and 2015 and rainfall type.
** Average annual precipitation considering the period 1989 and 2015 and rainfall type.

4. CONCLUSIONS

The runoff retention by three pilot-scale green roofs with different vegetation based on 18 rainfall events was investigated. Green roofs demonstrated to be efficient tools for decreasing rainwater runoff (46.7–61.6%) even though the study was carried out in the period of frequent rain events and short ADWPs (<5 days). Retention rates varied with rainfall intensity, with the highest retention for small (<10.0 mm) followed by medium events (10.0-24.9 mm). Annual runoff retention volume and retention rates by green roofs ranged from 615.7 to 838.8 mm and 43.8 to 59.7%. The difference in retention rates for the types of green roofs (grass, shrub and intercropping of the two plants) was not statistically significant. On the other hand, the substrate could have a decisive influence in rainfall retention. This study has provided evidence of green roof effectiveness at contributing to rainwater management and the data may contribute to the development of policy, regulation, and incentives for widespread green roof implementation in Brazil.

5. ACKNOWLEDGEMENT

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