







Green wall design for rainwater harvesting for human consumption

Diseño de muro verde para la captación de agua de lluvia para consumo humano

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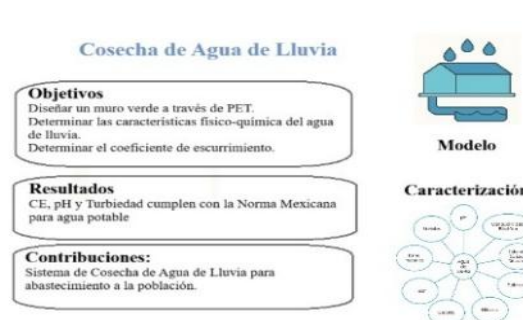
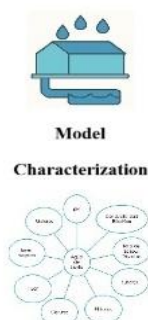


Abstract

Water is expected to become one of the main issues of conflict throughout the 21st century. These scenarios are no longer a thing of the future. Currently, large cities, where an estimated two-thirds of the world's population lives, require large volumes of drinking water to meet their needs. Rainwater harvesting can become an alternative to reduce pressure on traditional sources. It is considered the cleanest natural source available and can be easily used and consumed both domestically, commercially, and industrially. This research aims to design a green wall through PET and considering the physical and chemical characteristics of rainwater. Recycled bottles and easily available materials are used, and it is connected to a harvesting system made of concrete and galvanized sheet metal. The parameters evaluated to determine water quality are physical characteristics [odor, color, turbidity], chemical [pH, EC, and hardness], and heavy metals. Most comply with Mexican and World Health Organization standards.

Resumen

Es previsible que el agua se convierta en uno de los principales temas de conflicto a lo largo del siglo XXI este siglo, estos escenarios ya no son cosa del futuro actualmente las grandes ciudades donde se estima que viven dos tercios de la población mundial, requieren de grandes volúmenes de agua potable para satisfacer sus necesidades, la cosecha de agua de lluvia se puede convertir en una alternativa para disminuir la presión en las fuentes clásicas, se considera la fuente natural más limpia disponible y puede ser fácilmente usada y consumida tanto doméstico, comercial e industrialmente. Esta investigación tiene como objetivo diseñar un muro verde a través de PET y considerando las características físico – química del agua de lluvia. Se utilizan botellas recicladas y material de fácil adquisición, se conecta a un sistema de cosecha de concreto y lámina galvanizada, los parámetros que se evalúan para determinar la calidad del agua son características físicas [olor color turbiedad] química [pH, CE y dureza], además de metales pesados, la mayoría cumple con la norma mexicana y de la organización mundial de salud.



Rainfall Harvest System, Green Wall

Cosecha De Agua De Lluvia, Muro Verde

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Introduction

Since humanity decided to settle in a place throughout its history, water has been a vital resource in addition to being an important factor for the growth of great cultures, cities, even countries, but the fact that it is always present has led to not giving it the importance it really has, because of that, the details that make the presence of the liquid possible have been neglected. According to studies that have been carried out prior to the year 2025, it was estimated that 3 million people could lack the basic requirements of vital water [González et al. 2023; Vele, et al 2024]. Likewise, water is expected to become one of the main issues of conflict throughout this century. However, these scenarios are no longer a thing of the future.

Currently, large cities, where an estimated two-thirds of the world's population lives, require large volumes of drinking water to meet their needs. To do so, they turn to surface and groundwater sources located at great distances, generating strong social conflicts among residents affected by the hydraulic works they generate. Urban areas are estimated to receive a quarter of the world's annual rainfall [Alvarado, 2017; Chubaka, et al., 2018; Nandgude, et al., 2023].

For this reason, rainwater harvesting can become an alternative to reduce pressure on traditional sources. It is considered the cleanest natural source available and can be easily used and consumed domestically, commercially, and industrially [Qianqian Zhang et al., 2014; Fernandes, Terêrencia and Pacheco, 2015].

Rainwater harvesting is considered an important technological option for the sustainable management of water intended for cities [Moglia et al., 2016]. Its use in buildings has been used worldwide for years and can be used as drinking and non-drinking water [Stec & Kordana, 2015].

