DOI: 10.24850/j-tyca-14-01-06

Articles

Identification of sites with potential for rainwater harvesting in the Upper Mixteco River Basin, Oaxaca, Mexico

Identificación de sitios con potencial para captar agua de lluvia en la Cuenca Alta del Río Mixteco, Oaxaca, México

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Abstract

Rainwater Harvesting Systems (RWH) is an alternative to solve water supply problems in the Upper Mixteco River Basin (UMRB). However, the successful use of RHW depends mainly on its technical design and selection of a suitable site for its construction. The objective of this paper was to identify appropriate sites for the construction of RWH in the UMRB through hydrological modeling with QSWAT+ (QGIS Interface for Soil and Water Assessment Tool) and analysis of geographic information. It was determined that the sites with potential for the construction of RWH cover 7 % of the studied sub-basin surface. In these, check dams and percolation tanks can be built for macro-collection and storage of rainwater. In addition, gully plugs, terraces, contour barriers and trenches, to reduce the surface runoff velocity and soil erosion. In this way, the water availability in the basin for various uses will increase, and soil and water conservation will be favored.

Keywords: Rainwater harvesting systems, city of Huajuapan de León, Lazaro Cárdenas dam, hydrological modeling with QSWAT+, soil and water conservation.

Resumen

Los sistemas de captación de agua de lluvia (SCALL) son una alternativa para resolver los problemas de suministro de agua en la Cuenca Alta del Río Mixteco (CARM). Sin embargo, el éxito de la adopción de un SCALL depende en gran medida de su diseño técnico y de la selección de un sitio adecuado para su construcción. El objetivo de este trabajo fue identificar sitios apropiados para la construcción de SCALL en la CARM, a través de una modelación hidrológica con QSWAT+ (QGIS Interface for Soil and Water Assessment Tool) y el análisis de información geográfica. Se determinó que los sitios con potencial para la construcción de SCALL abarcan 7 % de la superficie de la cuenca, donde se podrán construir presas de contención y tanques de percolación, para macrocaptación y almacenamiento de agua de lluvia; además, terrazas, barreras y zanjas al contorno, para reducir la velocidad de escurrimientos superficiales y la erosión de los suelos. De esta forma aumentará la disponibilidad de agua en la cuenca para diversos usos y se favorecerá la conservación del suelo y agua.

Palabras clave: sistemas de captación de agua de lluvia, ciudad de Huajuapan de León, presa Lázaro Cárdenas, modelación hidrológica con QSWAT+, conservación de suelos y agua.

Accepted: 16/03/2021

Received: 20/09/2021

Introduction

The pressure on water resources in many regions of the world can be mitigated by using alternative sources such as rainwater harvesting. The main purpose of Rainwater Harvesting systems (RWH) is to increase water availability by collecting rain in a given area for local use or its transfer to another area (Adham *et al*., 2018). However, this supply technique also has a long-term positive impact on local water resources by reducing demands for the extraction of surface and underground water (Abdulla, 2019), favoring the reduction of rain runoff (Guo & Baetz, 2007; Sample & Liu, 2014), retard soil erosion and allow aquifer recharge (Ramakrishnan, Bandyopadhyay, & Kusuma, 2009; Aladenola & Adeboye 2010).

In Mexico, inhabitants of arid or semi-arid regions have traditionally used various rainwater harvestings techniques, such as water pans, jagüeyes, or aljibes. Artificial jagüeyes are a particular case of rainwater capture, which has been known in the country since pre-Hispanic times (Pérez-Osorio, Arriola-Morales, García-Lucero, Saldaña-Blanco, & Mendoza-Hernández, 2016), to capture rainwater during the rainy season and use it as a water trough source during the dry season (Sagarpa, 2017). These techniques can be adopted to increase water availability.

In the Upper Mixteco River Basin (UMRB), where factors associated with the degradation of natural resources have led to a decrease in water availability, rainwater collection is seen as an alternative to solve the insufficient water supply for various uses. However, to be successful, they must be implemented in sites with the potential to capture rainwater. The selection of suitable sites represents a great challenge in large areas (Oweis, Oberle, & Prinz, 1998) because, in the design of RHW, various biophysical aspects must be analyzed, such as slope, land use, soil type, and coefficient runoff. For this reason, the objective of this work was to identify appropriate sites for the construction of RHW in the UMRB through hydrological modeling with QSWAT + (QGIS Interface for Soil and Water Assessment Tool) and the analysis of geographic information.

Materials and methods

Study site

The UMRB is located in the Mixteca region in Oaxaca, Mexico, and covers an area of 91 011 ha (Figure 1). The exit site of the basin is the Lázaro Cárdenas dam (Yosocuta dam), fed by the Mixteco River, Balsas River tributary of Hydrological Region No. 18. In this region, the average natural availability of water is low, and the degree of pressure on water resources is high (Conagua, 2010). The mean annual precipitation between 1970 and 1992 varies from 580 mm to 760 mm (Figure 2). The rainiest area is located in the southwest of the basin, while the least rainy is in the northeast.

