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Article

Effect of Green Roof Configuration and Hydrological Variables on Runoff Water Quantity and Quality

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Abstract: This study assessed the hydrological performance and runoff water quality of 12 green roof (GR) modular systems located at the Universidad de los Andes campus (Bogotá, Colombia). Based on 223 rainfall events spanning a 3-year period, average rainfall retention was 85% (SD = 25%). T-tests, Welch Test, multiple linear regressions and correlation analysis were performed in order to assess the potential effect of air temperature, substrate type, vegetation cover, relative humidity, antecedent dry weather period (ADWP), rainfall duration and rainfall maximum intensity. In some cases, GR design variables (i.e. growing media and type of vegetation) were found to be significant for describing rainfall retention efficiencies and, depending on the GR type, some hydrological variables were also correlated with the rainfall retention. Rainfall and GR runoff were monitored for Total Kjeldahl Nitrogen (TKN), Nitrates, Nitrites, Ammonia, Total Phosphorus (TP), Phosphates, pH, Total Dissolved Solids (TDS), Total Suspended Solids (TSS), Color, Turbidity, Biological Oxygen Demand (BOD), Chemical Oxygen Demand (COD), Total Coliforms, metals and Poliaromatic Hydrocarbons (PAHs). The results obtained confirmed that GR systems have the ability to neutralize pH, but are source of the rest of the aforementioned parameters, excluding PAHs (with concentrations below detection limits), Ammonia, TSS, Se and Li, where differences with reference values (rainfall and plastic panel runoff) were not statistically significant. Substrate type, event size and rainfall regime are relevant variables for explaining runoff water quality.

Keywords: Green roof; water retention efficiency; runoff quality; hydrological performance.

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1. Introduction

With the passage of time and the continuous development of society, migration from rural to urban areas has increased at an accelerated pace [1, 2]. This has meant that in the last 60 years urbanization rates have increased significantly [3] and for the first time in history more than half of the world's population live in urban areas [1]. An environmental problem created by the urbanization process is the increase of impervious areas in urban watersheds which leads to significant reductions in infiltration rates thus causing more frequent flash floods and failures of the sewer systems [2].

Urban growth therefore demands more sustainable urban drainage systems. There is a need to return to pre-development hydrologic conditions by attenuating runoff flows generated by impervious areas, as well as improving the runoff water quality [4]. One of the most popular technologies within the framework of sustainable urban drainage systems are green roofs (GRs) [5]. GRs involve the installation of a natural vegetated cover on a building's roofs [6] in order to reduce the impervious area and therefore the runoff that flows into the sewer system or directly into

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receiving streams. Although the aim of GRs is to change runoff generation patterns, it has been shown that they also alter the rainfall water quality [7].

A GR modifies the patterns of urban runoff generation by attenuating and delaying peak flows and reducing runoff volumes [2]. The effect of GRs on the amount of runoff is a widely studied phenomenon, and all related studies suggest that GRs have significant percentages of water retention [2]. Although there is a general consensus on the positive effect of GRs regarding water retention, varying results are reported in the research literature. On one hand, Dietz [8] reported average retention values for different climatic conditions ranging between 60% and 70%, with an average value of 63%. On the other, Carpenter & Kaluvakolanu [9] found an average retention range of 20% to 100%, while more recent studies have estimated retention rates ranging between 77% and 82% [1, 10, 11]. The variation in the retention rates found in previous studies is explained by the fact that this phenomenon relies on the configuration of the GR (e.g. type of substrate and its depth, vegetation, slope, and filter system) and the specific climatological conditions of the study area (e.g. rainfall depth and evapotranspiration), as well as the characteristics of rainfall events, such as maximum intensity, duration and dry antecedent period [2, 12, 13] GRs are promoted for their potential to provide high runoff retention efficiencies; however, the effect that a GR may have on the runoff water quality is still not fully understood [14] due to non-conclusive, and even contradictory findings in the research [1, 3, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25]. The high variability concerning GR's runoff water quality is mainly a result of its high dependence on the substrate, vegetation, and hydrological variables of each specific site [2]. Because of the relevance of GRs as a strategy for sustainable water management in urban centers [26], it is important to better understand the role of GR configuration and local hydrological variables on runoff quantity and quality. This is even more relevant in tropical climates like Colombia's as there is not much research on GR performance that considers the GR configurations typical to these regions and local hydrological conditions [27]. This research aims to improve understanding of the retention capacity and changes in GR runoff water quality in a tropical climate, through an instrumented experimental setup located at the Universidad de los Andes campus in Bogotá (Colombia).

2. Materials and Methods

2.1. Study Site

This research was carried out at the main campus of the Universidad de los Andes in Bogotá (Colombia), which is located at an altitude of 2640 m.a.s.l. There is a main road near to the experimental site and no industrial activity in the neighboring area. The main surrounding land uses are official, commercial and residential. The experimental setup was located on the rooftop of the Physics Department building (Figure 1). Bogotá has a subtropical highland climate, with a mean annual temperature of 14.5°C, varying monthly between 12 and 15°C [28]. The mean annual rainfall depth ranges between 600 and 1200 mm, and the rainfall regime is bimodal, with two rainy seasons (April – May and October - November) and two dry periods (January – February and July - August) [28].

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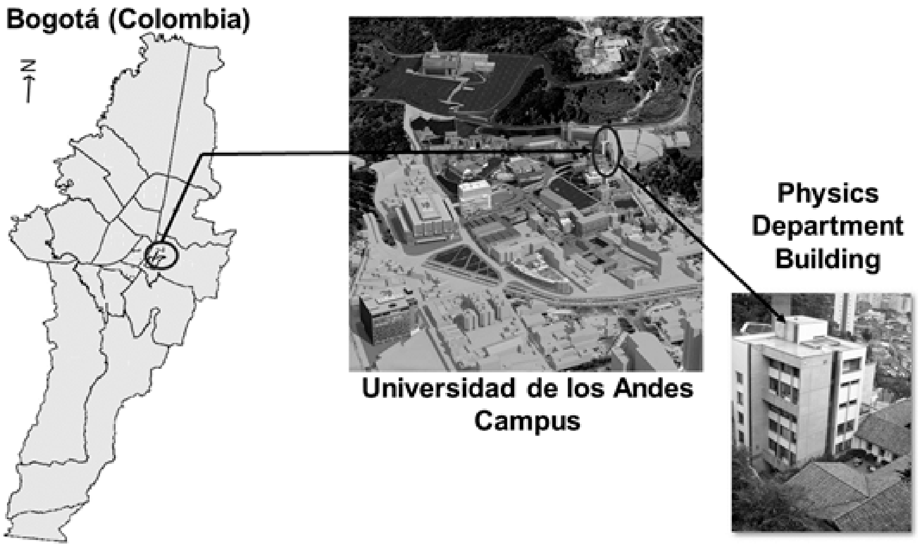

Figure 1. Study Site Location

2.2. Experimental Setup

The experimental setup consisted of different modular GRs implemented over a three-year period in order to reproduce different extensive, intensive and productive GR configurations. The general vertical composition of the modules is as follows (from surface to bottom): 1) vegetation layer; 2) substrate layer or growing medium, 3) filter layer (nonwoven geotex Sika 1800 or recycled textile felt), and 4) drainage layer (Sika T-20 Garden). These layers were confined within the walls and bottom of the module (by means of plastic or cold rolled steel sheet) acting as a waterproofing membrane as if it were the decking of a conventional roof. Throughout the monitoring period all modules were leveled horizontally with a drainage slope of less than 1%. No additional water was provided to any GR module during this study. In order to compare the water quality performance of GRs with raw rainfall and runoff from conventional roof surfaces (control cases), a rainfall harvesting tank and a plastic roofing panel were installed on the same rooftop.

