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Rainwater storage in urban environments using green roofs

Almacenamiento de agua de lluvia en medios urbanos utilizado techos verdes

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Abstract

This article discusses the use of green roofs as rainfall water storage in its soil matrix. The methodology is analytical based on mathematical models, where runoff produced in an urban area is compared with current conditions of ordinary roofs with ceramic or bituminous materials as the original scenario, against another where green roofs are used. The study area is located in the Palavecino municipality of Lara state in Venezuela, in the flood zone of Quebrada Tabure. In this research, a quantitative comparison of the direct runoff hydrographs of the proposed scenarios was used, obtaining as a main result the reduction of runoff between 60% and 80% according to the period of return. An interesting point of this research was the incorporation of the routing of hydrographs on the roofs, reducing even more the peak flow over 90%, and delaying the peak time of the generated hydrographs between 10 and 12 minutes while the total duration of the hydrographs increase more than three times.

Keywords: Green roofs, runoff, hydrographs, peak flow, rainwater storage, routing hydrographs.

Resumen

El siguiente artículo de investigación trata sobre el uso de techos verdes como almacenadores de agua de lluvia en su matriz de suelo. La metodología es analítica basada en modelos matemáticos, en donde se compara la escorrentía producida en un urbanismo con condiciones actuales de techos ordinarios con materiales cerámicos o bituminosos como escenario original, contra otro donde se usan techos verdes. La zona de estudio se ubica en el municipio Palavecino del estado Lara en Venezuela, en la zona de inundación de la Quebrada Tabure. En esta investigación se empleó la comparación cuantitativa de los hidrogramas de escorrentía directa de los escenarios planteados, obteniendo como resultado principal, la reducción de la escorrentía. Un punto interesante de esta investigación fue la incorporación del tránsito de hidrogramas en los techos, reduciendo aún más el caudal pico y el tiempo al pico de los hidrogramas generados.

Palabras clave: Techos verdes, escorrentía, hidrogramas, caudal pico, almacenamiento de agua de lluvia, tránsito de hidrogramas.

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1 Introduction

Land use change due to urbanization has a significant impact on the local hydrology accompanied by other negative effects. Continuous growing of cities has increased the proportion of impervious areas in them. The progressive and uncontrolled waterproofing of surfaces alters the hydrological cycle (Figure 1), decreasing the response of a basins to a rain event, increasing the volume of drained water and, therefore, decreasing in the recharge of aquifers.

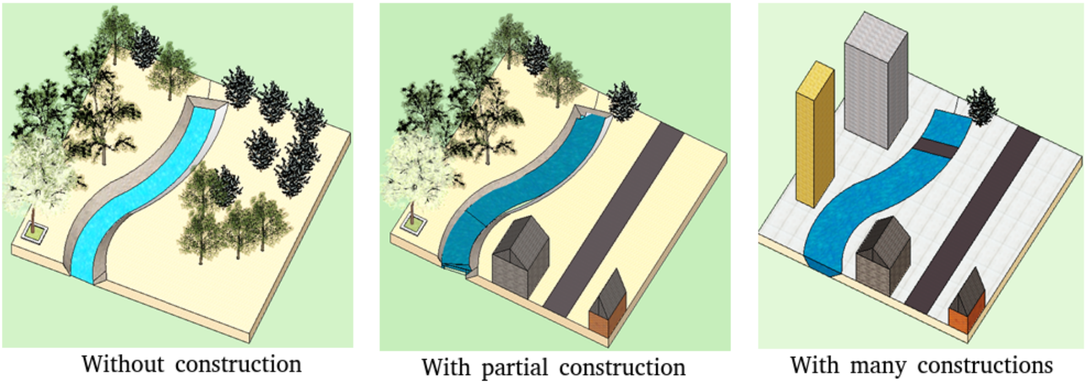

Figure 1. Effect of construction in hydrological cycle.

In addition, the growth of cities without planning can cause the alteration of natural courses, generating the need to build artificial channels that eventually will lead to worse problems in terms of urban drainage such as floods, collapse of longitudinal and transversal road drainages and delays during working hours of the inhabitants, in addition with the social tension caused by the aforementioned reasons. Water has a cycle that maintains a balance among evaporation, runoff, precipitation, infiltration, evapotranspiration, among others, which can be translated according to Chow et al. (1994) as shown in Equation 1. Where P is the total precipitation thickness, P_e is the effective precipitation thickness which generates runoff, I_a is the initial abstraction, F_a is the quantity of water retained in the basin, E is the evaporation related with vegetation or the properties of the basin.

$$P = P_e + I_a + F_a + E \tag{1}$$

In these processes, natural channels take dimensions to be able to transit the generated runoff, a process that is naturally slow, depending of the characteristics of the basin, soil, vegetation, among others. In the case of urban areas, the infiltration process is reduced, thus runoff generated is much higher and natural channels are not able to circulate the new maximum flow. Another problem generated by the construction without repositioning of green areas is the heat island effect, which is generated in areas that are significantly warmer than nearby rural areas, since the production of oxygen decreases and that of carbon dioxide increases (Arabi et al., 2015). Besides it is necessary to consider rainfall intense events increased by Climate Change (Olivares, 2018; Serrano et al., 2012, 2017; Ilbay-Yupa et al., 2019). Moreover, ceramics and bituminous materials retain much more heat than soil with vegetation, contributing to this effect as well. According to EPA (2018), green roofs can be defined as a roof with vegetation. Components of green roofs can vary, but basically they consist of vegetation, growth substrate, filter layer, drainage layer, waterproofing layer and root barrier (Minke, 2017; Vijayaraghavan, 2016).