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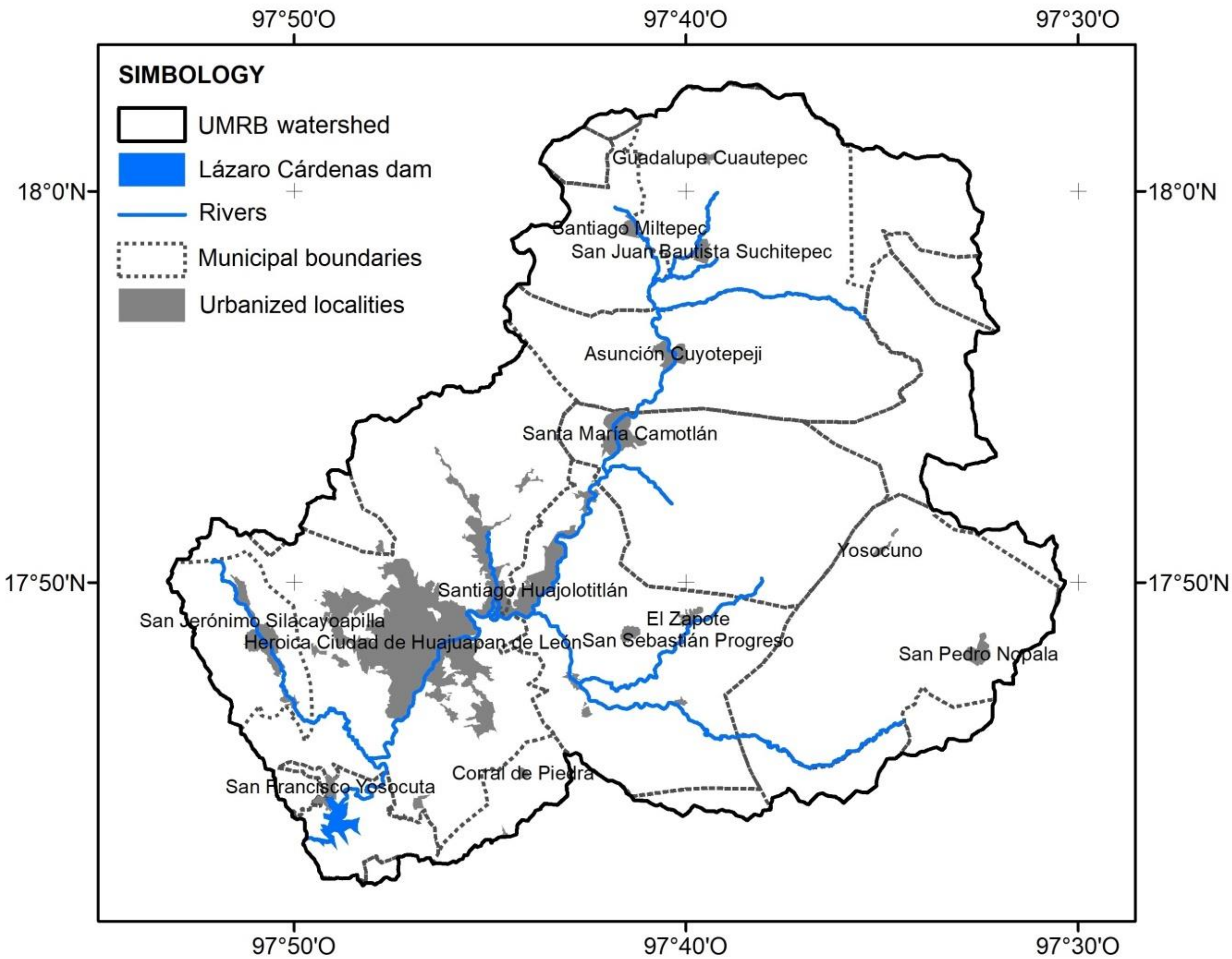

Figure 1. Location of the Upper Mixteco River Basin (UMRB).

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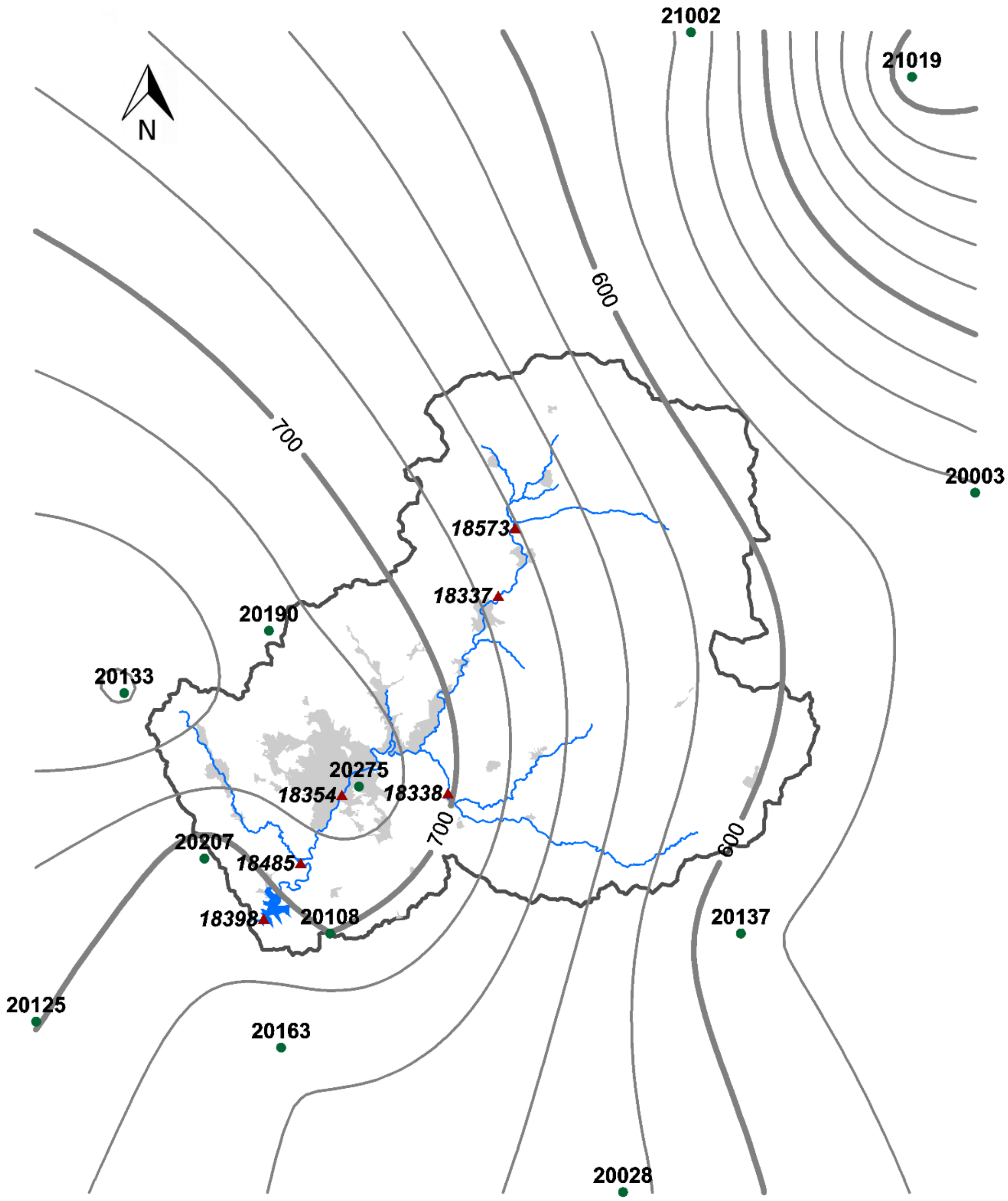

