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EVALUATION OF RAIN BARRELS AND GREEN ROOFS FOR FLOOD MITIGATION IN A WARM SUB-HUMID CLIMATE - STATE OF COLIMA, MEXICO

EVALUACIÓN DE BARRILES DE LLUVIA Y TECHOS VERDES PARA MITIGAR INUNDACIONES EN CLIMA CÁLIDO SUBHÚMEDO, ESTADO DE COLIMA, MÉXICO

AVALIAÇÃO DE BARRIS DE CHUVA E TELHADOS VERDES PARA MITIGAÇÃO DE ENCHENTES EM CLIMA QUENTE SUBÚMIDO, ESTADO DE COLIMA, MÉXICO

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RESUMEN

Las inundaciones en las áreas urbanas se presentan con mayor frecuencia producto del intensivo cambio de uso de suelo y los efectos del cambio climático. Los Sistemas Urbanos de Drenaje Sostenible (SUDS) buscan replicar el ciclo hidrológico local y con ello, reducir las inundaciones. Se evaluaron dos tipologías: los Barriles de Lluvia (BLL) y los Techos Verdes (TV). El objetivo fue determinar qué técnica alcanza mayor eficiencia en la reducción de volúmenes de escorrentía en la ciudad de Villa de Álvarez, Colima, México. La simulación se realizó, a través del software Storm Water Managment Model (SMWW), y los resultados indicaron que los BLL y TV lograron reducir el volumen de la escorrentía un 14.36% y 26.40% respectivamente, bajo la condición más crítica.

Palabras clave
inundaciones, sustentabilidad, cambio climático, hidrología

ABSTRACT

Flooding in urban areas is becoming ever more frequent due to intensive land-use change and the effects of climate change. Sustainable Urban Drainage Systems (SUDS) aim to replicate the local hydrological cycle and, thereby, reduce flooding. Two typologies were evaluated: Rain Barrels (RB) and Green Roofs (GR). The objective is to determine which technique is more efficient in reducing runoff volumes in the city of Villa de Álvarez, Colima, Mexico. The simulation was carried out using the Storm Water Management Model (SWMM) software, and the results indicate that RB and GR reduced runoff volume by 14.36% and 26.40% respectively, under the most critical conditions.

Keywords
floods, sustainability, climate change, hydrology.

RESUMO

As enchentes em áreas urbanas estão ocorrendo com mais frequência como resultado da intensa mudança no uso da terra e dos efeitos das mudanças climáticas. Os Sistemas Urbanos de Drenagem Sustentável (SUDS) têm como objetivo replicar o ciclo hidrológico local e, assim, reduzir as inundações. Duas tipologias foram avaliadas: barris de chuva (BLL) e telhados verdes (TV). O objetivo foi determinar qual técnica alcança maior eficiência na redução dos volumes de escoamento na cidade de Villa de Álvarez, Colima, México. A simulação foi realizada usando o software Storm Water Management Model (SMWW), e os resultados indicaram que o BLL e o TV foram capazes de reduzir o volume de escoamento em 14,36% e 26,40%, respectivamente, sob a condição mais crítica.

Palavras-chave:
enchentes, sustentabilidade, mudanças climáticas, hidrologia.

INTRODUCTION

Changes in land use due to urbanization represent a relevant anthropogenic process in floods. Urban components such as buildings, roofs, streets, and parking lots reduce soil permeability (Zúñiga-Estrada et al., 2022), and impermeable surfaces in urban areas significantly alter the local hydrological cycle; therefore, rainwater infiltration is reduced, and the volume and speed of runoff is increased (Lizárraga-Mendiola et al., 2017)—these factors overload drainage systems, which increases the risk of floods. In addition, as part of the effects of climate change, more frequent and intense rain events are expected (Zuniga-Teran et al., 2020).

Green infrastructure has been promoted recently. This consists of implementing nature-based solutions to obtain ecosystem benefits, especially for water regulation. These practices are known as sustainable urban drainage systems (SUDS) in the United Kingdom, low-impact developments (LID) or best management practices (BMPs) in North America, and alternative techniques (ATs) in France (Fletcher et al., 2015).

These practices seek to mitigate the maximum runoff peaks generated by urbanization's waterproofing of the soil, mimicking preexisting natural hydrology. They include green roofs, infiltration wells, permeable pavements, wetlands, green ditches, and rain barrels (Liu et al., 2015). These solutions promote evapotranspiration, infiltration, and the recharge of aquifers and improve runoff quality by eliminating pollutants (Lizárraga-Mendiola et al., 2017).

