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Analysis of the Influence of Green Roofs in the reduction of the stormwater runoff hydrograph of a high Andean city in Ayacucho, Peru

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I. Introduction

In recent years, rapid urban growth has caused negative impacts on the environment; causing an increase in impermeable surfaces that prevent or significantly reduce infiltration, interception, detention, retention, transpiration, and evapotranspiration of water; thus, affecting the hydrological cycle and weather patterns [1]. The increase in impervious surfaces generates an increase in the volume of runoff that runs over the urban surface, this being one of the most harmful effects of the urbanization process, as well as the denaturalization of the urban environment [2]. Another effect is the response of a basin under any rain event, decreasing the concentration time and increasing the peak discharge flow, generating recurring floods and, in the case of urban basins, problems with the storm drainage system [3]. In addition, the development of cities with an evident lack of urban planning can cause the alteration of natural channels, causing the need to build artificial channels, eventually generating more damaging difficulties such as floods, and flows that exceed the design flow in drainage networks [4].

Urban development in Peru, a country that is characterized by having different regions with very particular climatic characteristics, the situations describe above are repeated with certain particularities. In the case of the Peruvian Andes region, rainfall is generally intense. The urbanization process is taking place quickly and disorderly, with an evident lack of territorial planning, because infrastructure, such as storm drainage systems, is not considered necessary. According to [5] the percentage of urban areas that do not have urban storm drainage service in Peru is of the order of 98 %.

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Implementation of urban storm drainage systems in areas where the population has already settled is usually expensive, not only because of the direct cost, but also because of the inconvenience generated by intervening in areas that have already been built.

Due to the situation previously described, systems have been proposed and put into practice to mitigate the effects generated by waterproofing of urban areas; among the multiple alternatives as possible solutions are the so-called Sustainable Urban Drainage Systems (SUDS), including Green Roofs (GR). The main advantage of GRs, compared to other types of SUDS, is the extension of surfaces available for their installation, since they can be installed on the roofs of buildings, which cover a considerable proportion in urban areas [6].

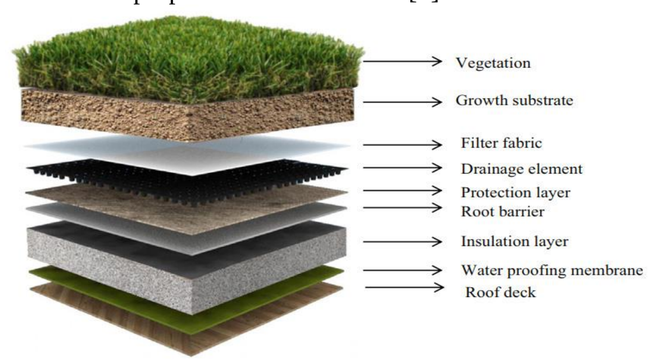

Fig. 1 Components of a green roof [8].

The Green Roof is an artificial system that provides a natural green space [1] is also defined as a multi-layer construction, each one with a specific purpose that allows the operation and overall performance of the roof [7]. Green roofs are divided into two types, the intensive green roof and the extensive green roof. The first case requires a thickness greater than 15 cm to accommodate a variety of plants ranging from shrubs to trees and the second case requires a thickness less than 5 to 15 cm with plants such as sedum and succulents [1]. The components of green roofs are variable, but are generally a vegetation layer, growth substrate, filter layer, drainage layer, waterproofing layer, and root barrier [8]; as seen in Figure 1.

The green roof is a system that, apart from managing the quantity and quality of stormwater runoff, has numerous other benefits such as mitigation of the heat island, improvement of air quality, reduction of noise levels [7] and provide habitat for wildlife and enhancement of biodiversity [6].