Figure 2. Average annual rainfall (mm, 1970-1992) and location of climatological (circles) and hydrometric (triangles) stations.

UMRB is located in the territory of 20 municipalities in Oaxaca and one in Puebla. It also contains 67 urbanized localities, of which Asunción Cuyotepeji, Santa María Camotlán, Santiago Huajolotitlán, and San Jerónimo Silacoayapilla have more than 1 000 inhabitants (INEGI, 2020). However, the municipality of Heroica Ciudad de Huajuapan de León has a larger population, with 78 313 inhabitants and one of the highest population growth rates (2.3 %) in the state of Oaxaca (INEGI, 2015).

Hydrometeorological data

The steps followed in this investigation are described in Figure 3. The first stage consisted of collecting cartographic and hydrometeorological information. From the CLICOM (Climate Computing Project) database, the daily rainfall and temperature data recorded in 12 conventional weather stations were obtained by the National Meteorological Service of the National Water Commission (Conagua). The location and description of the stations are shown in Figure 2 and Table 1, respectively. The period of available records is from 1950 to 2016. However, the selected data was from 1970 to 1992 to coincide with the period of hydrometric records.

Since eight stations have no data in some years, the inverse distance weighted interpolation method (Shepard, 1968) was applied to deduce the missing information, considering two support stations and a distance exponent equal to two.

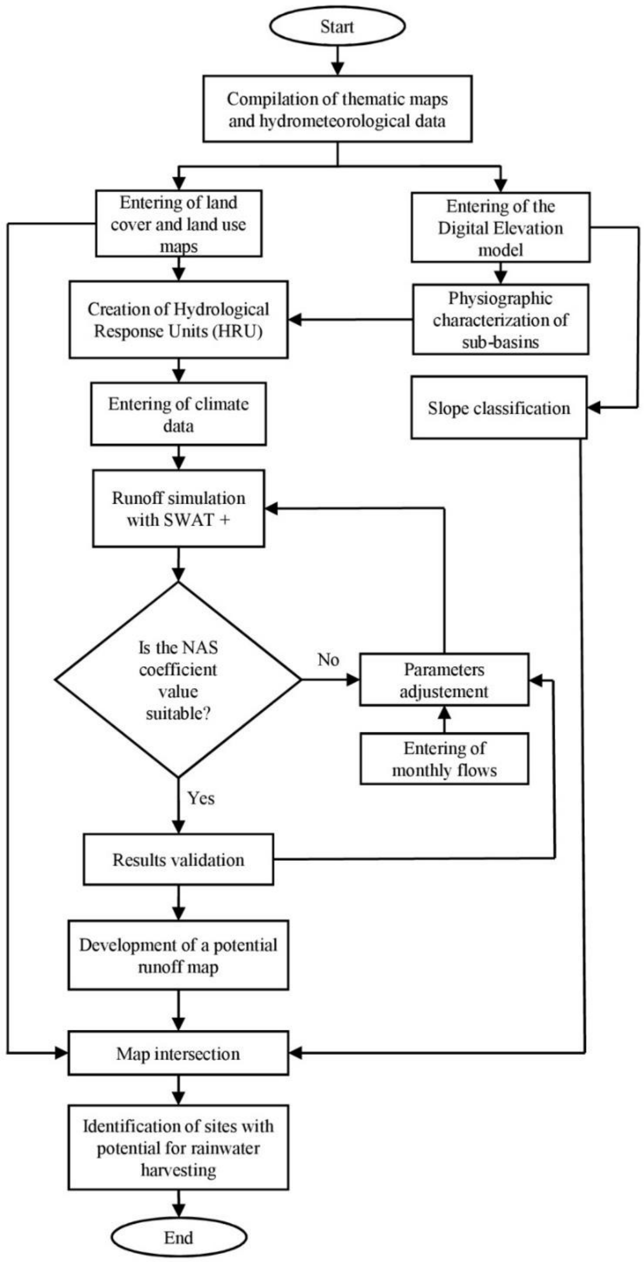

Figure 3. Methodological flow diagram.

Table 1. Characteristics of the selected climatological stations.