Different plant species were evaluated during the monitoring period: homogeneous configurations of Sedum Sexangulare, Sedum Rupestre, Radish, Lettuce, and Grass; a heterogeneous mixture of Water Lily, Bergenia and Lavender, and two different types of heterogeneous Sedum mixtures (Sedum Mixture Mat 1: Sexangulare, Chatre, Album, Acre, and Kamtschaticum and Sedum Mixture Mat 2: Blue, Acre, Fino, Sexangulare, Chatre and Oregano). In the experimental setup, four different types of substrates were tested: Extensive Substrate 1 (standard extensive substrate), Extensive Substrate 2 (extensive substrate enhanced for runoff volume reduction), Intensive Substrate, and Productive Substrate (for vegetables). A summary of the characteristics of the GR modules is shown in Table 1.

Table 1. Experimental Setup Description

Period	**Number of GR Modules**	**Number of Monitored Rainfall Events**	**Vegetated Modules**	**Non Vegetated Modules**	**Module size and material**
1. 25/09/2013-07/11 /2013	Vegetated: 2 Non Vegetated: 1	6	Radish and Lettuce over 6 [cm] of productive substrate	Extensive substrate (Type 1)	Plastic modules of 0.70x0.54x13 [cm]

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Period	Number of GR Modules	Number of Monitored Rainfall Events	Vegetated Modules	Non Vegetated Modules	Module size and material
2. 08/11/2013 – 03/12/2013	Vegetated: 2 Non Vegetated: 1	11	Radish and Lettuce over 6 [cm] of productive substrate	Extensive substrate (Type 1)	Plastic modules of 0.70x0.54x13 [cm]
3. 08/03/2014 – 03/04/2014	Vegetated: 2 Non Vegetated: 1	4	Sedum Sexangulare, Sedum Rupestre over 6 [cm] of extensive substrate type 1	Productive substrate	Plastic modules of 0.70x0.54x13 [cm]
4. 04/04/2014 – 08/05/2014	Vegetated: 2	15	Sedum Sexangulare and Sedum Rupestre over 6 [cm] of extensive substrate type 1	None	Plastic modules of 0.70x0.54x13 [cm]
5. 18/10/2014 – 30/11/2014	Vegetated: 3 Non Vegetated: 2	17	Sedum Sexangulare over 6 [cm] of extensive substrate type 1 and Sedum mixture mat of 5 species and Grass over 6 [cm] extensive substrate type 2	Productive substrate and enhaced extensive substrate (Type 2)	Modules 1 to 3 Plastic of 0.70x0.54x13 [m] and Modules 4 to 6 Metallic of 0.7x0.7x0.13 [m]
6. 14/08/2015 – 31/01/2017	Vegetated: 3 Non Vegetated: 3	170	Two different configurations of Sedum mixture mat of 5 species each one, over 6 [cm] extensive substrate type 2 and Intensive plant mixture of 5 species over 6 [cm] of intensive substrate	Two configurations of enhanced extensive substrate (Type 2) and Intensive substrate	Metallic modules of 0.7x0.7x0.13 [m]

2.3. Monitoring System

GR runoff quantity was monitored using a sampling rate of one minute, using tipping bucket rain gauges (DAVIS model rain collector II). In order to capture the experimental on-site hydrologic conditions, temperature and humidity were measured at the same sampling rate using a DAVIS weather station model VANTAGE Pro 2. The schematic representation of the assembly of different GR modules during the last monitoring period (14/08/2015 to 31/01/2017) is shown in Figure 2.

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2.4. Sampling and Laboratory Characterization

Water samples were taken from the storage units for each GR, as well as from the reference roofing panel and rainfall collected after a rain event (Figure 2). Water quality parameters (Table 2) were determined in the laboratory, following the methods outlined in Eaton [29]. Additionally, pH, conductivity and temperature were also monitored using a YSI multiparameter probe model 600R and Global Water probes, models WQ-201 and W-cond.

Table 2. Water Quality Parameters Monitored

Category	Parameter
Phosphorus	Total Phosphorus (TP), Phosphates
Nitrogen	Total Kjeldahl Nitrogen (TKN), Nitrites, Nitrates, Ammonia
Physical	Total Suspended Solids, Turbidity and Color
Biological	Total Coliform
Organic Matter	Biological Oxygen Demand (BOD) and Chemical Oxygen Demand (COD)
Metals	Zinc, Copper, Nickel, Lead, Selenium, Aluminum, Barium, Boron, Calcium, Strontium, Iron, Lithium, Magnesium, Manganese, Potassium, Sodium
Hydrocarbons	Polycyclic Aromatic Hydrocarbons

2.5. Definition of Rainfall Categories

Taking into account that for a better understanding of extensive GR performance it is necessary to evaluate both “significant” and “routine” rainfall events to avoid misleading results that bias conclusions [30]; we categorized rainfall events and regimes when conducting our analyses.

2.5.1. By Similarity

A cluster analysis was performed using the collected rainfall database in order to establish groups of rainfall events with similar characteristics. This categorization was carried out according to values of variables such as antecedent dry weather period (ADWP), maximum 1-minute intensity, duration and depth, defining which events can be treated as small, intermediate or large. This categorization was made in order to understand if the event size would have an effect on rainfall retention and quality.

