

Article

The Spatiotemporal Estimation of the Chupaderos Aquifer Groundwater Recharge for 2020 Based on the Soil Moisture Approach and Remote Sensing

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Abstract: Groundwater, which is widely used in arid regions due to scarcity of surface sources, has excellent quality and, under certain conditions, can be consumed directly. Human activities have caused climate change, leading to decreased precipitation and increased temperatures, which reduces water recharge and increases underground extraction volume. To estimate the natural recharge of the Chupaderos aquifer, located in the State of Zacatecas, México, a spatiotemporal analysis methodology was used, using a soil moisture balance, which includes satellite information on precipitation and temperature, to obtain infiltration, evapotranspiration, and moisture. Using a Geographic Information System (GIS), a distributed spatial model was created in which the potential recharge areas that can be defined by raster images. The results show that there is a maximum annual recharge of 137 mm in the soil where Fluvisol and Kastanozem predominate, an indicator of a texture of sandy soil and franco-sandy area, which is mainly covered by forest and scrub. This result confirms that these characteristics are indispensable for the use of water in soil. Therefore, the preservation of the ecosystem is essential for aquifer recharge.

Keywords: natural recharge; remote sensing; soil moisture; aquifer; groundwater



Citation: López-Cuevas, M.; Pacheco-Guerrero, A.; Olmos-Trujillo, E.; Ramírez-Juárez, J.E.; Badillo-Olvera, A.; Ávila-Sandoval, C.; Badillo-Almaraz, H. The Spatiotemporal Estimation of the Chupaderos Aquifer Groundwater Recharge for 2020 Based on the Soil Moisture Approach and Remote Sensing. *Hydrology* **2024**, *11*, 218. <https://doi.org/10.3390/hydrology11120218>

Received: 18 October 2024

Revised: 12 December 2024

Accepted: 14 December 2024

Published: 20 December 2024



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1. Introduction

Groundwater is generally the most important water resource in arid areas to supply the population and industrial and agricultural activities. In areas of high evapotranspiration and limited precipitation, groundwater provides natural storage of water which is protected from surface evaporation and is well distributed spatially [1–3].

However, in semiarid regions groundwater resources are threatened by overextraction and high pollution, with the large scale deployment of wells for extraction and the lack of effective regulation leading to problems of falling water levels and deterioration of water quality [4–8]. Another factor altered by human activities is climate change, which causes reduced precipitation and, in turn, alters the water flow regime, reducing recharge and increasing groundwater use [2,9]. For this reason, there are several ongoing studies that estimate water recharge in aquifers where results should be obtained, which can represent water balance parameters such as precipitation, evapotranspiration, soil moisture, and water flow [10]. The application of a water balance model that contains soil moisture data requires knowledge of vegetation and soil types within the entire study area [11–14]. Several models for water recharge are currently available, but these methods are complex

when studying a semiarid zone due to the complexity of geohydrological conditions and the uncertainty associated with the meteorological data from a given site [15–18]. In recent years, some innovative technologies, such as satellite information and geographic information systems (GIS) have played a key role in providing information for water resource management [6,19]. Several studies use this technology, which allows real-time information on climatology and the accurate scaling of results [20,21]. However, these data are low resolution, and several areas are inaccessible, making it difficult to collect data in the field and causing them to be scarce, which is why research is focused on the application of remote sensing data. The methodologies used show the flow distribution or the spatial and temporal variation of soil moisture, using a combination of field and satellite measurements to estimate recharge from a series of mathematical models [22–24].

The objective of this research was to estimate the natural recharge of the Chupaderos aquifer, located in the State of Zacatecas, México. The importance of this aquifer is that nowadays it is not available to extract water from new wells due to the volume of irrational extraction of groundwater, presenting a deficit of $-188,453,226 \text{ m}^3$ [25]. Based on a spatiotemporal analysis using a soil moisture model, the same model was used in diverse studies [23]. In the model, the retention of rainwater, infiltration, runoff, potential evapotranspiration, actual evapotranspiration, initial soil moisture, and final soil moisture were obtained to determine the water recharge. For the acquisition of the aquifer's data, climatological information (temperature and precipitation), type of vegetation in the area, and soil texture are required. Other important factors for the balance are root depth, field capacity, permanent wilt point, apparent density, leaf retention coefficients, slope infiltration, and vegetation cover. To obtain a spatial model, it is necessary to use satellite and GIS information where the potential recharge zones are defined with a spatial distribution according to the actual conditions and hydrometeorological events that occur. The implementation of this method allows for a comprehensive analysis of factors that influence infiltration, creating a complete and efficient study for the estimation of natural water recharge. Because of their breadth in the analysis, the results are close to the real conditions [23]. It is important to note that the study has certain limitations, one of them being that the results are specific to the time and place of analysis.

Investigations such as those performed in the analysis using the model proposed for the estimation of recharge using a moisture balance indicate a spatiotemporal approach. The distribution of data was modeled by GIS where it was possible to identify recharge zones and confirm that higher values persist in the areas where soil units are predominantly franco-sandy with forest-dominated cover [24,26–29].

2. Materials and Methods

To calculate the recharge, data on precipitation and average monthly temperature for the year 2020 were required. Both data were obtained from the NASA GIOVANNI server [30].

For temperature data, an image with a resolution of 0.1 degrees from the FLDAS model was used with monthly measurement in Kelvin units [31]. For precipitation data, 0.25-degree resolution of the TRMM model was used with monthly measurement in millimeters per hour [32].

To capture the spatial distribution of recharge, areas with similar characteristics were determined, such as slope, soil texture, root depth, and vegetation cover. Subsequently, a raster was created in ArcGIS 10.8 for each mentioned feature; this tool facilitated the overlay of values for each variable. When all the information was gathered in a raster, the model was applied using map algebra, thus achieving a spatial variability of the recharge results.

2.1. The Study Site

The Chupaderos aquifer (Figure 1), defined with code 3226 in the geographic information system for groundwater management (SIGMAS), is located in the eastern portion of Zacatecas, on the border with San Luis State Potosí, between parallels $22^{\circ}42'$ and $23^{\circ}25'$ north latitude and between meridians $102^{\circ}07'$ and $102^{\circ}39'$ W, covering an area of approximately 2483 km^2 [25].

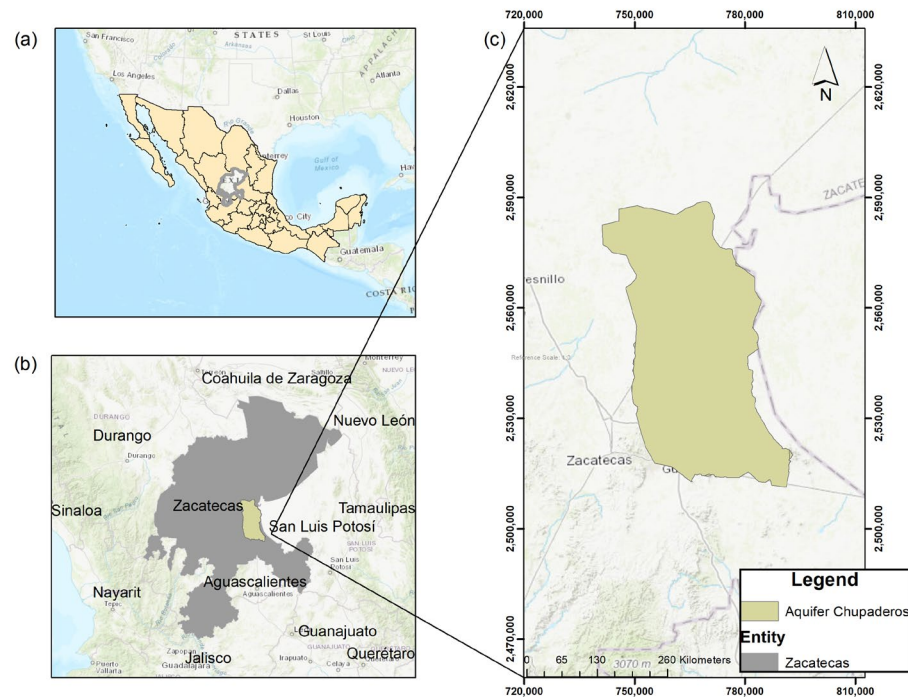


Figure 1. (a) The study area showing the location of Mexico, (b) the Mexican state of Zacatecas, and (c) the map showing the extent of the Chupaderos aquifer.

