

Conceptual Prototype of Blue and Green Infrastructure for Domestic Stormwater Management in Semi-Arid Zones

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Abstract: This paper presents the conceptual design of a blue and green infrastructure (BGI) prototype focused on decentralized stormwater collection, treatment, and storage in urban dwellings located in semi-arid regions. The proposal is presented as an adaptation strategy to address water scarcity, considering the limited performance of conventional water supply systems in such vulnerable contexts. The BGI system integrates two complementary strategies: direct collection from rooftops and the collection of surface runoff generated on impervious sidewalks, which is conveyed through permeable pavement to a bioretention cell composed of vegetation and recycled construction aggregates. This configuration allows runoff water to be collected, filtered, and stored for later use. Local climate data were used to estimate surface runoff, infiltration within the system layers, and potential storage through a preliminary water balance. The design was applied to a typical home with a roof area of 39.2 m² and a daily consumption of 724.9 liters (for five inhabitants, using water-saving devices). The results indicate that, during representative rainfall events, the volume captured partially covers this allocation for at least one day, demonstrating the hydraulic viability of the system in urban environments with limited space. It should be noted that the water balance does not account for losses due to evaporation or evapotranspiration, as the objective was to provide a preliminary estimate for conceptual sizing. It is concluded that the BGI prototype represents a viable and sustainable alternative for rainwater harvesting in homes with limited space and restricted access to conventional water sources, thus contributing to a circular water economy.

Keywords: nature-based solutions, rainwater harvesting, decentralized water management

Introduction

Secure, continuous access to water is one of the main challenges facing large regions of the world, especially countries of the Global South, such as Mexico. It is estimated that more than 10 million people in the country lack reliable access to drinking water (Lluch-Cota, 2022), a situation that is exacerbated in arid and semi-arid regions, where low rainfall and limited infrastructure increase water vulnerability among the population (Carril-Ferreira *et al.*, 2024). This problem is further intensified by unplanned urban growth, which has led to an increase in impervious surfaces and, with it, reduced rainwater infiltration, increased surface runoff, and decreased water availability (Gregory, 2021).

In this context, it is therefore a priority to develop decentralized solutions that enable the collection, treatment, and reuse of stormwater locally. It is essential to recognize that stormwater may originate from both direct rainfall on surfaces such as roofs and sidewalks, and from runoff generated on urban surfaces. This broader approach to water collection maximizes the use of water resources that would otherwise be lost. Blue and green infrastructure (BGI) systems, also known as nature-based solutions, contribute to this effort and have been widely promoted as sustainable strategies for urban stormwater management (Vázquez-Rodríguez *et al.*, 2024). Recent research highlights their ability to reduce runoff volume, improve water quality, and promote aquifer recharge, while enhancing climate resilience (Fletcher *et al.*, 2015; Liu *et al.*, 2020; Zúñiga-Estrada *et al.*, 2024).

In particular, the integration of systems such as permeable pavements and bioretention cells has proven effective for stormwater management in densely populated urban areas (Brown *et al.*, 2015). Furthermore, these solutions align with the principles of the circular economy by encouraging the local reuse of stormwater, reducing dependence on conventional water sources, and promoting more efficient and sustainable management of resources. Within this framework, this study proposes a conceptual design for a household-scale BGI system for stormwater collection, treatment, and reuse, adapted to a low-income housing unit located in a semi-arid region of central Mexico. The BGI system integrates permeable pavement and a bioretention cell. The proposal is based on local climate analysis, the

characterization of the dwelling, the estimation of domestic water demand, and the calculation of the water balance of the BGI system. The main contribution of the study is the development of a preliminary and replicable solution for low-income housing that reduces dependence on conventional water supplies through the use of stormwater.

Materials and Methods

Study area

The study micro-watershed is located in the Colinas de Plata subdivision, in the municipality of Mineral de la Reforma, Hidalgo, Mexico, at an average altitude of 2,433 m above sea level and with an area of 1.43 km² (Figure 1). The climate is classified as temperate semi-arid, characterized by intense, short duration rainfall occurring from May to October, with annual precipitation ranging from 160 to 700 mm and an average temperature of 14 °C. The area presents an average slope of 9.5% and a predominant Phaeozem soil type with a sandy clay texture. Previous studies in the area have reported that more than 70% of annual rainfall is lost through evaporation, while urbanization has significantly increased surface runoff (Bigurra-Alzati et al., 2021). These conditions justify the selection of the study area for evaluating strategies for stormwater harvesting and reuse through BGI systems.