Station	Name	Longitude (degrees)	Latitude (degrees)	Registration period	Years with records between 1970 and 1992	Average annual rainfall in mm (1970-1992)
20003	Astatla	-97.417	17.967	1955-2016	18	563.6
20028	Santa María Chilapa de Díaz.	-97.617	17.570	1970-2000	22	625.7
20108	San Francisco Yosocuta	-97.783	17.717	1970-2002	23	700.1
20125	Santa Catarina	-97.950	17.667	1970-2001	22	700.9
20133	Santiago Chilixtlahuaca	-97.900	17.853	1970-2004	23	763.2
20137	Santiago Teotongo	-97.550	17.717	1969-2002	22	583.0
20163	Tezoatlán de Segura y Luna	-97.811	17.652	1963-1996	23	662.2
20190	Zapotitlán Palmas (SMN)	-97.818	17.888	1950-2004	23	727.1
20207	Magdalena Tetatepec	-97.854	17.759	1971-2002	22	687.9
20275	Huajuapan de León (DGE)	-97.767	17.800	1976-2002	17	736.8
21002	Acatepec	-97.578	18.228	1954-1980	11	555.8
21019	Caltepec	-97.453	18.203	1954-2002	21	383.6

The selected hydrometric stations are described in Table 2. The hydrometric data were extracted from the National Bank of Surface Water

Data (BANDAS) of Conagua. It was determined that the La Junta station is the one with the best amount of information. Therefore, the monthly data of this station were chosen to be used in the calibration and validation stage. Currently, none of the hydrometric stations shown in Figure 2 are operating. Therefore, the viable period for hydrological analysis was from 1970 to 1992. In this, we have the best amount of hydrometric and climatological data.

Table 2. Characteristics of the hydrometric stations located in the Upper Mixteco River.

Station	Name	Longitude (degrees)	Latitude (degrees)	Registration period	Years with records between 1970 and 1992
18337	Camotlán	-97.6875	17.9083	1963-1969	0
18338	Xatán	-97.7161	17.7963	1963-1969	0
18354	Huajuapan de León	-97.7763	17.7953	1964-1967	6
18398	San Francisco Yosocuta	-97.8208	17.7250	1965-1969	0
18485	La Junta	-97.7998	17.7566	1969-1992	17
18573	Yundoo	-97.6779	17.9466	1979-1988	10

Thematic mapping

To determine the hydrographic network, the limit of sub-basins, and the variation of the slope in the UMRB was used the Digital Elevation Model with a resolution of 15x15 m, extracted from the Continuum of Mexican Elevations 3.0 from INEGI (National Institute of Statistic and Geography).

From the map made by Blanco-Andray *et al.* (2001), the soil units were obtained according to the FAO-UNESCO (1988) classification. By analyzing the ArcBrutile Bing layer satellite imagery in ArcMap 10.4, the boundaries between the soil units were redefined, and the current land use and vegetation polygons were generated. For areas in which, due to their complexity, it was not possible to identify the different types of soils, land use, and vegetation cover, field inspections were programmed to verify and make the necessary corrections (polygon adjustment) and ensure the quality of the maps.

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Hydrological modeling

Selecting suitable sites for the construction of rainwater harvesting systems requires carefully evaluating parameters that vary spatially, such as the potential for runoff, slope, and land cover (Napoli, Cecchi, Orlandini, & Zanchi, 2014).

In this investigation, the magnitude of the runoff was determined from the model called Curve Number of the Soil Conservation Service (NC-SCS) of the United States Department of Agriculture (Mockus, Hjelmfelt, & Moody, 2004). This model was used as a basis for the identification of suitable sites for rainwater harvesting by various researchers, such as Adham *et al.* (2018), Napoli *et al*. (2014), Kale, Pande, Pawar, and Sankhua (2010) , and Ramakrishnan *et al*. (2009).

The NC-SCS method was applied through the QSWAT + tool (QGIS Interface for Soil and Water Assessment Tool) version 1.2.2, developed by the U.S. Department of Agriculture (Dile, Srinivasan & George, 2019). In this tool, direct runoff is estimated by Equation (1):

$$Q = \frac{(P - 0.2S)^2}{P + 0.8S} \quad (1)$$

where Q is the accumulated runoff or excess rain (mm), P is the daily rain (mm), and S is the retention parameter (mm). Runoff occurs for rainfall heights greater than 0.2S otherwise, runoff is equal to zero.

The parameter S, defined in Equation (2), is related to *NC* (Curve Number) that represents the potential for runoff as a function of the hydrological soil group, the cover, and the antecedent humidity conditions (Neitsch, Arnold, Kiniry, & Williams, 2011):

$$S = \frac{25\,400}{NC} - 254 \qquad (2)$$

In the modeling with QSWAT +, the following were used as input information: 1) Digital Elevation Model of the UMRB, 2) land use map, 3) map of soil types, 4) daily rainfall data, and 5) daily maximum and minimum temperature data. The estimated runoff, together with the monthly runoff observed at the La Junta station between 1972 and 1981, were used to calibrate the model using the IPEAT + UI v0.8.8 tool (Yen *et al*., 2019). The *NC* values of the Hydrological Response Units (URH) defined by QSWAT+ were adjusted to improve the results. Subsequently, the runoff for the period 1972-1992 was again estimated. In addition, the monthly data for the periods 1986-1988 and 1991-1992 were used to validate the model.

Selection of sites for the construction of RHW

The rainwater harvesting technique is the practice (work or technical procedure) of increasing the amount of rainwater stored on the ground or in structures to be used later during the dry season. In general, they are techniques that involve the construction and management of works that allow the collection, derivation, conduction, storage, and distribution of rainwater. These techniques are classified into broad modalities: micro-catchment, macro-catchment, atmospheric water harvesting, and water harvesting from roofs and other impermeable structures (FAO, 2013).