To the north, it is bordered by the Guadalupe de las Corrientes aquifer, to the northeast by Puerto Madero, to the southeast by La Blanca, to the south by Ojocaliente, to the southwest by Guadalupe Banuelos, and to the west by the Calera aquifer—all belonging to the State of Zacatecas; to the east, it is bordered by the El Barril aquifer, belonging to the State of San Luis Potosí. Geopolitically, the area that includes the aquifer belongs to the following municipalities: mostly, Trancoso, Pánuco, and Vetagrande; mainly, Guadalupe, Fresnillo, and Villa de Cos; and small portions of the General Pánfilo Natera and Ojocaliente municipalities [25,33].

For this aquifer, the volume of groundwater extraction is 188,453,226 m³ per year. The deficit is 101,853,226 m³ per year, which is being extracted at the expense of depleted aquifer storage, and the aquifer is not available to extract more water from new wells [25].

2.2. Schosinsky Method

It is an aggregated monthly model developed by Schosinsky in 2006 and applied in Costa Rica. Although the geographical conditions are not the same for arid and semi-arid areas, the methodology was selected because it has the advantage of requiring data that are available or can be obtained remotely. However, the same values cannot be assumed for each parameter; therefore, the value was allocated according to the climatic and geographical conditions of this region.

The model works with the values of precipitation and temperature in the area, using the temperature and the evapotranspiration values obtained by Equation (8) and the percentage of monthly sunlight hours with precipitation determined as the quantity of water that infiltrates the soil to bring it to the field capacity (CC), which corresponds to the superior limit of available water and represents the moisture of the soil after drainage of the water contained in the macropores by gravity action. When the amount of infiltration is sufficient to bring the soil to CC and satisfy the need for evapotranspiration, the excess of water infiltration percolates to recharge the aquifer. As it is a semiarid area, evapotranspiration is always higher than precipitation, and therefore, the infiltration is too low. The month of the start for the balance will be chosen based on when the evapotranspiration does not exceed the precipitation to avoid too many negative values in the final results.

Water retention in foliage is the water that precipitates but never infiltrates due to its retention in vegetation. The infiltration is estimated from the infiltration coefficient as a function of the cover, slope, and permeability of the saturated soil [23]. The runoff is calculated as the excess of precipitation after removal of retention in foliage and infiltration [34].

2.3. A Fraction of Rain That Is Intercepted by Foliage (Retention)

Since rainfall of less than 5 mm monthly does not generate infiltration, it is important to consider that, in a month of rain, 5 mm is retained by the foliage without reaching the ground. The value of (Cf_o) for the land use of the area is provided in Table 1.

Table 1. The foliage retention coefficient [23,24].

Classification	Cf_o
Irrigation agriculture	0.10
Rain-fed agriculture	0.09
Forest	0.20
Scrub	0.07
Grassland	0.09

To calculate the total monthly rainfall intercepted in the foliage, Equations (1) and (2) are applied:

$$R_{et} = Cf_o * P \quad (1)$$

where

- R_{et} = Retention (mm/month);
- Cf_o = Foliage interception coefficient (dimensionless);
- P = Precipitation or rain (mm/month).

$$\text{If } P < 5 \text{ mm then } R_{et} = P$$

$$\text{If } (Cf_o * P) > 5 \text{ mm then } R_{et} = (Cf_o * P)$$

$$\text{If } > 5 \text{ mm and } (Cf_o * P) < 5 \text{ mm then } R_{et} = 5 \text{ mm} \quad (2)$$

2.4. The Infiltration Coefficient

One of the factors that most influence the infiltration of rain into the soil is the infiltration coefficient due to the texture of the soil, obtained by the following Equation (3):

$$P_i = C_i * (P - R_{et}) \quad (3)$$

In calculating the monthly infiltrating precipitation, the following factors are considered: monthly precipitation, monthly rain retention in the foliage, and the infiltration coefficient, based on the following Equation (4):

$$\text{If } (K_{fc} + K_v + K_p) > 1 \text{ then } C_i = 1$$

$$\text{If } (K_{fc} + K_v + K_p) < 1 \text{ then } C_i = (K_{fc} + K_v + K_p) \quad (4)$$

where

- C_i = Infiltration coefficient (dimensionless);
- K_{fc} = Infiltration fraction by texture (dimensionless);
- K_v = Fraction of infiltration by vegetation (dimensionless);
- K_p = Fraction of infiltration by slope (dimensionless).

For the infiltration coefficients per slope and per plant cover, see Table 2.

Table 2. Components of the infiltration coefficient by slope and components of the infiltration coefficient by vegetation cover [23].

Type	Slope	K _p
Somewhat flat	1–2%	0.15
Average	2–7%	0.10
Steep	Greater than 7%	0.06
Vegetation cover		K _v
Agriculture–Livestock–Forest	0.10	
Crasicaule scrub	0.20	
Desert scrub	0.20	
Halophilic grassland	0.18	
Induced grassland	0.18	
Natural grassland	0.18	
Halophilic vegetation	0.20	

A factor that influences the infiltration of rain into the soil is the infiltration coefficient due to soil texture (K_{fc}), which is obtained by Equation (5). Table 3 provides the values of fc for each soil type and texture.

$$\begin{aligned}
 &\text{If } Fc > 1568 \frac{\text{mm}}{\text{day}} \text{ then } K_{fc} = 1 \\
 &\text{If } 16 < Fc < \frac{1568 \text{ mm}}{\text{day}} \text{ then } K_{fc} = 0.267 * \ln(Fc) - 0.000154 * Fc - 0.723 \\
 &\text{If } Fc < 16 \text{ then } K_{fc} = 0.0148 * \left(\frac{Fc}{16}\right)
 \end{aligned} \tag{5}$$

where

- Fc = Base infiltration (mm/day).

Table 3. Base infiltration [23].

Type	Texture	Base Infiltration (Fc)
Cambisol	Clayey–Loam	180
Kastanozem	Sandy–Loam	600
Phaeozem	Clayey–Sandy	404
Fluvisol	Sandy	780
Leptosols (Lithosol)	Loam	360
Leptosols (Rendzina)	Clayey	72
Solonetz	Clayey	72
Gypsisol	Clayey–Sandy	404
Solonchack	Clayey	72

2.5. The Calculation of the Surface Runoff

The surface runoff generated by monthly rainfall corresponds to monthly precipitation minus rain retention in the foliage minus infiltration. The monthly runoff is calculated by Equation (6):

$$ESC = P - R_{et} - P_i \tag{6}$$

where

- ESC = Runoff (mm/month);
- P = Precipitation (mm/month);
- R_{et} = Retention (mm/month);
- P_i = Precipitation that infiltrates (mm/month).