Prototype housing

Three types of housing were identified within the study micro-watershed: small, medium, and large, based on built area and occupancy capacity. The medium category, known as “popular housing”, was selected as the prototype housing, as it is the most representative in the area studied. This type of housing is designed to accommodate up to five residents and has a total lot area of 90 m² (Figure 2). The catchment areas for rainwater and runoff were delineated using Google Earth Pro software.



Figure 1. Aerial view of the micro-watershed study, located in Mineral de la Reforma, Hidalgo. Image obtained from Google Earth

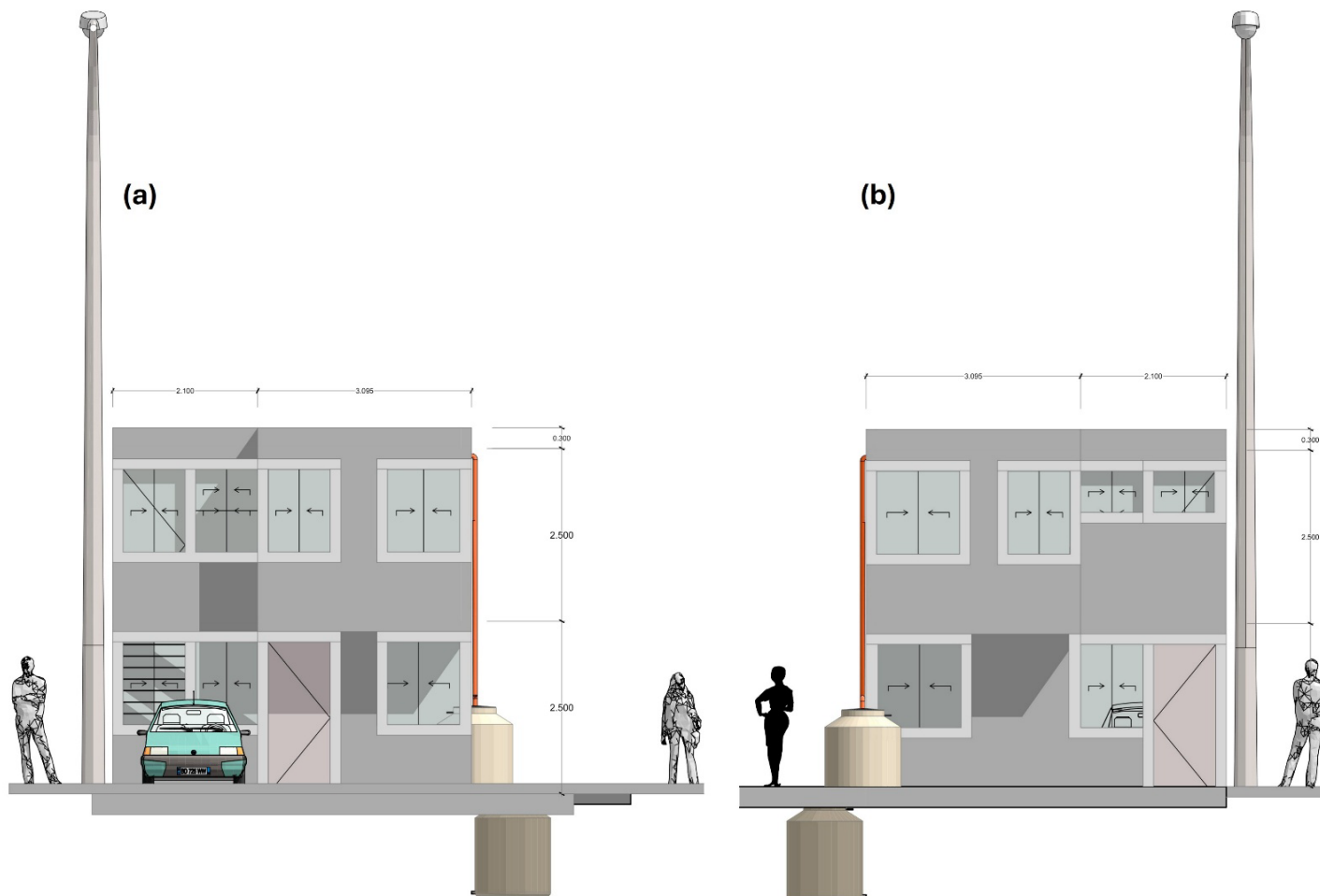


Figure 2. Architectural diagram of the prototype middle-class housing unit. (a) Main facade; (b) rear facade

Estimation of monthly rainfall volume collected

To estimate the volume of rainfall that can be collected from the prototype house’s roof surface, historical climate data for the period 1981–2023 were compiled. Precipitation data were obtained from weather stations 13022 and 13056, selected for their geographic proximity and climatic representativeness relative to the study area, operated by the Comisión Nacional del Agua (CONAGUA). Based on the precipitation records, net rainfall was calculated using the methodology proposed by Anaya-Garduño (2011). This value represents the amount of water available for collection, accounting for losses due to splashing, evaporation, surface friction, and drop size. The formula used to estimate net rainfall is Equation 1:

$$PN = P * \eta \tag{1}$$

where **PN** is the net rainfall (mm), **P** is the mean rainfall (mm), and **η** is the rainwater capture efficiency; the value considered for this parameter was 0.765, according to Anaya-Garduño (2011).

Once the value of **PN** was obtained, the monthly net capture volume (V_m , in m^3) was calculated considering the catchment area **A** (m^2), as shown in Equation 2. The calculation was performed monthly to identify the periods with the highest water availability.

$$V_m = \frac{PN \cdot A}{1000} \tag{2}$$

Estimating water demand in the prototype home

