Journal of South American Earth Sciences 151 (2025) 105261

Contents lists available at ScienceDirect

Journal of South American Earth Sciences

journal homepage: www.elsevier.com/locate/jsames

Estimation of potential groundwater recharge in a growing touristic neotropical dry forest area

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A R T I C L E I N F O

Keywords:
La Tatacoa Desert
Groundwater management
Water balance-based recharge methods
ENSO
Groundwater supply
Colombia

A B S T R A C T

La Tatacoa Desert, Colombia's second most arid area after La Guajira, is one of the country's main tropical dry forest ecosystems and most attractive natural tourist areas. However, due to its climatic and hydrological conditions, this region presents a worrying panorama on water resources since 90% of the streams crossing La Tatacoa dry up during summer, affecting the water supply for human consumption, agriculture, and livestock. Therefore, groundwater in the area is an invaluable resource that could help meet future demand, and identifying the primary source of recharge becomes an urgent matter. In this paper, we intend to approach the subject only from the analysis of direct recharge for the three main hydrologic conditions in the region: neutral, dry (el Niño), and humid (la Niña), considering the influence of the ENSO. For this purpose, potential recharge was estimated using the SWB (soil water balance) method suggested by the USGS (United States Geological Service). Our results showed that direct recharge for humid conditions is around 380 mm/yr. For neutral and dry conditions, it ranges between 115 mm/yr and 160 mm/yr, corresponding to a recharged precipitation of 10% and 15%, respectively. These values are similar to those reported for semiarid areas, even though rainfall in La Tatacoa ranges between 1000 and 1500 mm/yr. Such low values of direct recharge, compared with the reported use of groundwater in the area, might suggest that there is a complementary source of recharge, probably from the perennial rivers surrounding La Tatacoa (Magdalena or Cabrera), but this is something that is yet to be proven. This study enhances our understanding of groundwater recharge in arid regions, offering new insights for sustainable groundwater management. However, further studies are needed to assess the impact of climate change on direct recharge so that more sustainable water management can be implemented in La Tatacoa, especially concerning supply for the increasing touristic activities.

1. Introduction

Groundwater accounts for 30% of the world's freshwater supply and constitutes the water source for more than two billion people worldwide (Ajami, 2020). Increases in population, different environmental concerns, prolonged droughts, and inadequate water system management present challenges worldwide and require urgent attention from entities responsible for groundwater management (Nieto, 2011; Yazdian et al., 2021), particularly in various areas of Latin America (Nieto, 2011). Furthermore, the 2030 United Nations agenda and development goal number 6, "Clean water and sanitation", seeks to guarantee this vital resource for different regions' populations (United Nations – UN, 2018).

When several actors share a groundwater system, and there are differences between water supply and demand, it generates uncertainty and debates on how water should be distributed equitably (Mooselu et al., 2019) without intensive use, which can be attained by quantifying and monitoring the aquifer's water volumes (Singh et al., 2019). Hence, direct recharge by precipitation must be estimated. This component of the hydrological cycle depends, besides rain, on physical characteristics such as soil properties, topography, land use, and vegetation cover (Maréchal et al., 2009).

In semiarid and arid areas, recharge is irregular and occurs during periods of heavy rainfall. However, recharge rates in dry areas also depend on soil characteristics, especially considering that vegetation is scarce (Owuor et al., 2016). A global-scale summary of 140 sites in such regions showed an estimated average annual recharge rate of 0.2–35

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https://doi.org/10.1016/j.jsames.2024.105261
Received 26 August 2024; Received in revised form 14 November 2024; Accepted 14 November 2024
Available online 15 November 2024

mm/year, representing about 0.1–5% of the mean annual precipitation (Scanlon et al., 2005). Intermittent recharge resulting from infrequent, high-intensity precipitation events constitutes the majority of groundwater recharge in arid environments (Thomas et al., 2016). Therefore, long-term imbalances in groundwater recharge are expected to occur in arid regions due to variations in precipitation associated with climate change (Hashemi et al., 2015).