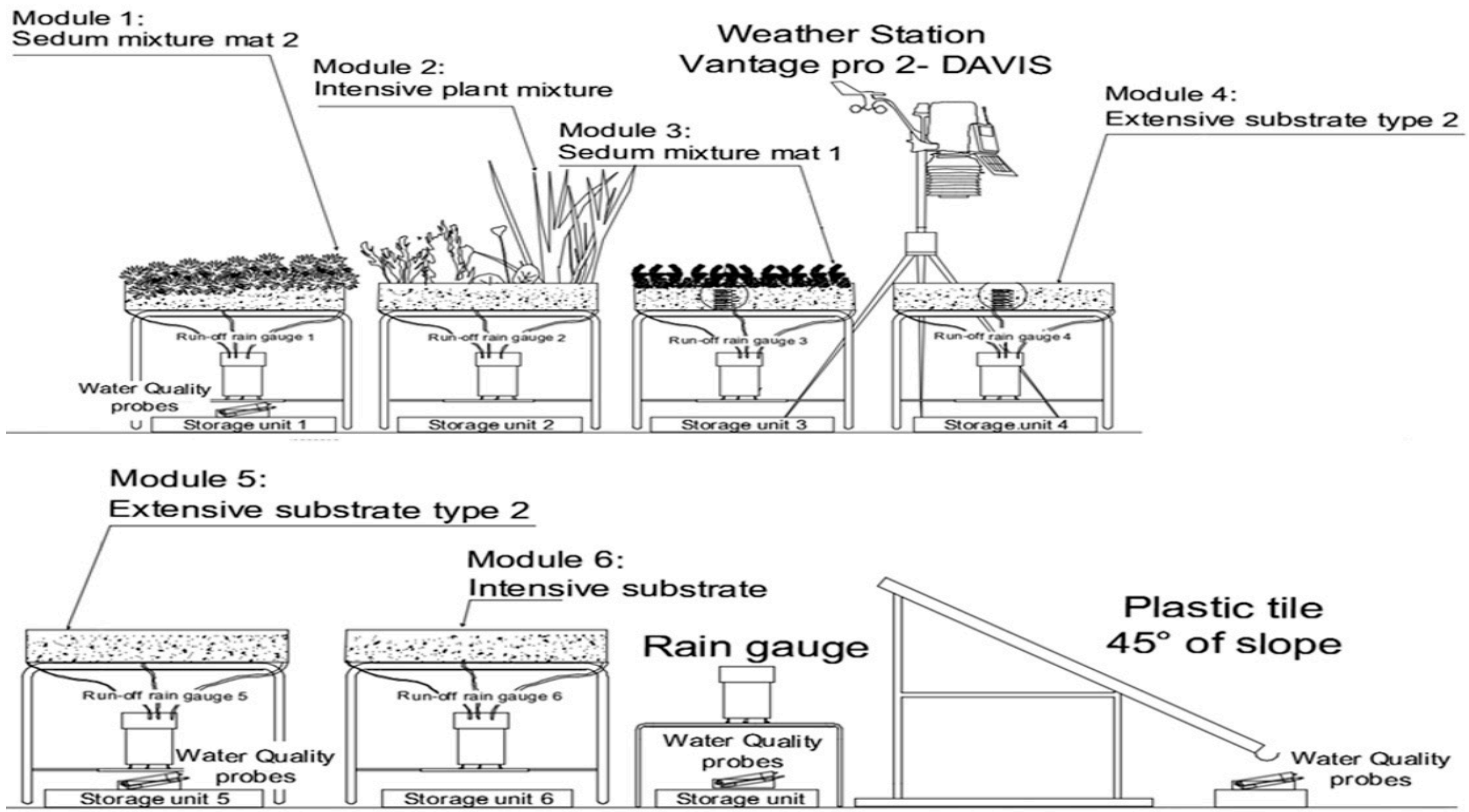

Figure 2. Experimental Setup in the Last Monitoring Period (26/08/2015 – 31/01/2017)

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2.5.2. By Rainfall Regime

As mentioned, rainfall conditions in Bogotá follow a bimodal pattern, seeing annually two rainy and two dry seasons of 2 months each [28]. Based on this pattern, each rainfall event was classified either as occurring during a rainy, dry or intermediate period. These three periods of 4 months each were defined in order to evaluate their retention on GR modules. The months corresponding to the rainy period are April, May, October and November. Dry period months include January, February, July and August. The rest of the months (March, June, September and December) correspond to the intermediate period.

2.6. Statistical Analysis

2.6.1. Water Quantity Analysis

To identify differences between the GR runoff retention efficiency of different substrates and vegetation types ANOVA, Welch's test, post hoc tests (i.e. Bonferroni and Games and Howell), t-tests and boxplots were performed. To complement the previous analyses, multiple linear regressions were used to identify statistically significant rainfall variables correlating with the runoff retention process. For a subset of the monitoring database, k-means cluster analysis was performed to establish groups of events with similar characteristics (ADWP, maximum intensity, rainfall depth and duration), establishing three analysis groups as mentioned before: small, intermediate and large events. Welch's tests were carried out to quantify the effect of the rainfall regime and event characteristics on the runoff quantity and quality.

2.6.1. Water Quality Analysis

Five different analyses on water quality data were conducted according to the following descriptive variables: i) runoff source (rainfall, conventional roof with plastic roofing panels and GR), ii) substrate type, iii) vegetation type, iv) event characteristics, and v) rainfall regime. For each analysis, descriptive statistics, t-tests and boxplots diagrams were performed in order to assess the effect of the GR, substrate, vegetation, event size, and rainfall regime on the water quality transformation process.

3. Results and Discussion

This section may be divided by subheadings. It should provide a concise and precise description of the experimental results, their interpretation as well as the experimental conclusions that can be drawn.

3.1. Water Quantity

The two variables measured in order to estimate the water retention efficiency were rainfall and runoff depths, with the difference between the two representing the retention depth. For this estimation, 223 rainfall events distributed between October 2013 and January 2017 were analyzed. Table 3 summarizes the rainfall characteristics during the monitoring periods.

Table 3. Rainfall Events Characteristics for the Different Monitoring Periods

Period	Number of Characterized Rainfall Events	Rainfall Events Characteristics					
		Duration (minutes)		Depth (mm)		Maximum Intensity (mm/hr)	
		Mean	Deviation	Mean	Deviation	Mean	Deviation
1. 25/09/2013 – 07/11/2013	6	147.80	120.73	5.80	5.19	10.60	9.38

Period	Number of Characterized Rainfall Events	Rainfall Events Characteristics					
		Duration (minutes)		Depth (mm)		Maximum Intensity (mm/hr)	
		Mean	Deviation	Mean	Deviation	Mean	Deviation
2. 08/11/2013 – 03/12/2013	11	325.60	448.79	7.01	6.85	10.00	9.01
3. 08/03/2014 – 03/04/2014	4	183.60	95.94	12.55	11.13	21.35	7.59
4. 04/04/2014 – 08/05/2014	14	82.00	59.57	3.20	2.83	6.40	6.29
5. 18/10/2014 – 30/11/2014	17	142.00	138.31	7.84	12.46	14.47	20.29
6. 14//08/2015 – 31/01/2017	188	235.00	223.62	6.93	10.03	9.61	16.32
7. Global Average	223	224.12	225.72	6.91	10.00	9.98	16.21

3.1.1. Effect of Substrate on Water Retention Efficiency

An overall average retention efficiency of 85% with a standard deviation of 25% was obtained when considering all monitoring periods. However, in the results, an important descriptive variable for the retention process was the type of substrate, confirming results obtained by Czemiel Berndtsson [2], Dunnett et al. [31], Morgan et al. [32], Getter et al. [33] and Shafique et al. [34]. Results evidenced average retention values of 69% for modules using Extensive Substrate 1 (SD = 36% and n = 72), 85% for modules using Extensive Substrate 2 (SD = 25% and n = 727), 63% for modules using Productive Substrate (SD = 34% and n = 54), and 92% for modules using Intensive Substrate (SD = 17% and n = 339) (see Figure 3).

