Assessment of Runoff Quantity And Quality For Extensive Green Roof Modular Systems

Évaluation de la quantité et la qualité des eaux de ruissellement pour les systèmes modulaires de toiture végétalisée extensive

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RÉSUMÉ

Cette étude a évalué l'efficacité de rétention et la qualité des eaux de ruissellement de 15 systèmes modulaires de toitures végétalisées (TV). Les systèmes modulaires ont été placés sur le campus de l'Université des Andes à Bogota en Colombie. Les résultats de cette recherche sont basés sur 69 évènements pluvieux sur une période de deux ans. La rétention hydraulique moyenne des évènements pluvieux mesurés est de 73%. Des analyses statistiques (ANOVA et régressions linéaires multiples) ont été réalisées pour identifier les variables qui affectent la rétention (température de l'air, type de substrat, humidité du sol, période de temps sec entre les évènements pluvieux, durée de la pluie et intensité de la pluie). Les caractéristiques de conception (type de substrat et végétation) et dans certains cas les variables climatologiques ont été jugées pertinentes pour évaluer l'efficacité de rétention. L'azote Kjeldahl (NTK), les nitrates, les nitrites, l'ammoniac, le phosphore total (TP), les phosphates, le pH, les solides dissous totaux (TDS), les matières en suspension (MES), la couleur, la turbidité, la DBO, la DCO, les coliformes totaux, les métaux, et les hydrocarbures aromatiques polycycliques (HAP) ont été mesurés dans les échantillons de pluie et dans les eaux de ruissellement. Les résultats obtenus ont confirmé que les systèmes de TV ont la capacité de neutraliser le pH, mais sont la source du reste des paramètres mentionnés ci-dessus, à l'exclusion des HAP, avec des concentrations inférieures aux limites de détection pour tous les points de mesure. En outre, les résultats montrent des charges variables en fonction du substrat des TV et de la végétation. L'analyse de la réutilisation de l'eau a présenté les usages agricoles et d'élevage de bétail comme des usages potentiels pour la réutilisation des eaux de ruissellement des TV.

ABSTRACT

This study assessed the hydrological performance and runoff water quality of 15 green roof (GR) modular systems located at the Universidad de Los Andes campus (Bogotá, Colombia). Based on 68 rainfall events, spanning a 2-year period, average rainfall retention for the evaluated systems was 73%. Analysis of Variance (ANOVA and Multiple Linear Regressions) were carried out, in order to assess variables that could potentially control runoff retention values such as air temperature, growing media, type of plant species, humidity, antecedent dry weather period (ADWP), rainfall duration and rainfall maximum intensity. Design variables (i.e. growing media and type of plant species) were found to be relevant in some scenarios for the retention efficiency and depending on the set-up, climatological variables were also correlated with the retention. Rainfall and GR runoff were monitored for Total Nitrogen Kjeldahl (TNK), Nitrates, Nitrites, Ammonia, Total Phosphorus (TP), Phosphates, pH, Total Dissolved Solids (TDS), Total Suspended Solids (TSS), Color, Turbidity, Biochemical Oxygen Demand (BOD), Chemical Oxygen Demand (COD), Total Coliforms, metals and Poliaromatic Hydrocarbons (PAH_s). Obtained results confirmed that GR systems have the ability to neutralize pH but are source of the rest of the aforementioned parameters, excluding PAH_s, with concentrations below detection limits for all measurement points. Furthermore, pollution loads results showed variability depending on the GR growing media and vegetation. Water reuse analysis indicated agricultural and livestock as feasible usages for GR runoff.

KEYWORDS

Extensive Green Roofs, Water Quality, Runoff Retention, Bogotá (Colombia)

1 INTRODUCTION

In the last decades urban population have increased and consequently urbanization rates are incrementing progressively (United Nations, 2011). A well-known consequence of urbanization is an increase of impervious areas such as parking lots, streets and impermeable roofs (Berndtsson, 2010). In the last decades, new strategies for solving urban drainage problems generated by urbanization known as Best Management Practices (BMP) or Sustainable Urban Drainage Systems (SUDS) have been successfully implemented in several countries under different configurations and typologies (Marlow et al, 2013). One of these technologies, mainly applied in highly urbanized areas are GR systems, which have shown benefits in terms of stormwater retention (Hutchinson et al, 2003; Johnston et al, 2004; VanWoert et al, 2005; Carter & Rasmussen, 2006; Mentens et al, 2006; Teemusk & Mander, 2007; Uhl & Schiedt, 2008; Berghage et al, 2009; Voyde et al, 2010; Stovin et al, 2012; Volder & Dvorak, 2014; Harper et al, 2015) and runoff water quality transformations (Berndtsson, & Jinno, 2009; Alsup et al., 2012; Gnecco et al., 2013; Lizhu & Zhang, 2014; Speak et al., 2014).