Groundwater in arid and semiarid areas is critical. It alleviates the pressure on surface water resources that are often scarce in these regions, favors drinking water supply, supports irrigation, and maintains essential native terrestrial ecosystems (Jackson et al., 2001; Pereira et al., 2023). Therefore, a correct estimation of potential water resources available for extraction is necessary, and recharge is one of the main variables concerning groundwater management. Overestimating available groundwater resources could result in poor water resource management, so interpretations based on the results must be carefully considered. The limitations of these estimation methods should always be kept in mind.

Groundwater recharge in arid zones like La Tatacoa Desert faces challenges due to climate variability. Carrillo-Rivera et al. (2013) and Van Wyk et al. (2024) highlight the complexities of assessing recharge in such environments; Jasechko and Perrone (2020) emphasize the global vulnerability of groundwater resources and the need for a deeper understanding of recharge processes; research by Green et al. (2011) has explored the impacts of climate change on groundwater recharge; and, finally, Wada et al. (2016) and Gleeson et al. (2012) stress the need for integrated management approaches, especially where tourism and population growth increase water demand.

There are different methods to estimate recharge: direct measurements, Darcy techniques, plotting techniques, empirical methods, and water balance (Lerner et al., 1992; Samper, 1997). Water balance methods are based on the equation of continuity, where the difference in inflows and outflows must equal the change in water storage (Samper, 1997). Existing water balance models include the HBV (Hydrologiska Byråns Vattenbalansavdelning model) (Bergström, 2019), PRMS (Precipitation Runoff Modeling System) (Regan and LaFontaine, 2017), SWAT (Soil and Water Assessment Tool) (Bailey et al., 2020), and SWB (Soil Water Balance) (Westenbroek et al., 2010), among others. Most of these techniques do not measure the actual value of the aquifer's recharge but make a potential estimate, defined as the water that infiltrates but does not necessarily reach the aquifer (Rushton, 1988).

In Colombia, according to the Institute of Hydrology, Meteorology, and Environmental Studies (IDEAM), groundwater represents 72% of the total water resources, sixty-four (64) aquifer systems have been identified, and almost 70% of those systems do not have enough information for sustainable use (IDEAM, 2010, 2015, 2019). Among those is the Neiva-Tatacoa-Garzón aquifer system (SAM 2.37 according to the terminology used by IDEAM), where La Tatacoa Desert (LTD) is located. Although LTD is not technically a desert but a tropical dry forest, the heavy deforestation over the past six hundred years turned it into Colombia's second largest arid zone, with an area of more than 300 km^2 around the town of Villavieja, where 90% of the streams dry up during drought periods (Alcaldía de Villavieja, 2016). Hence, the Neiva-Tatacoa-Garzón aquifer system becomes, in many cases, the only supply source of water for the over 7000 permanent inhabitants of LTD and the thousands of tourists who visit each year (CAM, 2015). Consequently, quantifying the recharge of the aquifer is relevant to ensuring water availability for the Villavieja community and the region's tourist plans.

When trying to understand groundwater dynamics in La Tatacoa Desert, one of the main research questions is related to the recharge areas. Here, we propose two possible sources: direct recharge by precipitation and indirect recharge from the perennial water bodies in the area (Magdalena River and Cabrera River). We decided to address the first option under the hypothesizes that direct recharge in the study area will be similar to those reported for arid and semiarid regions worldwide, even though La Tatacoa has an average precipitation of 1100 mm/yr (Rojas et al., 2000), but it would not be enough to account for all the groundwater that is reported and used in the area. Therefore, our study's main goal was to estimate the magnitude of potential direct recharge of the aquifer by precipitation for neutral, dry, and humid conditions using the Soil Water Balance (SWB) method, which we performed based on applying geographic information systems (GIS).

2. Study area

The study area, known as La Tatacoa Desert (LTD), has an extension of 354 km^2 and is located in the central-southern part of Colombia, in the Huila and Tolima departments, specifically in the municipalities of Villavieja and Natagaima. Precipitation is approximately 1100 mm/year, the average temperature is 28 °C (Rojas et al., 2000), and has a dry forest vegetation cover (Hermelin, 2016). The area's hydrography includes several main streams, such as the Magdalena River to the west, the Cabrera River to the east, and the Las Lajas Creek to the south; these streams were used to define the boundaries of the recharge simulation (Fig. 1).