The Intensive Substrate had the best performance, with statistically significant differences from Extensive Substrate 1 (p-value = 0.000), Extensive Substrate 2 (p-value = 0.000) and Productive Substrate (p-value = 0.000). Extensive Substrate 2 had higher retention efficiency than Extensive Substrate 1 with statistically significant differences (p-value = 0.003). The Productive Substrate showed the lowest average retention efficiency, with statistically significant differences compared to the Extensive Substrate 2 (p-value = 0.000) but not to the Extensive Substrate 1 (p-value = 0.789).

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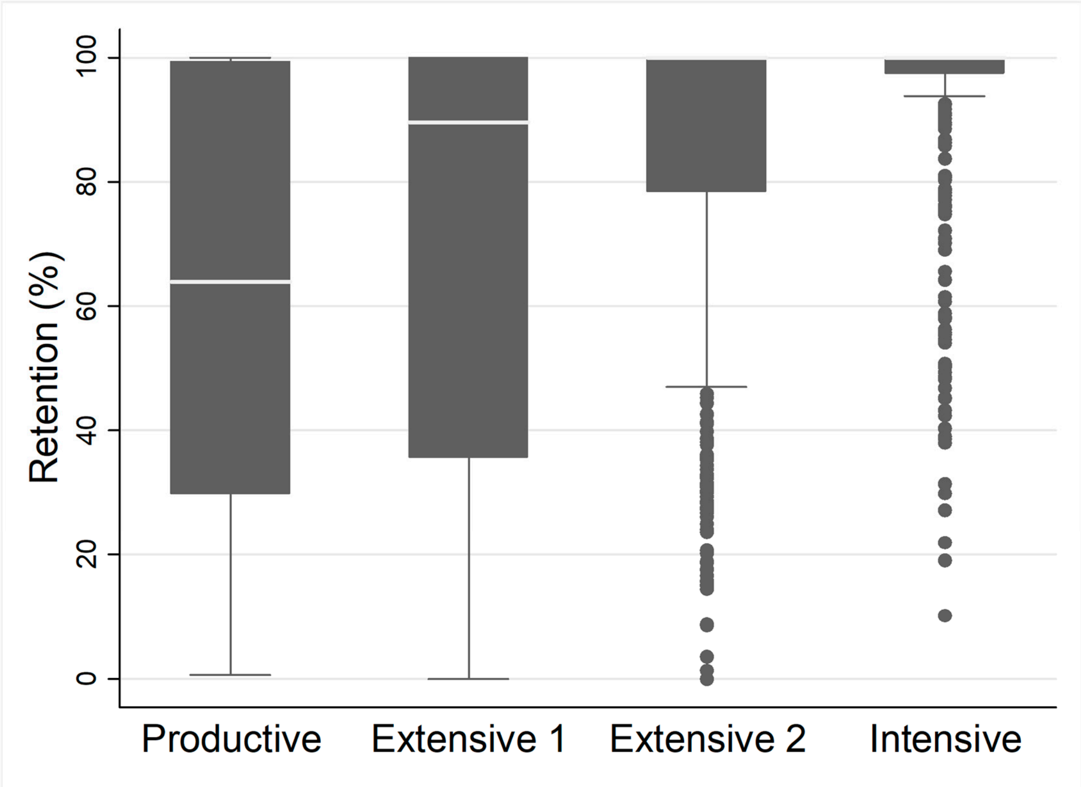

Figure 3. Effect of Substrate on Water Retention Efficiency

3.1.2. Effect of Vegetation on Water Retention Efficiency

In order to establish the effect of vegetation on retention of storm water runoff, an analysis comparing vegetated and non-vegetated modules was performed. Figure 4 presents the box and whisker diagram for the vegetated and non-vegetated modules. It is possible to identify similarities between the retention efficiencies for vegetated (85.65%) and non-vegetated (84.76%) modules. The results of the t-test indicate no statistically significant differences between the two groups (p-value = 0.548), obtaining similar results as in some previous studies [31, 35, 36], which have stated that vegetation does not have a clear effect on water retention efficiency for GRs.

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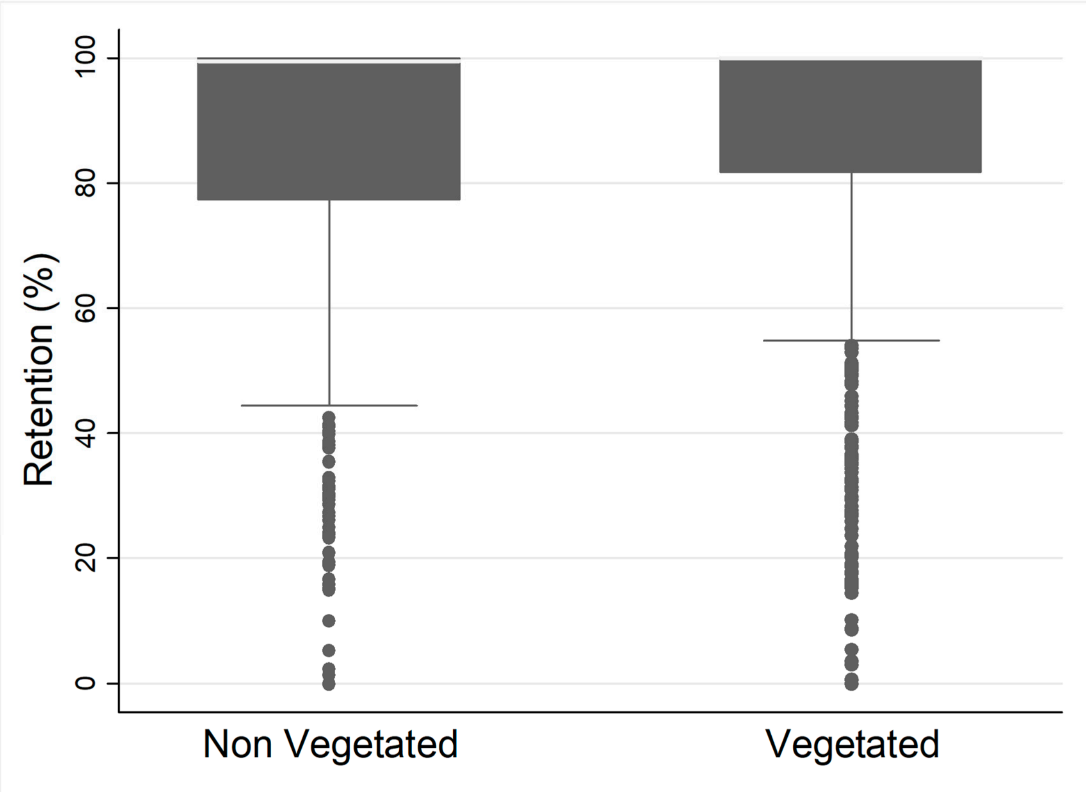