According to Berardi et al. (2014); Minke (2017), green roofs can be classified into two types, based on growth substrate thickness; (i) extensive green roofs, generally have a thickness of growth substrate below 20 cm, a maximum weight of 150 kg/m^2 and they do not need irrigation because their vegetation is common, such as moss, herb, grass; and (ii) intensive green roofs, that have a thickness of growth substrate over 20 cm, generating a total weight above 300 kg/m^2 and they need drainage and irrigation because of the vegetation used in them correspond to small trees. Green roofs have multiple applications, and one of those is to retain and storage rainwater, decreasing runoff, and thus the impact of the heat island effect (EPA, 2018) and deforestation in urban environments, decreasing the negative impact on the local fauna.

Another benefit is that green roofs could be a valuable solution as an alternative to recover green spaces in urbanized areas (Berardi et al., 2014). Green roofs have a lot of benefits, according to BCIT (2018); Minke (2017); Berardi et al. (2014); Technology (2018) as expand roof life until 60 years; recover dead spaces and transform them into garden spaces; reduce stormwater runoff and the "heat island" effect (EPA, 2018); decrease smog, noise, energy demand and carbon monoxide impact and improve air quality; prevent combined sewer overflow; remove nitrogen pollution from rain; neutralize acid rain effect; restore habitat for wildlife; enhance urban air quality, among others.

Green roofs are an important part in Sustainable Urban Drainage Systems (SUDS), that try to recover the natural cycle of water in the city. SUDS are within the strategies used to improve the functioning and sustainability of the urban development of cities. Green roofs take a good role in SUDS applications because of their capacity to decrease storm water runoff generation in terms of runoff reduction, peak time and concentration time delay (Fioretti et al., 2010). The behavior of the hydrograph is modified significantly when the peak flow is reduced only by the change in roof use (conventional to green roof), and it is even more noticeable when making a transit for each roof using weir-like structures additional to green roofs.

The access to green spaces in Latin America is very limited specially in peripheric areas, due to the planning perspective is in service of neighborhoods with socio-economic power (Escobedo et al., 2006; Reyes and Figueroa, 2010; Romero and Vásquez, 2005; Vásquez and Romero, 2008), in this context the objective is to fight for environmental and spatial justice that allows all citizens to claim for green urban access, currently the recommendation from OMS is to have 9 $m^2/person$ of green space in a city; nevertheless, there are many neighborhoods with less than 1 $m^2/person$. This analysis allows to think that the space construction it has been shaped excluding to many cities' areas, and the environmental and spatial justice strategies can help to recover the city spaces for urban and peri-urban forestry that can be complemented with green roofs. All these efforts can enhance the urban ecosystems and allows to improve the life quality of people.

Green roofs are one of the best tools for stormwater management in urban areas by decreasing the possibilities for flash flooding; furthermore, vegetation on the top of the roofs increases the evapotranspiration. The growing plants absorbs an amount of rain- water, decreasing the peak flow, peak time and runoff. Green roof has ability to capture the dangerous fine dust particles from the air that could help to improve the comfort of population in highly crowded urban areas (Shafique and Rafiq, 2018). Green roofs help to reduce air pollution by two different ways. Firstly, the greens capture the fine dust particles or called air pollutants through stomata. Secondly, the green roofs diminish the surface temperature which helps in fossils burning to meet energy requirements (Yang et al., 2008).

According to Huang (1994), 1000 m^2 of green roofs are capable to remove since 160 kg to 220 kg per year of dust, which results in the environment improvement. A grand total of 1675 kg of air pollutants was removed in only one year by 19.8 hectares of green roofs, with a O_3 accounting for 52% of the total, 27% of NO_2, 14% of PM_{10} and 7% of SO_2. The highest level of air pollution reduction occurred in May and the lowest amount in February. The annual reduction per hectare of green roof was about 85 kg/ha/year according to (Yang et al., 2008). The author mentioned that green roofs could be complementary strategies in the urban planning, the primary strategy is forestry and the possibility to introduce public places as parks. In addition, Connelly and Hodgson (2013) proved that green roofs are able to reduce noise frequency by 10 and 20 dB, also, they have the ability to absorb the sound waves and reduce the sound level in comparison to non-vegetated roofs.

Green roofs and green walls are not the only techniques for urban ecology reconciliation, private gardens, public parks, and planting of urban trees are as well (Francis and Lorimer, 2011). According to MacIvor and Lundholm (2011),a variety of species of insects, common and uncommon, were collected from some green roofs, supporting the idea that these habitats help to sustain and restore biodiversity in cities.

2 Theoretical bases

The main objective is to determine rainwater storage in green roofs by using hydrographs and routing them; therefore, a correct method to calculate runoff and hydrographs is necessary in order to fulfil the objective. There are multiple methods to determine peak flows, depending of the basin area and available data, such as the rational method or the dimensionless unitary hydrograph method (Chow et al., 1994). The rational method is recommended for basins whose areas are lower than 200 hectares. The results of this method are limited to the peak flow value, therefore, the variation of runoff through the time is not possible to obtain.

Dimensionless unitary hydrograph method allows to determine the behavior of the discharge through the time with a hydrograph. Even though, the rational method could be applicable in this research (roof surface is lower than 200 hectares), the dimensionless unitary hydrograph was used to estimate the real volume of rainwater. In this method, basin hydrographs are calculated based on a unitary dimensionless hydrograph, which is obtained from the observation of real hydrographs. Estimation of precipitation and infiltration are necessary to determine the hydrograph of a basin. Maximum precipitation events (the ones that causes flooding) can be estimated using an Intensity-Duration-Frequency (IDF) curves, used in this research. Whereas, several methods can be used to estimate infiltration such as Horton, Green-Ampt, and the curve number proposed by the Soil Conservation Service of United States of America (SCS) (Viola et al., 2017).