The importance of this vital liquid has led to research leading to new discoveries in its use, seeking sustainability. Scientific reports agree that "rainwater harvesting is a strategy and alternative source for water use in places where it is scarce" [Matos et al., 2015]. These were used by pre-Hispanic cultures. The Mayans used the so-called "Chultunes" to provide water during the dry season.

In Mesoamerica, these practices have been common since ancient times. In the Mediterranean and Middle East, the system was already used by the Mesopotamians and widespread by the Greeks and, especially, the Romans throughout the region. The Arabs continued to use it.

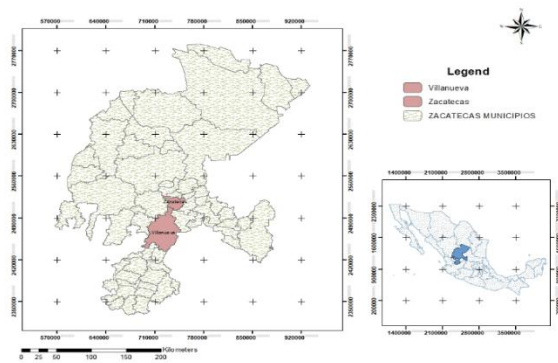
On the other hand, the increase in air and soil pollution, deforestation, chemical use, and the destruction of fauna and flora are human activities that have currently endangered the continuity of the water cycle, making the process increasingly difficult. To obtain it and be able to bring it to everyone who needs it, it is therefore necessary to generate scientific knowledge using technological advances to offer new paths to obtain it.

This research proposes designing a green wall that stores rainwater through the roofs of houses or even buildings, in the city of Zacatecas and rural communities, as an alternative source of drinking water in urban housing in the city of Zacatecas in order to take advantage of rainwater for human activities. The objectives of this work are a) to characterize the homes by evaluating precipitation, catchment area, runoff coefficient; b) to design a green wall through PET; and c) to determine the physical and chemical characteristics of rainwater.

Methodology

The state of Zacatecas is located between the coordinates 22° and 23° North latitude and 102°-103° West longitude, it has a territorial area of 75,484 km²; divided into 58 municipalities [Figure 1], it has a population of 1,622,138 [INEGI, 2020], the conurbation area called Zacatecas-Guadalupe where the green wall was developed and installed, has a population of 450,000.00 inhabitants and the community of Malpaso Villanueva, Zacatecas with coordinates 23 ° 37'30.83 "N 102 ° 36'20" W.

The city of Zacatecas [22 ° 44' 58.37 "N 102 ° 34' 52.99" W], has an average rainfall record of 502 mm per year and Malpaso 428 mm during the last 30 years. The population at the last analysis point is approximately 10,000 inhabitants.

Box 1**Figure 1**

Study area location

Obtaining the water demand

Demand or supply per capita is the amount of water a person needs daily to fulfill their physical and biological functions. Therefore, its estimate is based on the number of inhabitants who will benefit from the rainwater harvesting system [Garduño and Martínez, 2007]. The mathematical expression for calculating water demand is as follows:

$$D_j = \frac{Nu * Dot * Nd_j}{1000} \quad [1]$$

$$D_{annual} = \sum_{j=1}^n D_j * 12 \quad [2]$$

where D_j = water demand in month j , m^3 /month/population; Nu = number of system beneficiaries; Dot = water supply, in l/person/day; Nd = number of days in month j ; D_{annual} = water demand for the population; J = number of months [$j = 1, 2, 3, \dots, 12$]; 1000 = conversion factor for liters to m^3 .

Net rainfall calculation

The efficiency of rainwater harvesting depends on the runoff coefficient of the catchment area materials, which ranges from 0.3 to 0.9 according to the literature [Zhou et al., 2023].

Equation [3] is used to estimate net precipitation:

$$PN_{ijk} = P_{ijk} * \eta_{captacion} \quad [3]$$

where:

PN_{ijk} = net precipitation for day i , month j , and year k , [mm], P_{ijk} = total precipitation for day i , month j , and year k [mm], $\eta_{capture}$ = rainwater harvesting efficiency, 0.765.