Figure 4. Effect of Vegetation on water retention efficiency

Having found that the type of substrate is an important variable for determining the runoff retention efficiency, an additional analysis was carried out in which different groups were categorized based on the type of substrate, and differences between non-vegetated and vegetated modules were analyzed within each group. The modules with Extensive Substrate 1 showed statistically significant difference, with a significance of 10%, but not with a significance of 5% (p-value = 0.084). Of the vegetated modules Sedum Rupestre vegetation performed best, with an average retention of 84.81%, while the Sedum Sexangulare module and the non-vegetated module averaged 65.52% and 60.17% respectively. The modules with Extensive Substrate 2 showed statistically significant differences (p-value = 0.0001) and the Games and Howell post hoc test showed differences between the Grass and the Sedum Variety 1 vegetated modules (p-value = 0.024), with an average retention capacity of 54.73% and 85.34% respectively. The Grass and the Sedum Variety 2 vegetated modules (p-value = 0.007) had an average retention of 54.73% and 91.05% respectively. The Sedum Variety 2 module exhibited a significantly higher retention than the non-vegetated Extensive Substrate 2 module, confirming findings from Beecham & Razzaghmanesh [1], Teemusk & Mander [19] and Morgan et al. [32], where it was indicated that vegetation was a relevant variable in the increase of retention rates. Productive and intensive substrates showed no statistically significant differences between vegetated and non-vegetated modules. Our results do not coincide with some recent research in tropical climates in which non-vegetated GR were observed to be more efficient than vegetated GR [37].

3.1.3. Effect of Hydrological on Water Retention Efficiency

Multiple linear regressions were carried out to identify statistically significant rainfall variables correlating with the runoff retention process. The independent variables included in the multiple linear regressions were air temperature, air humidity, ADWP, rainfall at maximum intensity and rainfall duration. In order to avoid problems of multicollinearity and to identify the correlations between the independent variables as well as each independent variable with the dependent variable, a correlation matrix was performed. The observed correlation between independent

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variables was lower than 0.728 in all cases, and correlation with retention efficiency depended highly on the specific independent variable.

Due to the relevance of the type of substrate in the process of rainfall retention, the decision was made to carry out a general regression analysis on all the data, as well as independent regression models for each type of substrate, with significances of 1%, 5% and 10% (Table 5 shows regressions coefficients for each of the regressions). When all data was analyzed together using a multiple linear regression model, all variables were significant at 1% significance. The adjustment coefficient R2 was 0.229 with a total of 1114 observations.

The global model showed the relevance of the variables selected, since all were significant at 1% significance. When classifying by type of substrate, air humidity was not significant for the Productive Substrate and the Extensive Substrate 1. Similar results were obtained for air temperature as it was not significant for the Extensive Substrate 1 and was only significant for the Productive Substrate at a 10% significance level. For all substrates, the rainfall characteristics (ADWP, maximum intensity and duration) were significant both at 5% and 1% significance. The determination coefficient (R2) for the Extensive Substrate 1 and Extensive Substrate 2 were 0.353 with 72 observations and 0.229 with a total of 675 observations respectively. The Productive Substrate yielded a R2 of 0.514 with 54 observations and for the Intensive Substrate, the coefficient of determination resulted at 0.373 with a total of 313 observations.

Table 4. Multiple Linear Regressions for Runoff Retention Rate Filtering Data by Type of Substrate

Variable	Global	Extensive 1	Extensive 2	Productive	Intensive
	Regression Coefficient				
Temperature	-0.0205***	0.0261	-0.035***	0.0720*	-0.0267***
Humidity	-1.2202***	-0.6067	-1.5386***	1.0441	-1.1228***
ADWP	0.0076***	0.0342**	0.006***	0.0226**	0.0045**
Max. Intensity	-0.0042***	-0.0069**	-0.0036***	-0.0092***	-0.0038***
Duration	-0.0002***	-0.0004**	-0.0002***	-0.0004***	-0.0002***
Observations	1114	72	675	54	313
R-squared	0.229	0.353	0.228	0.514	0.373

*** p<0.01 ** p<0.05 * p<0.1

3.2. Effect of Event characteristics and Rainfall Regime on Water Retention Efficiency

Using the hydrological variables database (ADWP, rainfall maximum intensity, rainfall duration and rainfall depth), a k-means cluster analysis was performed to categorize event groups according to their characteristics. Figure 5 shows the range of values of the groups for each variable. Although statistical differences were found for all variables, rainfall depth and maximum intensity were the most important variables to take into account when establishing the categories. According to the previous categorization, 3 event groups were defined (small, intermediate and large events). Performing Welch's test showed that significant differences exist between the mean retention of these groups (p-value=0.000) supporting the findings of Teemusk and Mander [19] and Carpenter et al. [38] that confirm a difference in retention due to event size. GRs show the highest retention for small events (96.1%) followed by intermediate events (78.9%) and the lowest retention corresponding to large events (62.6%).

Taking into account the type of substrate, the GRs with Intensive Substrate showed statistically higher retentions than those with Extensive Substrate 2, corresponding to small and intermediate events at 1% significance. Coverage was also analyzed, and results showed that GRs with vegetated coverage have higher retentions for small events (p-value = 0.077). No significant differences were found for neither intermediate nor large events.

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Mean retention of GRs was calculated for each rainfall regime. Welch's test showed that retention in the rainy period (85.3%) is statistically lower than those in the intermediate (90.8%) and dry period (91.8%). This behavior matches the findings of Sims et al. [12] where drier climate conditions were associated with higher average retention efficiencies.

Analyzing the relevance of the substrate and coverage in different conditions, the Intensive Substrate showed a higher retention performance than the Extensive Substrate 2 for dry and intermediate periods at 5% significance and for the rainy period at 10% significance. Vegetated GRs yielded a significantly higher retention than non-vegetated GRs for dry and intermediate periods. No statistically significant differences were found for the rainy period. According to results obtained by Viola et al. [13], climate regime appears to be a relevant determinant for the retention performance of GRs.