Green roofs have the potential to retain water, allowing the volume of runoff to be reduced. In a number of investigations, it has been observed that the retention of rainwater from green roofs can vary between 10 % to 25 % [3], 27 % to 61 % [9], 45 % to 78 % [6]; This could prevent saturation in the storm drainage system and increase the flow of water, in order to mitigate possible flooding in urbanizations. The retained volume depends on the characteristics of the GR, such as thickness, so for an extensive green roof the volume could be reduced by 65 % and for an intensive green roof by 85 %. [1]. In addition, green roofs have been found to reduce peak flow by up to 52 % [10], 17 % to 34 % [1], and by at least 6 % to 17 % [3]. Regarding the lag time of peak flow, it has been shown to increase 1.14 minutes [3], 8 minutes [10], and up to 8 to 9 [1] minutes with respect to a conventional ceiling. These effects could help to alleviate storm drainage and mitigate storm flooding.

This study focuses on the application engineering of Green Roofs in a high Andean region of Peru, the considerations and methodology used to analyze stormwater runoff without and with the implementation of Green Roofs on an experimental model designed under central meteorological conditions are presented. Rainfall intensities correspond to the location of San Pedro de Larcay, town located in Ayacucho, Peru.

II. Materials and Methods

A. Description of the experimental model

An experimental model was adapted at the National Engineering University (Lima, Peru), within the National Hydraulics Laboratory (LNH), consisting of a structural support, an experimental platform, a sprinkler system, and an Arduino data reading system.

The structural support is the main body of the model, it presents a design based on the American Institute of Steel Construction and the NTE 090 of metallic structures [11]. It is mainly composed of a substructure (foundations and trusses), a superstructure (main beam, secondary beams and joists), and a lifting system that allows the platform to change the slope.

The experimental platform is composed at the base of fiber cement sheets and a fiber cement box as perimeter formwork with a height of 35 cm, the platform has an area of 17.71 m2 (3.72 m x 4.76 m), in which two types of roofs were implemented. The net area was divided in half so that each parcel occupies a surface of 8.85 m2 (1.86 m x 4.76 m). Both parcels were separated by a central boundary that divides the entire platform in half. Overall, the drainage of each roof was implemented through gutters at two levels (surface runoff and seepage) for each of the roofs. These gutters drain through ½" diameter pipes and have flow sensors installed that measure the passage of the flow.

The sprinkler system recreates the artificial rainfall and is composed of a suction pump that drives the water from a cistern towards the sprinkler nozzles through 3/4" diameter pipes. The sprinkler nozzles are of the FullJet 1/4HH-14WSQ type, 6 equidistantly located nozzles were installed for a good distribution of the rain. In addition, a gate valve that controls the amount or flow of water that passes through the system was installed, as well as a ¾" flow sensor that measures the flow.

The Arduino data reading system allows one to record the flows that circulate in the pipes. It is made up of 3 installed flow sensors (1 ¾" sensor in the delivery pipe and 2 ½" sensors in the roof drainage pipes), and these sensors connected to an ESP32 development board that sends the data to a PC that contains the Arduino code where records of flows that circulate in the pipe at each instant of time are read and stored.

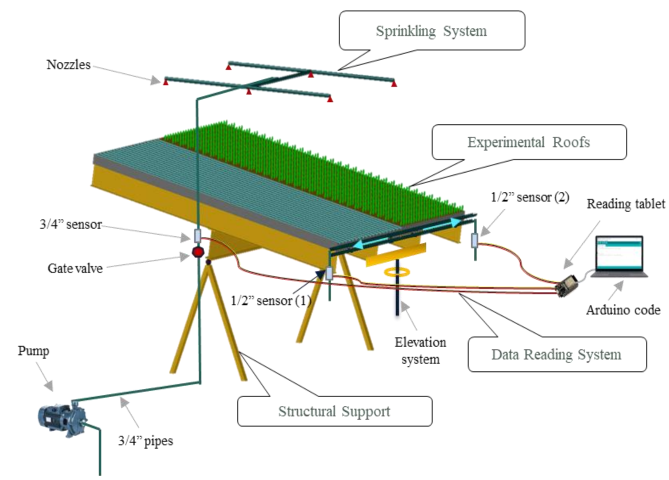

Fig. 2 Components of the experimental module


Fig. 3 Experimental module at the National Hydraulics Laboratory.

B. Design and Composition of Green Roofs

The implemented Green Roof was designed taking as general considerations the structural load, maintenance, sustainable drainage, climatic conditions, irrigation needs, and the slope that it must have for proper operation.