2.1 Total precipitation thickness

Generally, precipitation do not have a linear behavior or intensity along the time but it changes. Precipitation can be expressed along the time with a precipitation hyetograph, which distributes the total thickness of rainwater in several time intervals, with a constant or variable distribution. The Soil Conservation Service (SCS) proposes a method to determine the precipitation hyetograph, using the dimensionless hyetograph (Chow et al., 1994). The precipitation hyetograph needs to estimate the total thickness of rainfall that produces runoff; thus, it is necessary to build the Intensity-Duration-Frequency (IDF) curves. According to the concentration time of the basin (time in which a drop of water lasts to travel the distance from the most distant point of a basin to its output) and the rainfall intensity given a certain return period, the total thickness of rainwater could be determine using Equation 2.

$$P = I * T \tag{2}$$

Where I is the rainfall intensity (mm/h), P is the rainfall thickness (mm), T is the rainfall duration (hour). Intensity is estimated with IDF curves, which are generally known according to the region of study. The concentration time can be calculated by using the Kirpich's equation (Equation 3). With T_c is the basin concentration time (minutes), L is the channel length (ft, m) and S is the channel average slope (ft/ft, m/m).

$$T_c = 0{,}0078 * \frac{L^{0{,}77}}{S^{0{,}385}} \tag{3}$$

2.2 Distribution of total precipitation thickness

To distribute the total thickness of rainfall, the alternating block method was used (Chow et al., 1994). In this method the concentration time is divided in subintervals (ΔT) and the cumulative intensity of rainfall is calculated using an IDF curve for a selected return period. For each subinterval of time, the partial intensity of rainfall is calculated and the thickness of rainfall (P) is determined using equation 1. A reorganization of P is necessary, in order to plot in a graphic (P in the vertical axis vs ΔT in the horizontal axis), the highest value of P in the center of horizontal axis, and then the second highest value of P just in the right side of highest value of P, and the third highest value of P in the left of the highest value of P, and so on (Figure 2).

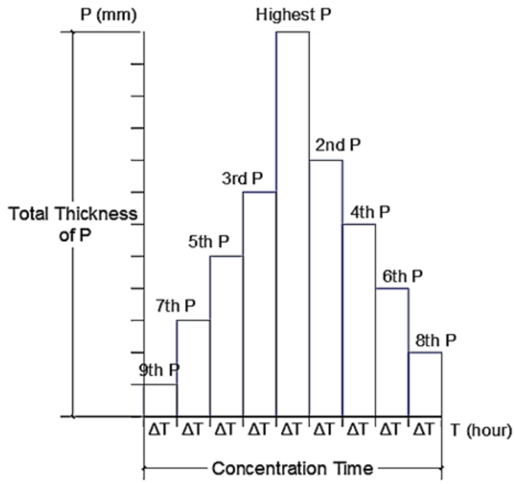

Figure 2. Precipitation hyetograph.

2.3 Infiltration

Infiltration was calculated using the curve number method (Chow et al., 1994), whose infiltration depends on the soil type, initial abstractions and antecedent humidity. Infiltration can be calculated using Equation 4 (Chow et al., 1994). Where CN is the curve number obtained from NRCS (1973). In this research, CN II was used due to the zone of study, which presents regular rainfall along the year. S is the total water retention capacity of the soil (mm). Infiltration in green roofs is restricted by the thickness of the soil matrix (Sims et al., 2016; Liu et al., 2019).

$$S = \frac{2540}{CN} - 25{,}4 \tag{4}$$

2.4 Runoff hydrograph estimate

Partial runoff thickness is calculated using Equation 5, which represents the portion of rainfall water that soil cannot absorb. S is the soil total water retention capacity (mm), P is the rainwater runoff (mm) and Q is the portion of rainfall water that soil cannot absorb (mm). If the expression $P - 0{,}2 * S$ is lower than zero, there is no runoff because infiltration is higher than rainwater in mm. The dimensionless constant 0.2 is known as the initial abstraction, and it represents the estimated portion of the soil that effectively retains water. Once the value of Q is calculated for each value of P, hydrograph for the basin of study can be obtained by applying the unitary hydrograph, in which vertical axis represents dimensionless runoff, and horizontal axis represents dimensionless time for runoff.

$$Q = \frac{(P - 0{,}2 * S)^2}{(P + 0{,}8 * S)} \tag{5}$$

In order to build the hydrograph, the unitary hydrograph must be affected by the concentration time and the total runoff thickness. To transform the unitary hydrograph into the real hydrograph, peak flow for each runoff thickness must be calculated using Equation 6. Where qp is the peak flow (m^3/s), A is the basin area (km^2), Q is the rainfall thickness (mm), T_p is the peak time, estimated as 60% of the concentration time.

$$qp = 0{,}208 * \frac{(A * Q)}{T_p} \tag{6}$$

Concentration time is the time in which rainfall reaches the point of study (Chow et al., 1994). For urban drainage and small basins, the use of equation 3 usually delivers short concentration times. However, it is known that runoff starts after the surface is saturated which could take several minutes and take longer than the calculated concentration time. In addition, the relation between rainfall intensity and duration is assessed considering the concentration time of the drainage surface. Such relation show that rainfall intensity tends towards infinity with short rainfall duration and thus the design with these intensities might be unrealistic. In order to avoid these issues, a 10-minutes concentration time has been considered if the value obtained by equation 3 is too short. This time is commonly used in drainage manuals (Ramke, 2018; TxDOT, 2019) for small catchments and urban areas.

2.5 Runoff hydrograph routing

Routing hydrographs is used to properly simulate the green roof water storage capacity and its effect to runoff generation. In order to decrease the magnitude of peak flow and extend the duration of hydrographs, a routing of them must be applied. Transit of hydrographs is a procedure that allows to calculate an attenuated output hydrograph given an input hydrograph. When a routing hydrograph is used, the peak flow time is delayed and its value is reduced. In some cases, if the input hydrograph is being routed with a possibility of storage, the output hydrograph would have a minor volume than the input hydrograph.