2.6. Soil Balance

The following are the physical properties of soil:

Texture: It indicates the relative content of particles of different sizes, such as sand, silt, and clay in the soil.

Effective depth (P_r): It is the space into which the roots of common plants can penetrate without major obstacles in order to obtain water and essential nutrients.

Apparent density (DA): It refers to the mass per volume of the soil. Compact soils have apparent densities close to 2.65 gr/cm^3 .

Field capacity (CC): It corresponds to the superior limit of available water and represents the moisture of the soil after drainage of the water contained in the macropores by gravity action.

Permanent wilting point (PMP): It is the water content that is part of the soil and that is retained.

Available water (AD): It is the difference between the field capacity and the permanent wilting point.

Sheet of available water (LAD): It expresses the amount of water that a soil can store between the limits of the field capacity and the permanent wilting point at the effective root depth of the scop studied (as shown in Equation (7)). In the model, the actual evapotranspiration is proportional to the soil moisture calculated as the difference between the field capacity (CC) and the permanent wilting point (PMP)

To obtain the values of PMP, CC, DA, and the root depth, Table 4 is used.

$$\text{LAD} = (\text{CC} - \text{PMP}) * \text{DA} * P_r * 100 \quad (7)$$

Table 4. The permanent wilting point and field capacity in percentage by soil weight of different soil textures and root depths [23].

Edaphology	Soil Texture	PMP %	CC %	DA (gr/cm^3)
Fluvisol	Sandy	2–4	6–12	1.55–1.80
Kastanozem	Sandy–Loam	4–8	10–18	1.40–1.60
Leptosols (Lithosol)	Loam	8–12	18–26	1.35–1.50
Cambisol	Clayey–Loam	11–15	23–31	1.30–1.40
Phaeozem	Clayey–Sandy	13–17	27–31	1.25–1.35
Gypsisol				
Leptosols (Rendzina)	Clayey	15–19	31–39	1.20–1.30
Solonetz				
Solonchack				
Classification	Crop	Millimeters		
Irrigation	Chili	1200		
agriculture				
Rain-fed	Bean	700		
agriculture				
Forest	Forest	3000		
Scrub	Scrub	5100		
Grassland	Grassland	1700		

2.7. Potential Evapotranspiration

Potential evapotranspiration is based on climatic variables, does not consider soil moisture, and has a real evaporation transpiration and an adjustment that involves soil parameters.

For potential evapotranspiration, Equation (8) is used, and the temperature percentage from Table 5 is used:

$$\text{ETP} = (8.10 + 0.46 - T) * P_s \quad (8)$$

where

1. ETP = Potential evapotranspiration (mm/month);
2. T = Monthly average temperature (°C);
3. Ps = Percentage of monthly sunlight hours (%).

Table 5. Percentage of monthly sunlight hours relative to latitude [35].

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
%	7.58	7.17	8.40	8.60	9.30	9.20	9.41	9.05	8.31	8.09	7.43	7.46

For actual potential evapotranspiration, the following Equation (9) is applied:

$$ETPR = \frac{H_{si} - PMP}{CC - PMP} * ETP \quad (9)$$

where

- ETPR = Actual potential evapotranspiration (mm/month);
- H_{si} = Moisture at the beginning of the month (mm/month);
- PMP = Permanent wilting point (mm/month);
- CC = Field capacity (mm/month);
- ETP = Potential evapotranspiration (mm/month).

2.8. Humidity Coefficients C1 and C2

At the beginning of any month, the soil will have initial humidity (H_{si}). If there were no evapotranspiration, the infiltrating precipitation (P_i) would increase the humidity in the soil, allowing for greater evapotranspiration. If evapotranspiration is not considered, the humidity coefficient at the end of the month will be C1. See Equations (10) and (11).

$$C1 = (H_{si} - PMP + P_i) / (CC - PMP) \quad (10)$$

$$\begin{aligned} \text{If } \frac{(H_{si} - PMP + P_i)}{CC - PMP} < 1 \text{ then } C_i &= \frac{H_{si} - PMP + P_i}{CC - PMP} \\ \text{If } \frac{H_{si} - PMP + P_i}{CC - PMP} > 1 \text{ then } C1 &= 1 \end{aligned} \quad (11)$$

where

- C1 = Humidity coefficient at the beginning of the month without ETP (dimensionless);
- H_{si} = Moisture at the beginning of the month (mm/month);
- PMP = Permanent wilting point (mm/month);
- CC = Field capacity (mm/month);
- P_i = Precipitation infiltrated into the soil (mm/month).

The minimum humidity coefficient considering that evapotranspiration occurs after the infiltration, the humidity coefficient at the end of the month will be C2. Apply Equations (12) and (13).

$$C2 = (H_{si} - PMP - ETPR + P_i) / (CC - PMP) \quad (12)$$

$$\begin{aligned} \text{If } \frac{(H_{si} - PMP - ETPR + P_i)}{CC - PMP} > 1 \text{ then } C2 &= 1 \\ \text{If } \frac{(H_{si} - PMP - ETPR + P_i)}{CC - PMP} < 0 \text{ then } C2 &= 0 \end{aligned} \quad (13)$$

where

- C2 = Humidity coefficient at the end of the month without ETPR (dimensionless);

- H_{si} = Moisture at the beginning of the month (mm/month);
- PMP = Permanent wilting point (mm/month);
- CC = Field capacity (mm/month);
- P_i = Precipitation infiltrated into the soil (mm/month).

2.9. Actual Evapotranspiration and Available Moisture

Available moisture is the moisture that can be taken up by plant roots to perform their functions. It is expressed by the following Equations (14)–(16):

$$ETR = \frac{C1 + C2}{2} * ETP \quad (14)$$

$$HD = H_{si} - PMP + P_i \quad (15)$$

$$\text{If } \frac{(C1 + C2)}{2} - ETP < HD \text{ then } ETR = \frac{C1 + C2}{2} * ETP$$

$$\text{If } \frac{C1 + C2}{2} * ETP > HD \text{ then } ETR = HD \quad (16)$$

where

- ETR = Average actual evapotranspiration of the area during the month (mm/month);
- ETP = Potential evapotranspiration (mm/month);
- C1 = Humidity coefficient at the beginning of the month without ETP (dimensionless);
- C2 = Humidity coefficient at the end of the month without ETP (dimensionless);
- H_{si} = Moisture at the beginning of the month (mm/month);
- PMP = Permanent wilting point (mm/month);
- CC = Field capacity (mm/month);
- P_i = Precipitation infiltrated into the soil (mm/month).

2.10. Final Moisture (H_{sf})

To calculate the recharge to the aquifer, it is necessary to know the final soil humidity of the month, which cannot be greater than the field capacity obtained as follows:

$$\text{If } (HD + PMP - ETR) < CC \text{ then } H_{sf} = (HD + PMP - ETR)$$

$$\text{If } (HD + PMP - ETR) > CC \text{ then } H_{sf} = CC \quad (17)$$

2.11. Initial Soil Moisture (H_{si})

In addition to calculating the soil humidity at the end of the month, it is necessary to know the humidity at the beginning of the month (initial humidity), which is equal to the soil moisture at the end of the previous month.