Numerous studies have been conducted on the behavior of urban runoff when implementing different techniques. Guo et al. (2019) developed an LID model in Tsingtao, one of the pilot sponge cities in China, where rain barrels, green roofs, rain gardens, and permeable pavements were implemented, managing to reduce runoff by 20.7% to 63.2%. Andrés-Doménech et al. (2018) analyzed the hydrological behavior of green roofs in Valencia, Spain, and demonstrated its effectiveness even in Mediterranean climates, where the runoff coefficient was reduced below 75%. On the other hand, Chapman and Hall (2021) analyzed the behavior of runoff in different scenarios in which they applied bioretention cells, green roofs, and permeable pavements, highlighting that the available area for effective SUDS decreases with increasing housing density, which forces the adaptation of green infrastructure, prioritizing green roofs in homes.

Evaluating these solutions requires simulating their effects in a hydrological model, a somewhat complex process due to the multiple variables involved. The Storm Water Management Model (SWMM) program, developed by the United States Environmental Protection Agency (EPA), allows modeling the hydrodynamic behavior of rainwater (Mendoza González et al., 2017). The SWMM has a LID editor that models sustainable technologies and estimates the basin's response regarding runoff volume, water quality, infiltration, evaporation, and pollutant load (Zúñiga-Estrada et al., 2022).

This study highlights the city of Villa de Álvarez, located in western Mexico, as an example of an urban area that has suffered recurrent floods during the rainy season between June and October. This research evaluates two types of SUDS commonly applied in homes: rain barrels (RB) and green roofs (GR). SWMM is used to simulate and compare the hydrological behavior of both models and determine the technique that provides the best results. This evaluation is based on runoff volume, peak runoff, and runoff coefficient for different precipitation intensities.

METHODOLOGY

LOCATION AND CLIMATE

Villa de Álvarez is located in the state of Colima, Mexico. It has a population of 149,723 inhabitants and is the third most populous city in the state (Figure 1). The city has experienced remarkable population growth, above the national average, leading to dispersed urban development and inadequate infrastructure (Ramírez-Rivera et al., 2021).

According to the National Institute of Statistics and Geography (INEGI), the city has a warm sub-humid climate, an average annual temperature of 25°C and an average annual rainfall estimated at 900 mm, with rain predominating in summer, between June and October (INEGI, 2016). Villa de Álvarez has experienced an increase in the frequency of floods in the last two decades, mainly due to tropical storms associated with hurricanes and mesoscale convective systems (MCS). Examples include Hurricanes Jova (2011), Manuel (2013), and Patricia (2015), which recorded accumulated rainfall of 200 mm in 24 hours. Floods also occur due to intense, short-lasting rains (Pérez-González et al., 2017), a product of the MCS, which are complicated to monitor.

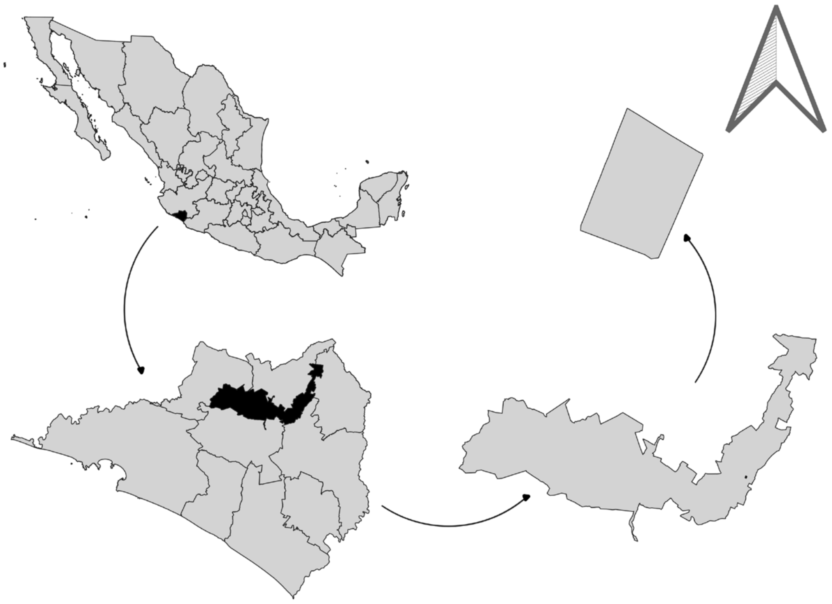

Figure 1. Study area location. Source: Preparation by the authors.