The PN criterion is that when average monthly rainfall is less than 50 mm and of low intensity [mm/hr], it is recommended not to consider it, especially if it occurs during dry seasons, since the quantity and quality of the rainwater will not be considered for storage.

Calculation of volume of rainfall to collect

The rainwater catchment area is obtained using equation [4]

$$A = a * b \quad [4]$$

where A = Catchment area [m^2], a = Width of the house [m], b = Length of the house [m]

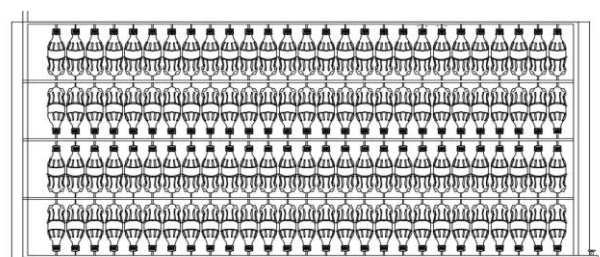
If the catchment area [SCALL] does not exist, it will be designed based on the annual demand of the inhabitants to benefit and the annual net rainfall [Equation 5]:

$$A_{ec} = D_{annual} \sum_{j=1}^n \bar{P} \quad [5]$$

where A_{ec} = is the catchment area needed to supply the water demand of a family or community [m^2], D_{annual} = annual water demand needed by a population, \bar{P} = sum of the average monthly net rainfall that causes runoff [mm], j = Number of rains in the month, $j=1, \dots, 12$.

Green Wall Design [PET]

The green wall design will be made with materials such as PET [plastic bottles], PVC pipes, and an aluminium structure to help support the bottles [Figure 2]. The PVC pipes will serve as a pipeline to convey the water to the bottles, where it will be stored for later use. The PVC pipes can vary in size, as they will be adjusted to suit the bottles used.

Box 2**Figure 2****Green Wall Design**

Veyna-Gómez, Ana Isabel, JÚnez-Ferreira, Hugo Enrique, González-Trinidad, Julián and Robles-,Rovelo Cruz Octavio. [2025]. Green wall design for rainwater harvesting for human consumption. Journal of Technological Engineering. 9[22]1-8: e4922108.

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To increase the rainwater collection volume, the green wall is connected to a 10,000 to 50,000-liter cistern. This cistern is made of ferro-cement [Figure 3], but a high-density polyethylene [HDPE] cistern can also be adapted.

Physical-Chemical Analysis of Collected Rainwater

Water quality assessment is a multi-pronged process that studies the physical, chemical, and biological nature of water in relation to its natural quality, human effects, and aquatic health. Analysis of any water reveals the presence of gases, minerals, organic elements in solution or suspension, and pathogenic microorganisms.

The physical analysis of the samples was performed in the Hydrogeochemical Laboratory of the Electrical Engineering Academic Unit to obtain data and compare them with the guidelines of the Mexican standard NOM-127-SSA1-1994, modified in 2021, and the [World Health Statistics 2022, s/f] standard for human consumption [Table 1].

Box 3

Table 1

Analysis methods and maximum permissible limit

Physical parameter	Reference	Permissible limit in Mexico [mg/l]	Permissible limit WHO [mg/l]
Odor	APHA, 2020	Odorless	Odorless
Taste	APHA, 2020	Ok	Ok
True Color	APHA, 2020	15 [UC]	15
Turbidity		4.0 [UNT]	4.0
Chemical Parameters			
pH	APHA, 2020	6.5-8.5	
Electrical Conductivity	APHA, 2020	700	700
[μS/cm]			
Hardness	APHA, 2020	500	500
[CaCO ₃]			
Alalinity	[NOM-AA-036-SCFI-2001,]	300	300
Chlorides	[NOM-AA-073-SCFI-2001]	250	150
Nitrates [N-NO ₃]	APHA, 2020	10	
Sulfates	APHA, 2020	400	400
Sodium	APHA, 2020	200	
Heavy Metals			
Iron	APHA, 2020	0.3	0.2
Zinc	APHA, 2020	3.0	2.0
Lead	APHA, 2020	0.01	0.01
Mercury	APHA, 2020	0.006	0.006
Arsenic	APHA, 2020	0.025	0.01

Results

According to the research objectives, the following results were obtained and discussed in relation to the work reported in the literature.