To initialize the balance, it is necessary to select the month in which the precipitation exceeds the evapotranspiration value, with the H_{si} value equal to the field capacity.

2.12. Recharge

The recharge is expressed by Equation (18):

$$R = P + H_{si} - ETR - H_{sf} \quad (18)$$

where

- R = Aquifer recharge (mm/month);
- P = Precipitation (mm/month);
- H_{si} = Initial soil moisture (mm/month);
- H_{sf} = Final soil moisture (mm/month);
- ETR = Actual evapotranspiration (mm/month).

3. Results

The foliage retention coefficient (C_{fo}) and infiltration by vegetation cover (K_v) and infiltration by texture results are presented in Figure 2. Base infiltration (F_c), infiltration by slope (K_p) and the infiltration coefficient (C_i) are presented in Figure 3.

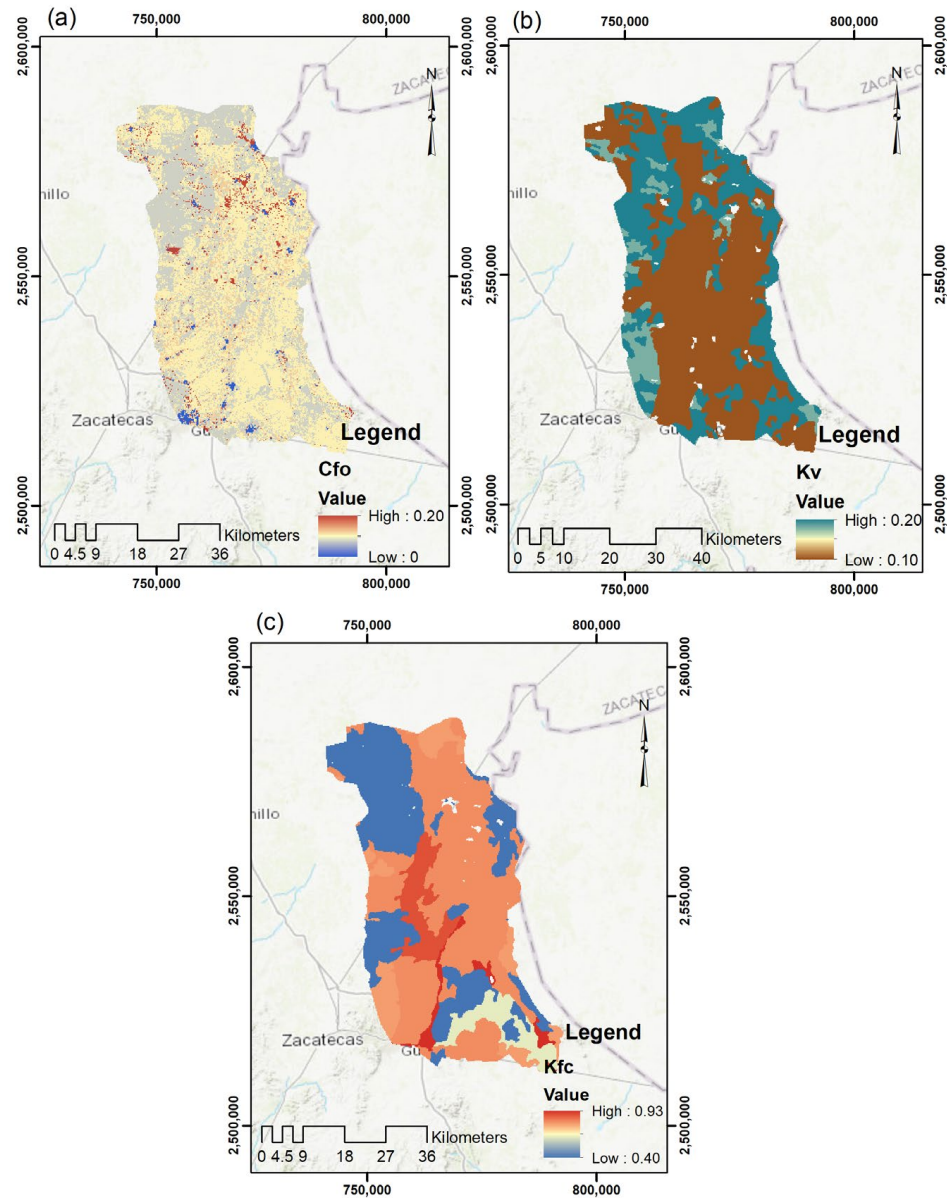


Figure 2. (a) C_{fo} is defined as the foliage retention coefficient. It is the percentage of monthly rain that is retained by foliage, which ranges from 0% for bodies of water and urban areas to 20% for the forest and its different vegetative species, which include grassland, scrubland, beans in rain-fed agriculture, and chili peppers in irrigation agriculture (Table 1). (b) Infiltration by vegetation cover (K_v), is the fraction of rain that infiltrates due to the effect of vegetation cover, with a range of values from 0.1 to 0.2. (c) Infiltration by texture (K_{fc}), is defined as a fraction of rain that infiltrates due to the effect of soil texture, which allows for obtaining monthly infiltrated rain using that concept. It is within the range of a minimum of 0.40 and a maximum value of 0.93.