The most common method to routing a hydrograph is the 3^{rd} order Runge-Kutta method (Chow et al., 1994), based on the continuity equation shown in Equation 7 (Fenton, 2009). Where dS is the stored water volume, I_t is the input flow for an instant of time, Q_H is the output flow for an instant of time in a height of the reservoir (in this case of study, the weirs in the green roofs). The term dS could be expressed as the change of volume due the elevation in a reservoir, as shown in Equation 8.

$$\frac{dS}{dt} = I_t - Q_H \tag{7}$$

$$dS = A(H)dH \tag{8}$$

Where $A(H)$ is the area according to the elevation H, therefore, Equation 6 could be rewritten as shown in Equation 9. The solution for Equation 8 consists in the subdivision of the slope $\frac{dH}{dt}$ by three increments to transform the differential equation into $\frac{\Delta H}{\Delta t}$, where ΔH is calculated as shown in Equation 10. Where ΔH_1 and ΔH_3 are calculated as shown form equations 11 to 13.

$$\frac{dH}{dt} = \frac{I_t - Q_H}{A(H)} \tag{9}$$

$$\Delta H = \frac{\Delta H_2}{4} + \frac{3\Delta H_3}{4} \tag{10}$$

$$\Delta H_1 = \frac{I(t) - Q(H)}{A(H)}\Delta t \tag{11}$$

$$\Delta H_2 = \frac{I\left(t + \frac{\Delta t}{3}\right) - Q\left(H + \frac{\Delta H_1}{3}\right)}{A\left(H + \frac{\Delta H_1}{3}\right)}\Delta t \tag{12}$$

$$\Delta H_3 = \frac{I\left(t + \frac{2\Delta t}{3}\right) - Q\left(H + \frac{2\Delta H_2}{3}\right)}{A\left(H + \frac{2\Delta H_2}{3}\right)}\Delta t \tag{13}$$

Values of $Q(H)$ are obtained by constructing the "height-surface-capacity" curve, in which the total height of the reservoir (the matrix of soil in this case) is subdivided in intervals, and the volume for each interval is calculated using Equation 14. The values of $Q(H)$ are obtained by an interpolation, once calculated the respective height for a value of the input flow (Chow et al., 1994).

$$V_H = \Delta_H * A \tag{14}$$

3 Methodology

Methodology applied to calculate the estimate rainwater storage using green roofs was by a direct comparison between the runoff produced by a common roof and the runoff produced by a green roof. The necessary information to generate the hydrographs was obtained using a free license software, Quantum Gis (QGIS, 2014), in order to create a mosaic to cover the urbanization area near the "Quebrada Tabure" in the Palavecino municipality of Lara State, Venezuela, using photographs (.img extension files) and contour lines as shown in Figure 3. Roof distribution at each house was simplified into two sections with their respective slopes, thus two polygons were used to simulate each roof surface. IDF curves were calculated using maximum precipitation data from the nearest precipitation stations in the region of study, and applying a type I extreme distribution; the IDF curves are shown in Figure 4.

For each roof, hydrographs were calculated by applying the methodology explained in point 2, using a curve number value of 98 and 86, for a conventional roof with bituminous materials and green roofs (related to grass), respectively. Rainwater inputs were estimated using different return periods. Once the hydrograph is built, volumes of water generated by runoff can be estimated using equation 15. With V as the volume between an interval of time. Q_{i+1} and Q_i, are two consecutive flow values according to an interval of time and Δt is a user selected interval of time. Areas for each roof were calculated using Qgis.

$$V = \sum_{i}^{n} (Q_{i+1} - Q_i)\Delta t \tag{15}$$

Figure 3. Region of study, based on López et al. (2014).

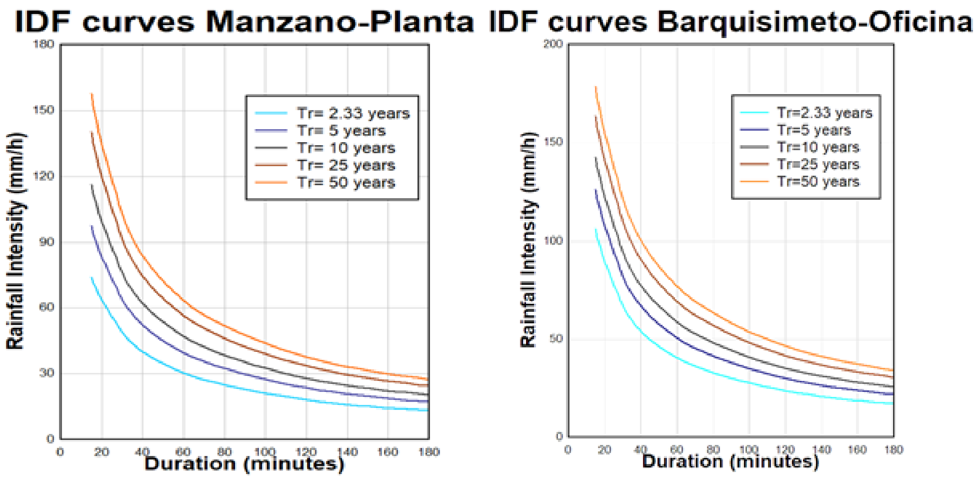

Figure 4. IDF curves for station "Manzano-Planta" and "Bqto-Oficina". Images based on López et al. (2014).