To estimate residential water demand, daily per capita water consumption was first calculated based on average consumption for various domestic activities, such as showering, using the toilet, using a washing machine, cooking, washing dishes, and cleaning the home. To do this, we used data from scientific literature and official sources. Once the individual allowance was obtained, the total monthly demand for the prototype home was estimated, assuming it is occupied by five people. This estimate was made under two scenarios: (i) assuming the use of traditional devices and (ii) considering the implementation of water-saving devices. This comparison allowed for an evaluation of the potential impact of efficient water use on total consumption. In both cases, Equation 3 proposed by Anaya-Garduño (2011) was applied to calculate the monthly demand.

$$D_j = \frac{Nu \cdot Dot \cdot Nd}{1000} \quad (3)$$

where D_j is the monthly water demand, expressed in cubic meters per month (m^3 /month); Nu is the number of beneficiaries or inhabitants of the household (persons); Dot is the daily per-capita water allocation (liters/person/day); and Nd is the number of days in the month considered.

Conceptual design of the prototype

A water balance was performed to estimate the volume of water entering the BGI system from rainfall on impervious surfaces. This analysis allowed the quantification of the inflow, infiltration, and storage flows associated with the hydraulic performance of the proposed system. For the analysis, a rainfall event lasting one hour, with an intensity of 0.045 m/h and a return period of 25 years, was selected, in accordance with the isohyets prepared by the Secretaría de Comunicaciones y Transportes (SCT) for the city of Pachuca, Hidalgo. The water balance was calculated considering three main units of the BGI system: the impervious sidewalk, the permeable pavement, and the bioretention cell. To estimate the maximum surface runoff flow, the rational method (Bigurra-Alzati *et al.*, 2021) was used, applying Equation 4.

$$Q = 0.278 \cdot Ce \cdot i \cdot A \quad (4)$$

where Q is the maximum runoff flow (m^3/s); Ce is the runoff coefficient (dimensionless); i is the rainfall intensity (mm/hour); and A is the area considered (m^2). The Ce values used were 0.9 for the impervious sidewalk, and 0.3 for the permeable pavement and the bioretention cell. To calculate the infiltrated volume, the same equation was used, substituting Ce with $1 - Ce$.