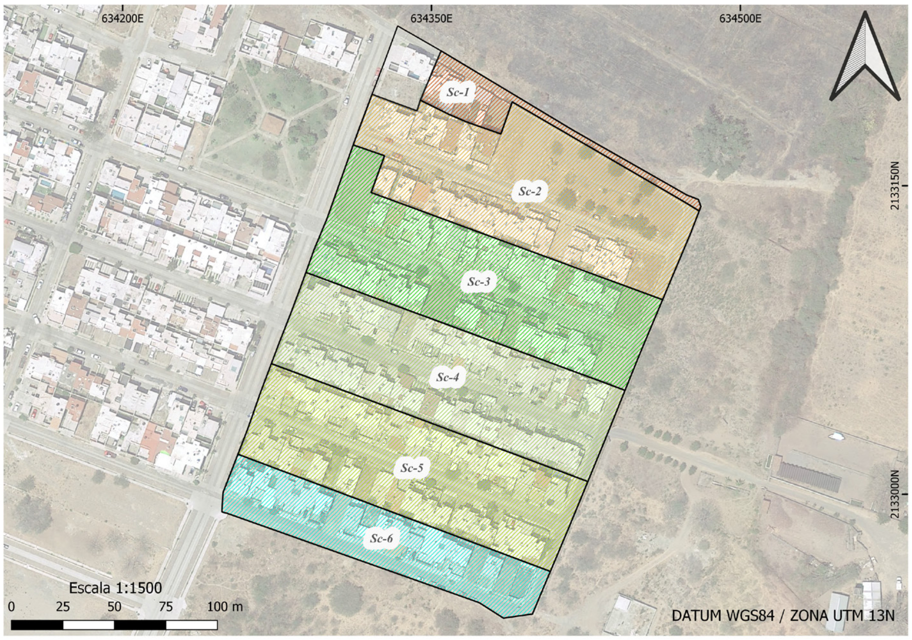

Figure 2. Marking out of sub-basins. Preparation by the authors.

GENERAL DESCRIPTION OF THE STUDY AREA'S CHARACTERISTICS

Urban growth in Villa de Álvarez has spread to the north, increasing impervious surfaces and resulting in recurrent flooding in low-lying areas. However, conventional solutions based on expanding storm drainage have not mitigated the problem. Hence, a new perspective on stormwater management that adopts green infrastructure harmonizing urban development with the natural hydrological cycle is needed.

The study area was chosen based on the need to implement upstream SUDS techniques to efficiently manage water in low-lying areas, considering the average rooftop area and future vulnerability to flooding.

The research used QGIS with vector data from the National Geostatistical Framework of Mexico (INEGI,

Table 1. Minimum requirements to build the model. Source: Ponce de León García (2022).

Parameters	Definition	Units
Basin area	Total area of each sub-basin	Hectares
Basin length	Total distance of the basin	Meters
Basin width	Ratio between area and length	Meters
Basin slope	Percentage ratio between elevations and distance	Percentage
%-Imperm	Percentage of impermeable area	Percentage
N-Imperm	Manning's value for the impermeable fraction	Dimensionless
N-Perm	Manning's value for the permeable fraction	Dimensionless
Curve number	Soil Conservation Service (SCS) Infiltration Model	Dimensionless

Table 2. General characteristics of the study area. Source: Preparation by the authors.

Sub-basin	Area	Length	Width	Slope	%-Imperm	N-Imperm	N-Perm
1	0.13	140.61	9.25	2.29	68.01	0.014	0
2	0.85	161.72	52.56	2.14	53.99	0.014	0.06
3	0.82	158.73	51.66	2.69	63.11	0.014	0
4	0.78	157.50	49.52	2.16	63.58	0.014	0
5	0.77	156.09	49.33	2.53	63.53	0.014	0
6	0.44	152.89	28.78	1.83	64.46	0.014	0

2023). The study area of 3.80 hectares is characterized by a predominantly residential land use, which covers 74.15%, reflecting a high housing density. Cobblestone streets represent 20.93%, and green areas constitute the remaining 4.92%. Continental relief rasters with a resolution of 5 m and a scale of 1:10,000 (INEGI, 2019) were used to mark out the sub-basins.

Based on the topography, it was possible to mark out six sub-basins in the study area (Figure 2). In addition, it was observed that surface runoff runs north to south along the streets. This is due to the lack of a storm drainage system to facilitate adequate water channeling.

To build the model in SWMM, it was necessary to identify the minimum characteristics required by the system (Table 1).

The parameters were determined using QGIS. However, the impermeable area percentage was determined considering the land use of each sub-basin, and its respective runoff coefficient was used, taken from Table 2.4 of the Manual for Drinking Water, Sewerage, and Sanitation: Storm Drainage (CONAGUA, 2019, p. 57). Manning values for the impermeable and permeable fractions were obtained from Table 5-6 of the Hydraulic Book on Open Channels (Chow, 1994, p. 108). The curve number was estimated using vector data on surface hydrology and soil science (INEGI, 1981; INEGI, 2007) and soil and vegetation of the National Commission for the Knowledge and Use of Biodiversity (CONABIO, 2021). Using the vector data, the soil type was classified according to its physical properties and permeability. For this, the values of Table No.11 (Díaz Herrera, 1987, p. 64) were used, and it is highlighted that it belongs to a type B soil classification. Finally, the curve number was calculated considering the soil classification and its use. The values in Table 2-2a of the book Urban Hydrology for Small Basins, TR-55 (Cronshey et al., 1986, pp. 2-5) for a type B soil and land use with human settlements were used; hence, the value designated to the curve number was 92.