The high Andean city under study, San Pedro de Larcay, is located in the Sucre province, Ayacucho department at an altitude of 3395 masl and presents particular characteristics, which will be considered for the choice of the appropriate type of green roof.

According to the characterization of the area, it was identified that most of the houses are built with adobe walls and galvanized sheet metal roofs. For this reason, it is proposed that the green roof be as light as possible. In addition, since the roofs in the area are restricted access and cannot withstand much overload, the green roofs to be installed are required to be low maintenance. The study area presents floods and erosion damage to the paving of the streets, due to the lack of storm drainage; therefore, it is essential that the green roof to be installed is a sustainable urban drainage system. The climatic characterization of the area shows extreme conditions such as droughts, floods, and frosts; so green roof vegetation must be able to withstand these conditions. The characteristic slopes of the roofs of the houses range from 10 % (5.71°) to 20 % (11.31°), therefore, for the study, slopes of 10 %, 15 % and 20 % will be analyzed. Under these considerations, the type of extensive green roof was taken as the best alternative for the study área.

Thus, on half of the experimental platform, the extensive green roof system was built, which is composed of an impermeable layer with anti-root system, a drainage and filter layer, a layer of growth substrate and a layer of vegetation.

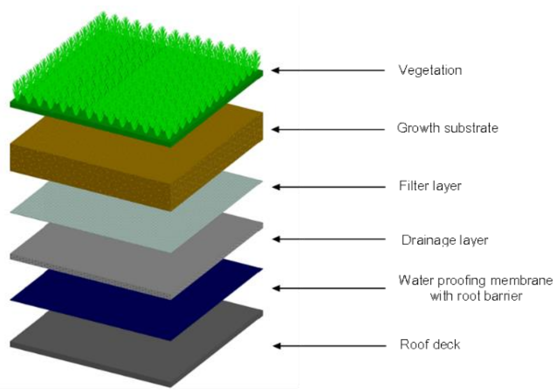

Fig. 4 Components of the experimental green roof.

The waterproof layer with anti-root system covered the experimental platform and a certain height of the fiber cement formwork for the waterproofing of the roof. The material used in this layer was a 1mm HDPE geomembrane that also has the function of a root penetration barrier, its installation is detailed in Figure 5.

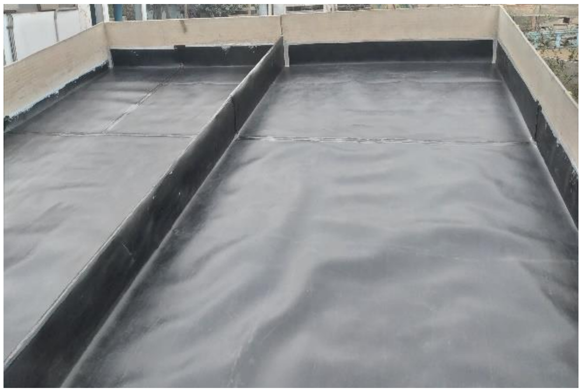

Fig. 5 Waterproof layer with anti-root properties, 1mm HDPE geomembrane.

The drainage and filter layer were placed on top of the impermeable layer. This layer is made up of a planar geodrain, which is the union of non-woven geotextiles (they perform the filtration function) and a draining network (a medium in charge of transporting the water that passes through the filter). The nonwoven geotextile has an apparent opening size of 0.180 mm, permittivity of 2.9 s-1, permeability of $46x10^{-2}$ cm/s, and flow rate of 8109 $l/min/m^2$. The drainage network has a thickness of 5.8 mm, a compressive strength of 700 kPa, and a tensile strength of 4.8 kN/m. It is worth mentioning that the installed a planar geodrain has a capacity to drain up to 0.21 l/s-m for a pressure of 10 KPa with a hydraulic gradient of 0.1 [12]. Its installation is shown in Figure 6.

Fig. 6 Drain and filter, planar geodrain

The growth substrate layer is made up of 50% farmland, 30% semi-compound rice husk, 10% compost and 10% fine washed sand: dark brown in color, semi-slow decomposition, light compaction, medium liquid retention capacity and an approximate weight of 846 kg per cubic meter. An 8-cm layer was installed, which allows the system to be light, and works as a sufficient nutrient medium for the vegetation.