2.1. Geology

Colombia is divided into 16 hydrogeological provinces (HP), which are, in turn, subdivided into aquifer systems (AS). The study area is located in the Upper Magdalena Valley HP, bounded north and west by the pre-Cretaceous rocks of the Central Cordillera, to the southeast partially by the Algeciras-Garzón Fault System, and to the northeast by the Bituima-La Salina Fault System (Fig. 1).

Several authors have described LTD's geology, such as Rodríguez and Fuquen (1989), Guerrero (1993, 1997), and Montes et al. (2021, Fig. 1a). The lithology corresponds to Miocene clastic sedimentary rocks from the Honda Group, divided into Villavieja and La Victoria formations. The Jurassic Saldaña Formation outcrops to the north and east of the study area, constituting the topographic highs.

The La Victoria Formation has five beds: San Alfonso, Cerro Gordo, Chunchullo, Tatacoa, and Cerbatana. The first four are mainly formed by sandstones, and the last by conglomerates. The Villavieja Formation is divided into tree beds: Cerbatana (which corresponds to the base of the Villavieja Formation), La Venta red bed, and El Cardón red bed; the last two are predominantly composed of fine-grained sedimentary rocks. In addition, Montes et al. (2021) mapped the presence of fine-grained dissected deposits, other coarse-grained units, colluvium, and alluvial deposits.

2.2. Hydrogeology

The area is part of the Neiva-Tatacoa-Garzón aquifer system (Fig. 1a–d), with a surface area of 4277 km^2 and thicknesses reaching up to 800 m (IDEAM, 2015). It is formed by several free, semi-confined, and confined aquifers (IDEAM, 2015). The National Water Study of 2010 (ENA by its Spanish acronym; IDEAM, 2010) proposes a basic hydrogeological model for the Upper Magdalena Valley, describing the Honda Group as part of a primary porosity aquifer. This group is also described by Universidad Nacional (2006) as two hydrogeological units (HGU): HGU1 corresponds to the La Victoria Formation for which three (3) strata were defined, from base to top, as conglomeratic sandstones with variable thicknesses between 20 and 40 m; sandy siltstones with thicknesses between 20 and 40 m; sandstones underlain by siltstones with variable thicknesses between 10 and 40 m. This HGU1, limited by sandy siltstones, is classified as a semi-confined unit. HGU2 corresponds to the Villavieja Formation, composed of sandy siltstones and clays that prevent easy water extraction due to their low permeability and do not represent hydrogeological interest for the area.