The main characteristics of the sub-basins are shown in Table 2.

SELECTION OF DESIGN RAINS

The design precipitation was estimated using historical records of the National Water Commission (CONAGUA, 2020). The climatological station 6052-E.T.A 254 Comala was selected for its influence on the study area. Monthly maximum rainfall data were collected from this station from 1975 to 2017.

The collected data were subjected to statistical tests to validate their use in the research, which includes the detection of outliers, the Helmert test, Student's t, Cramer's test, and Anderson's independence test (Escalante Sandoval & Reyes Chávez, 2002). The satisfactory results of these tests confirm that the maximum rainfall series in 24 hours is independent and free of trends.

Once the hypotheses for frequency analysis have been validated, the technique is implemented to build the intensity-duration-return period (I-D-Tr) curves, which allow rainfall lasting less than 24 hours to be estimated. Frederick Bell's method was chosen because its application best fits return period conditions between 2 and 100 years and durations between 5 and 120 minutes. Bell's formula is expressed in Equation 1 below (Campos Aranda, 1998, pp. 4–56).

$$P_t^T = (0.35\, Ln\, T + 0.76)(0.54t^{0.25} - 0.50)P_{60}^2$$

(Equation 1)

Where:
T is the return period.
t is the duration of the storm.
P_{60}^{2} storm precipitation for a 2-year return period lasting one hour.

The storm duration, also known as concentration time, is determined using Kirpich Equation 2 (CONAGUA, 2019, p. 41). The concentration time in the study area is one hour.

$$t_{cs} = 0.0003245\left(\frac{lt}{\sqrt{S_{lc}}}\right)$$

(Equation 2)

Where:
lt is the length of the main channel (m).
S_{lc} average slope of the channel (dimensionless).

The construction of the I-D-Tr curves allows obtaining precipitation design hyetographs for return periods of 2, 5, and 10 years, which assume a storm duration of one hour. The design rainfalls for these periods were 47.90 mm, 63.23 mm, and 74.82 mm, respectively. Figure 3 presents the hyetographs used in SWMM to build the model.

ESTIMATION OF EVAPOTRANSPIRATION

Soil moisture is important for processes such as infiltration and evaporation. The hydrological model requires evapotranspiration data to accurately represent soil moisture during the simulation period, especially at the beginning of the rainfall event (Andrés-Doménech et al., 2018).

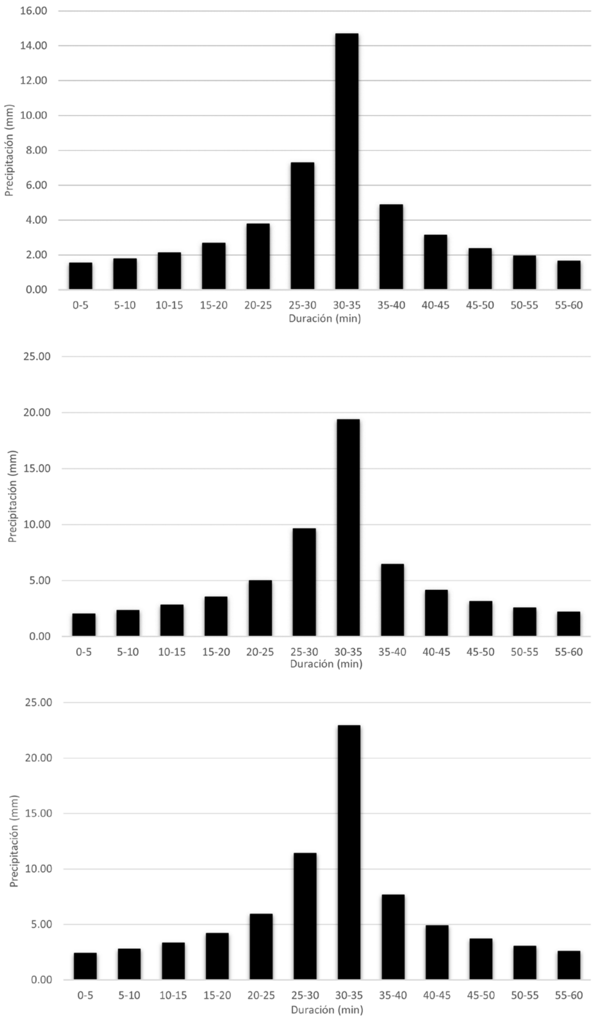

Figure 3. Hyetographs for different return periods: a) 2 years, b) 5 years, and c) 10 years. Source: Preparation by the authors.

