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Use of Analytic Hierarchy Process Method to Identify Potential Rainwater Harvesting Sites: Design and Financial Strategies in Taxco de Alarcón, Southern Mexico

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Abstract: Mexico is among the countries that are facing the greatest water stress, where factors such as climate change, contamination of surface water, groundwater sources, and inefficient management have limited the availability of water resources. Consequently, new supply sources need to be implemented. Rainwater harvesting systems (RHS) are viable and sustainable alternatives, the implementation of which primarily depends on identifying suitable sites and applying technologies that are appropriate for different users. This research used the Analytical Hierarchy Process (AHP) technique in a GIS environment to select the optimal sites for designing RHS, taking into account hydrological, biophysical, and socioeconomic criteria. After determining the ideal sites, the study presents proposals and costs for the design of an urban and rural RHS based on the characteristics of the region and the needs of the community. The findings show that implementing RHS in the study area can be a practical, economical, and efficient alternative for water resource management, since these projects are aimed at sustainability.

Keywords: rainwater harvesting systems; multi-criteria evaluation; Analytical Hierarchy Process

1. Introduction

Over recent years, water scarcity has become one of the main problems to be faced by many societies worldwide [1,2]. Factors such as urbanization, climate change, and pollution have resulted in water stress in many parts of the world [3]. Water demand for domestic and industrial use is estimated to increase by 50% to 80% over the next three decades [4]. In Mexico, one of 25 countries that are facing high water stress [5], various regions are suffering from a lack of water, due to exponential population growth in urban areas and problems resulting from poor water management [6] (Figure S1: World Bank urban population graph for Mexico), as well as factors that reduce the expectation of future water availability, such as drought [7,8]. Increasingly erratic weather patterns have caused seasonal changes that have resulted in fluctuations in the supply of water to society [9]. According to the drought monitor, 34.3% of the country is abnormally dry, 12.91% has moderate drought conditions, 1.81% has severe drought conditions, and 0.15% is experiencing extreme drought, mostly in northern and central Mexico [10]. (Figure S2: Drought Monitor in Mexico, 2022).

As a result, efficient water management alternatives are needed [11]. One viable alternative is rainwater harvesting [12,13]. Harvested rainwater plays a crucial role in increasing water security, and it can provide safe water to be used for various purposes [14,15]. The implementation of rainwater harvesting systems (RHS) has spread rapidly around the world [16–18], given that they contribute to the social well-being of the population, especially those with limited or no access to water. These systems generally do not consume electricity, and the water that is captured can be stored for long periods of time [19–21]. Nevertheless, their application primarily depends on precipitation at the site, they require occasional maintenance, and the initial costs can be high if the basic infrastructure is not available. In Mexico, rainwater harvesting systems are an option for supplementing the water supply. The national government launched initiatives (in 2016 and 2020) that use a more sustainable approach by installing RHS in public buildings and residential homes [22,23] and using that water for domestic activities, such as cleaning and watering gardens. However, despite RHS being a priority alternative, little research has been conducted on the different types of systems and design methods, particularly on methodologies to analyze the feasibility of their installation and ensure that they function by performing a comprehensive analysis to choose the ideal site.

The success of rainwater harvesting systems (RHS) depends primarily on identifying optimal sites and using technologies that are suitable for the needs of a particular population. Optimal selection can be made by integrating and analyzing hydrological data and biophysical and socioeconomic criteria [11,24,25]. Several studies have demonstrated that geographic information systems (GIS) in conjunction with multi-criteria evaluations are efficient and powerful tools for selecting optimal sites for rainwater harvesting [11,12,25]. These methods integrate multiple variables to identify the most suitable sites. One of the most widely-used multi-criteria evaluation techniques is the Analytical Hierarchical Process, better known as AHP. This technique weights various criteria according to the objectives of the project, for example, precipitation volume, soil texture, slope, vegetation use and cover, elevation, runoff potential, distance to points for transporting the collected water, road access, and evaporation [25–29]. In this way, the best sites for collecting rainwater are identified. The final results show the best areas for installing RHS, considering the needs of the population (urban and water pots), and also serve as a support for decision-making in order to improve the management of water and economic resources [28–31].

The relationships and importance of the various criteria need to take into account the collection method, water quality, type of system, type of use, the appropriate size of storage tanks, and cost [31–33]. An adequate and efficient design will consider these variables so that the system is highly functional and the costs are affordable for all types of populations and in different types of environments and regions to meet the demand for water [25,33–35].

The search for efficient and sustainable water supplies has led to analyzing optimal models for the implementation of RHS to address drought and scarcity conditions, which has become a task for decision-makers around the world. In Mexico, government initiatives and programs have implemented these systems, but not all cases have been successful because they have not taken into account the characteristics of the area, the suitability of structures, and the related costs. This work proposes integrating geographic information systems (GIS) with a multi-criteria evaluation to identify potential sites for RHS. It also proposes RHS designs and provides implementation costs. Decision-makers and planners will benefit from the proposed methodology since it will allow them to easily identify the best method for harvesting rainwater at a site, achieve the optimal use of water resources, and maximize economic resources.

Population growth in the municipality of Taxco de Alarcón, Guerrero, has led to increasing demand for water for domestic and productive activities. In this region, only 58.8% of the population has access to piped water [36], and surface water bodies have constantly been contaminated by the exploitation and transformation of precious metals by mining activities, which have been occurring since colonial times. These activities have posed a potential risk of harm to human health and the environment, making water resources unfit for human use and causing water stress in the municipality, especially in the urban area [37,38]. The objectives of this research include the following: (1) use the Analytical Hierarchical Process (AHP) in a GIS environment to select the optimal sites for installing HRS; (2) evaluate the quality of rainwater for domestic use; (3) propose HRS in accordance with the characteristics of the optimal sites; and (4) analyze the economic feasibility of installing two HRS in the study area.

2. Materials and Methods

2.1. Study Area

The municipality of Taxco de Alarcón is located in the northern region of the state of Guerrero, Mexico (Figure 1). It measures approximately 651 km^2, and its total population is 105,586 inhabitants. In the state of Guerrero, the gross domestic product is USD 3,341. The average annual growth rate of GDP in the last three years is negative, −3%, ranking 22 of 32 states in the country, which has resulted in thousands of people living in poverty [36]. At the municipal level, there is an unemployment rate of 10.5% [39].