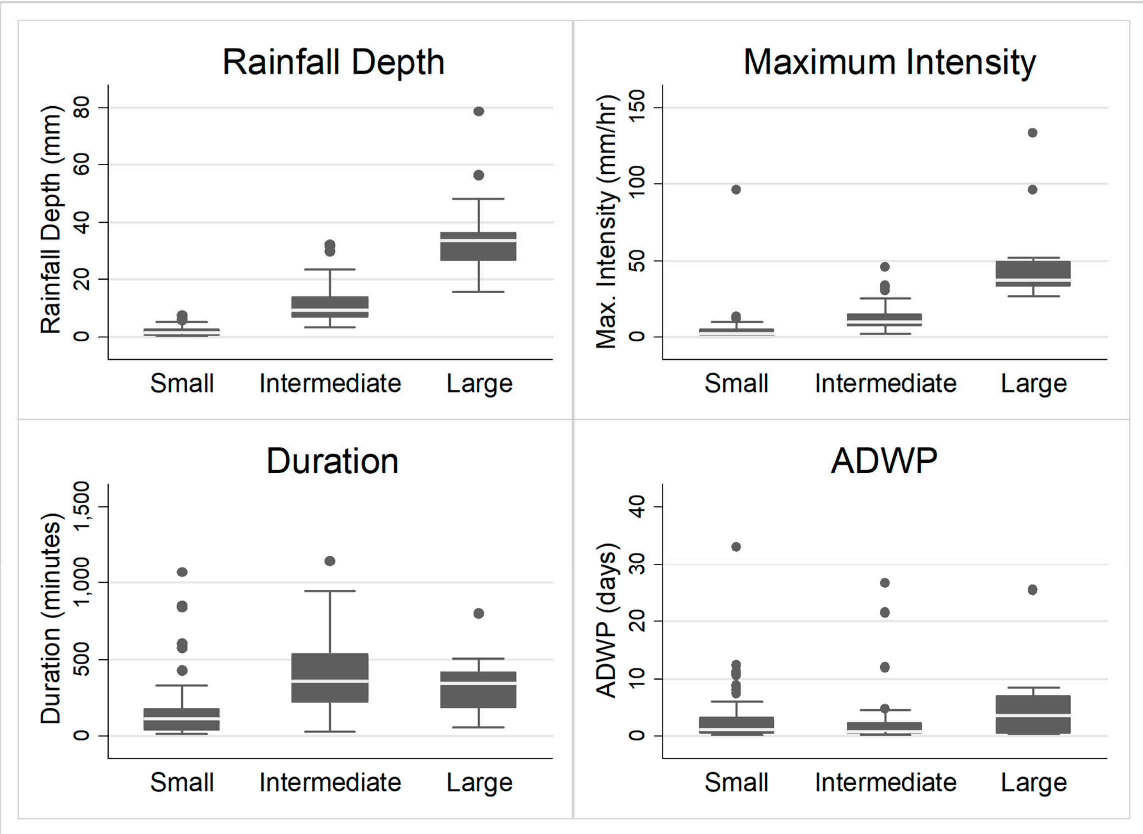

Figure 5. Characteristics of Hydrological Variables for Each Event Size Group

3.3. Water Quality Results

For the runoff water quality analysis, 12 rain events were characterized over a period of 14 months. The characteristics of these events are summarized in Table 5.

Table 5. Characteristics of Rainfall Events for Water Quality Analysis

Variable	Mean	Deviation	Minimum	Maximum
Rainfall Depth (mm)	29.14	14.66	8.40	56.20
Maximum Intensity (mm/h)	33.41	39.15	4.80	133.00
Event Duration (Minutes)	651.14	471.30	57	1900
Antecedent Dry Weather Period (Days)	6.37	10.00	0.21	25.45

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3.3.1. Effect of Green Roofs on Water Quality

For pH and conductivity (Table 6) the GRs and the control cases showed statistically significant differences, in both cases obtaining higher averages for the GR group. Similar results were obtained for organic matter (Figure 6), phosphorus and coliforms, with concentrations for GRs that were significantly higher than the control cases' concentrations (Table 6). These are similar to results presented in previous studies, indicating GRs as a source of organic matter [7, 39], phosphorus [16, 18, 19, 39, 40], pathogens [42] and Total Dissolved Solids [1, 24], as well as the pH neutralization effect from GRs [1, 16, 19, 20, 25, 40, 43, 44, 45].

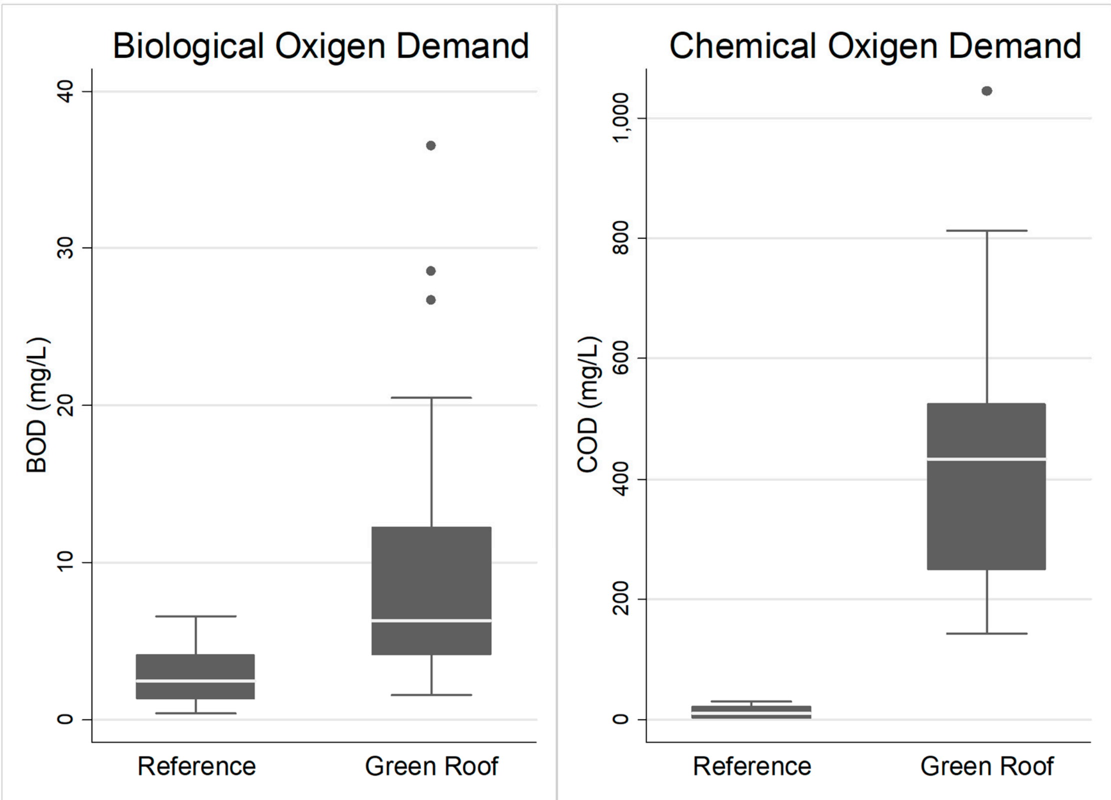

Figure 6. Effect of Green Roofs on Organic Matter Parameters

GRs had significantly higher concentrations for TKN, nitrates and nitrites than the control cases, confirming the findings of Aitkenhead-Peterson et al. [40], Greogoire & Clausen [46], Moran et al. [47], and Whittinghill et al. [48], in contrast to concentrations of ammonia, where in the average GRs' concentrations were below those found in the control cases and where no statistically significant difference (Table 6) was found. These results are similar to those presented by Berndtsson et al. [15] and Buffam et al. [16,]. This phenomenon might be due to the transformation and utilization of nitrogen compounds during the biological and chemical processes of the GRs' vegetation. When looking at the physical parameters (Table 6), color was significantly higher for GR samples, indicating color contributed by vegetated structures and confirming Li & Babcock's [7] findings, that can be explained by the organic content of the GRs' substrates [48]. The t-test for turbidity only showed differences with a significance of 5%, indicating a higher presence of TDS due to GR contributions. In the case of TSS, the t-test showed no statistically significant difference, confirming the high performance of the filter layers used in the GR modules. Finally, although there were higher averages for metals from the GRs in all cases (Table 6), the t-tests showed statistical similarity for selenium and lithium indicating that GRs do not markedly contribute to these parameters. For the rest of the metals (zinc, copper, nickel, lead, aluminum, barium, boron, calcium, strontium, iron,

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magnesium, manganese, potassium and sodium) statistically significant contributions were found in GRs, confirming the findings of Berndtsson et al. [15], Buffam et al. [16] and Vijayaraghavan & Joshi [20]; the presence of these metals in GR leachate can be associated with the composition of the substrate.