Fig. 7 Growth layer.

The vegetation layer is composed by Aptenia cordifolia, that belong to the succulent plants´ species. It was chosen as the most suitable for the study area due to its high life expectancy, high resistance to climatic conditions in the area, low root depth, low need for nutrients, low need for irrigation and low maintenance; A total of 96 plants distributed on the platform in an equidistant manner were cultivated. A period of two months was waited once transplanted to carry out the tests.

Fig. 8 Vegetation on simulated green roof, Aptenia cordifolia.

C. Conventional Roof Composition

The conventional roof is made up of a waterproof layer, wooden beams, and galvanized sheets. This design was raised because it is the system used in the construction of houses in the high Andean city under study.

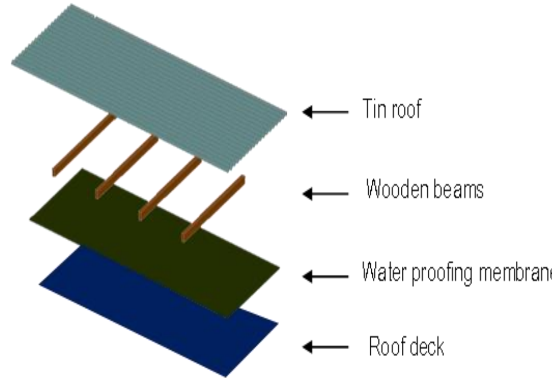

Fig. 9 Components of a conventional roof.

The waterproof layer that was installed had the function of collecting the water that passed through the overlaps of the calamine and could be measured; The material used was the 1 mm thick HDPE Geomembrane, as shown in Figure 10.

Fig. 10 Waterproof layer, 1mm HDPE geomembrane.

Wooden beams are spaced every 0.81 m for a good retention of the sheets, and these are fastened by means of nails with caps in the upper part of the wave, for protection against the passage of water. The wood used is of the radiata pine type of 2” x 4” x 1.85 m and a total of 7 units were used.

Fig. 11 Wooden beams

The galvanized sheets used to conform the tin roof are 1.80 m long and 0.80 m wide with 11 waves. A total of 9 units were used to cover the study area.

Fig. 12 Galvanized sheets

D. *Design storms*

The intensity of precipitation selected was for three return periods 2-, 5- and 10-years using Intensity Duration Frequency (IDF) curves of the study area, Figure (12). The return periods are those commonly used for urban drainage design, as recommended by the Peruvian standard. Data was obtained from the "Paucaray" SENAMHI (Peru) rainfall station, the closest and which represents the rainfall of the high Andean city of San Pedro de Larcay.

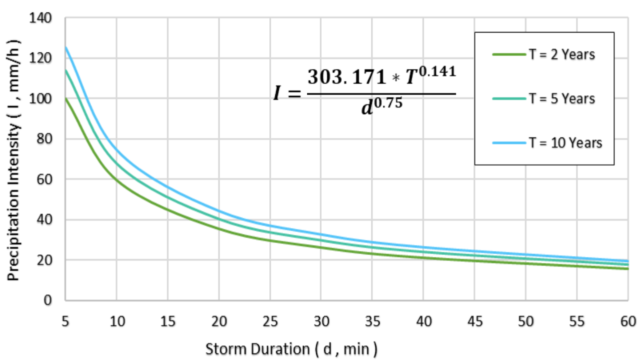

Fig. 13 IDF curves for the "Paucaray" rainfall station, for return periods of 2, 5 and 10 years.

To obtain the corresponding precipitation intensities for each return period, a concentration time of 10 minutes was used. This is the recommended minimum time for urban drainage, as detailed in Table I. With these intensity values, the tests were carried out in the rain simulator.

TABLE I
DESIGN INTENSITY

Return Period (year)	Time of Concentration (min)	Intensity (mm/h)
2	10	59.4
5	10	67.6
10	10	74.6

E. *Application and data recording*

Firstly, the calibration of the rain simulator was carried out to corroborate that the artificially generated rains resemble natural rain. For this, it was considered to calibrate three important characteristics of the rain: the intensity of precipitation, the distribution of uniformity and the size of drops.