Because the weather stations do not record the necessary data, the potential monthly evapotranspiration is calculated using Thornwaite's formula (Equation 3). This formula is based mainly on the average temperature and is adjusted according to the hours of sunlight at a specific site. Evapotranspiration is calculated for the same period of years as precipitation.

$$PE_m = 16N_m\left(\frac{10\overline{Tm}}{I}\right)^a$$

(Equation 3)

Where:
PE_m potential evapotranspiration (mm/month).
N_m monthly adjustment factor related to the hours of sunlight (without units).
T_m Average monthly temperature (°C).
a Constant (Equation 4).
I Annual thermal index (Equation 5).

$$a = 6.7 \times 10^{-7} I^3 - 7.7 \times 10^{-5} I^2 + 1.8 \times 10^{-2} I + 0.49$$

(Equation 4)

$$I = \sum_{m}^{i} = \sum \left(\frac{Tm}{5}\right)^{1.5}$$

(Equation 5)

The potential evapotranspiration was estimated in millimeters per month. To obtain the daily value, it was necessary to divide it by the number of days of the month because the rain simulation is based on a single precipitation event. The value for September, the month with the highest precipitation in the region, was chosen (Table 3).

Table 3. Potential evapotranspiration per day. Source: Preparation by the authors.

Month	PEm (mm/day)	Correction factor	Corrected PEm (mm/day)
January	2.55	0.95	2.43
February	2.74	0.90	2.47
March	3.00	1.03	3.09
April	3.52	1.05	3.70
May	4.14	1.13	4.67
June	4.40	1.11	4.87
July	4.15	1.14	4.72
August	4.07	1.11	4.50
September	3.84	1.02	3.92
October	3.79	1.00	3.79
November	3.37	0.93	3.14
December	2.88	0.94	2.72

Construction of the model

The model's simulation consists of three scenarios: A, the area's current state without interventions; B, RB implementation; and C, GR implementation. The RB capacity is 2500 liters for each house. This is determined based on commercial products. On the other hand, the roofs, the main receivers of rainwater in the research, have an average surface of 80m². In addition, it is considered that the GRs will cover the entire rooftop. Table 4 presents the GR design used in SWMM based on the parameters of Chapman and Hall (2021).

Table 4. Parameters used in the SWMM simulation. Source: Chapman and Hall (2021).

Tabla 4. Parámetros usados en la simulación SWMM. Fuente: Chapman y Hall (2021).

Type of SUDS	Parameter	Values used in the model
GR	Height of the ditch (mm)	20
	Vegetation volume fraction	0.05
	Surface area roughness (Manning n)	0.24
	Slope %	0
	Soil layer	
	Thickness (mm)	80
	Porosity (Volume fraction)	0.464
	Field capacity (Volume fraction)	0.20
	Withering point (Volume fraction)	0.10
	Conductivity (permeability - mm/hr)	119.40
	Conductivity slope	45.05
	Suction load (mm)	49.80
	Drainage material	
	Thickness (mm)	25
	Fraction of voids	0.50
	Roughness (Manning n)	0.30
RB	Barrel height (mm)	1320

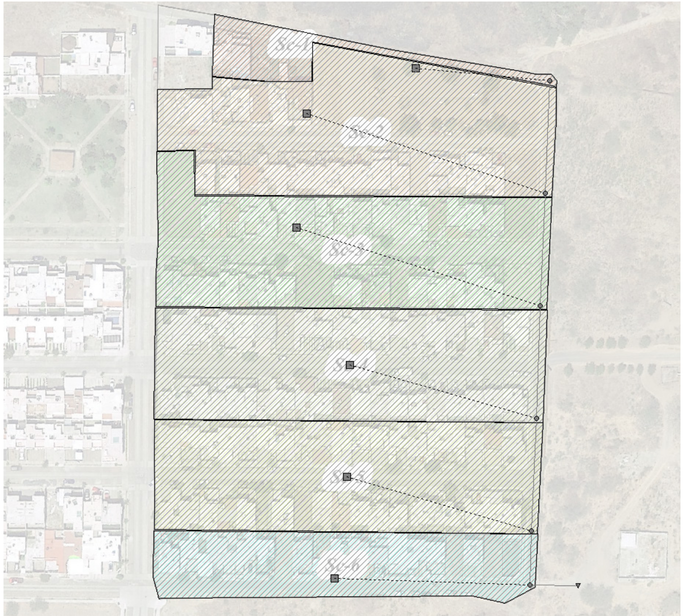

Figure 4. Construction of the model in SWMM. Source: Preparation by the authors.