Results and Discussion

Estimation of monthly rainfall volume collected

The average monthly precipitation values recorded between 1981 and 2023 are shown in Figure 3, indicating that most precipitation occurs from May to September, with a maximum in July (94.56 mm). In contrast, January, February, November, and December have significantly lower values, with precipitation below 40 mm. A Ce of 0.9 was used to calculate PN , based on Anaya-Garduño's (2011) findings for a concrete roof surface. Figure 4 shows the monthly values of estimated PN on the roof surface of the prototype house.

Figure 5 shows the monthly volume of rainwater collection, calculated from the PN values and the roof area ($39.2 m^2$). The highest volumes are recorded in June, September, and July, while February, December, and January have the lowest values. This reflects the limited collection potential during the dry season, when the average monthly collection volume is $1.79 m^3$.

The estimated monthly catchment volumes in this study (between 0.847 and $2.84 m^3$) for an area of ($39.2 m^2$) were compared with those reported by Lizárraga-Mendiola *et al.* (2015), obtained in the same geographical area on roofs of $45 m^2$. Both studies are based on comparable annual precipitation values (552 mm in this study and 585 mm in the

cited study); however, the catchment results differ notably. This is mainly due to the methodological approach adopted in each case. While this study considers a net catchment scheme that takes into account losses due to splashing, evaporation, and structural efficiency, the study by Lizárraga-Mendiola *et al.* (2015) used the gross precipitation of the rainiest year in the period 1980–2013 (2010), allowing the identification of maximum catchment potential to be identified under an extreme scenario, without applying adjustments for losses.