Although there are several recent studies, specially from North America, Australia and Europe that evaluated GR performance through monitoring, reported retention rates (Carter et al. 2005; Beecham et al. 2014; Volder et al. 2014) and runoff pollutant removal efficiencies (Berndsson et al in 2009; Berndtsson, & Jinno, 2009; Rowe; 2011 Seidl et al, 2013) varies widely among each study. On the other hand, there is a lack of understanding for the behavior of GR in tropical weather, so GR studies that describe the physical and chemical processes taking place are needed under such climatic conditions. This study analyzes quantitative evidence of how extensive GR affects storm water quantity and quality, involving variables such as type of vegetation, type of substrate, weather conditions and rainfall characteristics.

2 MATERIALS AND METHODS

2.1 Experimental setup

The experimental site of the study is located at the main campus of the Universidad de los Andes Bogotá, Colombia) and it consist of different modular GR trays implemented over a two years period in order to reproduce different extensive GR configurations. The general vertical composition of the different modules is as follows, from surface to bottom: 1) vegetation layer; 2) substrate layer or growing medium, 3) filter layer (nonwoven geotextile Sika 1800 or recycled textile felt); 4) drainage layer (Sika T-20 Garden), and 5) module walls (plastics or cold roll depending on the module) playing the role of waterproofing membrane and deck of a conventional roof. All modules along the monitoring period were leveled in the horizontal plane with a slope less than 1% and no watering was provided to any of the evaluated extensive GR modules throughout this study. In order to compare the water quality performance of GR with conventional roof surfaces and rainfall, a plastic tile of 1x0.7 [m] and a rainfall collection tank were implemented under the same climatic conditions of GR modules. Different plant species were evaluated along the monitoring period: homogeneous configuration of Sedum Sexangulare, Sedum Rupestre, radish, lettuce, grass, a heterogeneous mixture of intensive plants (consisting of: Water Lily, Bergenia and Lavender) and two different heterogeneous types of Sedum mixtures; Sedum mixture mat 1(consisting of varieties: Sexangulare, Chatre, Album, Acre, and Kamtschaticum) and Sedum mixture mat 2;(consisting of varieties: Blue, Acre, Fino, Sexangulare, Chatre and Oregano). In the experimental set-up, different types of substrates were tested according to each type of vegetation (two different types of extensive substrate, intensive substrate and productive substrate for vegetables). The different physical characteristics of the modules are shown in Table 1, and Table 2 includes a brief description of the monitored rain events during each period.

Table 1. Experimental Set-up Description

	Modules	Events	Observations	Plants	Substrate	Non vegetated modules	Module size and material
1. 25/09/2013-07/11/2013	4	6	24	Sedum Sexangulare, Sedum Rupestre, Radish and Lettuce.	Sedum plants over 6 [cm] of extensive substrate type 1. Vegetables over 8 [cm] of productive substrate.	Extensive substrate type 1 and polyurethane foam	Plastic modules of 0.70x0.54x13 [cm]
2. 08/11/2013 – 03/12/2013	4	11	43*	Sedum Rupestre , Radish and Lettuce.	Sedum plants over 6 [cm] of extensive substrate type 1. Vegetables over 8 [cm] of productive substrate.	Extensive substrate type 1	Plastic modules of 0.70x0.54x13 [cm]
3. 08/03/2014 – 03/04/2014	4	4	16	Sedum Sexangulare, Sedum Rupestre and Radish	Sedum plants over 6 [cm] of extensive substrate type 1. Vegetables over 8 [cm] of productive substrate.	Floral foam	Plastic modules of 0.70x0.54x13 [cm]
4. 04/04/2014 – 08/05/2014	2**	15	30	Sedum Sexangulare and Sedum Rupestre	Sedum plants over 6 [cm] of extensive substrate type 1	none	Plastic modules of 0.70x0.54x13 [cm]
5. 18/10/2014 – 30/11/2014	5	17	85	Sedum Sexangulare, Sedum Rupestre Sedum mixture mat of 5 species and Grass	Sedum plants over 6 [cm] of extensive substrate type 1 Sedum mixture mat over 6 [cm] of extensive substrate type 2	Extensive substrate type 1 and 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. 26/08/2015 – 10/11/2015	6	15	90	Two different configuration s of Sedum mixture mat of 5 species each one and Intensive plant mixture of 5 species	Sedum mixture mat over 6 [cm] of extensive substrate type 2 and intensive plants over 6 [cm] of intensive substrate	Two configurations of extensive substrate type 2 and Intensive substrate	Metallic modules of 0.7x0.7x0.13 [m]