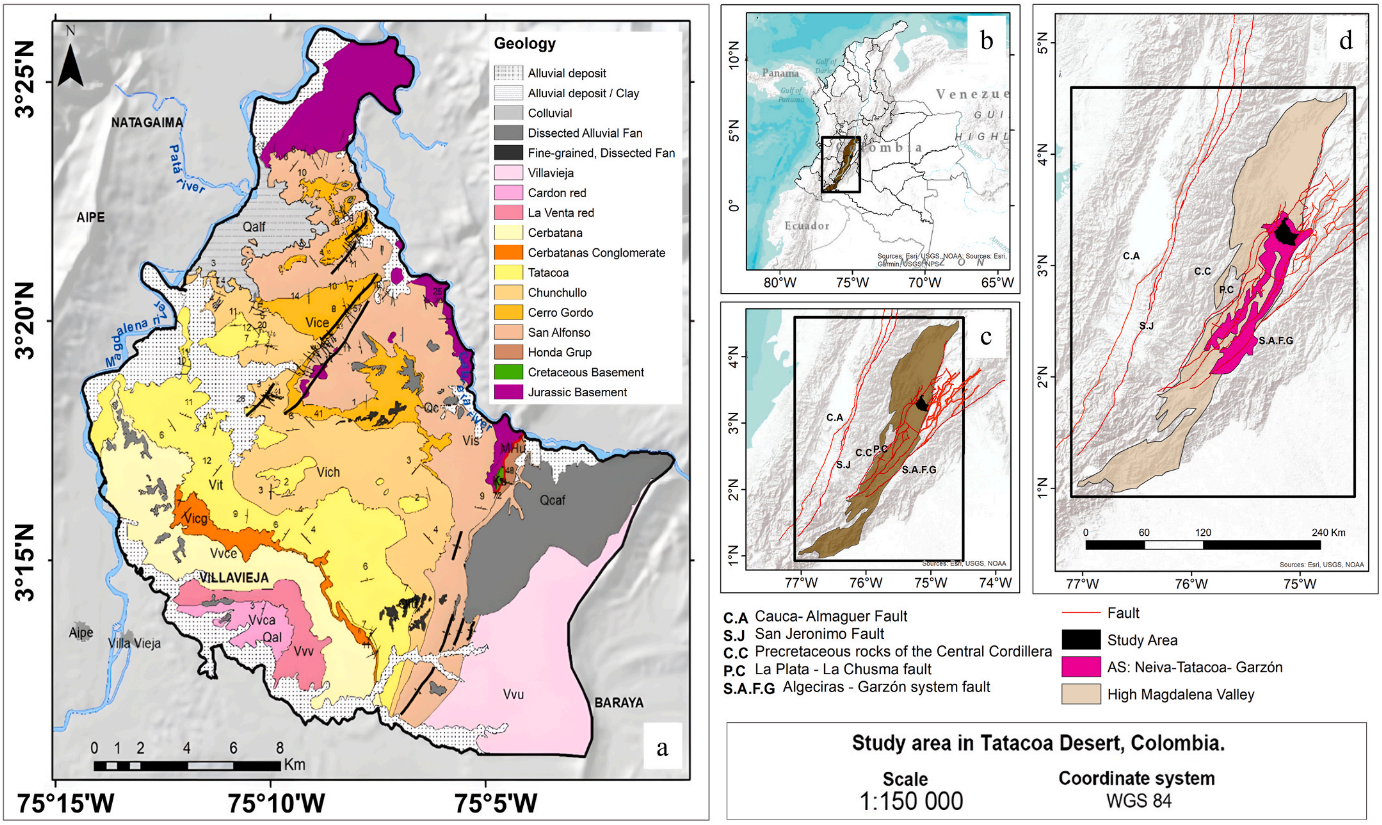

Fig. 1. Map of general information about the study area. a) Geologic map of the study area; b) Location of the Upper Magdalena Valley Hydrogeological Province (HP) (Montes et al., 2021); c) Boundaries of the Upper Magdalena Valley HP (IDEAM, 2010); d) Location of the study area within the HP and the Neiva-Tatacoa-Garzón Aquifer System (AS) associated with its hydrological limits (IDEAM, 2010).

3. Methodology

For this study, we used the soil water balance (SWB) model developed by the USGS in 2010, which calculates recharge with a daily mass balance (Westenbroek et al., 2010). We selected this method because it simulates the complexity of the basins' processes in a simple and effective spatiotemporal way. It is also fast and low-cost and allows working with the available information without too many assumptions. The method focuses on the relationship between the hydrological processes involved in producing recharge in a distributed manner (pixel by pixel), considering soil properties and topography.

One limitation of this method is that the only loss mechanism is recharge when evapotranspiration and soil moisture demands are met, which sometimes results in overestimating recharge values (Westenbroek et al., 2010). However, these overestimation errors can also occur when using soil water flow models with measured or estimated hydraulic conductivities and soil tension gradients (Gee and Hillel, 1988). In semiarid areas, direct soil recharge measurements would be ideal. However, this information is not available in the study area.

The SWB is based on geographic information systems (GIS) and calculates in each grid cell a potential recharge value using the water balance equation:

$$Recharge = (Precipitation + Inflow) - (Interception + Outflow + Evapotranspiration) - \Delta Soil\ moisture$$

This recharge model requires daily information on precipitation, minimum and maximum temperature, and raster information on surface flow directions, vegetation cover, and soil texture. Parameters and units used for SWB are presented below (Table 1).

Table 1
Parameter and units for SWB simulation.