4 Results

In this paper, only results from the roof with $I_d = 1$ will be shown because of the magnitude of data. The complete data for the hydrology is shown from Table 1 to Table 5 (Bqto-oficina data). The hydrograph of roof 1 is shown in Figure 5. Note that there is a notable decrease of runoff using green roofs, and it can be translated in water storage. The water storage is related to the matrix soil thickness, the vegetation species and soil porosity. The matrix soil thickness was estimated by adding the infiltration rate of the return 50-year return period, and assuming a total porosity of 20%, and an effective porosity of 10%, giving a thickness of 15 cm, but it was used as 20 cm. The hydrographs for roof 1 with and without green roof for each return period are shown from Figure 6 to Figure 8.

Table 1. Hydrology data for roof 1 (Tr=2.33 years).

Time (min)	Intensity (mm/h)	Cumulated water layer (mm)	Incremental water layer (mm)	Infiltration layer (mm)	runoff thickness (mm)
0	0	0	0	0	0
1.667	150	4.167	4.167	2.244	0
3.333	150	8.333	4.166	4.167	0
5	150	12.5	4.167	4.047	0.122
6.667	147.895	16.433	3.933	3.416	0.754
8.333	134.474	18.677	2.244	2.713	1.216
10	123.994	20.666	1.989	1.219	0.766

Table 2. Hydrology data for roof 1 (Tr=5 years).

Time (min)	Intensity (mm/h)	Cumulated water layer (mm)	Incremental water layer (mm)	Infiltration layer (mm)	runoff thickness (mm)
0	0	0	0	0	0
1.667	160	4.444	4.444	4.444	0
3.333	160	8.889	4.445	4.434	0.009
5	160	13.333	4.444	3.904	0.543
6.667	160	17.778	4.445	3.215	1.225
8.333	160	22.222	4.444	2.705	1.743
10	160	26.667	4.445	2.305	2.145

Table 3. Hydrology data for roof 1 (Tr=10 years).

Time (min)	Intensity (mm/h)	Cumulated water layer (mm)	Incremental water layer (mm)	Infiltration layer (mm)	runoff thickness (mm)
0	0	0	0	0	0
1.667	180	5	5	5	0
3.333	180	10	5	4.93	0.069
5	180	15	5	4.13	0.873
6.667	180	20	5	3.35	1.65
8.333	180	25	5	2.77	2.227
10	167.386	27.898	2.898	1.398	1.499

Table 4. Hydrology data for roof 1 (Tr=25 years).

Time (min)	Intensity (mm/h)	Cumulated water layer (mm)	Incremental water layer (mm)	Infiltration layer (mm)	runoff thickness (mm)
0	0	0	0	0	0
1.667	190	5.278	5.278	5.278	0
3.333	190	10.556	5.278	5.157	0.12
5	190	15.833	5.277	4.228	1.05
6.667	190	21.111	5.278	3.408	1.873
8.333	190	26.389	5.278	2.798	2.478
10	190	31.667	5.278	2.348	2.934

Table 5. Hydrology data for roof 1 (Tr=25 years).

Time (min)	Intensity (mm/h)	Cumulated water layer (mm)	Incremental water layer (mm)	Infiltration layer (mm)	runoff thickness (mm)
0	0	0	0	0	0
1.667	200	5.556	5.556	5.556	0
3.333	200	11.111	5.555	5.376	0.183
5	200	16.667	5.556	4.326	1.235
6.667	200	22.222	5.555	3.455	2.103
8.333	200	27.778	5.556	2.825	2.733
10	200	33.333	5.555	2.345	3.205

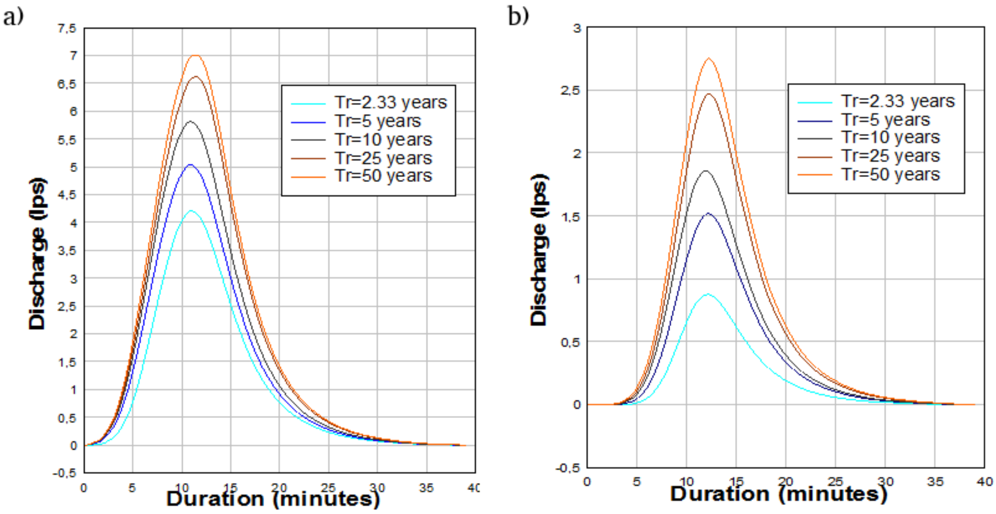

Figure 5. Hydrographs of roof 1 for different return periods with a) and without b) green roofs.

It is observed that there is a considerable peak flow reduction, also there is a retarding of peak time but not too significant, as shown in Table 6. The total volume of rainwater that theoretically could be stored in the green roofs is determined through the effective porosity of the soil matrix. Assuming that effective porosity is about 10%, the total volume storage for the roof 1 is shown in Table 7, and for all roofs is shown in Table 8.