* Two observations are missing because of measuring equipment failure, **Data was analyzed from only two modules

Table 2. Rainfall Characteristics for the Different Periods

	Rainfall Characteristics								
	Duration (min)			Precipitation (mm)			Max. Intensity (mm/hr)		
	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max
1. 25/09/2013-07/11/2013	21.2	147.8	275.2	0.6	5.8	15.8	1.2	10.6	26.4
2. 08/11/2013 – 03/12/2013	12.2	325.1	1587.2	0.2	7	22.2	1.2	9.9	29.6
3. 08/03/2014 – 03/04/2014	57.6	183.6	316.8	2.2	12.5	30.4	9.6	21.3	29
4. 04/04/2014 – 08/05/2014	14.4	82	230.4	0.4	3.2	9	1.2	6.4	20.3
5. 18/10/2014 – 30/11/2014	14.4	142	476.6	0.4	7.8	51	1.2	14.5	79.2
6. 26/08/2015 – 10/11/2015	14	230.5	864	0.4	3.6	14	1.2	4.3	12

2.2 Monitoring system

The following variables were monitored online with a sampling rate of one record every minute except for runoff which was measured at a rate of one record every 10 seconds: GR volumetric water content (using DECAGON ® EC-5 sensors), GR soil temperature (using thermocouples type H) and GR runoff (using an adapted system of tipping bucket rain gauges DAVIS ® model rain collector II). Additionally the following water quality related variables were monitored: pH, conductivity and temperature using YSI multiparameter probe model 600R and Global Water ® probes model WQ-201 and W-cond. In order to measure the experimental site climatic conditions, the following meteorological variables were measured continuously at a rate of one record per minute using a DAVIS ® weather station model VANTAGE Pro 2: rainfall, atmospheric pressure, wind speed and direction, Outside Temperature, Inside Temperature, relative humidity, Incoming and reflected solar radiation, and ultraviolet radiation index. The schematic representation of the different modules assembly at the present (26/08/2015 – 10/11/2015) is shown in the Figure 1.