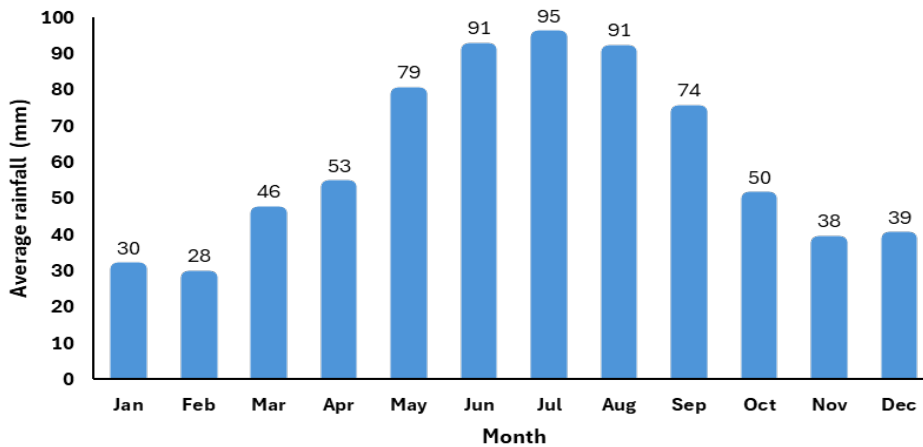


Figure 3. Average monthly precipitation recorded during the period 1981–2023

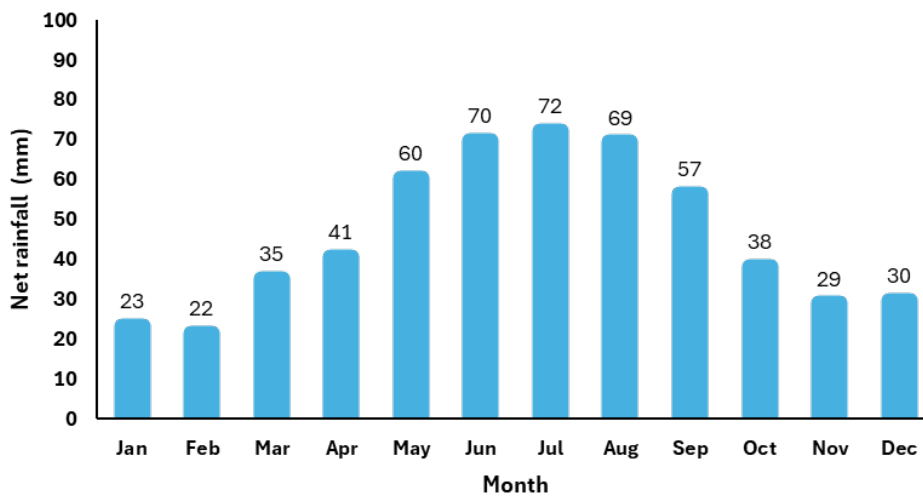


Figure 4. Net rainfall for the roof surface of the prototype house

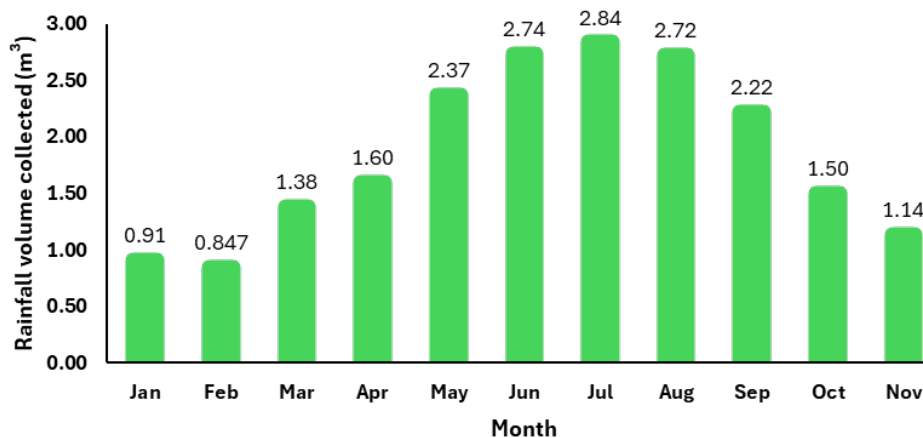


Figure 5. Rainwater collection volume on the roof of the prototype house

Estimation of water demand in the prototype dwelling

Per capita water use was estimated for two scenarios: traditional devices and water-saving devices (Table 1). A difference of 90.76 L/person/day was observed, with values decreasing from 235.74 L/person/day in the scenario with traditional devices to 144.98 L/person/day with water-saving devices, representing a 38.5% reduction. This decrease is mainly attributed to more efficient water use in showers and toilets, which together account for the highest consumption.

Table 1. Daily per capita water consumption by household activity for scenarios with traditional and water-saving devices.

Activity	Traditional (L/person/day)	Water saving (L/person/day)
Shower	109.6	62.4
WC	65.8	35.7
Dishwashing	42	30.7
Washing machine	7.71	5.6
House cleaning	1.03	1.03
Irrigation	8	8
Food preparation	1.6	1.6

The average shower duration was estimated at eight minutes per person per day (Kordana *et al.*, 2014; Kenway *et al.*, 2019). Toilet use was estimated at an average of seven flushes per person per day (Lizarraga-Mendiola *et al.*, 2015; Crouch *et al.*, 2021; Wilkes *et al.*, 2005). Dishwashing was estimated at three sessions per day, each lasting seven minutes, totaling 21 minutes per household per day (Shan *et al.*, 2015; Pavlou *et al.*, 2024). For washing machine use, three cycles per week were assumed, equivalent to 0.43 cycles per household per day (Beemkumar & Mathews, 2015; Pakula & Stamminger, 2009; Rosas-Flores & Morillón-Gálvez, 2010). Household cleaning was estimated at 36 liters per household per week, equivalent to 5.14 liters per day (Otsuka *et al.*, 2013; Dobroski, 2016), and watering of green areas or planters was calculated at five minutes per household per day (Willis *et al.*, 2015; Devkota *et al.*, 2015; Sandr *et al.*, 2016). Finally, the volume used for food preparation was set at eight liters per household per day (Ismail *et al.*, 2024; Makki *et al.*, 2013; Ramírez-Escobar & Buriticá-Arboleda, 2021). For activities shared by all household members, the total volume was divided by five to obtain the daily consumption per person. This approach enabled more accurate identification of the impact of efficient devices on potential water savings in the domestic sphere.

Conceptual design of the blue and green infrastructure prototype

Based on Figure 6, a prototype of the BGI system is proposed that integrates two main strategies for capturing, treating, and utilizing stormwater at the household level: direct rainwater harvesting and runoff collection from impervious surfaces.