N° Rows	311
N° Columns	277
Cell size	100 × 100 m
Daily precipitation	Inches
Daily temperature	degrees Fahrenheit
Available water capacity	in/ft of thickness

3.1. Precipitation

Precipitation was acquired from the Climate Hazards Group Infrared Precipitation with Station data (CHIRPS) product (Funk et al., 2015), which incorporates 5566 m resolution satellite imagery with data from in situ stations to create different series with spatial and temporal variability of precipitation. The time series' temporality was defined with a 30-year record from 1990 to 2019.

Considering that Colombia is affected by a climatic phenomenon known as "El Niño Southern Oscillation" (ENSO), which increases or decreases precipitation in certain areas, model simulations were performed for dry (El Niño), humid (La Niña), and neutral conditions. The selection of humid, dry, and neutral periods was based on information from the SOI index (NOAA, 2023), which allows for determining the development and intensity of El Niño or La Niña events in the Pacific Ocean and is calculated based on the pressure difference between Tahiti and Darwin. SOI values less than −0.5 are defined as dry climatic conditions (El Niño) with less precipitation, SOI values greater than 0.5 are classified as periods of humid conditions (La Niña) with more precipitation, and SOI values between −0.5 and 0.5 are defined as periods without ENSO influence (neutral conditions). Considering this information, the years between 1990 and 2019 were classified as humid, dry, or neutral (Table 2).

3.2. Temperature

We used the ERAS5 (Hersbach et al., 2020) database for temperature data, managed by the European Center for Medium-Range Weather Forecasts (ECMWF). Despite its lower resolution compared to the study area, this database's global coverage made it suitable. Like the precipitation data, we classified the minimum and maximum temperatures for dry, humid, and neutral climatic conditions.

3.3. Digital elevation model – flow direction

The digital elevation model (DEM), with a spatial resolution of 12.5 m, was downloaded from ASF Alaska from the ALOS PALSAR satellite (Dataset: © JAXA/METI ALOS PALSAR L01.01, 2011). Furthermore, a surface flow direction layer was defined using the GIS tools D8 method (O'Callaghan and Mark, 1984), allowing the recharge model to determine the connection and flow exchange between adjacent cells.

3.4. Land cover

A LANDSAT-8 image with a resolution of 30 m integrates NASA's Science Mission Directorate's worldwide program and provides users with high-resolution visible and infrared imagery (USGS, 2021). The imagery was downloaded free from the Earth Explorer platform provided by the USGS. The input map was developed based on the normalized difference vegetation methodology (NDVI) proposed by Tucker (1979), widely used in both international research (Bagherzadeh et al., 2020; Ramadhani et al., 2021) and local research (Poveda et al., 2001; Casamitjana et al., 2020; Perea-Ardila et al., 2021), in which vegetation is classified based on the near-infrared band (NRI) and the red band (RED), which for LANDSAT corresponds to Bands 5 and 4, respectively.

The raster obtained was reclassified according to Table 3, as Olivo (2017) suggests, and categorized according to Anderson's level II classification (Anderson et al., 1976) to obtain the relationship between soil type, soil cover, and the curve number. This information was used to calculate surface runoff and assign a maximum soil moisture capacity for each grid cell (Westenbroek et al., 2010). The results were validated by comparing them with a recent satellite image of the area from Google Earth.

3.5. Soil texture

Soil texture information was downloaded from the 1:100,000 mapping of the Agustin Codazzi Geographic Institute from Colombia (IGAC, 2017). This information allowed the model to define variables that condition recharge, such as soil available water capacity (AWC) and the hydrological group in which the soil is categorized. AWC was assigned according to the table by Thornthwaite and Mather (1957) and recommended by the SWB Manual (Table 4).

The hydrologic group information was entered as a map in ASCII format classified from the Soil Hydrologic Groups of the Soil Conservation Service (SCG, 1964 in Bradbury et al., 2000), as seen in Table 4. The soil's infiltration rate was considered for the classification, and integer values from 1 to 4 were assigned for groups A to D, respectively.

Table 2
Classification of climate conditions for 1990 to 2019 using the SOI index (NOAA, 2023).