Table 6. Descriptive Statistics and t-test Results for the Effect of Green Roofs on Water Quality Parameters

Parameter	Group	Mean	Deviation	Observations	p-Value
pH (Units)	Reference	6.51	1.25	29	0.000
	Green Roofs	8.22	0.57	20	
Conductivity (us/cm)	Reference	29.47	36.50	30	0.000
	Green Roofs	1080.80	762.88	30	
Organic Matter Parameters					
BOD (mg/L)	Reference	2.77	1.65	24	0.000
	Green Roofs	9.15	7.49	43	
COD (mg/L)	Reference	12.85	10.10	19	0.000
Phosphorus Parameters					
Total Phosphorus (mg/L-P)	Reference	0.08	0.07	23	0.000
	Green Roofs	4.06	3.97	46	
Phosphates (mg/L-P)	Reference	0.36	0.48	24	0.000
Coliform					
Total Coliform (MPN)	Reference	7.5*10^2	1.3*10^3	24	0.000
	Green Roofs	1.5*10^5	2.5*10^5	45	
Nitrogen Parameters					
TKN (mg/L-N)	Reference	1.08	0.56	23	0.000
	Green Roofs	11.91	6.03	46	
Nitrates (mg/L-N)	Reference	1.83	1.73	20	0.000
	Green Roofs	9.24	6.80	32	
Nitrites (mg/L-N)	Reference	0.02	0.01	24	0.005
	Green Roofs	0.10	0.18	46	
Ammonia (mg/L-N)	Reference	0.62	0.34	23	0.247
	Green Roofs	0.50	0.40	46	
Physical Parameters					
Color (UPC)	Reference	4.33	1.46	24	0.000
	Green Roofs	34.46	17.55	46	
Turbidity (NTU)	Reference	6.81	9.60	24	0.015
	Green Roofs	18.74	29.41	46	
TSS (mg/L)	Reference	23.42	41.91	24	0.545
	Green Roofs	31.19	54.77	46	
Metals					
Zinc (mg/L-Zn)	Reference	0.04	0.02	23	0.000
	Green Roofs	2.34	2.05	44	
Copper (mg/L-Cu)	Reference	0.03	0.00	23	0.002

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Parameter	Group	Mean	Deviation	Observations	p-Value
	Green Roofs	0.03	0.01	44	
Nickel (mg/L-Ni)	Reference	0.00	0.00	23	0.000
	Green Roofs	0.01	0.00	44	
Lead (mg/L-Pb)	Reference	0.01	0.00	23	0.000
	Green Roofs	0.05	0.04	44	
Selenium (mg/L-Se)	Reference	0.03	0.01	23	0.305
	Green Roofs	0.03	0.05	44	
Aluminium (mg/L-Al)	Reference	0.29	0.15	23	0.012
	Green Roofs	0.67	0.95	44	
Barium (mg/L-Ba)	Reference	0.01	0.01	23	0.000
	Green Roofs	0.04	0.04	44	
Boron (mg/L-B)	Reference	0.06	0.02	23	0.000
	Green Roofs	0.10	0.03	44	
Calcium (mg/L-Ca)	Reference	2.34	1.31	23	0.001
	Green Roofs	138.82	182.00	44	
Strontium (mg/L-Sr)	Reference	0.06	0.01	23	0.000
	Green Roofs	0.52	0.66	44	
Iron (mg/L-Fe)	Reference	0.13	0.14	23	0.000
	Green Roofs	0.44	0.42	44	
Lithium (mg/L-Li)	Reference	0.00	0.00	23	0.473
	Green Roofs	1.45	9.59	44	
Magnesium (mg/L-Mg)	Reference	0.18	0.14	23	0.000
	Green Roofs	14.82	18.63	44	
Manganese (mg/L-Mn)	Reference	0.01	0.00	23	0.000
	Green Roofs	0.02	0.02	44	
Potassium (mg/L-K)	Reference	0.44	0.62	23	0.000
	Green Roofs	189.67	224.54	44	
Sodium (mg/L-Na)	Reference	2.80	1.32	23	0.000
	Green Roofs	97.87	133.89	42	

3.3.2. Effect of Substrate on Water Quality

Our results showed that the effect of substrate on runoff water quality is highly dependent on the type of substrate, which makes selecting the most appropriate substrate for a GR challenging. Mean BOD and COD values obtained for the extensive substrates were 10.18 mg/L and 441.01 mg/L respectively, while the analysis for the Intensive substrate yielded mean values of 7.94 mg/L and 391.37 mg/L for the aforementioned parameters. T-tests showed no difference in significance for BOD and COD parameters between extensive and intensive substrates (p-values > 0.340). Total results for coliforms showed no significant differences between intensive and extensive substrates, with p-values above 0.264 for the t-tests performed, and mean values of 1.9x105 MPN for the extensive substrate and 1.1x105 MPN for the Intensive substrate. Different results were obtained for phosphorus, with significantly lower concentrations for the Intensive substrate (p-values < 0.002)

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confirming the findings of Harper el al. [3] and Kok et al. [49] that associate nutrient loadings with substrate media type.

TKN and nitrates evidenced significantly higher concentrations for the extensive substrate (mean values of 13.75 mg/L and 11.78 mg/L respectively) compared with concentrations for the Intensive substrate (mean values of 10.07 mg/L and 6.35 mg/L), with p-values of 0.038 for TKN and 0.018 for Nitrates t-tests, obtaining consistent results with those presented in Harper et al. [3]. For the other nitrogen parameters (nitrites and ammonia), mean values for the extensive substrates were 0.139 mg/L for nitrites and 0.46 mg/L for ammonia, while the results for the Intensive substrate were 0.05 mg/L and 0.54 mg/L for nitrites and ammonia; however, there is not enough statistical evidence to assert differences between groups (p-values > 0.05), which is why it is not possible to confirm a marked effect of the substrate for these cases.

A similar behavior was observed for the physical parameters, in which the Intensive substrate runoff had significantly less color (p-value: 0.002 with mean values of 42.17 UPC for the extensive and 26.74 for the intensive substrates) and turbidity (p-value: 0.073 with mean values of 26.643 NTU for the extensive and 10.834 NTU for the intensive substrates), but not for total suspended solids, the parameter in which the performance of the extensive substrate (mean value of 25.68 mg/L) was better than the Intensive substrate (mean value of 36.70 mg/L), but no statistically significant differences were found.