According to Table 6, the potential retention of water for small rainfall events is higher than for higher events, and it is related with the volume of rainfall and the storage capacity of the roof. Table 7 and Table 8 show the maximum usable water volume, according to a 10% of effective porosity, but the real infiltrated volume of water was estimated by using the Equation 16.

$$P = Q_i + Q + E \tag{16}$$

With P the total precipitation thickness (mm), Q_i is the total infiltration thickness (mm) and Q is the rainfall thickness (mm). E is the vegetation evapotranspiration (mm), for our purposes this is set $E = 0$. The real volume of rainwater storage for roof 1, is shown in Table 9. The volume shown in Table 9 must be affected by the effective porosity, in order to obtain the usable volume of water as shown in Table 10 and Table 11. According to (WRF, 2016), the quantity of water per household necessary is shown in Table 12.

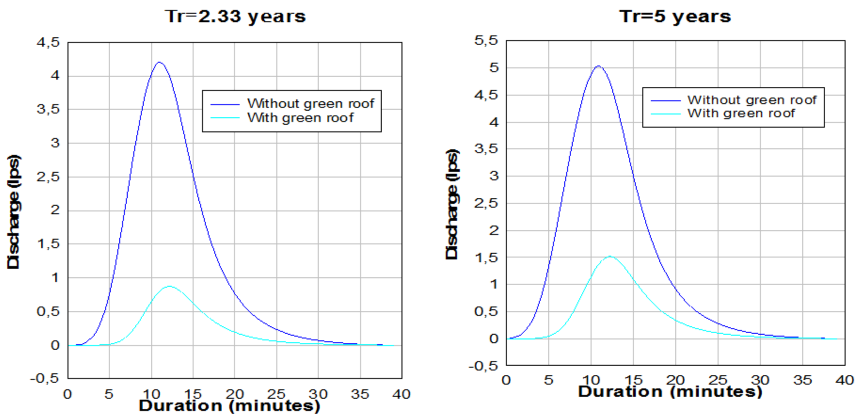

Figure 6. Hydrographs of roof 1 for 2.33 years 5 years of Tr.

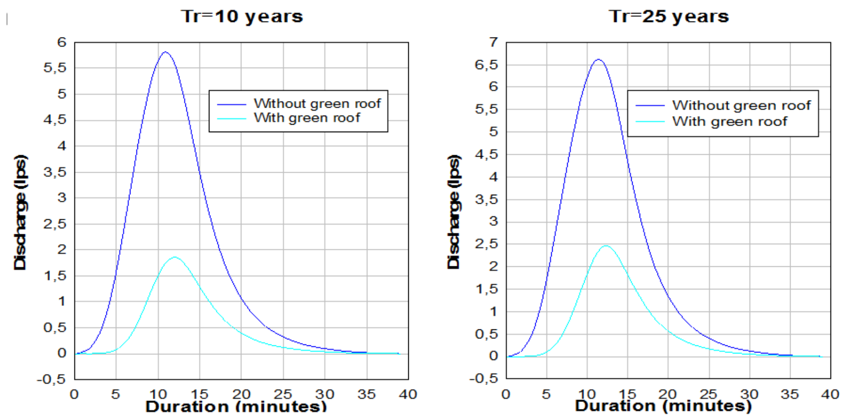

Figure 7. Hydrographs of roof 1 for 10 years and 25 years of Tr.

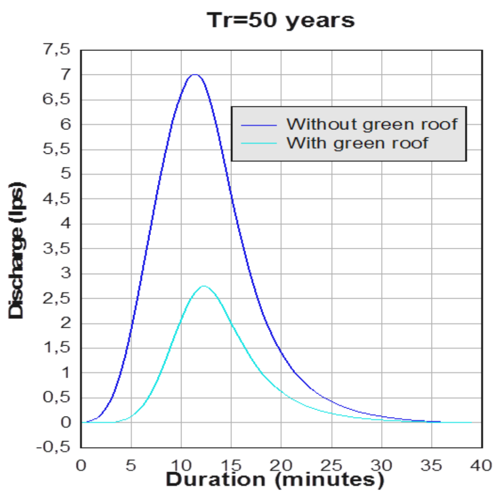

Figure 8. Hydrographs of roof 1 for 50 years of Tr.

Table 6. Peak flow reduction and increase of peak time for roof 1.

Tr	Without green roofs		With green roofs		Peak flow reduction (%)	Delay of peak time (times)
	Peak flow (lps)	Peak time (min)	Peak flow (lps)	Peak time (min)		
2.33	4.16	10.5	0.87	12	0.79	1.14
5	5.00	10.5	1.51	12	0.69	1.14
10	5.77	10.5	1.86	12	0.67	1.14
25	6.54	12	2.45	12	0.62	0.00
50	6.93	12	2.73	12	0.60	0.00

Table 7. Maximum usable volume of water in green roof number 1.

ID	Roof surface (m^2)	Soil thickness (cm)	Effective porosity %	Maximum usable water volume (m^3)
1	163.03	20	0.10	3.26

Table 8. Maximum usable volume of water for all roofs.

ID	Roof surface (m^2)	Soil thickness (cm)	Effective porosity %	Maximum usable water volume (m^3)
1-68	14 554.20	20	0.10	291.08

Table 9. Real infiltrate volume for roof 1.

ID	Roof surface (m^2)	Soil thickness (cm)	Effective porosity %	Maximum usable water volume (m^3)	Real infiltrate volume (m^3).				
					2,33	5	10	25	50
1	163.03	20	0.1	3.26	1.98	2.28	2.40	2.59	2.66

Rainwater stored in green roofs could be recycled for domestic water use. Indeed, rainwater cannot be used for drinking purposes without a correct treatment, but it can be used to supply other purposes such as toilet water and irrigation. According to (WRF, 2016), 125 liters per household/day (33.1 gphd), are needed for toilets usage. Considering that, in average, a toilet is used 5 times per person per day; if a part of the rainwater could be stored to be used by toilets, the own urbanism (68 houses) could supply, theoretically, the water demand as shown in Table 13, which is not negligible.