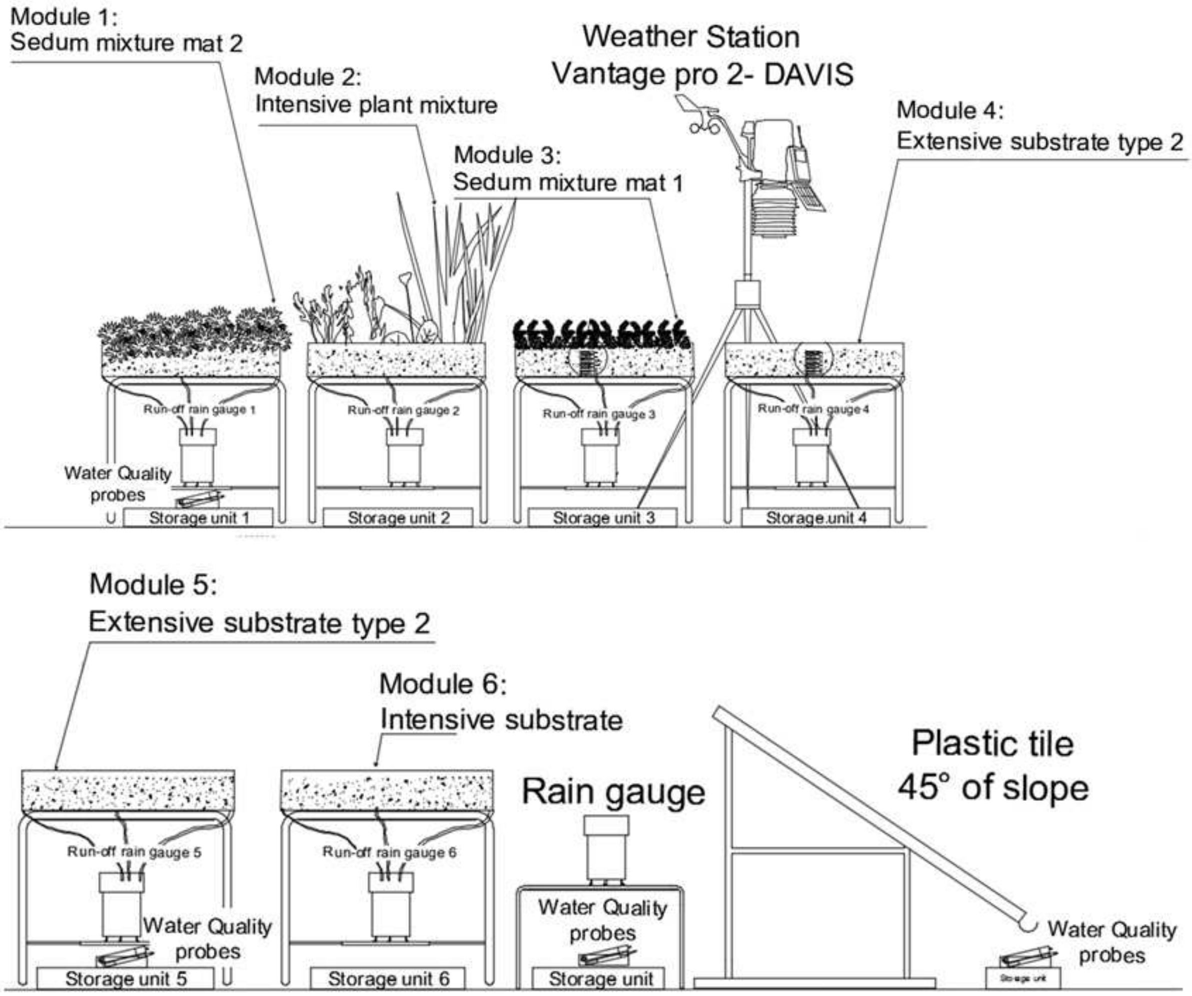

Figure 1. Experimental setup in the last phase of experimentation (26/08/2015 – 10/11/2015)

2.3 Analysis methodology

2.3.1 Statistical Analysis

For the analysis of climatological variables an average value of variables such as air temperature and humidity were used during rainfall events. With all the data collected through the monitoring periods, ANOVA tests were made to identify differences between the GR runoff retention efficiency of the different substrates and plant types used in the setup. To complement the previous analysis, multiple linear regressions were used to identify which variables are statistically significant and correlated with the runoff retention process.

2.3.2 Laboratory Analysis

Laboratory procedures were conducted following the methods of (Rice et al, 2012). Descriptive statistics were calculated evaluated in order to assess the effect of GR, substrate and vegetation analysis in runoff water quality transformations.

3 RESULTS AND DISCUSSION

3.1 Stormwater retention

Using 68 rainfall events, which represent 245 values of retention percentage when counting all the observations of the different set-ups, it was found that average retention efficiency is 73%. Average retention in this study agrees with the results reported by Michael (2007). The average retention of all the set-ups used in this study are summarized in Table 3. The retention of modules with vegetated coverage was compared with the retention of modules that have a substrate without any plant species; it was found that in average, the retention of planted modules is slightly higher than the retention of modules without vegetated coverage. According to these results, it is necessary to develop further analysis between types of substrates and within different plant types that grow in the same substrate, in order to evaluate the relevance of these two design variables.