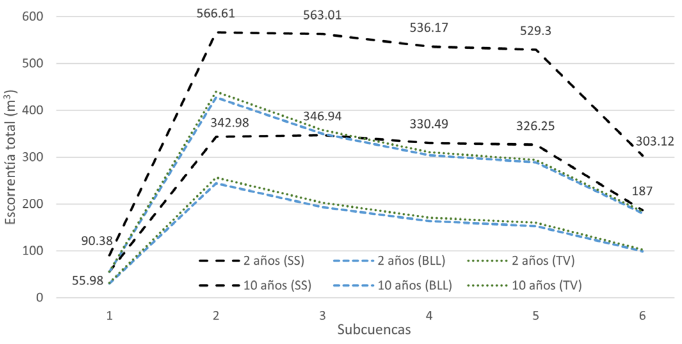

Figure 5. Runoff according to maximum and minimum values. Source: Preparation by the authors.

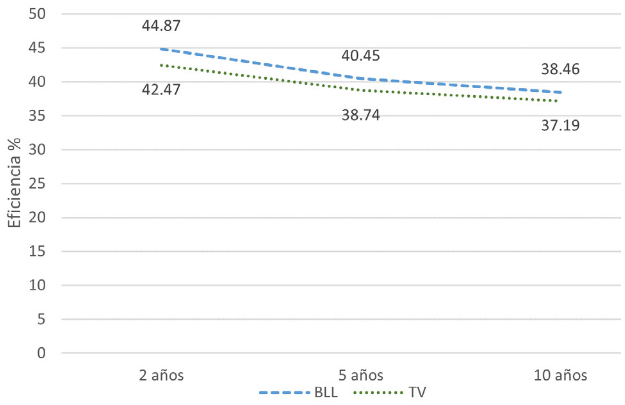

Figure 6. General efficiency ratio in the reduction of runoff volumes for different return periods. Source: Preparation by the authors.

The study area lacked a storm drainage system; the streets (7m wide and 15cm high) were modeled as rectangular open surface channels in SWMM to simulate water evacuation. The outlets of each sub-basin were established in nodes located at their ends, which simulate that the runoff generated descends to their lowest point and connects with the street that joins the sub-basins (Figure 4).

RESULTS AND DISCUSSION

Scenario A, without SUDS (SS), was simulated under three rainfall conditions (2, 5, and 10 years) lasting one hour, which allowed evaluating the hydrological behavior. Sub-basin 2 had the highest values according to the runoff volumes: with precipitation of 47.90 mm, it generated 342.98 m^3 of runoff and a maximum flow of 308.23 lps. With 63.23 mm of precipitation, these values increased to 469.46 m^3 and 436.61 lps, respectively. Finally, with 74.82 mm of rain, 566.61 m^3 of runoff and 536.09 lps of maximum flow were reached. According to the results, a direct relationship between the increase in precipitation intensity and runoff was evidenced.

Figure 5 shows the simulation results when considering the application of SUDS for precipitation events with return periods of 2 and 10 years. They represented the minimum and maximum intensities, respectively. Generally, the RBs and GRs show satisfactory results in water retention for the three precipitation conditions. Sub-basin 2 has the highest runoff volumes for a 10-year rainfall and experiences a significant reduction of 139.15 m^3 with the RB and 126.94 m^3 with the GR. However, sub-basin 5 achieves the highest absolute reduction, reaching 240.75 m^3 with RB and 235.35 m^3 with GR.

The RBs and GRs follow a similar behavior for a 2-year rainfall event. Although the RBs manage the storm runoff slightly better than the GRs, the difference between the two is not significant according to the descriptive analysis. The percentages of efficiency in the volume for sub-basin 2 with a 2-year rainfall event are 28.86% for RB and 25.30% for GR. Despite their high efficiency in 2-year storms, the RBs have overflows even in events of this magnitude. However, even with overflows, their performance is superior to GR in higher-intensity rainfall. In the same sub-basin, with a 10-year rainfall event, the efficiency of the RBs reach 24.56%, while the GRs reach 22.40%.

Figure 6 shows the efficiency of both technologies in general and demonstrates that their effectiveness depends on the magnitude of the precipitation. The RBs perform better in any precipitation condition. However, their efficiency decreases with increasing rainfall intensity due to their limited storage capacity (2500 l). The overflows that occur when exceeding this capacity increase the surface runoff. Conversely, the GRs have a lower performance than the RBs in all the evaluated precipitation conditions. Both techniques are functional for the analyzed return periods in the study area—however, both decrease efficiency with higher-intensity rainfall.