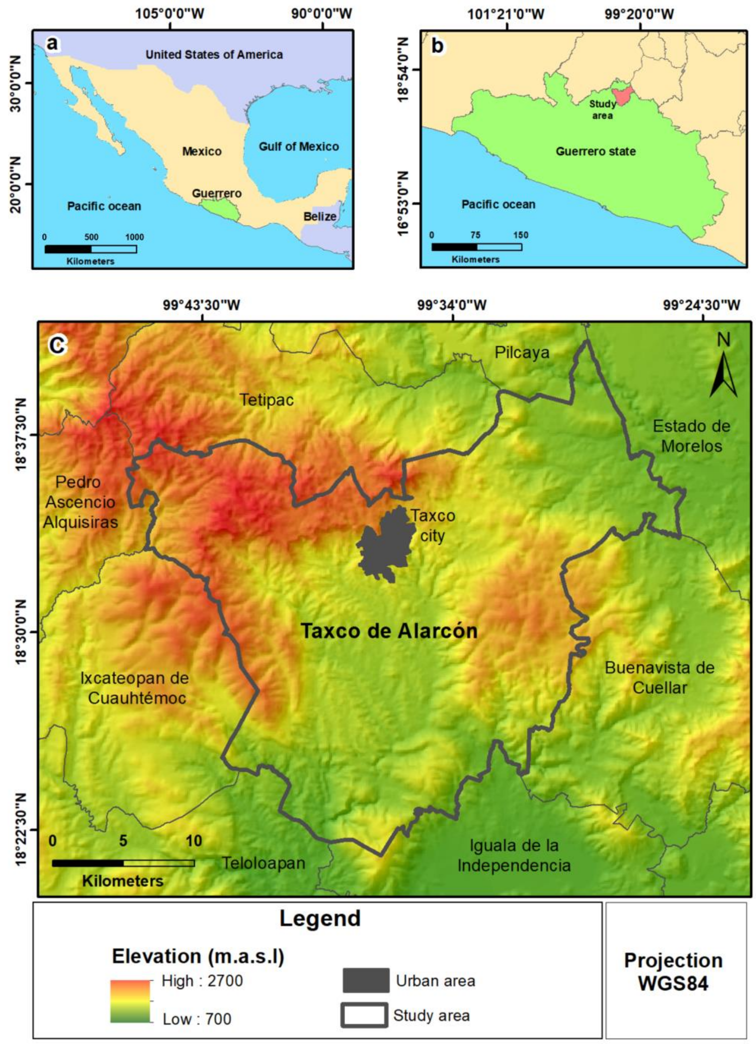

Figure 1. Location map. (**a**) Mexico, (**b**) the state of Guerrero, and (**c**) the study area.

The climate in the study area is defined as warm sub-humid (Cw), with a tendency towards sub-humid semi-warm in the mountainous areas. The average annual temperature is 18 °C in the mountains and over 20 °C in the plains. The hottest months are March, April, and May, and the coldest is December. Annual precipitation is approximately 1252 mm [40].

Taxco is recognized as an important tourist center and an international producer of handicrafts and precious metal jewelry, mainly silver [38]. Until 2009 it was known for mining exploitation, which began during pre-Hispanic times and has negatively affected natural resources such as water [37].

Over recent years, access to water for domestic and human use has become limited due to population growth in urban and semi-urban areas, with dug wells, springs, and the San Marcos dam system being unable to meet the population's demand for water. In addition, the quality of the water resources in this region is not desirable, and the water is not viable for those uses [38,41].

2.2. Compilation of Cartographic, Hydrometeorological, and Socioeconomic Information

This study collected hydrometeorological (precipitation, temperature), cartographic (digital elevation model, land use and vegetation), and socioeconomic (population density, distance to localities) information. The data were downloaded from DAYMET (https://daymet.ornl.gov/ accessed on 3 March 2022) the United States Geological Survey (USGS), and the Mexican National Institute of Statistics, Geography, and Informatics (INEGI, in Spanish). Figure 2 shows the methodology adopted for this research.

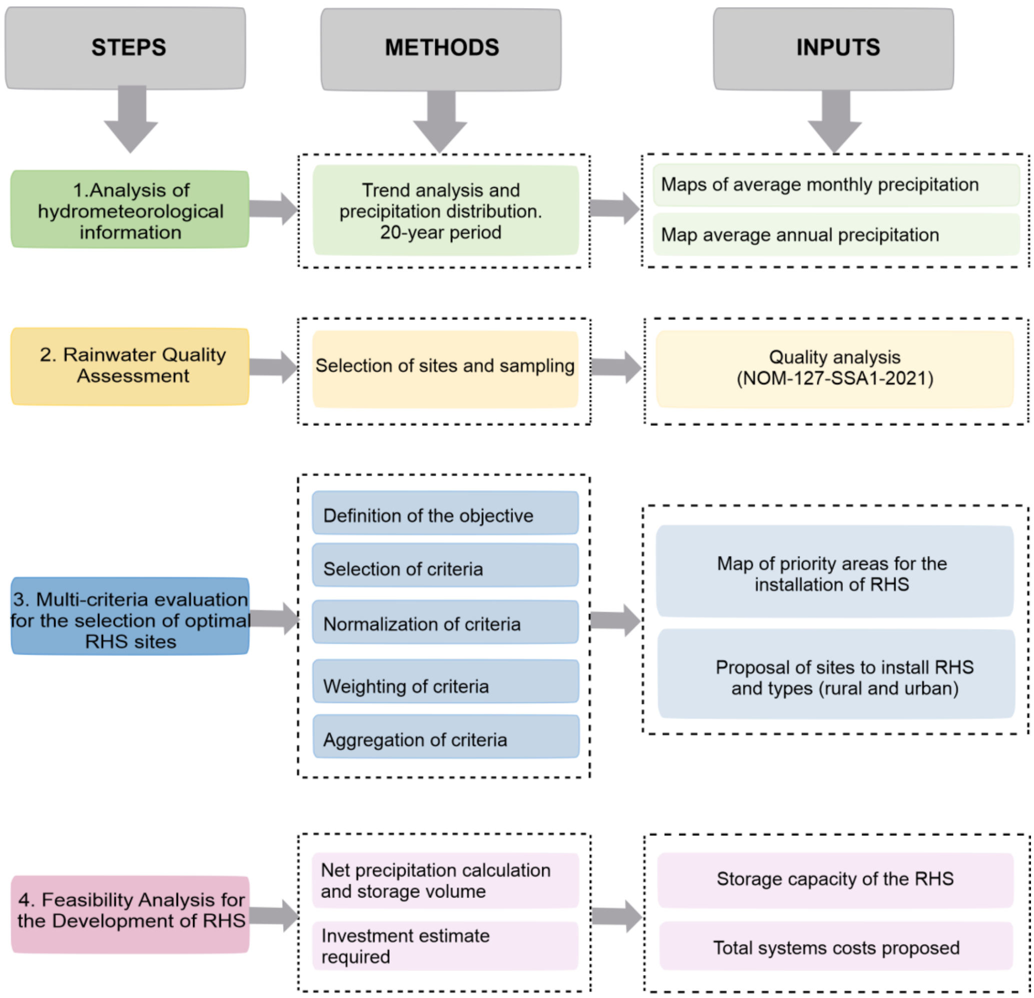

Figure 2. Methodological strategy.