In addition, a considerable peak flow reduction could be obtained if structures such as rectangular weirs are used in ceilings, as shown in Figure 9. Applying the routing of hydrographs using 2 weirs of 10 cm in length and 10 cm in height, the output hydrograph of roof 1 for each return period is shown from Figure 10 to Figure 12. Green roofs are a good peak flow reducer, but when combining them with weirs the reduction of peak flow is even better, although the volume produced is the same, i.e., without additional storage of water for the use of weirs. Finally, the total peak flow for each period of return is shown in Table 14 and Table 15.

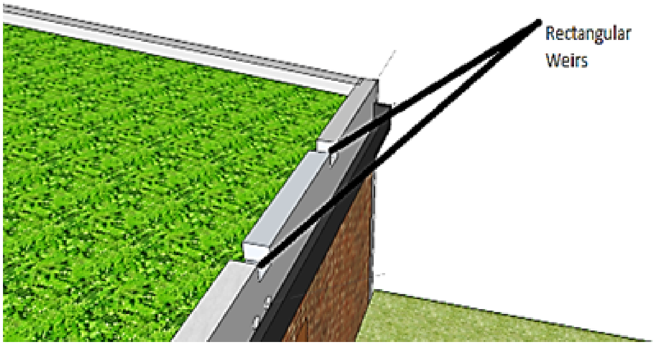

Figure 9. Rectangular weirs in green roofs.

Table 10. Real usable volume for roof 1.

ID	Roof surface (m^2)	Soil thickness (cm)	Effective porosity %	Maximum usable water volume (m^3)	Real usable volume (m^3).				
					2,33	5	10	25	50
1	163.03	20	0.1	3.26	0.20	0.23	0.24	0.26	0.27

Table 11. Real usable volume for all roofs.

ID	Roof surface (m^2)	Soil thickness (cm)	Effective porosity %	Maximum usable water volume (m^3)	Real usable volume (m^3).				
					2,33	5	10	25	50
1-68	14 554.2	20	0.1	291.08	17.65	20.31	21.44	23.09	23.76

Table 12. Quantity of water needed in liters per household per day. Source WRF (2016).

Water use	Quantity (lphd)
Toilet	125.3 (24 %)
Shower	106.4 (20 %)
Faucet	99.6 (19 %)
Clothes washer	85.9 (16 %)
Leak	64.4 (12 %)
Other	20.1 (4 %)
Bath	13.6 (3 %)
Dishwasher	6.1 (1 %)
Total	521.3 (100 %)

According to Table 14, peak flow reduction is over 96 %, assuming CN II and a first rainfall, but these results could be affected for continuous rainfall events. Another benefit of using green roofs and their routing is the design of urban drainage, and according to Table 16, a considerable decrease in volume (conventional roof vs green roof) and duration of the hydrograph (green roof vs green roof and weirs), which means a positive impact on the drainage system. The decrease in peak flow will require pipes with smaller diameters and lower slopes that make up the drainage system. Using the manning equation, the diameter of the pipes through which the total flow of urbanism will flow (Equation 17). With Q the discharge, S is the pipe slope, A is the flow area, R is the hydraulic ratio and n is the pipe rugosity.

$$Q = \frac{\sqrt{S} * A * R^{\frac{2}{3}}}{n} \tag{17}$$

Table 13. Supply days for toilets (68 houses).

Tr	Water storage (liters)	Supply days
2.33	17 652.68	2.08
5	20 308.50	2.39
10	21 441.40	2.52
25	23 086.58	2.72
50	23 755.79	2.79

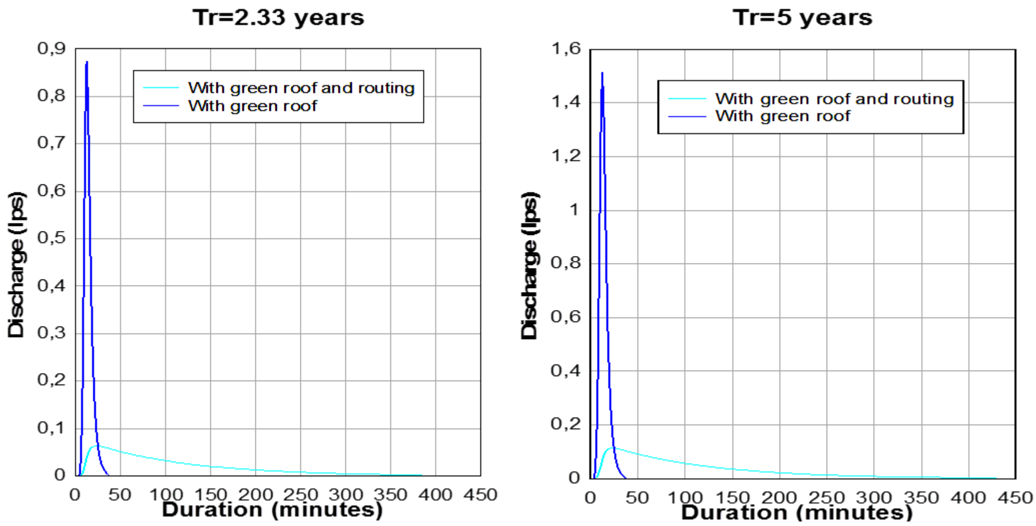

Figure 10. Hydrographs of roof 1 for 2.33 years and 5 years of Tr.

Table 14. Peak flow for each scenario (roof 1).