Table 3. Green Roofs Runoff Retention Averages

Extensive Substrate 2		**Extensive Substrate 1**		**Productive Substrate**		**Intensive Substrate**	
Species	**Mean**	**Species**	**Mean**	**Species**	**Mean**	**Species**	**Mean**
S. Mixture mat 1	82%	**S. Sexangulare**	64%	**Radish**	60%	**I. Mixture**	88%
S. Mixture mat 2	89%	**S. Rupestre**	83%	**Lettuce**	68%		
Grass	52%	**Without Plant**	60%	**Without Plant**	63%	**Without Plant**	92%
Without Plant	75%						
TOTAL	75.6%	**TOTAL**	68.1%	**TOTAL**	63.5%	**TOTAL**	89.9%

3.1.1 Differences between types of substrates and types of vegetated coverages

ANOVA test for the four substrates analyzed in this study showed that there are significant differences between their retention efficiencies (p-value: 0.0047). A Bonferroni test, which allows knowing which substrates have different retentions, showed that there are significant differences between the retention of extensive substrate 1 and intensive substrate (p-value: 0.026), and also between the productive substrate and the intensive substrate (p-value: 0.005). In both cases the intensive substrate has a higher retention, however the intensive module was monitored for a shorter period of time, making it necessary to collect more data in order to be able to confirm that the intensive substrate has the best retention.

It was necessary to perform ANOVA tests for types of plants used with the same substrate to be able to determine which ones exhibit a better performance. For extensive substrate 1, it was found that mean retention of the *Sedum Rupestre* is statistically higher than the other modules with this substrate (p-value: 0.08). Coverages used with extensive substrate 2 have significant retention differences (p-value: 0.02); differences in retention efficiency are statistically significant between *Sedum mixture* mat 1 and grass, and *Sedum mixture* mat 2 and grass. Sedum mixtures present the best retention efficiencies when using substrate 2. There are no significant differences between retention of modules with productive substrate (p-value: 0.77). Analyzing modules with the intensive substrate, it was found that there are no significant differences between their retentions. As mention before, further information is required to confirm if the presence of intensive plant species does not improve significantly runoff retention.

3.1.2 Linear Regression Models

Correlation analyses between the variables of interest and runoff retention were developed resulting in higher correlations of air temperature and rainfall duration with values of 0.44 and -0.44 respectively. When all the data was analyzed together with a multiple linear regression, all the variables (temperature, humidity, ADWP, maximum intensity and duration) were statistically significant at 1% of significance. However, when disaggregating the information by type of substrate and type of plant, it was possible to make a more exhaustive analysis. When classifying by substrate, air temperature and ADWP seemed to affect only the retention efficiency of extensive substrate 1 and productive substrate, this behavior might be highly related with the type of plant used in the substrates that do not present this correlation (Sedum and intensive species), because they can store important amounts of water for long periods. For productive species such as lettuce and radish, these two variables do affect the retention process. Humidity appears to be uncorrelated with the retention in most of the evaluated configurations, only for extensive substrate 2 and for sedum species; it was a significant variable at 10% of significance. Rainfall characteristics were found to be correlated with the runoff retention process, especially the rain event duration, which is significant in all the scenarios. Maximum intensity was also correlated with runoff retention in some modular configurations. However, when the same analysis that was carried out for temperature and ADPW was developed for maximum rainfall intensity, having Sedum and intensive species, it was found that the effect of the maximum intensity seems to set aside in the retention process.

3.2 Runoff water quality

Water quality analysis included eight rain events, spanning the period from 16/10/2013 to 7/11/2015.

3.2.1 Green roofs effect analysis

The matrix analysis allowed identifying a repeating pattern over all parameters characterized in laboratory. In all cases GR showed to be a source of pollutants, with higher averages than those obtained for rainwater and the plastic tile runoff, confirming GR as a major pollutants source and reaffirming several previous findings that concluded that GR represented a pollution source for water (Beecham & Razzaghmanesh, 2015; Zhang et al., 2014; Hashemi et al., 2015; Whittinghill et al., 2015; Aitkenhead et al., 2011; Berndtsson et al., 2009).

3.2.2 Substrate effect analysis

The substrate effect analysis allowed identifying this variable as a crucial factor to determine the contribution of pollutants of GR runoff. Total coliforms, TP and TKN presented variable concentrations for the different substrates; therefore, Table 4 ranks the performance for each of the substrates analyzed, being one the substrate with the lowest contributions, and four the substrate with the highest input of pollutants.