The distribution and trends in the variability of precipitation in the municipality of Taxco were analyzed based on data obtained from NASA's Daymet V4 portal, which is comprised of data from daily weather observations to produce gridded estimates of daily weather parameters. Raster data with a resolution of 1 km were obtained, which were collected monthly for a period of 20 years (2001 to 2021). TerrSet software was used to obtain average monthly precipitation by summing up the monthly precipitation over the 20-year period and calculating the average annual precipitation by analyzing the 12 resulting images.

2.3. Evaluation of Rainwater Quality

A pixel analysis of the average annual precipitation map was used to select sampling sites where the precipitation ranged from 900 mm to 1300 mm. A homogeneous distribution of the sites and easy access was sought (Figure 3). As a result of this project, six rainwater sampling stations were installed, whose characteristics are detailed in Table 1.

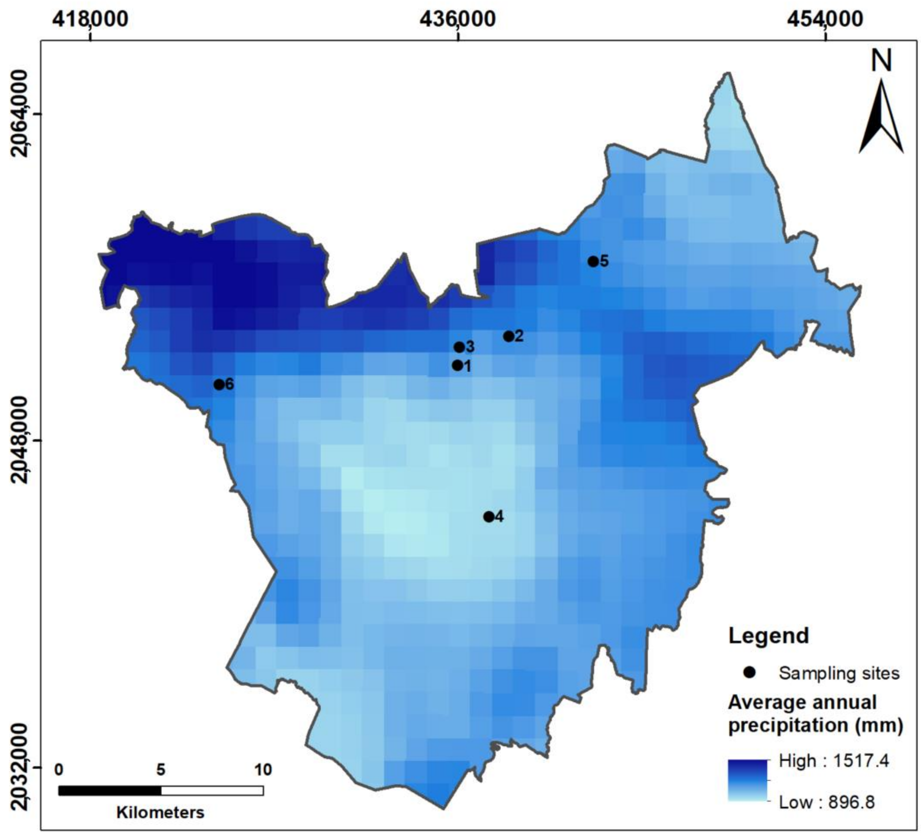

Figure 3. Average annual precipitation for the period 2001 to 2021 and sampling sites in the municipality of Taxco de Alarcón, Guerrero.

Table 1. Rainwater sampling stations.

Rainwater Sampling Stations					
Station id	Locality	x	y	z (m.a.s.l)	Installation date
1	Pilita	435,991.3	2,051,682.8	1761	2 June 2022
2	Casallas	438,504	2,053,110.8	1670	3 June 2022
3	Agua Blanca	436,093.7	2,052,571.3	1869	2 June 2022
4	Taxco el Viejo	437,541.1	2,044,278.3	1461	3 June 2022
5	Acuitlapán	442,667.2	2,056,779.4	1532	3 June 2022
6	Horconcito	424,323.5	2,050,737.1	2376	3 June 2022

A total of 18 rainwater samples were collected during the months of June, August, and October. Using the event accumulation method and a simple conventional collector, the rainwater was taken directly from the sky without it touching any roof surfaces. The sampling was based on procedures established by Mexican guidelines NOM-230-SSA1-2002 [42]. To determine the chemical composition of the rainwater, physicochemical and microbiological parameters were analyzed. Three samples were taken to analyze anions, cations, and fecal coliforms. For the analysis of anions and cations, the samples were filtered through a 0.40–0.45 µm membrane and then transferred to 125-mL polyethylene bottles. In the case of the cation samples, these were acidified with HNO_3 at a pH < 2. The fecal coliform samples were collected using sterile polyethylene containers and preserved at 4 °C until analysis in the laboratory. Fecal coliform analyses were performed in the laboratory based on the Most Probable Number (MPN) in multiple tubes, as stated in Mexican guideline NMX-AA-42-SCFI-2015 [43].

The anion and cation samples were analyzed at the Environmental Geochemistry Laboratory of the Geosciences Center at the National Autonomous University of Mexico (UNAM in Spanish), Mexico. Anion samples were analyzed using high-performance liquid chromatography (HPLC) with a Dionex ICS-1100 chromatograph. Cation samples were analyzed using inductively coupled plasma optical emission spectroscopy (ICP-OES) with a PerkinElmer ICAP 6500 Duo.

2.4. Multi-Criteria Evaluation for the Selection of Optimal RHS Sites

The multi-criteria methodology involved five steps: (1) defining the objective, (2) selecting the criteria, (3) standardizing, (4) weighting, and (5) aggregating the criteria. The methodological steps are described below.

1. Objective:

To identify and select the optimal sites for implementing rainwater harvesting systems in the municipality of Taxco de Alarcón, Guerrero.

2. Criteria selection:

The factors and constraints that affected the objective of the research were selected and are shown in Table 2.

Table 2. Criteria and data sources for the multi-criteria evaluation.

Factors	Source
Precipitation: period 2001 to 2021	Determined using monthly precipitation data obtained from Daymet [44].
Slope	Determined with the digital elevation model obtained from the United States Geological Survey [45].
Distance to localities	Determined using vector information obtained from the INEGI site [46].
Population density	Determined from vector information obtained from the INEGI site [46].
Real evapotranspiration: period 2001 to 2021	Determined based on monthly precipitation data and maximum and minimum temperatures obtained from Daymet [44].
Constraint	Source
Land use and vegetation	Obtained from INEGI site [46].