Tr	Peak flow (lps)			Peak flow reduction (%)		Hydrograph duration (min)	
	Conventional roof	Green roof	Green roof and routing (weirs)	Green roof	Green roof and routing (weirs)	Green roof	Green roof and routing (weirs)
2.33	4.161	0.874	0.064	78.995	98.462	40.0	>200
5	5.004	1.514	0.114	69.744	97.722	40.0	>200
10	5.778	1.86	0.15	67.809	97.404	40.0	>200
25	6.547	2.458	0.232	62.456	96.456	40.0	>200
50	6.936	2.738	0.27	60.525	96.107	40.0	>200

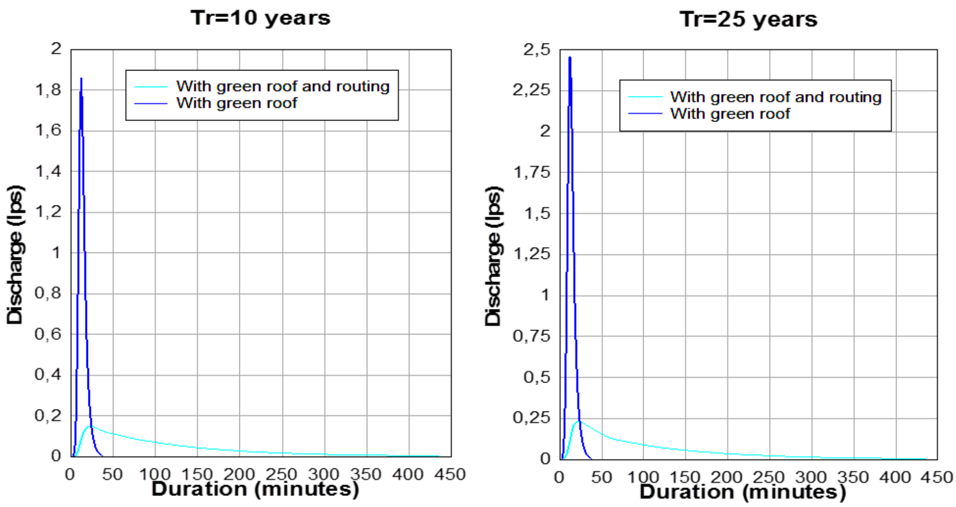

Figure 11. Hydrographs of roof 1 for 10 years and 25 years of Tr.

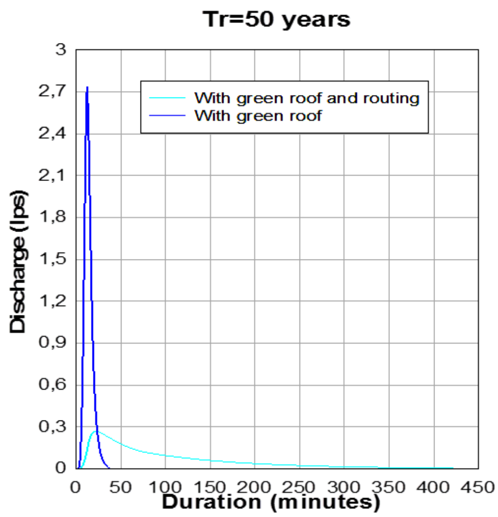

Figure 12. Hydrographs of roof 1 for 50 years of Tr.

Table 15. Peak flow for each scenario (all roofs).

Tr	Peak flow (lps)		
	Conventional roof	Green roof	Green roof and routing (weirs)
2.33	371.491	77.978	4.395
5	446.689	135.007	7.941
10	515.813	165.995	10.505
25	584.451	219.436	16.175
50	619.191	244.369	18.82

Note that there is a considerable reduction on diameters for urban drainage (Locatelli et al., 2014; Pradhan et al., 2019), almost 100% of reduction. It should be noted that these results are valid in cases of first wash or first rainfall, due to green roofs saturate faster their matrix of soil and for continuous rainfall the results for drainage can be affected.

Table 16. Required diameter for each scenario.

Tr	Conventional roof	Required diameter (mm)	Minimum slope (m/m)	Green roof	Required diameter (mm)	Minimum slope (m/m)	Green roof and routing	Required diameter (mm)	Minimum slope (m/m)
2,33	371,491	500	0,01	77,978	280	0,005	4,395	200	0,005
5	446,689	500	0,01	135,007	315	0,01	7,941	200	0,005
10	515,813	500	0,01	165,995	355	0,01	10,505	200	0,005
25	584,451	500	0,02	219,436	355	0,02	16,175	200	0,005
50	619,191	500	0,02	244,369	355	0,02	18,82	200	0,05

5 Conclusions

Green roofs, in addition to offering a good ecological alternative to replenish green areas in urban areas, also offer a viable alternative for the collection and storage of rainwater, which according to this study, can reach between 2 and 3 days of use for toilets in urbanisms (according to the intensity of the rainfall), which could represent savings for the inhabitants' economy and at a macro level for the state economy.

In addition to the paragraph above, the placement of flow-regulating structures as weirs offers a delay advantage in the production of the peak flow of the hydrographs of the roofs and therefore of the urbanization. According to the results for the urbanism, for first rains, the combined use of green roof and weirs offers a considerable delay on the total duration of the hydrographs, almost over three times in comparison with conventional roof (under the conditions studied in this research) helping with the urban drainage by reducing commercial diameters of the pipes almost to half of the size.

The harvest of water for various uses during the useful life of the house helps to preserve the water level of reservoirs and ecological flows of the natural channels and their cross section; the harvest of water rainfall proposed in this research has a good theoretical performing, not only to focus on the drainage but based on the fact that it delays the peak flow time of the urbanism and the hydrograph total duration; creates a gap between the hydrograph peak flow of the urbanism and the hydrograph peak flow of the natural channels for discharge, and decreases the risk of floods.

It is recommended to carry out a study on retaining water not only from the roof, but also from the hydrograph with storage structures to increase the capacity to harvest rainwater, as well as studies to determine the real CN for them.

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