Table 4. Classification of Performances of Extensive-1, Extensive-2, Intensive and Productive Substrates for Total Coliform, Total Phosphorus and TKN

	Total Coliforms	Total Phosphorus	TKN
Extensive 1	2	4	1
Extensive 2	4	2	4
Intensive	3	1	2
Productive	1	3	3

For color, BOD, COD, phosphates, nitrates, nitrites, ammonia, TSS and turbidity it was only possible to characterize the intensive and extensive-2 substrates. The results allowed detecting a repetitive pattern over all pollutants, with lower contributions for intensive substrate, which makes possible to confirm the intensive substrate as a better performance substrate over extensive substrate in terms of runoff water quality and confirms Li & Babcock (2014) findings that evidenced the substrate as a significant variable in the pollutants input process.

3.2.3 Vegetation effect analysis

Results were grouped by type of substrate and averages for vegetated and non-vegetated modules were analyzed obtaining results that reveal the effect of vegetation in each of the configurations with the same type of substrate. With exception of TSS and metals, which will be referred later in the document, the analysis identified that vegetated GR represented a minor source of pollutants comparing it with non-vegetated GR, potentially due to vegetation as a relevant buffering capacity. Different results were obtained for total suspended solids, with lower averages for non-vegetated modules in comparison with vegetated modules averages. Likewise, the sampling results for metals helped identifying the vegetated GR as a major source of zinc, copper, nickel, lead, aluminum, barium, calcium, strontium, iron, lithium, magnesium, manganese and potassium, comparing it with the non-vegetated extensive substrate module. This phenomenon is attributable to the constructive assembly that varied between vegetated and non-vegetated modules concerning the filter layer of each type of module; the filter layer for non-vegetated modules showed greater retention of particles and consequent retention of metals comparing it with vegetated modules.

3.2.4 On-line water quality measurements

On-line water quality measurements for conductivity identified that the effect of rain events does not generate major disruptions for rainwater and plastic tile runoff, with relative constant values along measurement periods ranging from 200 us/cm to 50 us/cm. In parallel, it was possible to identify substantial increases in conductivity in GR, indicating major contributions of total dissolved solids by these structures, which is consistent with previous findings (Beecham & Razzaghmanesh, 2015; Zhang et al., 2014).

The pH on-line measurements identified positive responses for GR and plastic tile runoff, with basic initial values (from 8 to 9) and final pH values near neutrality (between 7 and 8), confirming what was found by previous studies (Aitkenhead et al., 2011; Beecham & Razzaghmanesh, 2015; Chen, 2013; Mendez et al., 2011; Teemusk & Mander, 2007; Vijayaraghavan & Joshi, 2014). At the same time, the analysis for rainwater makes evident initial acid pH values (between 5 and 6) and progressive decreases in this value, reaching values near 4.5, which gives clear evidence of the effect of acidification by rainwater.

4 CONCLUSIONS

It was found that in average, extensive modular GR of the Universidad de los Andes campus experimental setup retain 73% of the rainfall. ANOVA analysis allowed stablishing the effect of the type of substrate and the type of plant. It was found that in average the intensive substrate and the extensive substrate 2, present the best retention efficiencies with values of 89.9% and 75.6% respectively.

Using multiple linear regressions it was possible to determine the relation between climatological variables and retention efficiency. When using all the data together, all the variables seem to be significant, however when segregating by type of substrate and type of vegetated coverage, it was found that duration of the rainfall event is always significant. Variables such as temperature, ADWP and maximum intensity are correlated when there is no presence of Sedum nor intensive species. Humidity appears to be uncorrelated with the retention in most of the set-ups, only for extensive substrate 2 and for sedum species, it was significant at 10%. The lack of information of intensive substrate and plant species, does not allow to conclude with certainty its retention efficiency.

Taking into account these results, it is recommended in places with similar climate conditions to those in Bogotá, to implement extensive modular roofs with substrates that are primarily compound of organic matter like substrates 1 and 2, together with any sedum species, thus sedum species improve retention in approximately 20% compared with setups that use productive species.

Water quality analysis concluded that for the majority of the parameters studied, except for pH, GR had a negative effect on water quality: higher effluent pollutant concentrations for GR systems. In the case of pH, the vegetated structures showed neutralization effect and consequent mitigation of rainwater acidification. The analysis discriminated by type of substrate and vegetation conclude that the type of substrate is crucial in explaining the contribution of pollutants to water. Presence of vegetation on roofs slightly mitigates pollutants contribution, except for total suspended solids and metals. A complementary analysis was made in order to assess the feasibility of reusing GR runoff according to Colombian legislation; agricultural and livestock usages were found to be adequate to allocate GR runoff.

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