2.1. Factor correlation analysis

Pearson's correlation analysis was conducted to determine the degree to which the selected factors were duplicated. This analysis was performed with TerrSet software using the PCA (principal component analysis) panel with a T-mode analysis, which generated a matrix representing the relationships among the images [47] (Table 3).

Table 3. Correlation matrix for the factors considered.

Correlation Matrix	Real Evapo-transpiration	Population Density	Distance to Localities	Slope	Precipitation
Real evapotranspiration	1	−0.18	0.37	−0.19	0.01
Population density	−0.18	1	−0.66	0.88	−0.09
Distance to localities	0.37	−0.66	1	−0.58	−0.08
Slope	−0.19	0.88	−0.58	1	−0.05
Precipitation	0.01	−0.09	−0.08	−0.05	1

3. Normalization

The factors were normalized to be comparable with each other (common scale bytes 0 to 255). This process used fuzzy logic normalization with the fuzzy module in the TerrSet software and increasing and decreasing sigmoid functions, as adapted to each factor. The increasing sigmoid function was used for precipitation, distance to localities, and population density, and the decreasing function was used for slope and evapotranspiration. The criteria were normalized according to Equation (1) [48]:

$$\mathrm{Xi} = \frac{(Ri - Rmin)}{(Rmax - Rmin)} \cdot SR \quad (1)$$

where Xi = new value, standardized per pixel; *Ri* = value of the factor, per pixel; *Rmin* = minimum value of the factor, per pixel; *Rmax* = maximum value of the factor, per pixel; and *SR* = maximum threshold of the range to be standardized (255).

The constraint (land use and vegetation) was converted into a Boolean map (0 and 1), with 0 representing areas where the implementation of RHS was not permitted and 1 representing those where it was permitted.

A value of 1 was given to urban and agricultural areas since RHS are designed to supply the population with water for domestic activities. A value of 0 was assigned to all vegetation areas where no human activities took place because they are difficult to access.

4. Weighting

Weighting involved assigning a value of importance to one factor with respect to another. This process was performed with the collaboration of a group of experts in hydrology, climate, and geography. After defining the importance of each factor, the group weighted them using the Analytical Hierarchical Process (AHP) technique. This process used the TerrSet WEIGHT module, which performs a pairwise comparison in order to obtain the weights of the factors. The consistency ratio (CR) was also calculated, according to Saaty [49], where the weighting coefficients are acceptable when CR is less than 0.1. Consistency was defined as:

$$\mathrm{CR} = \frac{CI}{RI} \quad (2)$$

where *RI* = random index, and *CI* = consistency index. The consistency index is calculated as follows:

$$\mathrm{CI} = \frac{\lambda\mathrm{max} - n}{n - 1} \quad (3)$$

where λmax = $\sum \lambda\, I$, where *i* = total; λ = weights per factor; and *n* = number of factors.

5. Aggregation of criteria

The weighted linear combination (WLC) method, considered to be the most widely-used method for evaluating multiple criteria, was used for the aggregation of the criteria. With this process, each factor was multiplied by the assigned weights, followed by a second multiplication of the prior result with the constraint (Boolean map). This combination was performed according to Equation (4) [50]:

$$S = \sum_{i=1}^{n} Wi\ Xi \cdot \prod Cj \tag{4}$$

where S = suitability; n = number of factors; Wi = weight of factor I; Xi = value of factor i; Cj = criterion score of constraint j; and Π = product of constraints (with $j = 1 \ldots n$).

The overlapping of the three priority categories (MCE result) with the total population per locality made it possible to identify the most viable locations for the implementation of RHS, as well as the type of RHS that best suited the needs of those areas.

2.5. Feasibility Analysis for the Development of Rainwater Harvesting Systems (RHS)

A feasibility analysis was performed for the installation of two types of RHS: urban (residential) and rural (water pot). The amount of water for domestic use that was required per person was considered for each case. This data was taken from the technical guidelines for the installation of RHS established by Mexico's National Water Commission (CONAGUA in Spanish) [22]. In addition, the amount of rainwater to be stored by the harvesting system to provide sufficient water to meet the population's demand was estimated. The following equation was used to calculate net precipitation [47]:

$$\mathrm{NP} = \mathrm{P} \times \mathrm{Hc} \times \mathrm{Rc} \tag{5}$$

where NP = net design precipitation; P = precipitation; Hc = harvesting coefficient; and Rc = runoff coefficient.

Precipitation data were obtained from the average annual precipitation map that was generated (Figure 3).

An estimated harvesting coefficient of 0.85 [51] was used, which discounts losses due to factors such as splashing and wind speed. The runoff coefficient value took into account the type of material in the catchment area. The most common coefficients are 0.8 for concrete and metal sheets and 0.9 for PVC geomembranes and roof tiles [22].

The cistern volume required to ensure the supply of rainwater to the population was calculated based on the mass balance. Using this method, a balance of inflows (monthly rainfall) and outflows (monthly demand) was calculated, their accumulated differences were obtained, and the maximum value was taken as the minimum volume that the storage system required. This balance was used for both urban and rural RHS and was defined by the following equation.

$$\mathrm{Vi} = \mathrm{Sci} - \mathrm{Dci} \tag{6}$$

whewhere Vi = storage volume for the month (m^3); Sci = cumulative supply per month (m^3); and Dci = cumulative demand per month (m^3).

Subsequently, the investment required for the installation of an urban RHS was estimated, which was divided into total costs (gutter, downspout, leaf filter, and storage structure) and total costs without a storage structure (gutter, downspout, and leaf filter). The components of the system were designed in order to determine the costs of the system. For collection and drainage, PVC material with a 6-inch pipe diameter was proposed for sufficient flow to carry the water during maximum rainfall and in accordance with the measurements of the selected catchment area. The investment required for the installation of a rural RHS was also estimated, where total costs included land leveling, excavation, and placement of geomembranes. The optimal ground measurements, labor costs, and quantity of materials required were quantified based on the results obtained from the mass balance.