The micro-catchment consists of capturing the rain runoff generated within the cultivated land in sites contiguous to the planted area. This increases the infiltration of water needed by the crops.

On the other hand, macro-catchment consists of capturing rain runoff generated in larger areas than micro-catchment and generally includes: 1) runoff producing area; 2) water conduction structures, such as canals, ditches, furrows, or ridges, and 3) storage structures for different purposes, such as water pans, dams, and dikes.

Rainwater harvesting is related to the concept of integrated hydrographical basis management, which refers to the development and management of resources in the basin to achieve sustainable production without deterioration of natural resources and without causing ecological imbalances. In places with water scarcity and soil and vegetation degradation, in addition to the construction of RHW, soil and water conservation practices must be implemented, such as terraces, contour barriers (vegetative and stone), and contour trenches. These practices not only prevent soil erosion but also obstruct the flow of surface runoff. Consequently, the obstructed water will increase the soil moisture and recharge the groundwater in the area (Sivanappan, 1997).

Sites suitable for macro-catchment and soil and water conservation were identified according to the criteria described in Table 3, which was developed from the investigations carried out by Ramakrishnan (2009), Kadam *et al*. (2012), and Mbilinyi, Tumbo, Mahoo, and Mkiramwinyi (2007). Areas where the slope is greater than 5 % were excluded from the construction of ponds due to the large amount of earthwork required. In addition, it was considered that the urban and agricultural land uses are inadequate for the construction of RHW and that the runoff catchment areas should have an area of at least 2 ha.

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Table 3. Selection criteria for potential sites for rainwater harvesting and recharging.

Structure	**Slope (%)**	**Runoff coefficient**	**Stream order**	**Watershed area (ha)**	**Land use**	**Permeability**
Farm ponds (water pans, jagüeyes or aljibes)	0-5	Medium/high	1	1-2	Scrub land/ Rangelands	Low
Check dams	<15	Medium/high	1-4	>25	Scrub land/River bed	Low
Percolation tank	< 10	Low	1-4	25-40	Scrub land	High
Gully plugs (loose stone dams, log dams, and gabions, among others)	15-20	High	1	-	Scrub land/River bed	Medium/high
Terraces, contour barriers, and trenches	5-30	-	-	-	Scrub land	Medium/high

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Results and discussion

Thematic maps

The thematic maps used and generated in the modeling are shown in Figure 4. The streams of order 1 correspond to the flow lines with collection surfaces of more than 2 ha without ramifications. Two streams of order 1 form one of order 2, two streams of order 3 form one of order 4, and so on (Aparicio, 1997). This way, it was determined that the main current that feeds the Lázaro Cárdenas dam has order 8 (Figure 4a). It should be noted that the sub-basin contemplated in the modeling has an area of 84 937 ha (93 % of the UMRB area) and has the La Junta hydrometric station as its starting point.