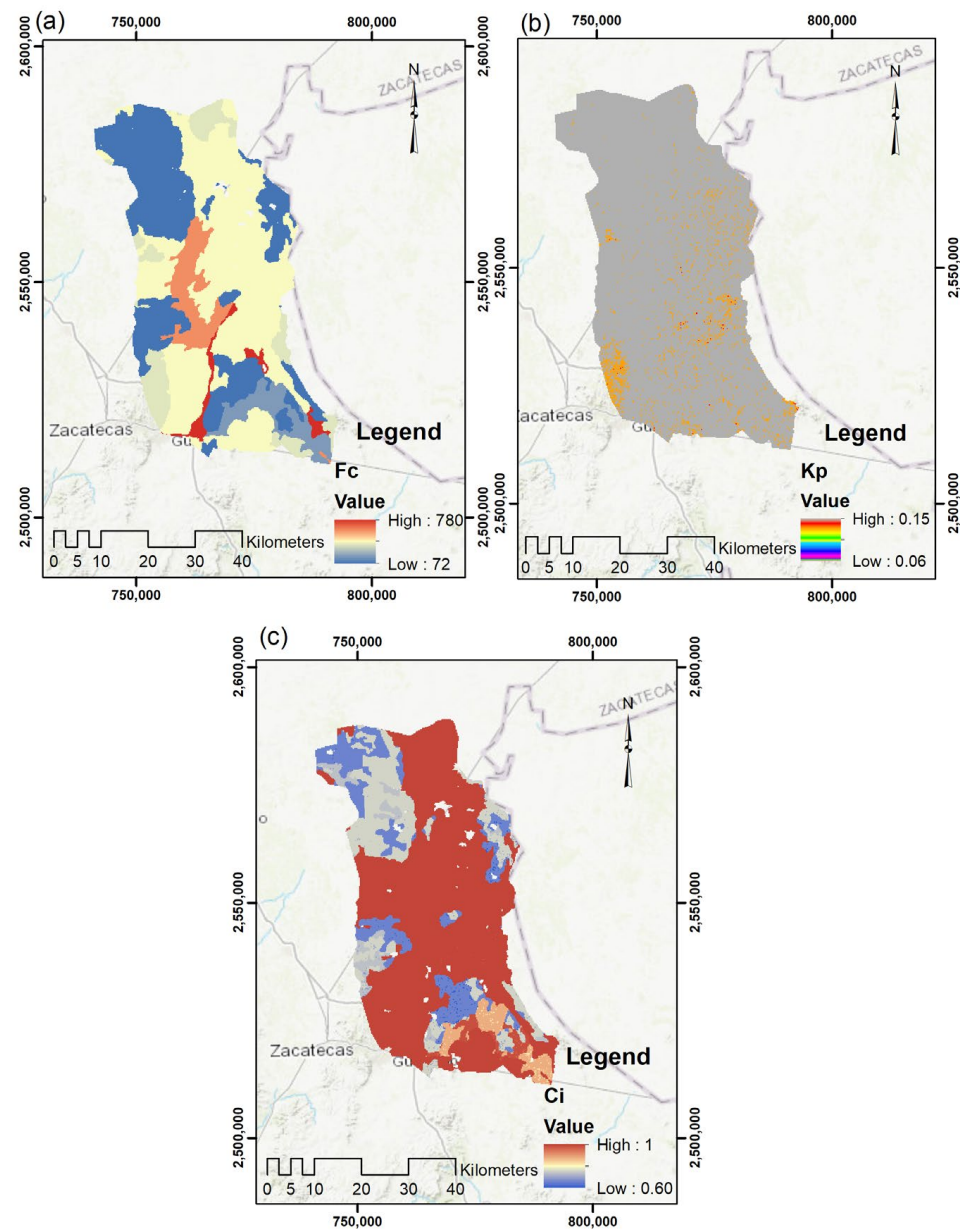


Figure 3. (a) Base infiltration (F_c), defined as the fluctuation of the basic infiltration rate according to the soil texture, in millimeters per day; (b) the second is by slope, which is defined as K_p . It is the fraction that infiltrates due to the slope effect. The lower the slope of the land and the greater the vegetation cover, the lower is speed of runoff, generating greater infiltration. The study area is mostly flat, and (c) infiltration coefficient (C_i), is the factor by which the monthly precipitation must be multiplied to obtain the monthly water infiltration into the soil, the value of which must not be greater than 1.

3.1. Coefficients of Soil Physical Properties

Apparent density (DA), effective depth (P_r), field capacity (CC), and permanent wilting point (PMP) are presented in Figure 4.

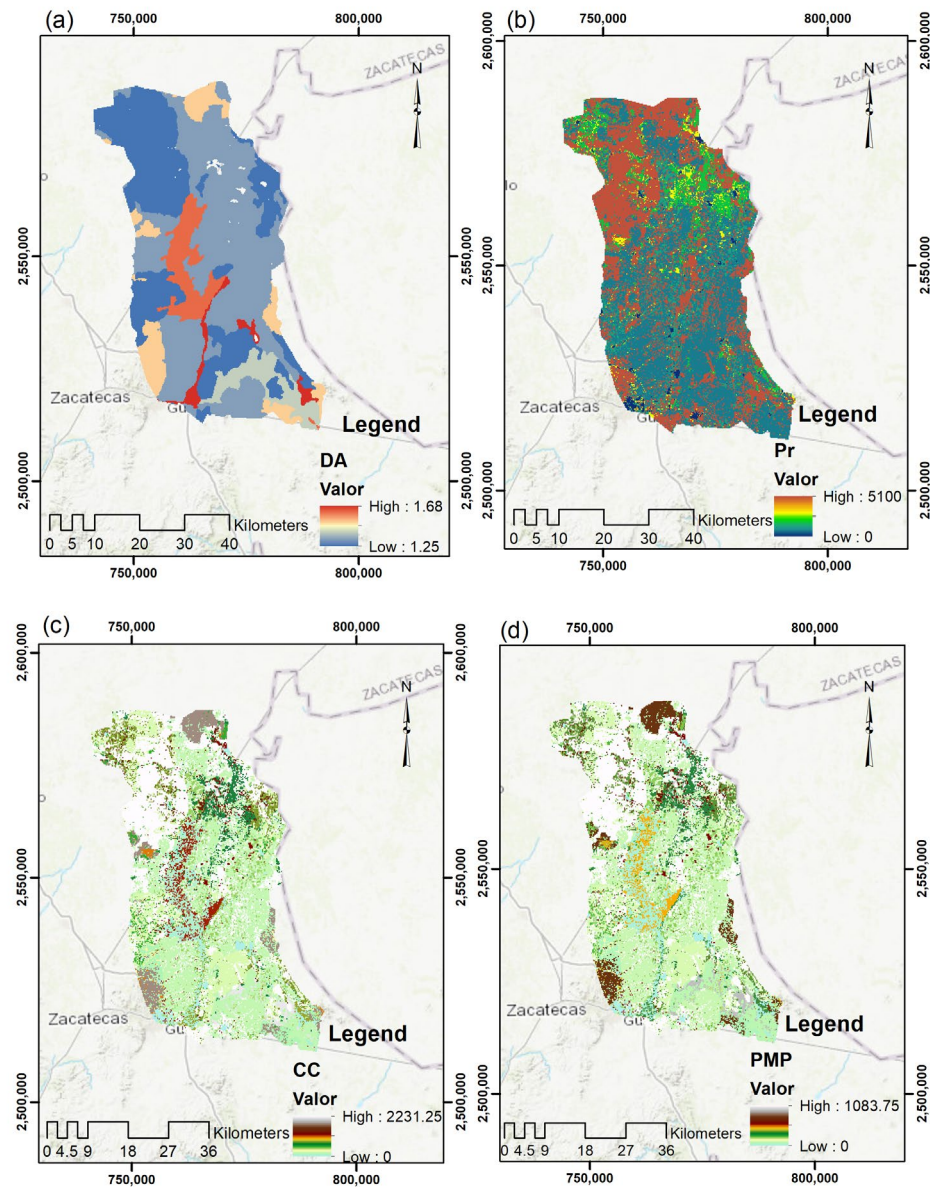


Figure 4. (a) DA: It allows us to see the ease of penetration of the roots into the soil, as well as the transmission of water. The change in soil porosity is responsible for the rapid drainage of excess water. It is a good indicator of soil quality. Its values range from 1.25 g/cm³ for areas where clay predominates to 1.68 g/cm³ for sandy soils. (b) P_r : It shows the root depth of the study area. The value 0 represents the areas where there are bodies of water and urban areas, while the deepest root is that of the scrub with 5.1 m depth. (c) CC: It is the maximum moisture that a soil can have without being saturated; it is when the plant has the maximum transpiration capacity, defined as the available water layer. The values range from 0 for bodies of water and urban areas to 2231.25 mm for soil where clay predominates. (d) PMP: When soil moisture reaches the PMP, the plant does not transpire and dies; just as CC is represented by the water layer, this results in a value of 0 mm for water bodies and urban areas up to 1083.75 mm, in relation to the soil texture.

3.2. Monthly Water Recharge Areas

The rasters presented above are the essential basis for the final calculation, and the same parameter values are taken into account for the balance, given that the characteristics and physical properties of the soil are assumed not to change over the course of the year. Figures 5–8 show estimated values for water recharge in each month and identify the areas where this event occurs.