Last, the cost per cubic meter of rainwater was obtained to determine the economic feasibility of implementing HRS, which was calculated using the following equation [52]:

$$\left(\$\mathrm{m}^3\right) = \frac{Total\ Costs(\$)}{Volume\ harvested\left(\frac{m^3}{year}\right)} \tag{7}$$

3. Results and Discussion

3.1. Analysis of Hydrometeorological Information

Figure 4 shows the results of the rainfall trends from 2001 through 2021. As can be seen, the most intense rainfall occurred during the summer season, with July being the rainiest month, followed by August, June, September, and October. Rainfall ranged from 50 mm to 290 mm or more during these months. Meanwhile, a significant decrease in rainfall was observed in November, with a range of less than 10 mm to 50 mm, a trend that continued until April. Last, May presented an increase in precipitation to between 50 and 80 mm. The northwestern portion of the municipality is at a higher altitude and received the most precipitation (as much as 300 mm in July), while in the center and southern areas of the municipality, precipitation was lower (between 170 and 200 mm in July). This variation in precipitation is attributed to differences in altitude.

3.2. Rainwater Quality Assessment

Rainwater quality was evaluated to identify whether it was feasible to use the water for domestic activities based on the maximum permissible limits stipulated by Mexican guidelines NOM-SSA-127-2021 for human use and consumption [48]. The results show that the rainwater met the criteria for human use and consumption and could therefore be used for domestic activities at nearly all of the sites. Only the Agua Blanca site presented iron that was slightly above the criterion of 0.3 mg/L, which occurred during the last sampling. Supplementary Table S1 shows the data that was obtained (Table S1: Physicochemical parameters (average, minimum, and maximum) measured at the sampling sites, evaluated in accordance with NOM-SSA-127-2021 [53]. pH: the potential of hydrogen in units. Fecal coliform: colony forming units (CFU/100 mL)).

3.3. Multi-Criteria Evaluation for the Selection of Optimal RHS Sites

This study analyzed five factors and one constraint. The factors included were: average annual precipitation, slopes, distance to locations, population density, and annual real evapotranspiration. The constraint was agricultural use/urban and vegetation areas Pearson's correlation analysis resulted in ranges from high negative to low positive correlations (−0.66 to 0.37) [54], indicating that there was no duplication of the factors analyzed. However, slope and population density presented a very high positive correlation (0.88). This density was due to the fact that the relief of the municipality of Taxco is rugged and the areas with a gentle slope (<15) had higher population density, for example, in the municipal capital and localities such as Taxco el Viejo and Acuitlapán.

The criteria analyzed were normalized on a common scale from not suitable (0) to very suitable (255) for the case of the factors, and the constraint was a Boolean image (0 = RHS implementation not permitted and 1 = RHS implementation permitted) (Figure 5).

After applying the AHP method, the weights of each factor were obtained taking into account the opinions of the group of experts. The results are as follows, in order of importance: 1. precipitation, 2. evapotranspiration, 3. population density, 4. slope, and 5. distance to localities. In addition, this function made it possible to calculate the consistency ratio (CR), which in this case was 0.07, indicating that the weighting was acceptable (Table 4).

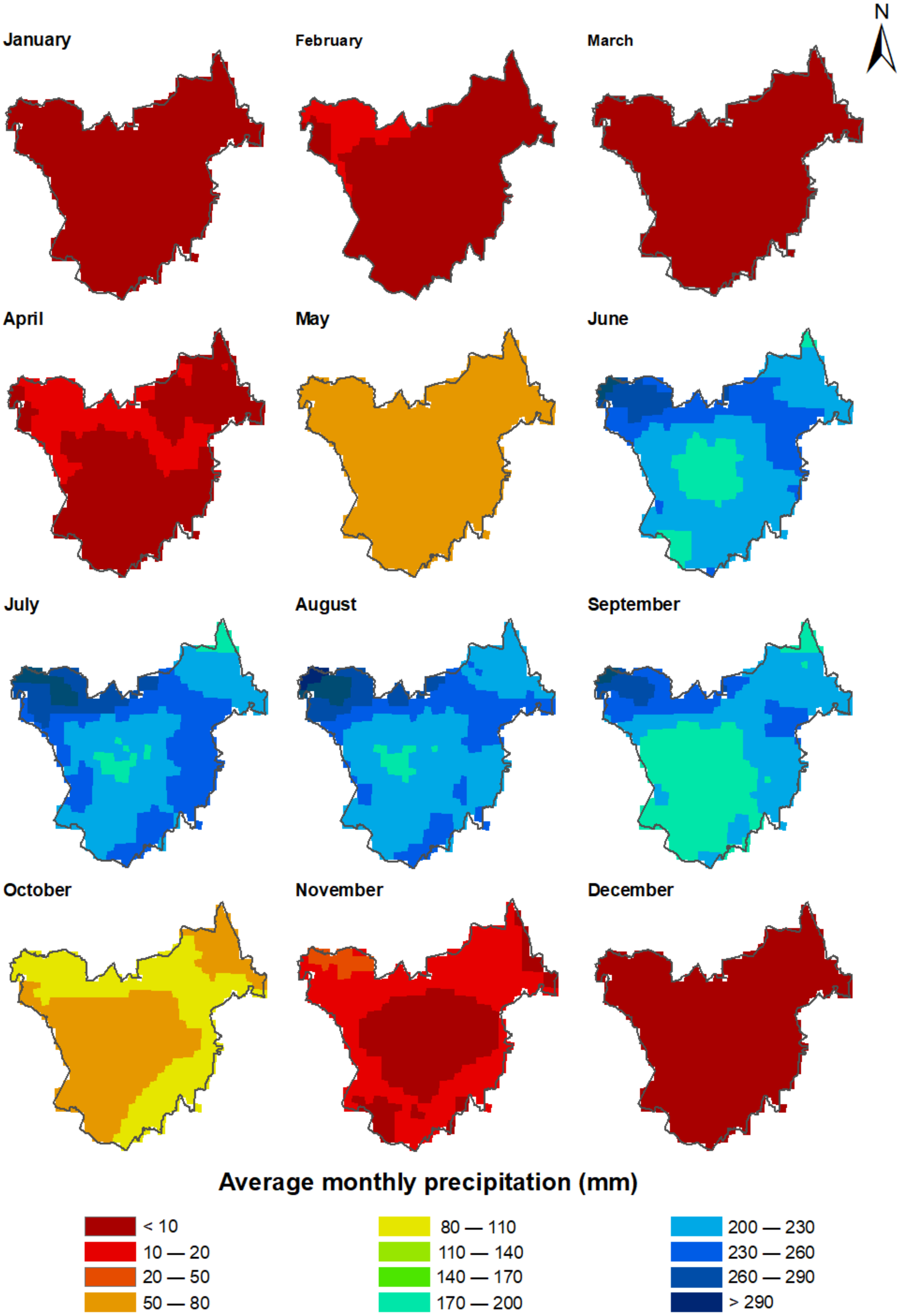

Figure 4. Monthly rainfall distribution and trends.