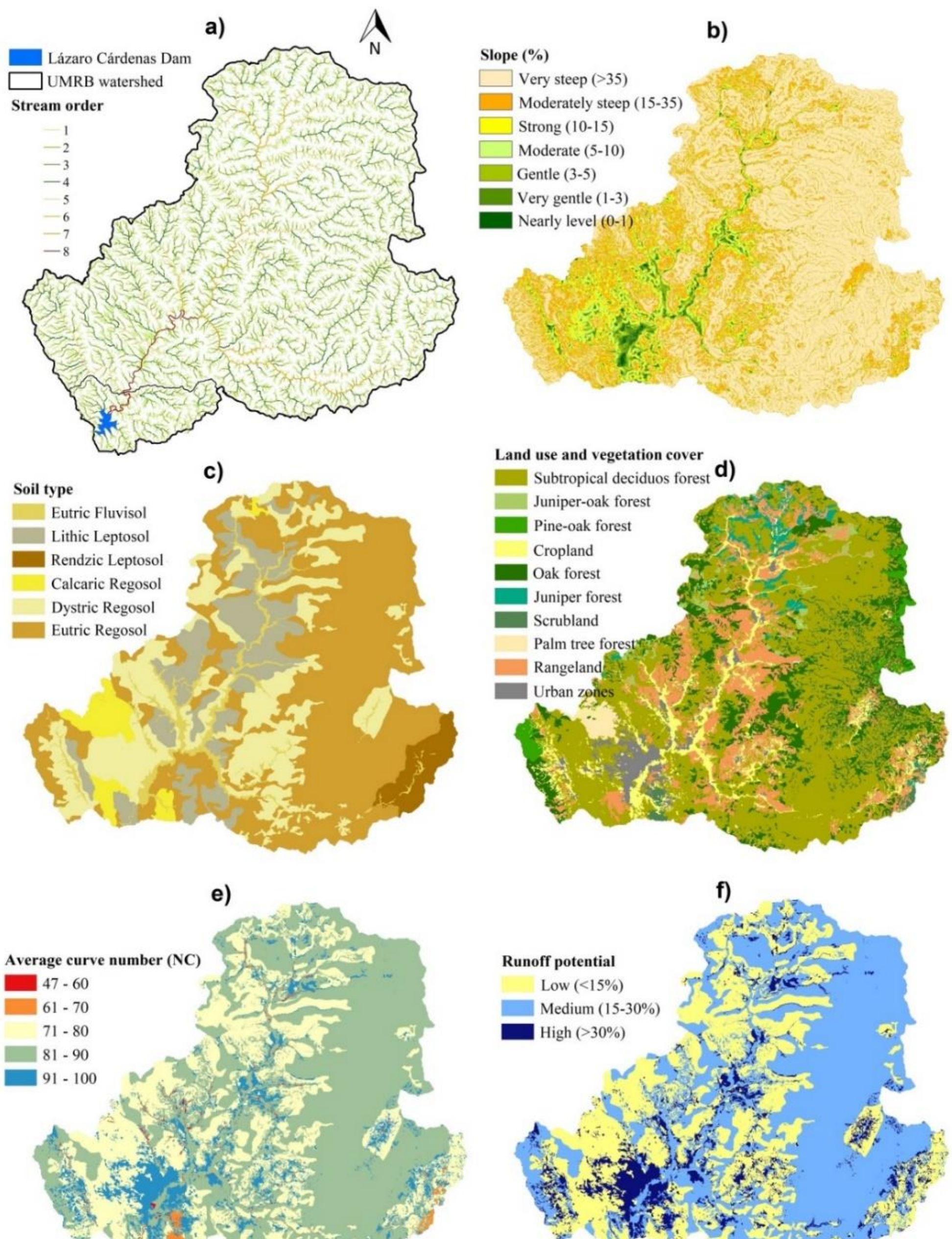

Figure 4. Thematic maps are used and generated in hydrological modeling.

In Figure 4b, the spatial variation of the slope is shown, which is one of the main criteria for selecting suitable sites for the construction of RHW (Ramakrishnan, 2009; Kadam *et al*., 2012; Mbilinyi *et al*., 2007). According to Mondal, Pandey, and Garg (2009), this variable also has a crucial role in groundwater recharge and is inversely related to infiltration. The data in Table 4 indicate that more than 50 % of the basin has a steep slope (greater than 35 %), for which this surface was not considered suitable for constructing RHW.

Table 4. Slope classes.

No.	Categories	% Slope	% Area
1	Nearly level	0-1	0.8
2	Very gentle	1-3	1.3
3	Gentle	3-5	3.7
4	Moderate	5-10	6.8
5	Strong	10-15	6.2
6	Moderately steep	15-35	24.6
7	Very steep	>35	56.6

Based on the types of soils in Figure 4c, the textures and hydrological groups described in Table 5 were considered. Group B soils have moderately low runoff potential when thoroughly wet. Water transmission through the soil is unimpeded. Group B soils typically have between 10 percent and 20 percent clay and 50 percent to 90 percent sand. Group C soils have moderately high runoff potential when thoroughly wet. Water transmission through the soil is somewhat restricted. Group C soils typically have between 20 percent and 40 percent clay and less than 50 percent sand. Group D soils have high runoff potential when thoroughly wet. Water movement through the soil is restricted or very restricted. Group D soils typically have greater than 40 percent clay and less than 50 percent sand (Mockus *et al.*, 1972).

Table 5. Texture and hydrologic groups assigned to soil units.

Soil unit	% Surface	Hydrologic group	Texture class
Rendzic Leptosol	3.3	C	Loam
Lithic Leptosol	14.7	C	Loam
Calcaric Regosol	3.9	C	Loam
Eutric Regosol	48.7	D	Clay loam
Eutric Fluvisol	4.5	B	Sandy loam
Dystric Regosol	25.0	C	Loam

In the basin, the soils that occupy the most surface area (48.7 %) are of the Eutric Regosol type, located mainly towards the eastern side. In second place are the Dystric Regosol soils, which cover 25 % of the surface. According to Blanco-Andray *et al.* (2001), in the basin, the soils are poorly or very poorly developed with little depth and are frequently rocky, except for the Fluvisols dedicated to agricultural cultivation.

The runoff coefficient was estimated from the runoff generated with QSWAT+. This coefficient represents the relationship between the runoff depth and the precipitation depth. The runoff potential was classified according to the runoff coefficient as low (< 15 %), medium (15-30 %), and high (> 30 %). In the study basin, it is observed that 54 % of the surface has medium runoff potential and is associated with Dystric Regosol soils (which are the most predominant) and with *NC* values between 81 and 90. The areas with high runoff potential cover 10 % of the basin surface and are related to urban land use and *NC* values greater than 90. The City of Huajuapan de León (located to the south of the basin) is the locality with a more urbanized surface and with a high runoff potential. The zones with low runoff potential represent 36 % of the basin surface and are associated with *NC* values less than 80, which include the Rendzic Leptosol, Lithic Leptosol, Dystric Regosol, and Calcaric Regosol.

Calibration and validation of the hydrological model

Figure 5 shows the series of monthly flows estimated with QSWAT+ before and after the calibration of the model and the flows observed at the La Junta station. The Nash–Sutcliffe Efficiency (*NSE*) and determination (R^2) coefficients obtained before calibration were 0.43 and 0.89, respectively. It was observed that the flows generated with the model were underestimated. For this reason, an adjustment of the *NC* parameter was made, considering an increase of 18.2763 in all the HRU. The NSE and R^2 coefficients obtained after model calibration were 0.77 and 0.89, respectively. The increase in the value of the *NSE* coefficient indicates that the adjustment generated better results.