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Housing Characterization

The aim is to adapt the regulations, designs, and shapes of current homes to capture a large amount of rainwater. This will allow them to meet the water demand of each user, thus generating a 90% utilization of the collected water.

This will reduce dependence on the drinking water network by three to four months. This will help reduce the volume of extraction from both surface and underground storage sources, and will also prevent rainwater contamination as it travels through the streets.

The rainwater collection area varies from 60 to 200 m² in the different strata [neighborhoods and subdivisions] that make up the urban area of Zacatecas City and the community of Malpaso, part of Villanueva, Zacatecas.

Determining Demand

To determine the demand for a typical house with 4 people [the number of inhabitants per house ranges from 2 to 6], based on a supply of 50 liters/inhabitant/day, the minimum requirement is estimated to be 100 liters/inhabitant/day [World Health Statistics 2022, s/f].

However, due to differential rainfall patterns, it is necessary to estimate that for future generations, the requirement should be adapted to 50 liters per inhabitant to ensure the sustainability of the population's activities, especially where rainfall is very low, also considering an average of 30.4 days per month. The demand is therefore:

$$\text{Monthly } d = \frac{4 * 50 * 30.4}{1000} = 6 \frac{\text{m}^3}{\text{month}}$$

$$\text{Annu } d = 6 \text{ m}^3 * 12 = 72 \text{ m}^3$$

It is estimated that water consumption in the so-called working-class neighborhoods is 10 m³/month for a household with 4 inhabitants.

Therefore, if 72 m³ is collected, there would be a period of approximately 7 months where water would not be consumed from the drinking water network.

It should be noted that the majority of the population of Zacatecas City does not drink water directly from the tap, but instead purchases jugs from water treatment plants.

A good percentage of the Malpaso community does drink water from their network, but some boil it before drinking it.

Net Precipitation

To determine monthly precipitation, it is necessary to analyze the climatological stations that cover the study area. This study considers the Malpaso and Zacatecas stations [Table 1 and 2] for the period 2009-2019. The data in red were estimated using the rational method, and monthly records are available.

Box 4

Table 2

Weather station in Zacatecas [2009-2019]

Year	Month											
	1	2	3	4	5	6	7	8	9	10	11	12
2009	0.0	0.0	10.0	5.0	10.0	86.3	72.0	126.3	88.3	30.5	53.0	21.5
2010	24.0	101.0	0.0	0.0	1.8	20.3	211.3	29.0	18.5	17.5	4.8	0.0
2011	0.0	0.50	0.0	0.4	1.2	1.4	88.3	51.8	81.6	21.7	0.0	0.0
2012	6.2	17.5	2.5	0.0	2.9	24.8	79.9	53.9	46.9	7.5	3.0	0.0
2013	21.3	0.0	0.0	0.0	14.2	42.9	33.1	72.7	197.2	57.5	20.3	82.8
2014	10.8	0.0	1.6	0.0	23.1	78.8	66.6	107.8	111.4	8.6	19.4	22.0
2015	24.1	51.1	120.5	25.3	47.9	245.5	155.8	66.6	134.2	115.1	14.2	18.7
2016	6.0	11.4	17.6	0.0	7.5	55.0	85.7	147.9	58.2	21.7	21.5	3.1
2017	0.0	0.0	4.8	10.0	5.9	20.6	216.3	186.0	108.6	25.3	0.0	16.3
2018	55.8	18.0	0.0	3.0	35.6	251.0	82.0	83.5	121.5	24.7	43.0	6.5
2019	12.0	0.0	4.5	0.0	25.6	36.3	66.6	79.0	120.8	43.3	0.0	0.0
MAX	55.8	51.1	120.5	25.3	47.9	251.0	216.3	186.0	197.2	57.5	53.0	82.8

According to [Garduño, 2011], precipitation greater than 40 mm must be taken into account, since lower values are not stored and the water is used to clean the catchment area.