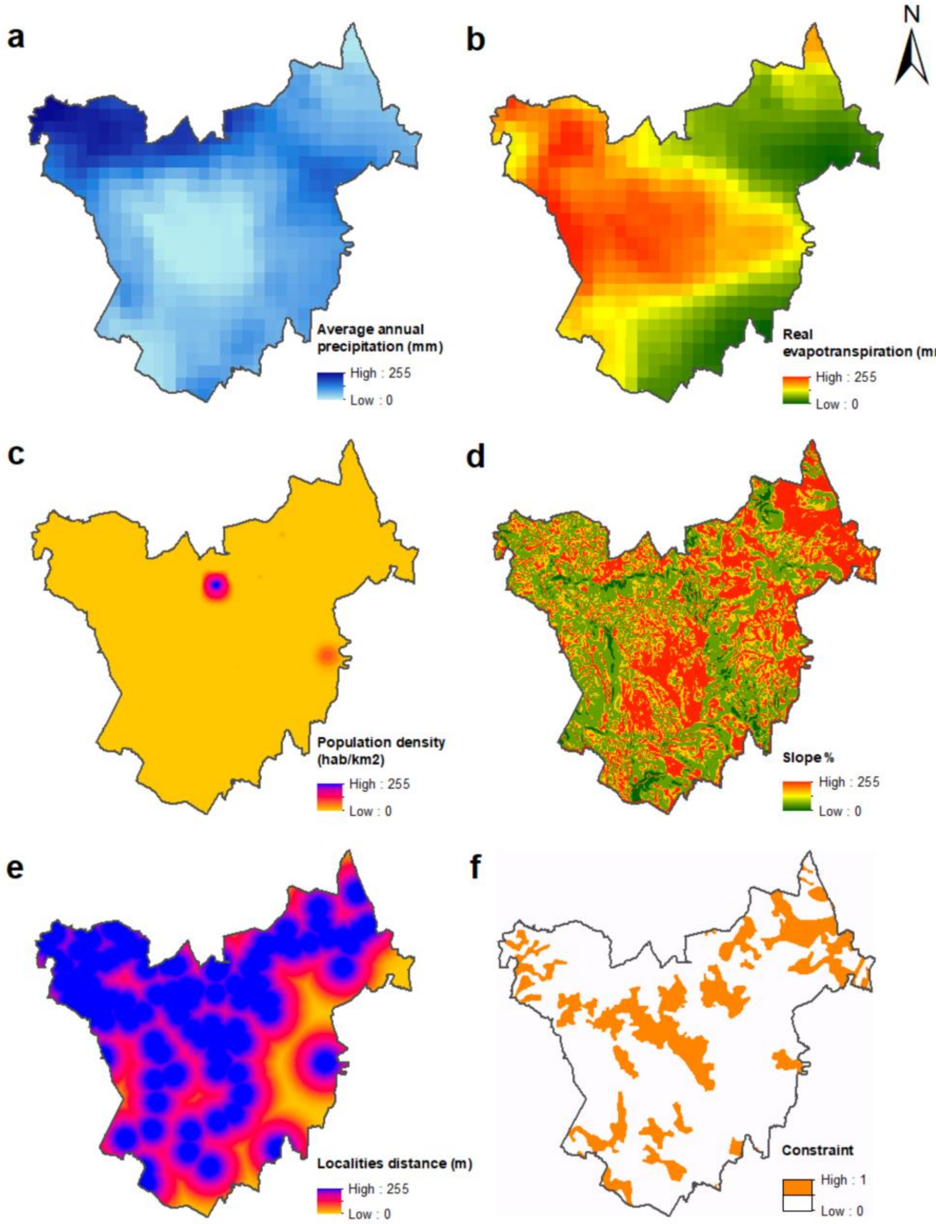

Figure 5. Normalized factors and constraint: (**a**) average annual precipitation, (**b**) real evapotranspiration, (**c**) population density, (**d**) slope, (**e**) distance to localities, and (**f**) constraint.

Table 4. Pairwise comparison matrix.

Factor	Population Density	Distance to Localities	Real Evapotranspiration	Slope	Precipitation	Weights
Population density	1					0.1149
Distance to localities	1/5	1				0.0321
Real evapotranspiration	3	7	1			0.2655
Slope	1/3	3	1/7	1		0.0574
Precipitation	7	9	3	7	1	0.5300

A suitability map was generated as a result of the MCE. This map was classified into three priority categories (high, medium, and low) to identify sites that were suitable for implementing an HRS. High-priority areas were notable in the northwestern portion of the municipality of Taxco, which is consistent with the weight obtained from the precipitation factor. Low- and medium-priority areas were located in the municipal capital. In addition, areas with low priority were distributed throughout the northeastern, central, and southern parts of the municipality, most of which were in the southern region. These areas had lower precipitation and higher evapotranspiration (Figure 6).

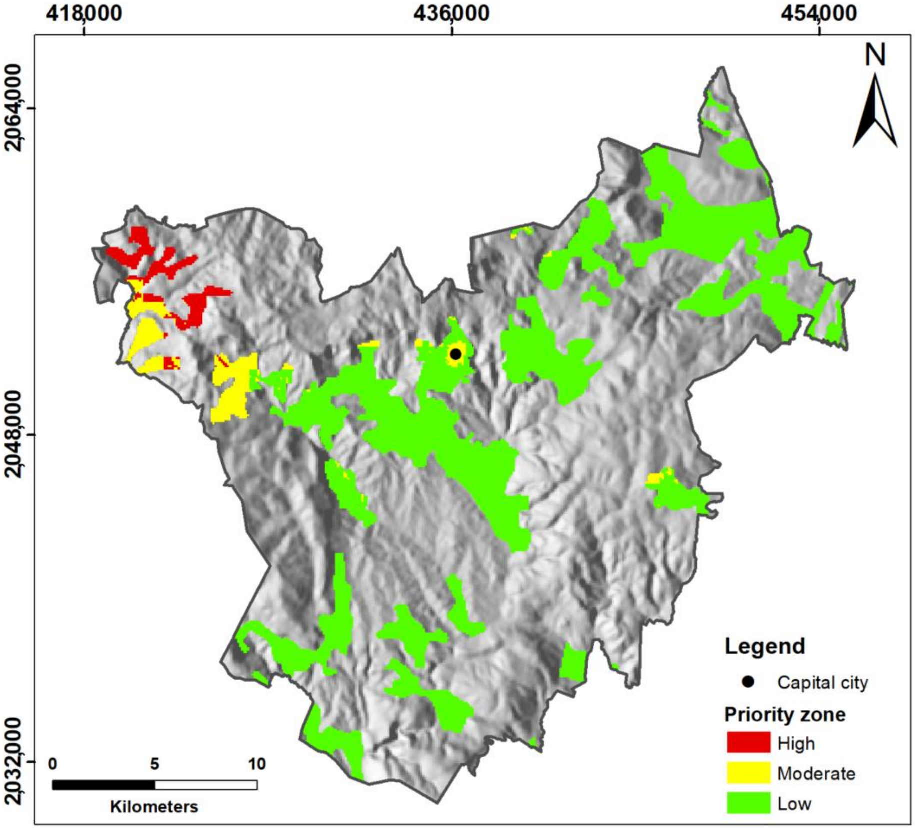

Figure 6. Priority areas for the installation of RHS.