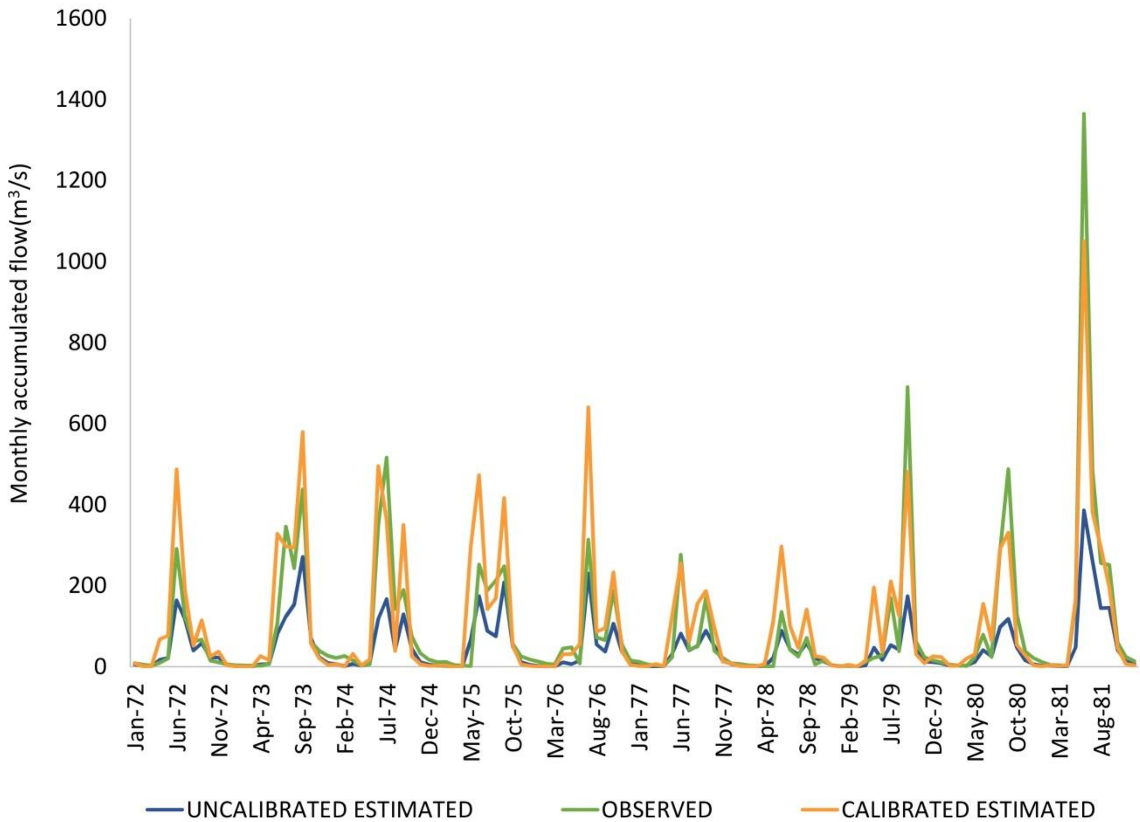

Figure 5. Estimated and observed flows.

Figure 6 corresponds to the estimated and observed flows considered for model validation. It is important to emphasize that in the simulation carried out with QSWAT+ for the runoff estimation, a land use map of the year 2020 was used. However, land use in the study area has changed over the years due to high deforestation rates in the region. The consideration in QSWAT+ that land use is invariant can cause inaccuracies in the information generated and could cause the flows estimated for the year 1991 are lower than those observed. However, the *NSE* and R^2 values obtained for the validation were 0.51 and 0.74, respectively. Since the *NSE* value is more than 0.5, the results were considered satisfactory, according to Moriasi *et al*. (2007).

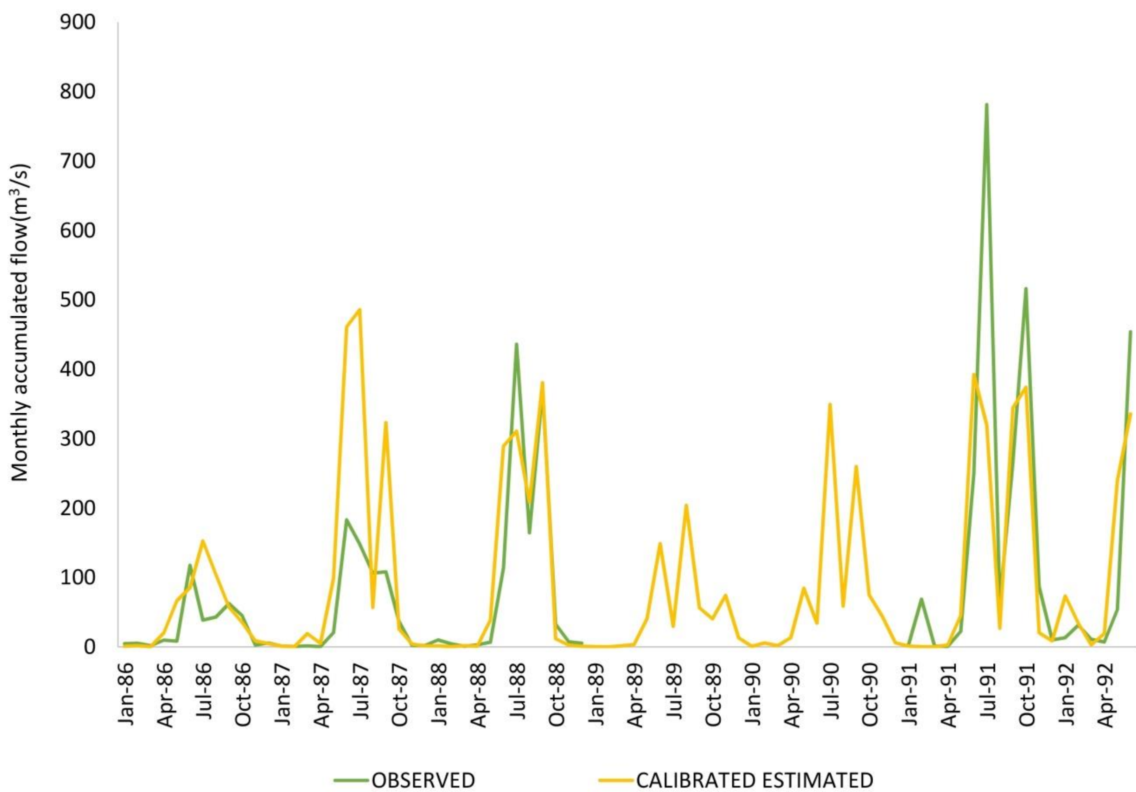

Figure 6. Flows used for model validation.