This research also considers the season of maximum rainfall, since some winter months have rain, but with a very small frequency interval; therefore, the months of June, July, August, September, and October are included.

Box 5

Table 3

Weather station in Malpaso [2009-2019]

Year	Month											
	1	2	3	4	5	6	7	8	9	10	11	12
2009	0.0	0.0	0.2	5.0	7.7	94.9	97.3	88.5	74.7	50.2	71.7	29.1
2010	36.2	91.6	0.0	0.0	0.0	27.3	48.5	52.6	56.0	0.0	0.0	0.0
2011	0.0	0.0	0.0	0.0	0.7	95.9	34.7	21.3	117.5	20.2	0.0	0.0
2012	0.7	17.2	0.0	0.0	0.0	26.3	40.1	30.2	89.7	13.0	0.0	0.0
2013	3.5	0.0	0.0	0.0	0.0	4.9	166.2	10.9	196.1	78.2	3.6	53.1
2014	9.5	0.0	0.0	0.0	30.0	88.1	76.6	50.0	64.6	29.0	16.5	27.2
2015	29.2	50.0	89.0	27.5	29.0	255.0	145.0	67.7	144.5	115.4	14.5	34.0
2016	0.0	11.0	0.8	0.0	22.0	73.5	120.0	180.2	40.2	42.0	29.5	1.5
2017	0.0	1.0	11.5	0.0	10.5	8.0	193.0	104.5	116.0	8.0	0.0	26.0
2018	53.0	21.5	0.0	0.0	61.0	144.0	61.0	39.5	185.5	20.0	7.7	4.5
2019	11.1	0.0	1.0	0.0	0.0	34.7	39.5	122.0	31.5	45.5	2.6	31.0
MAX	36.2	91.6	89.0	27.5	61.0	255.0	193.0	180.0	197.2	115.4	29.5	53.1

Rainfall records show that there is a space-time variation since considering the distance between the stations which is 20 km there is a difference of approximately 30 mm, assuming that if a rain of 1 millimeter fell in an area of one square meter there would be a volume of 1 liter then the difference would be 30 liters which could become the provision of one person, but if the catchment area increases this volume would be more favorable.

Green Wall Construction Process

The construction process for the wall begins with washing the bottles [chlorine, soap, and water] to remove sediment and bacteria. Once washed, the bottom of the bottles that will be placed at the bottom of the wall and the ones that will be connected to them are drilled. The hole is then glued to a 1-inch PVC union pipe and the previously drilled bottle nozzles are attached to 4 cm wide aluminum channels. The structure that will support the wall is assembled [Figure 4].

Box 6



Figure 3
Placement of bottles for catchment wall
[by the authors]

Quality of water collected in the wall

The issue of water quality is as important as water scarcity, yet it has received less attention.

This refers to the content of solids, cations, and anions present in suspension or solution [Clara, 2016]. Recent research has observed that rainwater carries with it pollution particles [phosphorus and nitrogen], bacteria, and pesticides. It was also found that it is highly dependent on ambient conditions and the type of roof Qianqian Zhang et al., [2014], The results showed that for roofs [wood, painted aluminum, galvanized steel], the pH, electrical conductivity, and zinc content increase significantly, while those made of concrete and asphalt show greater turbidity and color.

The values found in this investigation from a concrete roof were, with respect to color, this ranged from 18 to 68 on the platinum cobalt scale. La NOM 27 SSA-1 2021, determines that the maximum value allowed is 20 units on the platinum cobalt scale, so some data exceed this value. The highest values were obtained in the first rains, which causes a carryover of solids and this in turn raises the color units, and subsequent rains present a lower color.

Turbidity presented a behavior of 3 to 10 UTN, according to the Mexican standard the permissible limit is 5 UTN, having the same behavior as for color, that is, in the first rains there are high values and as subsequent rains are recorded smaller, these values were found in concrete and galvanized sheet roofs, Méndez et al. [2011], in their research report for different types of roofs the values of 0.083 in metal areas and 0.077 for concrete on average for the rain collection period. The chemical characteristics are shown in Table 3.