With the previously calibrated rain simulator, the test was conducted on the green roof and the conventional roof for 10 minutes, prior to the test with green roofs, the growth substrate was saturated with the rain simulator for 10 minutes and waited 2 hours for start rehearsing on the green roof, time that is taken as an interval to carry out each rehearsal.

In the green roof tests, the reading of the flow sensors installed in the gutter pipes was taken, the ½" sensor (2) recorded the flow values of the base runoff, for a period of 30 minutes. In the traditional coverage roof tests, readings were taken from the ½" (1) sensor connected to the gutter pipe, which recorded surface runoff, for a period of 15 minutes.

Three trials were carried out per intensity, with slopes of 10 %, 15 % and 20 %, making up a total of 9 tests. From the data recorded in the flow sensors, the hydrographs were obtained for each test, it should be noted that a hydrograph was obtained for each intensity.

With the hydrographs obtained, the comparative analysis of peak flow reduction, peak flow delay time and reduction of runoff volumes was carried out.

III. Results and Discussion

A. *Rainfall simulator calibration*

Each one of the parameters required for the calibration showed acceptable values that confirm the good generation of rains by the simulator. Below is a summary table of the values obtained in the calibration of the main characteristics of the simulated rain.

TABLE II
PARAMETERS OF RAINFALL CALIBRATION

Return Period (years)	Rainfall intensity			Coefficient of Uniformity	Drop size
	Theoretical (mm/h)	Generated (mm/h)	Relative Error (%)	Cu (%)	D (mm)
2	59.4	59.2	0.5	69%	2.52
5	67.6	67.6	0.1	70%	2.51
10	74.6	73.8	1.0	71%	2.36

The intensity of precipitation generated shows some difference to the theoretical values, as detailed in the Table, but they are not statistically significant.

The rainfall uniformity distribution presents acceptable values of Christiansen's Coefficient of Uniformity (Cu), close to and greater than 70%, which is considered reasonably acceptable [13].

The recorded droplet size of the simulated precipitation shows that the diameter of the drops is between 1 to 3 mm, which classifies the precipitation as "rain" type, according to [14]. Acceptable values for simulated precipitation, as natural rain.

B. *Experimental hydrographs*

The runoff hydrographs of the green roofs and traditional coverage roofs are shown in Figure 14, Figure 15, and Figure 16; for the three rainfall intensities tested.

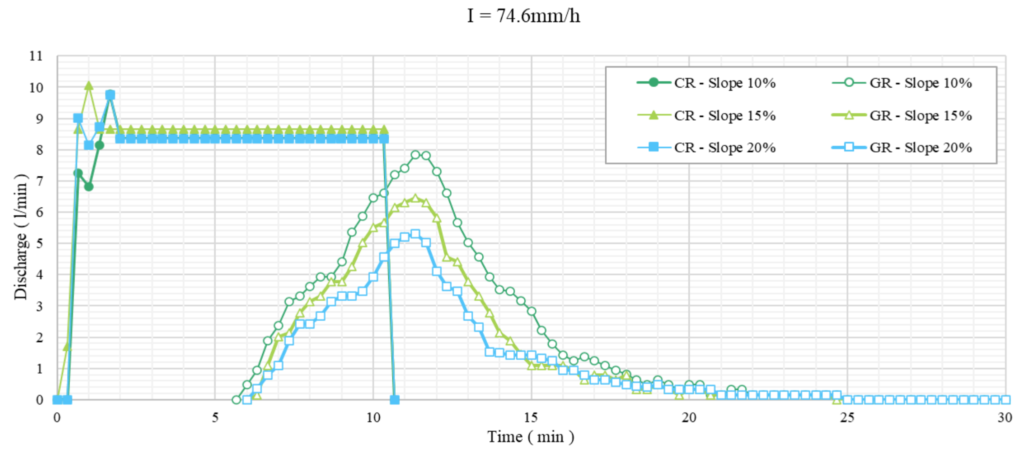

Fig. 14 Hydrographs for the Conventional Roof and Green Roof models for the intensity of 74.6 mm/h