The peak runoff refers to the maximum flow that flows through a basin during a rainfall event. The techniques managed to reduce the peak runoff (Figure 7). A noticeable difference in peak runoff reduction is observed between the GRs and the RBs. In contrast to the reduction of runoff volumes, where the RBs showed better performance, in the reduction of peak runoff, the GRs outperformed the RBs in terms of efficiency. Sub-basin 2 has a lower reduction of peak runoff due to the smaller number of techniques implemented, in contrast, Sub-basin 5 achieves a higher reduction thanks to its higher density of

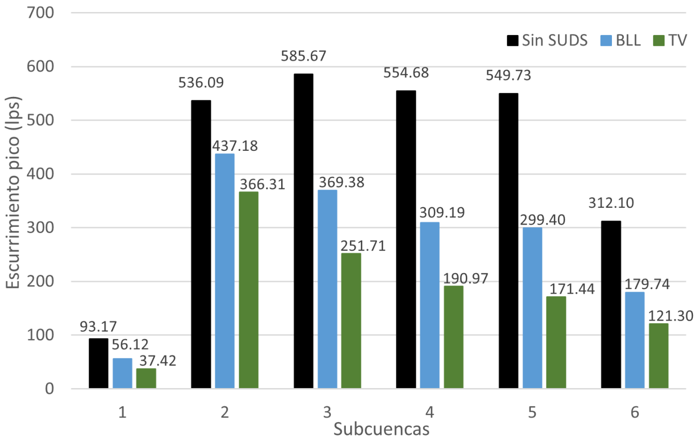

Figure 7. Peak runoff for a 10-year return period. Source: Preparation by the authors.

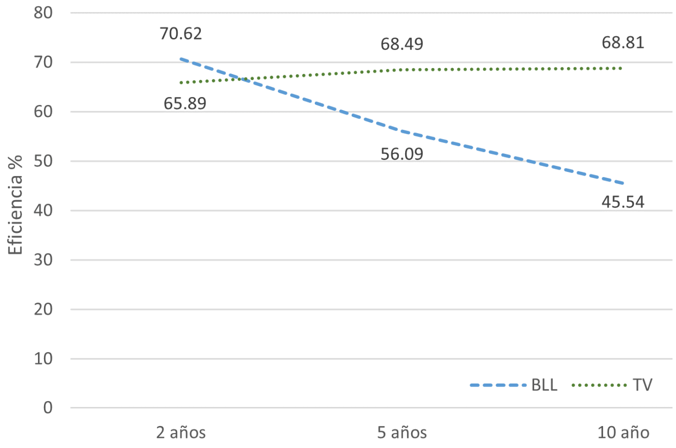

Figure 8. Comparison of the effectiveness of RB and GR in reducing peak runoff for different return periods. Source: Preparation by the authors.

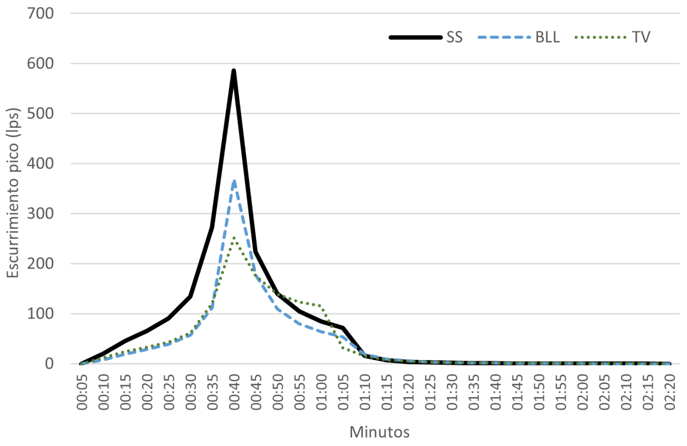

Figure 9. Hydrograph of sub-basin 3 for a 10-year return period. Source: Preparation by the authors.

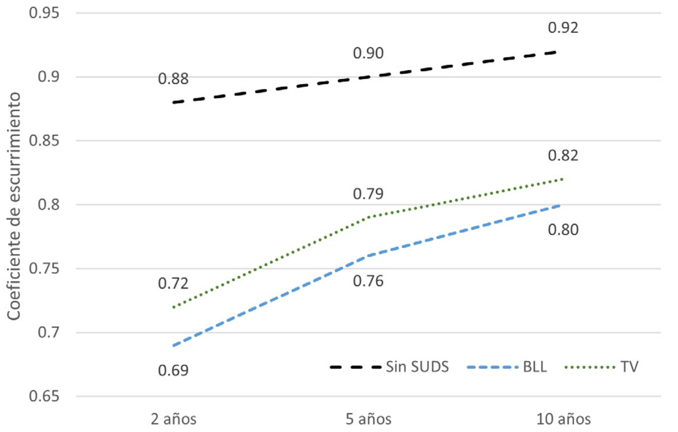

Figure 10. Comparison of the mean runoff coefficient in the sub-basins applying RB and GR. Source: Preparation by the authors.

dwellings, which allows a greater application of the catchment techniques.