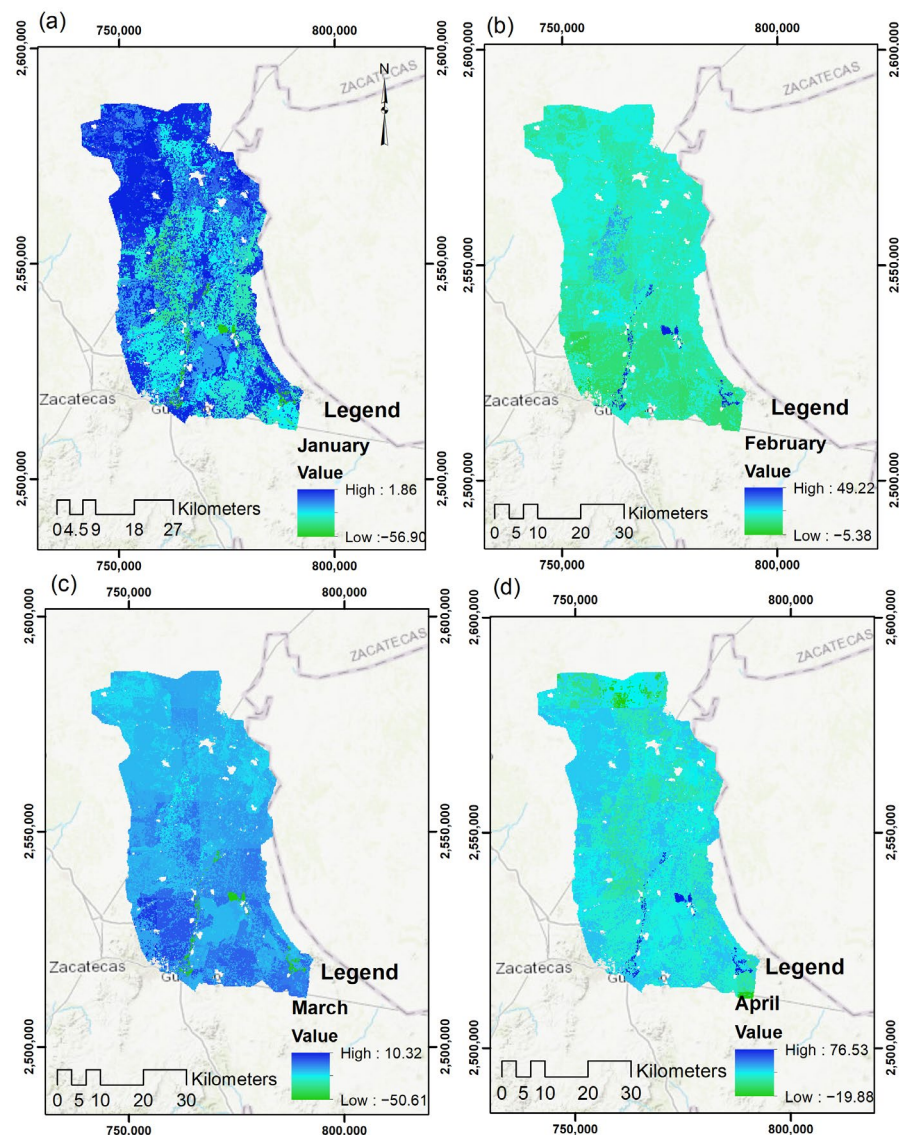


Figure 5. (a) Water recharge in January varies between -56.90 mm to 1.86 mm, with an average of -6.29 mm. The green color represents the lowest value, spreading out in some central areas, while blue predominates in the northern part, representing the highest values. In January, the recharge is somewhat scarce due to the presence of low rainfall. (b) February has low rainfall, so the balance shows an average recharge of 1.09 mm. It can be seen that there is a minimum recharge of -5.38 mm and that the green color, the same that represents the lower levels, predominates in the whole area, while the blue one is found only in some central portions. This difference in distribution is due to the fact that precipitation is not uniform and is considered as a maximum recharge of 49.22 mm. (c) In March, the recharge already begins to stabilize, and the balance obtained has a minimum of -50.61 mm and the maximum of 10.32 mm, with an average of 4.38 m. In March, the negative values are no longer predominant in the raster image because the sum of actual evapotranspiration and final soil moisture does not exceed the sum of initial soil precipitation and moisture. (d) The maximum recharge obtained can be observed in some areas south of the aquifer (76.53 mm) and the minimum of -19.88 mm is present in the central part to the north (these negative values are translated as a deficit of the recharge), with an average of 1.12 mm throughout the area.