Selection of potential sites for rainwater harvesting and recharging

The criteria described in Table 3 made it possible to identify suitable sites for collecting and recharging rainwater (Figure 7). The sites with the highest percentage of the basin surface correspond to terraces and retention dams, with 4.7 and 1.8 %, respectively. It was identified that the sites that cover the most surface of the basin correspond to terraces and check dams, with 4.7 and 1.8 %, respectively. The proposed sites for the construction of check dams are located mainly to the east. In the center and north, zones with potential for the construction of terraces, control dams, percolation tanks, and jagüeyes were identified, covering 0.1, 0.2, and 0.3 % of the basin surface, respectively.

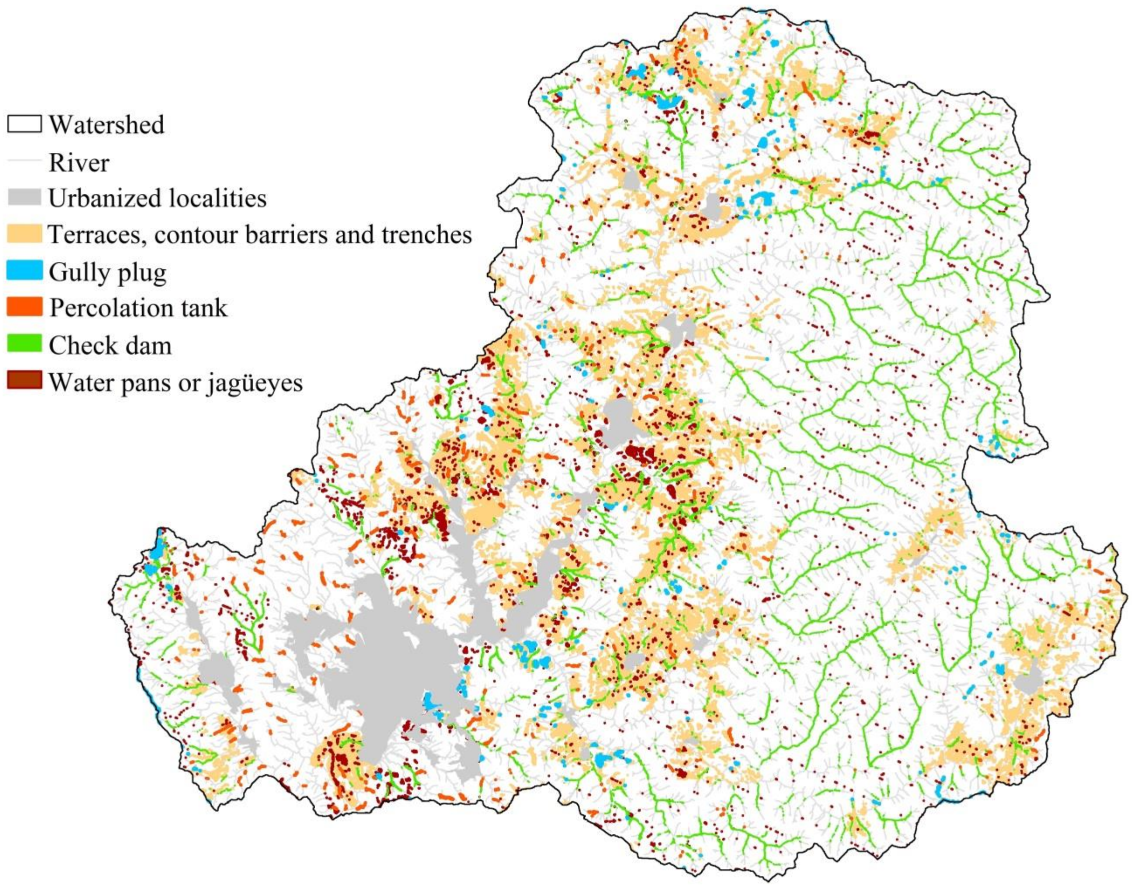

Figure 7. Potential sites for rainwater harvesting and recharging.

The information shown in Figure 7 can be used in the reconnaissance stage of an RHW construction site. However, detailed topographic surveys will be required to identify a narrow site for the dam in the case of dams. In addition, geological and geotechnical investigations, the design of the exceedance structure, and the estimation of operational levels, among other studies, will be necessary.

The water pans, jagüeyes, and check dams will allow rainwater storage for domestic use, livestock, and limited irrigation. Percolation tanks may be used as temporary water storage areas for various uses. While the terraces, barriers, and contour ditches will reduce the surface runoff velocity and soil erosion. On the other hand, the gully plugs will stop gully erosion and retain sediment. It is important to note that the reduction in surface runoff is associated with increased infiltration and water conservation (Sivanappan, 1997) and possibly with increased aquifer recharge.

Conclusions

Sites with the potential for constructing Rainwater Harvesting systems cover 7 % of the studied sub-basin surface, which are more suitable for terraces and check dams. The water pans, jagüeyes, and check dams will allow rainwater storage for various uses. In this way, rainwater harvesting will help reduce water scarcity in UMRB. On the other hand, gully plugs, terraces, contour barriers, and trenches will help soil and water conservation.

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Acknowledgments

The Academic Group members "Integral Water Management" (UTMIX-CA-43) carried out this research thanks to the financing granted by the Higher Education Undersecretary, through the Program for the Professional Development of Teachers for the Superior Type (PRODEP), under agreement number 511-6/2019-8460.

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