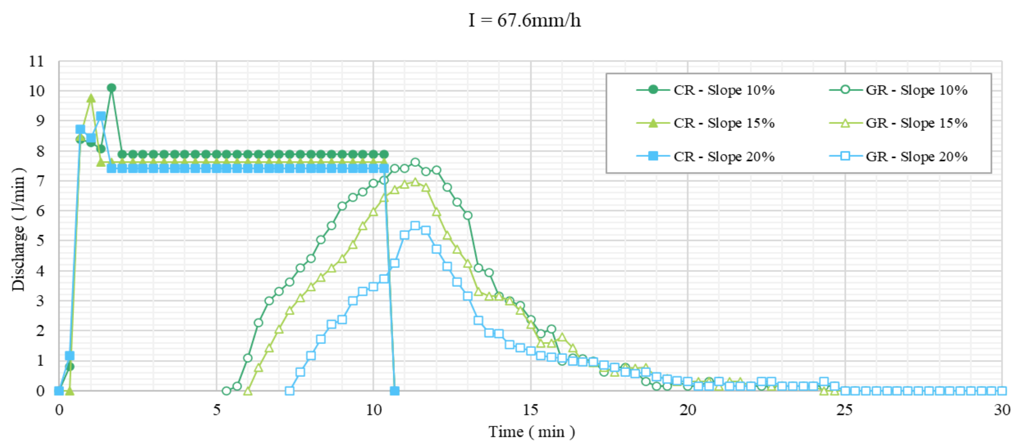

Fig. 15 Hydrographs for the Conventional Roof and Green Roof models for the intensity of 67.6 mm/h

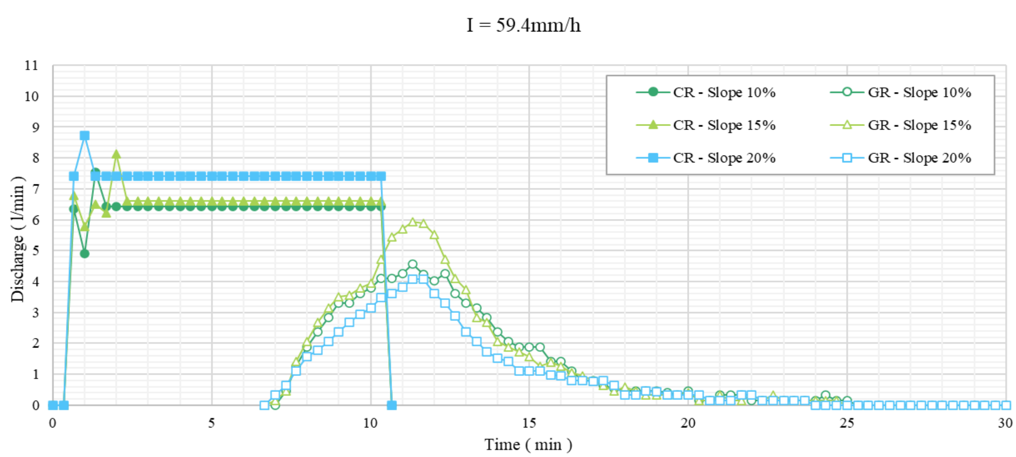

Fig. 16 Hydrographs for the Conventional Roof and Green Roof models for the intensity of 59.4 mm/h

From the analysis of the results shown in Figures 14, 15 and 16, it is observed that there is a difference when comparing the experimental discharges. Green roofs show a reduction and a delay in the occurrence of peak flows as compared to time required to reach a peak discharge in conventional roofs. This was observed for the three intensities and three slopes. The differences in peak flow and runoff volume for each case are shown in Table III.

The results obtained in the experimental phase reflect some similarities with other research works. From Table III it can be noticed a reduction in the peak flow that ranges from 20 % to 53 %, which indicates that by implementing the green roof, peak flow in a GR is considerably reduced with respect to the conventional ceiling. These results coincide with investigations carried out by [10] who obtains a value of 52 %, and [1] who obtains values ranging from 17 % to 34 %.