Direct rainwater harvesting

As a complement to the BGI system, the installation of a rainwater harvesting tank is proposed to collect water from the rooftop, which has a surface area of 39.2 m². A downspout system will convey the collected water to the cistern (Figure 6). Preliminarily, the use of a 100-liter tank is proposed, as this capacity allows storage of the estimated daily collection during July, the rainiest month of the year, in which a total volume of 2.84 m³ is recorded. This amount is distributed over 30.5 days, resulting in an average daily collection of approximately 93 liters. Although this amount represents only a fraction of the household's total consumption, estimated at 724.9 liters per day for a family of five with an individual allocation of 144.98 L/person/day, the continuous use of the collected water prevents the tank from reaching its maximum capacity. Thus, the resource is continuously utilized, and dependence on the municipal drinking water network is partially reduced, particularly during the months with the highest rainfall.

Surface runoff collection and treatment

The BGI system begins at the pedestrian access sidewalk, which is built with hydraulic concrete and covers an area of 7.875 m², generating surface runoff during rainfall events (Figure 6). This runoff is directed by a 2% slope toward a permeable pavement in the L-shaped pedestrian access area (13.929 m²), where infiltration begins. The permeable pavement is proposed to consist of 15 cm thickness to allow initial water infiltration; a 5 cm subbase, which distributes loads and stabilizes the system; and a 25 cm subgrade layer, which temporarily stores infiltrated water and conveys it to the next unit. Subsequently, through a controlled slope, the flow is directed to a bioretention cell, located in the lateral infiltration trench (22.301 m²). This cell has an inverted trapezoidal shape, with an upper section 90 cm wide and a lower base 30 cm wide, designed to facilitate the passage of filtered water to an underground cistern. The cell is composed, from top to bottom, of a 5 cm space at the top for managing excess water during heavy rains; 5 cm of soil, where *Chrysopogon zizanioides* (vetiver) can be planted to promote the removal of contaminants (Aguirre-Álvarez *et al.*, 2024); and 30 cm of filter material. The water that passes through this cell is finally collected in an underground storage tank located just at the end of the cell, represented in the image by white dotted lines (Figure 6). This tank stores treated water for later reuse.

In other studies, such as those by Brown *et al.* (2012), Anderson *et al.* (2013), and Tirpak *et al.* (2021), systems combining permeable pavement and bioretention cells were implemented for stormwater treatment. In all cases, favorable results were reported, including reductions in runoff volume and improvements in water quality. These systems proved effective at reducing nutrient concentrations (nitrogen and phosphorus), heavy metals concentrations (such as copper and zinc), suspended solids, and peak flows. In addition, their capacity to store and infiltrate stormwater was verified, enabling its reuse in activities that can use non-potable water. The implementation of these systems at scale in urban environments reinforces the technical viability of decentralized solutions based on BGI, similar to the conceptual design of the system proposed here.