Five rural localities, each with a population of less than 200 inhabitants, are located in northwestern Taxco where the high category was notable [36]. The installation of a water pot is recommended (a rural-type RHS) in these areas and is considered to be economically viable for the local population. The captured water is recommended for domestic use (washing clothes and bathroom), as well as for agriculture and livestock since the standards for the latter two are less stringent. The locality of Horconcito is proposed as its location (Table 5).

Table 5. Sites proposed for RHS installation.

Sites Proposed for RHS Installation				
Id	**Locality**	**x**	**y**	**z (m.a.s.l)**
1	Pilita	435,991.3	2,051,682.8	1761
2	Taxco el Viejo	438,705.1	2,042,909.7	1221
3	Acuitlapán	443,050.8	2,056,778.7	1573
4	Horconcito	423,441.8	2,053,396.7	2376
5	Santo Domingo	420,971.5	2,052,984.8	2093
6	Tlamacazapa	446,861.1	2,045,361.4	1986
7	Huahuaxtla	433,789.9	2,036,210.9	1254

Two RHS are proposed for the medium-priority category, one of which is suggested for the urban area of the municipality of Taxco (municipal capital). While this region does not present water shortage problems, this site was considered due to its high population density, large number of tourists, and high water demand. An urban type of RHS is recommended for this region, where the water that is harvested can be used for domestic use (watering gardens, cleaning, washing clothes, and personal hygiene). The Pilita neighborhood is proposed for its installation. The second site that is suggested is in northwestern Taxco, at the elementary and secondary schools in the town of Santo Domingo (Table 5). The water that is collected is recommended for bathroom use.

For the low category, which is notable in the northeastern, central, and southern areas of the municipality, four RHS sites are suggested to mitigate both the present and future effects of water scarcity. This suggestion is supported by the Secretary of the Environment (SEDEMA in Spanish) (2020), which indicates a minimum of 400 mm annual precipitation for installing an RHS, whereas the minimum precipitation in the municipality of Taxco is 896 mm (Figure 3). Currently, the localities of Tlamacazapala and Acuitlapán present water shortage problems and have a high population density, with the second and fourth largest number of inhabitants in the municipality, respectively [36]. The installation of urban-type RHS is proposed for Tlamacazapa, Acuitlapán, Taxco el Viejo, and Huahuaxtla (Table 5). It is recommended that they be installed in the educational facilities in these localities and the water used for bathroom purposes. Figure 7 shows the sites proposed for the installation of the RHS.

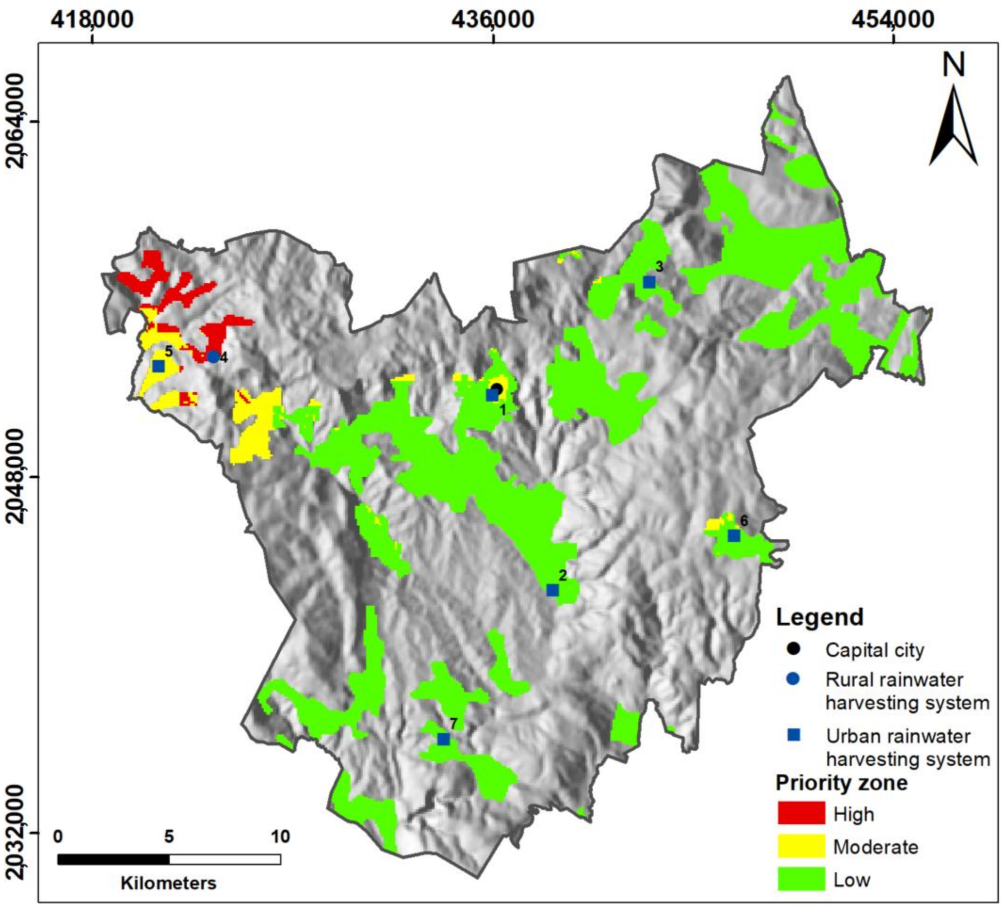

Figure 7. Suitable sites for the installation of a rural and urban RHS.

3.4. Feasibility Analysis for the Development of Rainwater Harvesting Systems (RHS)

The feasibility analysis for installing urban and rural RHS included two of the seven proposed sites, based on a minimum consumption per person of 100 L for case urban and 50 L for case rural [22].

The rural RHS was calculated for 308 inhabitants with a net precipitation of 1234 mm. The urban RHS was calculated for an average 5-person single-family household in the municipal capital, the site where the sampling was conducted, and where net precipitation was 731.34 mm. Two conditions were considered to obtain the storage capacity: supplying the storage tank with water throughout the entire year and supplying water only during the rainy season. Table 6 presents the results of the two rainwater harvesting systems.