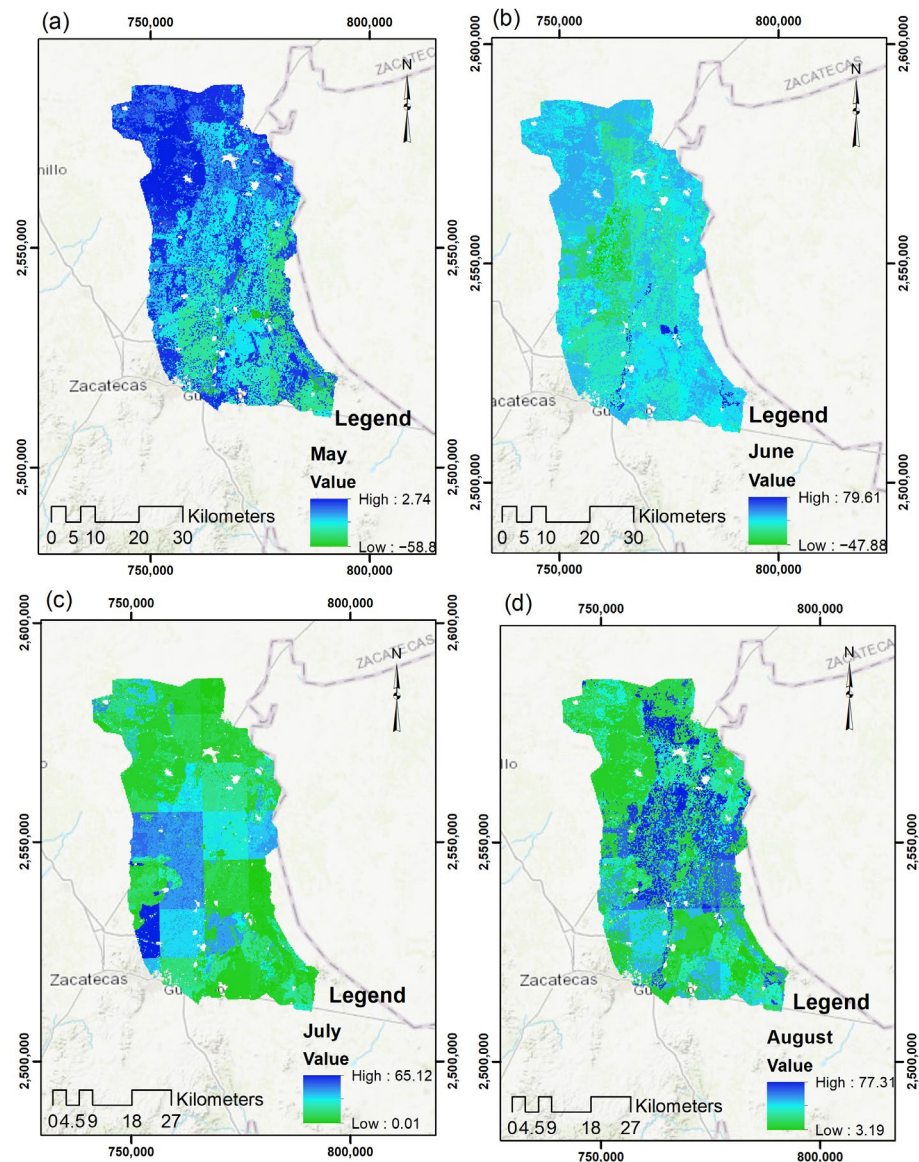


Figure 6. (a) In May, although the maximum recharge is not very high, the aquifer predominates in most of the area, specifically in the north with 2.74 mm and the minimum of -58.80 in the south, and the average of -11.63 mm becomes present in the central zone of the aquifer. (b) In June when the rains begin to be abundant, the temperature increases considerably, causing the actual evapotranspiration and moisture of the final soil to exceed the values of precipitation and moisture of the initial soil. The average recharge is -8.25 mm, the same as observed throughout the study area; the minimum of -47.88 is in the center, and the maximum of 79.62 mm occurs in minimal portions to the southeast of the aquifer. (c) July is the month when rainfall exceeds average precipitation levels. It is confirmed that despite high evapotranspiration rates, there are no negative values or deficit of recharge, an average of 12.64 mm, a minimum of 0.01 mm, and a maximum of 65.12 mm. (d) For the month of August, as in July, there are no deficit rates. The image shows the spatial distribution of recharge in different aquifer areas. The values obtained through the methodology show that the recharge is between 3.19 mm as the minimum and 77.31 mm as the maximum and an average of 31.55 mm.

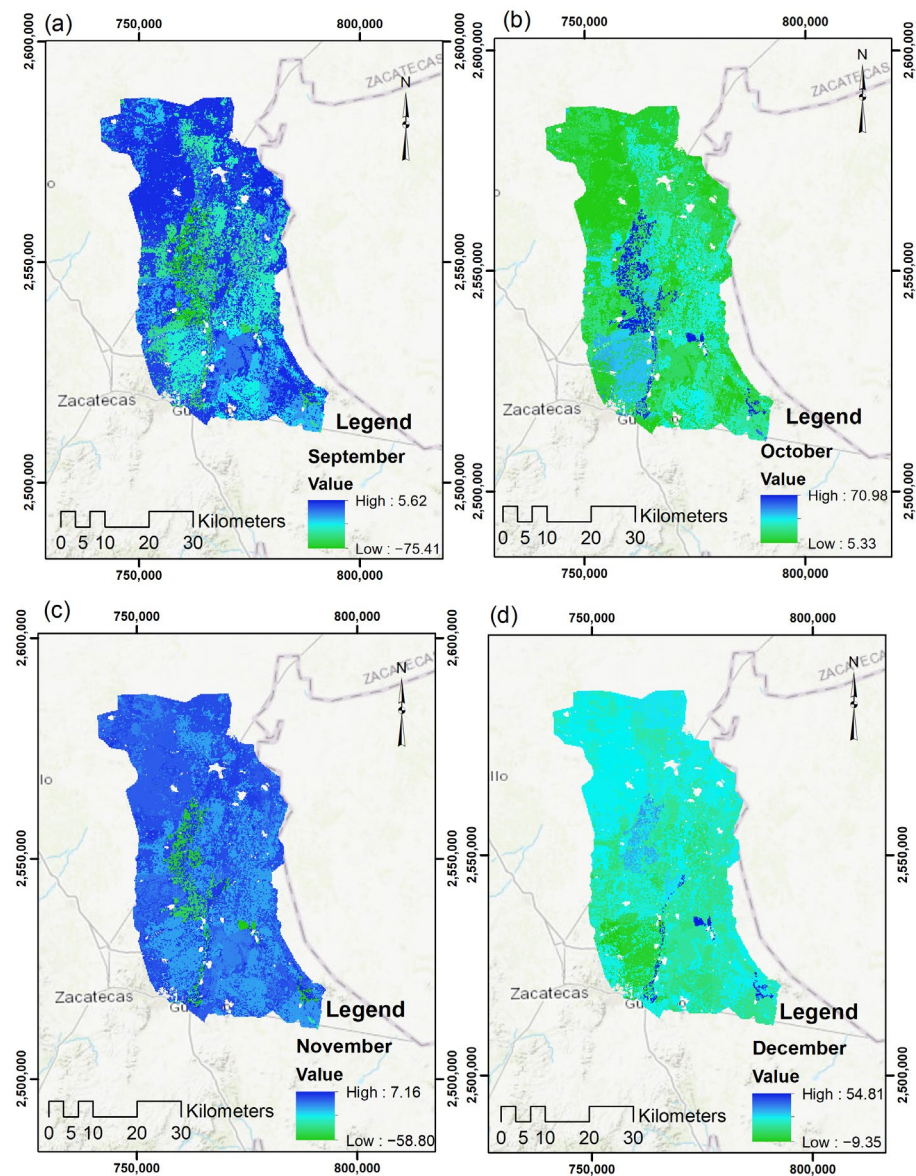


Figure 7. (a) in September, the recharge rate has already fallen to -75.41 mm, with a minimum of -16.02 mm, although negative values are already present. In the distribution, it can be seen that the maximum predominates in much of the aquifer. (b) in October, precipitation rates decrease considerably; however, temperature decreases are observed, which is attributed to low evapotranspiration and a high predominance of soil moisture. The balance shows that the average is 15.82 mm, the maximum is 70.98 mm, and the minimum is 5.33 . We can conclude that throughout the month, the infiltration of rain is constant. (c) In November, the balance shows that the average is 1.87 mm, the maximum is 7.16 mm, and the minimum is -58.80 mm. The initial moisture and the precipitation decrease allowing to the increase of evapotranspiration. The minimum values are present in the aquifer center area, whereas the average and maximum values are present in the rest of the aquifer. (d) In December, the minimum recharge is -9.35 and the average is 0.99 mm, with both values predominating throughout the rea; whereas, the 57.81 mm maximum is only present in small portions of the center and to the south of the aquifer.

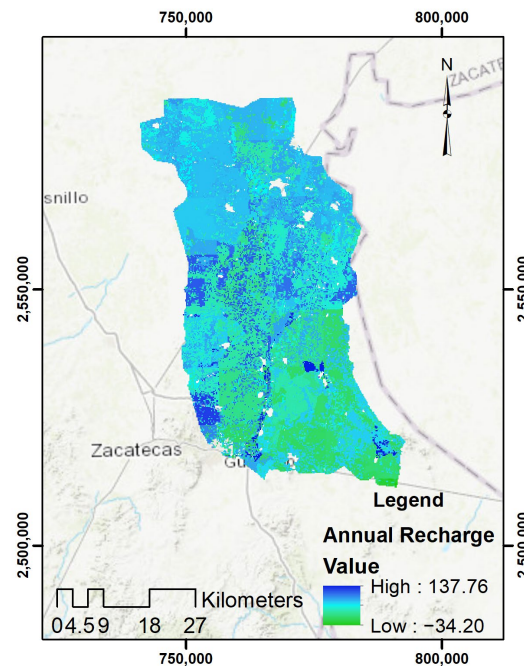


Figure 8. Finally, the annual natural recharge was obtained by adding all previous months, with the value for the average recharge being 27.27 mm, the minimum of -34.20 mm, and the maximum of 137.76 mm. The mean and maximum values are observed in the center, north, and southwest of the Chupaderos aquifer. The deficit or negative values are present in the southeast.