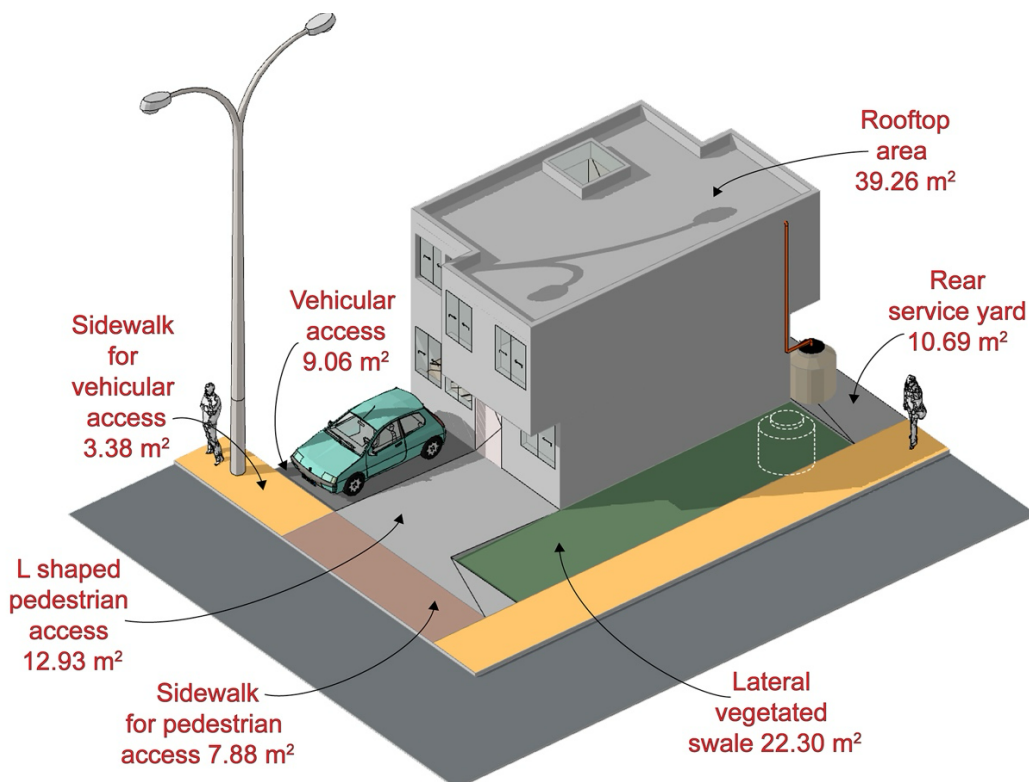


Figure 6. Spatial distribution of impervious surfaces and elements of the BGI prototype in the model house

Water balance of surface runoff collection and treatment

Figure 7 shows a conceptual diagram of runoff water flow through the BGI system for a precipitation event with intensity I (in m/h), accounting for losses due to retention and infiltration at each stage. The water balance is modeled

for three functional units: impermeable sidewalk, permeable pavement, and bioretention cell, before reaching the final storage tank (represented by dotted lines in Figure 7). Unlike traditional systems that favor infiltration into the subsoil, this design aims to maximize water recovery; therefore, both the pavement and the cell are proposed to be waterproofed with a geomembrane. This allows the collected water to be directed entirely to the storage tank, without losses due to deep infiltration. The balance is detailed step by step below.

During rainfall, precipitation first hits the impermeable surface of the sidewalk. This element generates a surface runoff volume of 0.355 m^3 per hour, identified as E . Of that volume, a small fraction ($0.035 \text{ m}^3/\text{h}$), called V_{ret} , is considered lost as it remains retained on the surface. The rest, equivalent to $0.319 \text{ m}^3/\text{h}$, runs off to the next component of the system: the permeable pavement. This surface runoff flow received from the sidewalk is designated as $Q1$. Simultaneously, the permeable pavement also receives rainwater that falls directly on its surface. This additional volume is estimated at $0.188 \text{ m}^3/\text{h}$ and is identified as $Q2$. Thus, the total volume entering the pavement is the sum of $Q1$ and $Q2$, totaling $0.507 \text{ m}^3/\text{h}$. Within the permeable pavement component, part of the volume infiltrated into the system (V_{inf1}) and another part advanced through the first porous layer of the pavement without completely infiltrating ($V_1 = 0.068 \text{ m}^3/\text{h}$). Both flows were directed by slope towards the bioretention cell, due to a geomembrane that prevents infiltration into the subsoil.