The implementation of the green roof generated a delay in the arrival time of the peak flow that goes from 9.3 to 10.3 minutes as observed in Table III, these results are similar to the investigations carried out by [1] who obtains values from 8 to 9 minutes, and [10] which gets a value of 8 minutes.

By performing the storage analysis of rainwater volumes on each roof, the experiment showed that the green roof retains a portion of the water volume. The results of the reduction of water volumes are shown in Table III, where it is observed that there are reductions ranging from 25% to 68%, these results show similar percentages to the research carried out by [9] that obtains values between 27 % to 61%, and [6] that obtains values between 45% and 78%.

TABLE III
COMPARISON OF HYDROGRAPHS PARAMETERS FOR CONVENTIONAL ROOF AND GREEN ROOF

Return Period (years)	Intensity (mm/h)	Slope (%)	Conventional Roof			Green Roof			Reduction in peak discharge (%)	Difference in time to peak (min)	Reduction in total volume (%)
			Peak discharge (l/min)	Time to peak (min)	Total Volume (l)	Peak discharge (l/min)	Time to peak (min)	Total Volume (l)			
2	59.4	10	7.55	1.3	66.0	4.57	11.3	29.4	39%	10.0	55%
		15	8.14	2.0	67.5	5.94	11.3	32.8	27%	9.3	51%
		20	8.73	1.0	75.6	4.08	11.3	23.9	53%	10.3	68%
5	67.6	10	10.10	1.7	80.8	7.62	11.3	52.4	25%	9.6	35%
		15	9.76	1.0	79.3	6.98	11.3	44.1	28%	10.3	44%
		20	9.17	1.3	77.8	5.51	11.3	27.6	40%	10.0	65%
10	74.6	10	9.77	1.7	86.2	7.83	11.3	49.6	20%	9.6	42%
		15	10.06	1.0	90.3	6.46	11.3	38.0	36%	10.3	58%
		20	9.76	1.7	87.7	5.31	11.3	30.4	46%	9.6	65%

IV. CONCLUSION

Experimental results show that green roofs offer a viable alternative as techniques to mitigate problems generated by urbanization. Some of the advantages are reduction in peak flows, an increase in lag time of the peak flow and reduction in runoff volume, regardless of the variation of the slopes.

Considerable reduction in the peak flow was observed, values ranging from 27 % to 53 % (for an intensity of 59.4 mm/h), 25% to 40% (for an intensity of 67.6 mm/h), and 20% to 46% (for an intensity of 74.6 mm/h), when comparing the green roof in humid conditions with respect to a conventional roof, and under conditions of exposure to sunlight. In general, it was observed that the greatest reduction in peak flow occurs for the intensity of 59.4 mm/h with a slope of 20 %, generating a reduction of 53 %. And the smallest reduction occurred when the rainfall intensity was 74.6 mm/h and the inclination was 10 %, generating a reduction of 20%.

In addition, a delay in the occurrence of peak flow was evidenced, ranging from 9.3 to 10.3 minutes (for an intensity of 59.4 mm/h), 9.6 to 10.3 minutes (for an intensity of 67.6 mm/h), and 9.6 to 10.3 minutes (for an intensity of 74.6 mm/h). It was observed that the time of the peak flow of the green roof occurs at 11.3 minutes from the start of the simulated rain, for the total of the intensities; and the peak flow of the conventional roof are given to the first minutes ranging from 1 to 2 minutes. The average peak flow delay time for all intensities is 9.9 minutes.

From the runoff volume analysis, a reduction was observed for all cases, values ranging from 51 % to 6 8% (for an intensity of 59.4 mm/h), 35 % to 65 % (for an intensity of 67.6 mm/h), and 42 % to 65 % (for an intensity of 74.6 mm/h). In general, it was observed that the greatest volume reduction was observed for the intensity of 59.4 mm/h and a slope of 20%, generating a reduction of 68%. The smallest reduction occurs for the intensity of 67.6 mm/h and a slope of 10 %. In the latter case, a reduction of 25 % was recorded.

Finally, the results show that the response hydrographs obtained are different, conferring an expected response in the green roof with a reduction in peak flow of up to 53 %, in the delay time of up to 10.3 minutes, and a volume reduction of up to 68 %.

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