4. Discussion

In the present work, the monthly and annual natural recharge for 2020 is estimated using a soil moisture balance model. This model was adapted based on other research for other types of soil [23]. It is a model with a fairly simple methodology, which is why the use of these formulas is limited in different geographical particularities, specifically in semiarid areas, since this method is mostly used for areas with abundant annual rainfall. So, when applying them to other areas with different types of climatology and geology, it is important to be extremely careful, especially with the use of evapotranspiration.

Another limitation presented in this study was remote sensing since the required data for the area were only obtained at resolutions of 0.1 and 0.25 degrees per pixel, which decreased the accuracy of this work. However, the available information obtained in the field was often inconsistent due to the lack of data available in the study area, limiting a comparison of information.

The selection of the method for semiarid areas is not an easy task; in such regions, precipitation typically presents a large spatial and temporal variability, and the quantification of evapotranspiration is difficult and constitutes a significant source of uncertainty in the regional water balance. The method used, which requires only temperature data, underestimates evapotranspiration in arid zones and overestimates it in humid climates [35].

The results obtained show that the area where the greatest infiltration of rain is concentrated, contains predominantly Fluvisol and Kastanozem, sandy soils and sandy-loam soils; these two are followed by Gypsisol, Phaeozem, and Leptosols, which are loam and clay-sandy soils. Sandy soils tend to allow water to penetrate more easily [36]. Vegetation plays an important role in the results of the method as the root depth increases the soil moisture value. For Herrera (2022), the root of plants works as a conductor to groundwater by increasing moisture in deep root areas [24]. The Chupaderos aquifer vegetation is mainly scrub. The root value ranges within five meters of depth. These five meters increase water recharge and its distribution mainly in Gypsisol, Phaeozem, and Leptosol soils. According to Delgado, (2018), vegetation creates more porous soils, protecting the soil from stagnation of precipitation, which can close natural gaps between

soil particles, and releasing the soil through the action of roots. This is why wooded areas have the highest infiltration rates [37].

Topography also has an influence as flat surfaces (where water can accumulate and thus infiltrate) allow moisture to be maintained for much of the year contrary to strongly inclined surfaces [38]. This can be observed in Figure 3 where the maximum moisture is just in the area where the slope is 2% to 7%.

NDMI values range from -0.16 to 0.07 , indicating that the moisture varies depending on the amount of rain falling in the area with an interpretation of low canopy coverage and low water stress. According to Delgado (2018), this is due to a decrease in plant cover and is associated with the reduction in precipitation and infiltration [37]. There is a change in land use when it is converted to agricultural irrigation areas in what was formerly the area of grasslands within the Chupaderos aquifer. In the State of Zacatecas, this has been recognized as one of the main causes of increased runoff [39,40]. Liquid water has strong light absorption in the short-wave infrared (SWIR) band, making the NDMI highly sensitive to total vegetation water content and facilitating the identification of water in the subsoil [41].

For irrigation, return is considered an agricultural area of 180.457 square kilometers representing 7.26% of the entire aquifer for the cultivation of chili, in which, as can be observed, there is a water recharge of up to 27 mm annually. Meanwhile, for CONAGUA (2023), the incidental recharge corresponds to 18.8% of the total vertical recharge. This, however, indicates that there is a lack of information on the value of 6.5 hm^3 and that 5% of the volume applied to agricultural use returns to the aquifer. So, 18.8% of the reload is a guess. It must be considered in detail since there is a drag of salts and agrochemicals, subsequently leached from soils permeable to groundwater affecting the quality of natural aquifer water [42].

The results obtained are of a single specific point and not distributed. Thus, by creating a detailed spatial model, it is possible to extend the visual capacity to the Chupaderos aquifer. The information extracted from satellites is not tiered if not distributed, specifying the results of the whole area [43].

This estimate should be conducted every few years since there is information documented by Gonzáles et al. (2017) on the Aguanaval aquifer where the authors present the variation in the years of 1987, 1992, 2002, and 2016 on arable land and pastures, mixed forest land, mixed grasslands, and other agricultural land and water. It is observed that there is a large percentage of change over time in these factors, which are influential for the recharge of aquifers [44].

In this paper, we present the monthly and annual raster generated by the balance sheet where each pixel of $0.002^\circ \times 0.002^\circ$ ($200 \text{ m} \times 200 \text{ m}$) contains information on climatology, type, and land use thus showing the variation of recharge value over each part of the aquifer in a neat way. It is important to highlight that the results obtained are valid for 2020; therefore, it is recommended to extend the study time for future research.

5. Conclusions

The results of applying the water recharge model for 2020 show recharge ranges that vary according to each part of the aquifer; these variations are especially associated with changes in land use and type.

Using the spatial distribution, it is observed that a specific type of soil, Gypsisol, predominates with its clay-sandy texture and is mainly occupied by irrigation agriculture, temporal agriculture, and some portions of grassland. Other types of soil occupied by agriculture are Phaeozem and Leptosols (Lithosol). In this area, there is a maximum annual recharge of 50 mm and a deficit of -10 mm . For the types of Fluvisol and Kastanozem, which are sandy and sandy loam in texture, the recharge is 137 mm per year, which is the maximum recorded during the study period, and the vegetation that predominates in the area is scrubland and forest. However, the recharge is more uniform and equitable in the area of Solonetz and Leptosols (Rendzina), which is equally abundant in a type of forest

and scrubland vegetation. This shows that vegetation and soil physical properties are an important factor contributing to aquifer recharge [34].

For future research, it is proposed that the study should extend its calculation years because this research was performed using the 2020 data and update the land use classification per year based on what has been observed in recent years. There is a change in vegetation due to human activities and climate change, which influences the volume of water recharge required for aquifer regeneration. This is to provide a better approximation of the results evaluated in the period.

The monthly raster data show that the variation of the recharge is considerable in different months of the year, months that are physically dry due to lack of rainfall, but no comparison can be made. At present, there are no studies estimating the spatiotemporal natural recharge of the Chupaderos aquifer. This contribution is, therefore, important for the analysis of potential recharge areas where rational groundwater extraction can be continued.

Nowadays, the available information taken from fields in the Chupaderos aquifer is scarce and incomplete. This research provides an alternative to several aquifers with a lack of field information to produce estimates of water recharge. Applying spatiotemporal analysis, such as the one reported, allows for conducting estimations at different time intervals.

The developed methodology offers an alternative to estimating water recharge, indicating how to adjust the model in a semiarid area, involving the necessary variables for soil moisture balance. The application of these techniques to determine the water recharge of the Chupaderos aquifer in a semiarid zone is innovative since it solves the problem of linear and point models, converting the results into a spatial and distributed model, as shown in Figures 5–8.

Author Contributions: Conceptualization, M.L.-C.; methodology A.P.-G., E.O.-T. and J.E.R.-J.; software, E.O.-T.; validation, A.P.-G.; investigation, M.L.-C.; writing-original draft, M.L.-C.; writing-review & editing, A.P.-G., J.E.R.-J., C.Á.-S., A.B.-O. and H.B.-A. All authors have read and agreed to the published version of the manuscript.

Funding: The results of this publication are the product of the master thesis of the first author, who thanks CONACyT for the financial support during the postgraduate course.

Data Availability Statement: Data are available upon request from the authors.

Conflicts of Interest: The authors declare no conflicts of interest.

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