Results for metals were highly variable depending on the specific metal under consideration. For zinc, nickel, aluminum, barium, calcium, strontium, lithium, magnesium and sodium, concentrations in the Intensive substrate runoff were higher than concentrations in that of the extensive substrate; however, t-tests only evidenced statistically significant differences for zinc, barium, calcium, strontium and magnesium (p-values < 0.05),therefore it cannot be said that the type of substrate strongly effects these parameters. Meanwhile, for copper, lead, selenium, iron, manganese and potassium, the extensive substrate had higher concentrations; t-tests evidenced only significant differences for copper and lead.

The same analysis was carried out for pollutant loads, and results evidence that the Intensive substrate had higher loads of most physicochemical parameters and all metals. However, differences were only significant for Total Phosphorus where the extensive substrate had a higher load (p-value: 0.030). For zinc, calcium, strontium, magnesium and sodium, the Intensive substrate showed significantly higher loads.

3.3.3. Effect of Vegetation on Water Quality

Results for organic matter, phosphorus and total coliform were consistent over all parameters. For organic matter parameters, vegetated modules presented mean concentration values of 9.15 mg/L and 464.08 mg/L for BOD and COD respectively. Mean concentration of total phosphorus was 4.16 mg/L and 5.40mg/L for phosphates in the vegetated modules. Total coliform MPN in vegetated modules was 1.8x105. In all cases, vegetated roofs yielded higher concentrations than those without any plant coverage. However, no statistical differences were found. The analysis of the effect of vegetation for pH and conductivity, where vegetated modules presented values of 8.24 and 1231.20 us/cm respectively, did not identify significant differences in any of the vegetation types compared with the values for the non-vegetated modules, yielding a mean pH of 8.17 and a mean conductivity of 930.40 us/cm. These results demonstrate that it is not possible to state that the presence of vegetation modifies the way in which GRs affect these parameters of water quality.

For nitrogen parameters (TKN, nitrates, nitrites and ammonia), although non-vegetated modules present higher concentrations, no statistical differences were observed in any case. According to these results, it is not possible to state that vegetation has a buffering effect on the levels of nitrogen. For turbidity and TSS, non-vegetated modules presented lower values (17.88 NTU and 20.91 mg/L) than vegetated modules (19.67 NTU and 42.41 mg/L). On the other hand, vegetated roofs (30.23 UPC) appeared to buffer the presence of color. The analysis for the physical parameters did not show evidence of the effect of vegetation.

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For metals, there was also no clear effect of the presence of vegetation in most of the parameters characterized. For copper, lead, selenium, aluminum, barium, boron, calcium, strontium, iron, magnesium, manganese, potassium and sodium, no effect was perceived. Only for zinc (p-value = 0.000) and nickel (p-value = 0.05) were there statistically significant contributions from vegetated modules.

Pollutant loads were also considered in order to evaluate the effect of the vegetation on runoff quality. Results showed that non-vegetated roofs produced higher loads than roofs with vegetated coverage for all physicochemical parameters excluding Total Phosphorus and for all metals except for zinc and lithium. Statistical tests evidenced that there are no significant differences; however, the consistent presence of higher pollutant loads in runoff from non-vegetated roofs confirm findings by Beecham & Razzaghmanesh [1] and Wang et al. [45] that mention enhanced pollutant removal for vegetated roofs.

3.3.4. Effect of Event Characteristics and Rainfall Regime on Water Quality

Analysis was carried out to find correlations between the water quality parameters of concentrations and loads, and the rainfall characteristics (ADWP, rainfall depth, rainfall maximum intensity and rainfall duration). Pollutant loads evidenced consistent and higher correlations with the rainfall depth and maximum intensity than with concentration values. However, when analyzing the effect of the event characteristics using pollutant loads, the t-test did not show evidence of these effects, only large rainfall events presented higher TP loads than intermediate events, at a 10% significance (0.099). For all the other measured parameters large events yielded higher loads, but no statistical evidence was found. On the other hand, concentrations analysis showed higher concentrations of COD (p-value: 0.013) and nitrates (p-value: 0.086) for intermediate events. Zinc, lead, calcium, strontium, magnesium, potassium and sodium concentrations are statistically higher for intermediate events than for large events. These results coincide with Teemusk & Mander's [19] conclusions asserting that low magnitude events can lead to higher concentrations in the water quality.

For pollutant loads, the effect of the rainfall regime was only appreciable for COD where the intermediate months yielded higher loads (p-value: 0.042). Carpenter et al. [38] determined that there are higher nutrient loads in the growing season (warm temperatures); however, in this study phosphorus loads were higher in the rainy period and nitrogen loads were higher in the intermediate. For the rest of the physicochemical parameters no effect was found. Regarding metals, there were higher loads in the intermediate period, with zinc, barium, calcium, strontium, magnesium, potassium and sodium being significant.

Buffam et al. [16] found a correlation between the air temperature and some parameter concentrations, resulting in higher concentrations in summer; however, in Bogotá's climate this correlation does not apply for every parameter, taking into account that the changes in temperature are not as dramatic as changes in countries with seasons. Concentration analysis showed statistically significant differences for organic matter, TSS and total coliforms. Dry months presented higher concentrations of BOD (p-value = 0.039) and TSS (p-value = 0.017). The rainy period yielded higher values of COD (p-value = 0.003) and total coliforms (p-value = 0.047). Rainfall regime effect was also identified for nickel, boron, calcium, strontium, magnesium, manganese, potassium and sodium (p-value < 0.05).

5. Conclusions

The water retention analysis identified the type of substrate as the most important variable when studying the performance of GRs in terms of water quantity, while the presence of vegetation was not evidenced to have an effect when conducting an analysis with all data. The second round of analysis, which consisted of grouping by affinity the modules with the same type of substrate, showed that vegetation is a relevant explanatory variable in the model, significantly increasing the retention efficiencies of the GRs. The rainfall event characteristics and the rainfall regime were found

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to be important for assessing rainfall retention. GRs perform differently depending on the event magnitude and the month of the year, with best results found in dry months and for small events.

Analysis looking for the effect of GRs on runoff water quality identified a significant increase in the presence of most of the parameters, except for ammonium, TSS, selenium, and lithium. On the other hand, the type of substrate was shown to be relevant in determining the presence of phosphorus, TKN, nitrates, color and turbidity, found in higher concentrations in runoff from modules with extensive substrate. Finally, analysis of the effects of different substrates on the presence of metals yielded highly variable results depending on the specific metal under consideration.

The evidence on the effects of vegetation was limited, because although the vegetated modules presented higher concentrations for most of the parameters, no statistically significant differences were found to support these findings. Similarly, for most of the metals analyzed, vegetated modules presented higher concentrations, however these were only significantly higher for zinc and nickel. Rain event characteristics had an effect on COD, nitrates, zinc, lead, calcium, strontium, magnesium, potassium and sodium, parameters for which intermediate events showed higher concentrations. The rainfall regime was relevant when looking at the concentrations of BOD, COD, TSS, total coliforms, nickel, boron, calcium, strontium, magnesium, manganese, potassium and sodium.

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