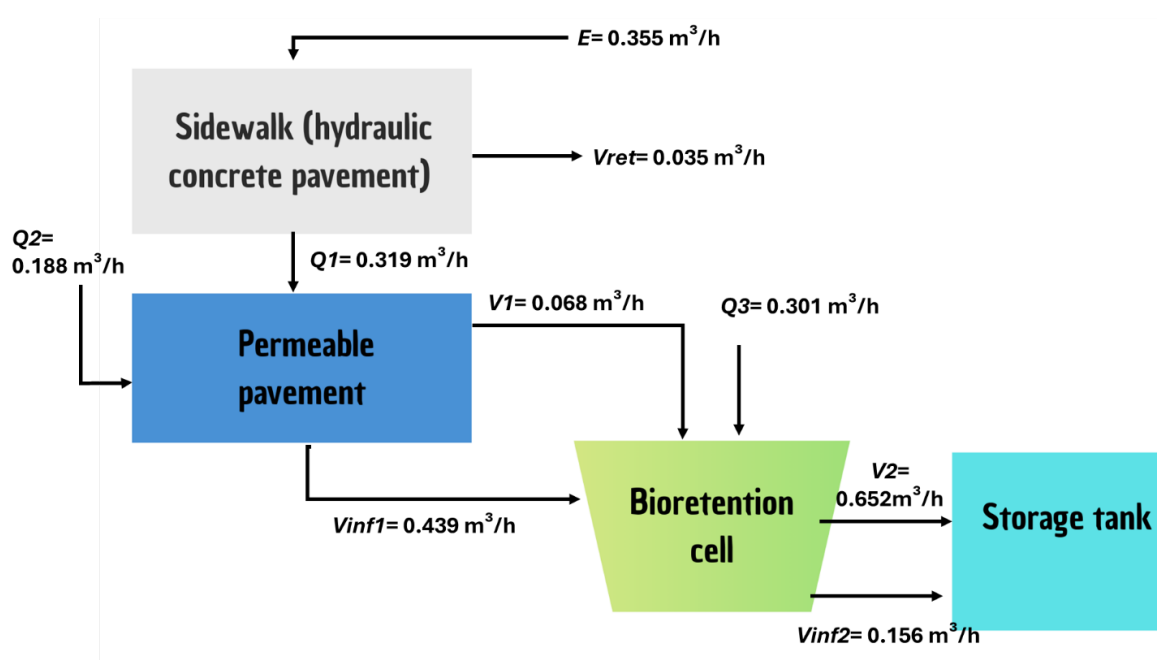


Figure 7. Water balance of the proposed BGI system for the model house

In addition to the flow coming from the pavement, the bioretention cell also captures rainwater that falls directly on its exposed surface. This additional flow, identified as $Q3$, has been estimated at $0.301 \text{ m}^3/\text{h}$. Thus, the total flow entering the bioretention cell amounts to $0.808 \text{ m}^3/\text{h}$. Inside the cell, part of the water infiltrates through the deeper layers (V_{inf2}), while the rest passes through the upper layers and is directed to the storage tank (V_2). In this way, the system uses both the runoff volume and the infiltrated volume to convey water to the storage tank. It is important to note that, possible losses from evaporation from the permeable pavement or evapotranspiration in the bioretention cell have not been considered at this stage, so it is assumed that the entire volume is used for treatment and reuse.

To estimate the flow rates and infiltration volumes, a runoff coefficient of 0.3 was used for the permeable pavement and the bioretention cell, based on the ranges reported by Fletcher *et al.* (2015) for urban drainage systems with green infrastructure. In the specific case of the bioretention cell, an adjusted infiltration coefficient was also applied, obtained by multiplying a vegetation correction factor of 0.7 and a water-substrate contact time of 1 h, in accordance with the methodology proposed by Kasprzyk *et al.* (2022). Finally, a hydraulic conductivity (K) of 0.01 m/h for the filter medium was considered, a typical value for soil mixtures with recycled aggregate and vetiver-type vegetation.

Conclusions

This decentralized system proposal, explicitly designed for arid and semi-arid areas, proved to be conceptually feasible by integrating two complementary strategies for rainwater harvesting: direct rooftop collection and surface runoff treatment using blue and green infrastructure. Through simplified water balance calculations, it was estimated that the volumes collected and infiltrated could partially cover domestic non-potable water demand requirements, representing a significant contribution in environments with high water vulnerability. The use of water-saving devices was decisive in reducing per capita consumption and, consequently, improving the relationship between supply and demand. It was assumed that the water collected from the rooftops may meet drinking water quality standards, although further treatment and validation are required. At the same time, the treatment of surface runoff through permeable pavement and bioretention cell seeks to expand its use for non-potable purposes. This differentiation allows prioritizing the potability of the resource collected from roofs and reserving the treated runoff water for other domestic activities, such as irrigation, cleaning, or toilet flushing.

Overall, the results confirm the technical feasibility of a stormwater harvesting, treatment, and storage system at the household level, adaptable to urban contexts with both water and space constraints. This approach represents an effective strategy for moving toward more resilient, decentralized, and environmentally integrated water management.

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