Box 7

Table 3

Weather station in Zacatecas [2009-2019]

Parameter	Range [mg/l]	Norm [mg/l]	Condition
Sulfates	1-3	400	Ok
Nitrates	0.5-1.4	10	Ok
Electrical	41.6-188.8	700	Ok
Conductivity	[μS/cm]	[μS/cm]	
pH	6.59-8.5	6.5-8.5	Ok
Total Dissolved Solids	2-52	1000	Ok
Total Hardness	0-66	250	Ok
Alkalinity	15-85	250	Ok
Chlorides	2.98-4.96		
Heavy Metals			
Aluminum	0-0.058 [ug/l]	0.20 ug/l	Ok
Arsenic	0.009-0.095 [mg/l]	0.025 mg/l	No
Lead	0.0024-0.043		
Zinc	0.93-1.5	5	Ok

The scientific literature has reported several studies regarding the quality of water collected from the roofs of cities or rural areas, in this regard [Gikas and Tsihrintzis, 2012], analyzed water in urban and rural areas, finding values of 0.9 to 1.6 mg / L for sulfates, similar values reported in this research, in general the sulfate content does not usually present a potability problem for drinking water. Regarding nitrates, several investigations indicate that their origin comes from water pollution by agriculture, on the other hand [Lee, et al., 2012], found that nitrate concentrations occurred on roofs where there was the presence of lichens, animal waste and semi-humid roofs, thus obtaining for concrete concentrations of 2.55 mg/L for concrete, 1.89 mg/L for tiles and 2.8 mg/L for galvanized steel, all these results are from the first rain. Compared to these reports, our data are below the aforementioned values.

The conductivity values are below the norm; some researchers, such as Méndez et al. [2011], obtained results averaging 34 μS/cm; similar values were found in this study. Regarding the pH [Gikas and Tsihrintzis, 2012], found an average of 6.39 to 6.99 in storage tanks due to the type of roof from which they were obtained and the contamination that occurred in the place, also found that the pH of the first rain was 6.59, however [Lee, et al., 2012] in their studies determined that in roofs of simple wood, concrete and clay tiles were higher than galvanized steel with a value of 7.2 for storage tanks and first rain due to their components, Qianqian Zhang et al., [2014], obtained that in concrete roofs it had a value of 7.58 attributes that this is due to the elements that the concrete contains.

Heavy metals have become a serious problem when assessing the quality of water for human consumption or irrigation purposes, since they generate a risk to human health if water or food containing high concentrations of these elements is consumed, it has been found that rainwater contains small amounts but when it comes into contact with the roofs of collection increases its concentration some investigations such as Méndez et al. [2011], and [Lee, et al., 2012], report concentrations above the norm in arsenic but not for aluminum, zinc or iron, in this investigation all values were below the norm with the exception of some samples for arsenic that are at the limit as reported by some researchers [Table 4].

Conclusions

The main source of water supplying the drinking water network of Zacatecas and Malpaso is groundwater. Due to extractions exceeding recharge levels, groundwater availability has decreased, resulting in a decrease in supplies and service rationing.

The increase in demand for this vital liquid and the decrease in groundwater recharge require the consideration of new, viable, ecological, and sustainable alternatives that help us reduce the excessive exploitation of drinking water bodies. The green wall is presented as one such alternative.

In general, the state of Zacatecas has an arid, semi-desert climate, causing the summer months [June, July, August, and September] to experience the highest rainfall, ranging from 140 to 200 mm. In exceptional cases, up to 700 mm have been recorded. However, this is wasted, taking away a great opportunity for the efficient use of this water. These data indicate the feasibility of the green wall, as combined with the catchment areas, it can be used to supply residents with basic domestic water needs, reducing the need for potable water supply by up to three months.

According to the Official Mexican Standard and the World Health Organization, the physical and chemical parameters evaluated for the water collected in the green wall and stored in the cistern meet the permissible values for drinking water use, with respect to pH, electrical conductivity, and hardness. However, pretreatment is required for parameters that did not meet the stipulated values, such as color, turbidity, arsenic, and mercury.

Declarations

Conflict of interest

The authors declare no interest conflict.

Author contribution

All authors contributed to the project idea, research method and technique.

Availability of data and materials

Further information could be requested to the main author.

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