The general performance of both techniques was evaluated under different precipitation conditions. Figure 8 shows that the RBs stand out in their efficiency for 2-year rainfall events, but their performance decreases in higher-intensity rains. On the other hand, the GRs perform better in more intense rainfall conditions. Generally, the GRs surpass the RBs in the peak flow reduction, primarily in events with greater intensity. The RBs reach their maximum efficiency (70.62%) in rains with a return period of 2 years, while the GRs demonstrate a significantly higher efficiency (60.81%) in rains with a return period of 10 years.

In Sub-basin 3, the peak runoff is reached 40 minutes after the onset of precipitation. The implementation of RB reduces this peak by 36.93%, while the GRs achieve an even greater reduction of 57.02% (Figure 9). The techniques show satisfactory performances in terms of reducing the peak flow rate. However, there is a significant difference between the two techniques. The RBs significantly reduce the peak flow rate with satisfactory behavior. On the other hand, the GRs far exceed this efficiency by attenuating the peak flow rate by more than 50% compared to the scenario without intervention.

It is observed that the concentration time in the scenario without intervention has a steep ascent and descent. However, the RBs reduce the peak flow; they

Table 5. Statistical significance of the differences between scenarios. Source: Preparation by the authors.

Year	AvsB Volume	AvsC Volume	CvsB Volume	AvsB flow rate	AvsC flow rate	CvsB Flow rate	AvsB coefficient	AvsC coefficient	CvsB coefficient
2 years	0.0049	0.004	0.008	0.0051	0.0059	0.0090	0.0002	0.0006	0.00003
5 years	0.0046	0.004	0.010	0.0057	0.0056	0.0059	0.0002	0.0006	0.00010
10 years	0.0044	0.037	0.014	0.023	0.0053	0.0047	0.0004	0.0007	0.00030

exhibit similar behavior, although on a smaller scale. In contrast, the GRs decrease the peak flow and flatten the hydrograph curve, defining them as the most effective technique.

The runoff coefficient was evaluated, showing a notable reduction in all cases. Figure 10 shows how the runoff coefficient in scenario A increases steadily with the increase in precipitation. However, both techniques reduce it considerably, with the RBs being the most effective. Despite the more significant reduction observed with the RBs, the GRs are more stable when facing more intense rains.

It was analyzed whether the reduction observed in the three variables was statistically significant. Although the descriptive analysis shows a decrease in absolute terms, it is essential to determine whether this reduction is statistically significant to confirm the effectiveness of the interventions for each scenario. t-tests were performed for paired samples, where a P-value <0.05 indicates significant differences between the scenarios. The results show statistically significant reductions in the analyzed variables (Table 5).

CONCLUSIONS

The simulation with SWMM allows us to observe the sub-basins' response to different rainfall conditions and their behavior when implementing sustainable techniques. The RBs achieve significant runoff volume reductions by performing better in higher-intensity precipitation events, unlike the GRs, which show their best behavior in less intense storms.

Both techniques reduce the volume, the peak flow, and the runoff coefficient. However, the GRs demonstrate superior performance (68.81%), exceeding the RBs (45.54%) in managing average peak runoff for 10-year rains; even the hydrograph shows that the GRs achieve more significant flattening of the curve than the RBs.

The results allow us to demonstrate the effectiveness of these sustainable solutions in managing runoff in the study area. By mimicking natural hydrological conditions, it is possible to recover the local hydrological cycle and mitigate the impacts of urban runoff for storms of different intensities. Implementing nature-based solutions to manage runoff, especially to reduce the peak flow and minimize the risk of floods, is essential.

This research evaluated the application of the techniques for 90% of the homes, a possibly unrealistic percentage. The study's main limitation is the model's lack of calibration due to the complexity of determining all the necessary parameters. It is suggested that future research focus on calibration and evaluation for different application percentages in homes.

CONTRIBUTION OF AUTHORS CREDIT

Conceptualization, S.J.F.A.; Data curation, S.J.F.A.; Formal analysis, D.A.C.F., J.L.C., J.A.G.V. and I.B.A.; Acquisition of financing D.A.C.F., J.L.C., J.A.G.V. and I.B.A.; Research, S.J.F.A.; Methodology, S.J.F.A.; Project management, D.A.C.F.; Resources; Software. S.J.F.A.; Supervision, D.A.C.F., J.L.C., J.A.G.V. and I.B.A.; Validation, D.A.C.F., J.L.C., J.A.G.V. and I.B.A.; Visualization, D.A.C.F., J.L.C., J.A.G.V. and I.B.A.; Writing - original draft, S.J.F.A.; Writing - revision and editing, D.A.C.F., J.L.C., J.A.G.V. and I.B.A.

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