Table 6. Results of the design of the two RHS.

RHS	Population	Net Precipitation (mm)	Annual Water Demand (m^3)	Catchment Area (m^2)	Storage Capacity	
					Annual (m^3)	Rainy Season (June–October) (m^3)
Rural	308	1234	5621	3000	180	60
Urban	5	731.34	182.5	180	40	10

The total cost to install both types of RHS was estimated. This study did not consider the cost of energy for pumping the captured rainwater since, in this case, both the urban and rural RHS designs that are proposed do not require electricity, but rather, water is extracted by gravity or manual pumping.

Given that total costs are primarily affected by the cost of the storage structure, which requires a larger financial investment, the cost of each type of RHS was calculated for two storage capacity conditions: annual and the rainy season. In the case of the rural RHS, a total cost of USD 11,945 was obtained for the annual supply and USD 10,576 for the rainy season supply, with a cost per m^3 of water captured of USD 4.8 and USD 4.7 dollars, respectively (Table 7). The total cost for the urban RHS was USD 2146.6 for the annual supply and USD 1176.6 for the rainy season supply, with USD 16.3 and USD 9.8 dollars per m^3 of water captured, respectively. Total costs were also estimated without a storage structure since it is possible to use some type of storage that already exists in the homes where it is desirable to install the systems. In this case, the cost obtained was USD 206.6, with USD 1.6 per m^3 of water captured for the annual supply and USD 1.7 for the rainy season supply. As can be seen, the costs per m^3 of water captured for the urban systems are considerably lower when the cost of the storage structure is not included (Table 7).

Table 7. Costs of the RHS.

	Rural RHS		Urban RHS	
Costs	**Annual Supply System**	**Rainy Season Supply System**	**Annual Supply System**	**Rainy Season Supply System**
Captured volume (m^3/year)	2469 m^3	2234 m^3	131.5 m^3	119 m^3
Storage volume (m^3/year)	180 m^3	60 m^3	40 m^3	10 m^3
Cost of gutters and downspouts (USD)	not applicable	not applicable	USD 206.6	USD 206.6
Total Cost (USD)	USD 11,945	USD 10,576	USD 2146.6	USD 1176.6
Cost (UDD/m^3)	USD 4.8	USD 4.7	USD 16.3	USD 9.8
Cost annual without storage (USD/m^3)	not applicable	not applicable	USD 1.6	USD 1.7

The collection of water only during the rainy season is recommended when the annual system cannot be built for financial reasons. Since the initial investment is high due to the cost of the storage system, many cases result in an RHS not being feasible. However, this cost is compensated by the low cost per cubic meter of water for both systems. In Taxco de Alarcón, the annual cost per cubic meter of water for an average family of five is roughly USD 17 (based on municipal water fees). Since this cost is higher than the per cubic meter of captured water (Table 7), the initial investment of the RHS is justified. In addition, as shown, the installation of an urban RHS is more economically viable when using existing storage structures. It is crucial to invest in rainwater collection systems because they not only generate an economic return but also have environmental advantages. Namely, water is not extracted from a supply source (municipal networks) or from the subsoil, so RHS do not affect the environment. Thus, the use of RHS promotes more sustainable methods for managing water resources.

In many cases, the initial investment in an RHS is high. Therefore, it is imperative to know the different financial assistance programs that are available for implementing these systems at both the municipal and national levels. Some of the most relevant programs in Mexico that provide this kind of aid follow:

- National Rainwater Harvesting Program and Ecotechnologies in Rural Areas (PROCAPTAR in Spanish) and National Water Commission (CONAGUA in Spanish) [55].
- Financing for tourism projects that use sustainable technologies such as rainwater harvesting. National Tourism Development Fund (FONATUR in Spanish) [56].
- Economic support for the use of sustainable technologies in rural housing, including rainwater harvesting systems. Ministry of Rural, Urban, and Land Development (SEDATU in Spanish) [57].

It is important to review each program's requirements and calls for proposals to know which one is most suitable for a project.

4. Conclusions

The findings of the present study highlight a potential solution to managing water scarcity problems by improving water supply in the near future. The main conclusions derived from this research include the following:

Rainwater quality in the study area was found to be optimal for domestic activities. The anthropogenic influence is minimal, a finding that is contrary to what has been discussed by other studies [58] and in other parts of Mexico [59]. The presence of Fe in rainwater in Agua Blanca during the month of October could be related to the lithology of the site due to the erosion of the volcanic rocks in the Tilzapotla formation.

This multi-criteria evaluation analyzed and normalized five factors and one constraint. The factors included average annual precipitation, slopes, distance to localities, population density, and annual real evapotranspiration. The constraint was agricultural use/urban and vegetation areas. To weight the factors, the AHP method was applied in a GIS environment, followed by the aggregation of criteria using the weighted linear combination (WLC) method, which assumes medium risk for decision-making. The result was a prioritization map for the installation of RHS, which was classified according to three categories: high, medium, and low. This map was superimposed on the total population per locality at the municipal level, resulting in the selection of seven rural and urban sites that are viable for implementing RHS to enable optimizing the hydrometeorological and socioeconomic resources. Therefore, this study demonstrates that multi-criteria analysis is a useful tool, as has been indicated by innumerable studies involving rainwater harvesting.

Rainwater harvesting in the municipality only during the rainiest season (June-October) is advisable when it is not possible to build a rainwater harvesting system for annual storage due to financial reasons since the initial investment is high. The installation of an urban RHS is more economically viable when existing storage structures can be used since investment costs are reduced by not acquiring new structures, which are usually expensive. Furthermore, the initial investment in the implementation of urban and rural RHS is compensated by the low costs per m^3 of water captured. These types of studies have been implemented in various parts of the world using different approaches [35,60,61]. Installing RHS is a practical, economical, and efficient alternative that can be implemented on a small scale to manage water resources in order to achieve sustainability for the population.

Despite the efforts that Mexico has already made to promote the implementation of rainwater harvesting systems, these alternatives must continue to be promoted in all areas and sectors. Rainwater harvesting represents a social challenge in terms of the revaluation of rainwater. Society needs to change its perception of the use of rainwater, and users must self-manage this water resource. Therefore, existing government programs should be ongoing and more inclusive.

Last, the methodology used can be replicated in other regions, where favorable results can be obtained depending on the available information.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su15108220/s1, Figure S1: World Bank urban population graph for Mexico. Figure S2: Drought Monitor in Mexico, 2022; Table S1: Physicochemical parameters (average, minimum and maximum) measured at the sampling sites, evaluated in accordance with NOM-SSA-127-2021 [53]. pH: the potential of hydrogen in units. Fecal coliform: colony forming units (CFU/100 mL)).

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