Year	Condition	Year	Condition	Year	Condition
1990	Neutral	**2000**	Humid	**2010**	Humid
1991	Dry	**2001**	Neutral	**2011**	Humid
1992	Dry	**2002**	Neutral	**2012**	Neutral
1993	Dry	**2003**	Neutral	**2013**	Neutral
1994	Dry	**2004**	Neutral	**2014**	Neutral
1995	Neutral	**2005**	Neutral	**2015**	Dry
1996	Humid	**2006**	Neutral	**2016**	Neutral
1997	Dry	**2007**	Neutral	**2017**	Neutral
1998	Neutral	**2008**	Humid	**2018**	Neutral
1999	Humid	**2009**	Neutral	**2019**	Neutral

Table 3
Classification of vegetation cover by NDVI values (Olivo, 2017).

NDVI	
<0	Water and/or Shaded areas
0–0.2	Bare ground
0.2–0.4	Scarce vegetation
0.4–0.6	Dispersed vegetation
>0.6	Dense vegetation

3.6. Recharge values and conditions of the model

The generated inputs were integrated into the execution of the SWB model. The recharge model offered by the USGS was used as a control panel, in which the coordinates (x,y) of the area of interest, number of rows, columns, and cell size of the ASCII files were entered. Also, within the control panel, the option of calculating evapotranspiration employing the Hargreaves and Samani (1985) method was selected because it can produce a spatially variable estimate of potential evapotranspiration if supplied with spatially varying minimum and maximum air-temperature grids for each daily timestep (Westenbroek et al., 2010).

Finally, the model output files were processed and reclassified according to the SWB model manual (Westenbroek et al., 2010) to generate the final maps of potential recharge under neutral, dry, and humid conditions. Future studies should explore the influence of actual evapotranspiration (AET) on the estimates since this could be the control variable in dry areas.

4. Results

Below are the processed precipitation results, thematic maps, potential groundwater recharge, and evapotranspiration for the study area.

Table 4
Available water capacity and Hydrologic group classification related to soil texture.

Soil texture	Available water capacity		Hydrologic group		
	(in/ft of thickness)	(mm/m of thickness)	Wet soil infiltration	Feature	Group
Sand	1.2	100.0	Fast	High IC > 76 mm/h	A
Fine sandy loam	1.8	150.0	Medium	IC 76-38 mm/h	B
Very fine Sandy loam	2.0	166.7			
Sandy clay loam	2.7	225.0	Slow	Low IC 36-13 mm/h	C
Silty clay	3.4	283.6	Very slow	Very low IC < 13 mm/h	D

*IC; Infiltration capacity.
Adapted from Thornthwaite and Mather (1957) and SCS (1964) in Bradbury et al. (2000).

4.1. Mean precipitation maps for dry, humid, and neutral conditions

The precipitation in the area is between 1000 and 1500 mm/year (Fig. 2), with the highest values to the north and west and the lowest to the southeast. For each climatic condition, the following average precipitation values were obtained: 1262 mm for neutral, 1133 mm for dry, and 1595 mm for humid conditions.

4.2. Thematic maps: flow directions, landcover, soil water retention capacity, and hydrologic group

A western direction dominates surface flow in 23% of the region because most basins drain into the Magdalena River on the area's western flank (Fig. 3a). Regarding vegetation cover, grasses and shrubs, represented in green, occupy 61% of the study area, and bare soils (in brown) are concentrated in the central zone and occupy 36% of the territory (Fig. 3b).

Soils in La Tatacoa (Fig. 3c) are dominantly sandy (66%), with a retention capacity of 100 (mm/m), followed by alluvium of varied size (20%) and a retention capacity of 150 (mm/m), and finally, sands and clays (14%) with the highest retention capacity of 166.7 (mm/m). Almost the whole study area (99%) was classified as hydrologic group A (Fig. 3d), i.e., zones with rapid infiltration associated with the sandstone and conglomerate beds of the La Victoria Formation.

A recent satellite image shows that the central zone is predominantly bare soil, while in the zones near the study area's limits, there is a little more vegetation cover. These results are consistent with the NDVI methodology (Fig. 4).

4.3. Recharge maps for the three climatic conditions

The spatially distributed results for estimated potential groundwater recharge under normal, dry, and humid conditions are presented below (Fig. 5). For all three scenarios, the potential recharge presents the lowest values to the east of the study area, becoming cero (absence of recharge) during the dry season (El Niño condition).

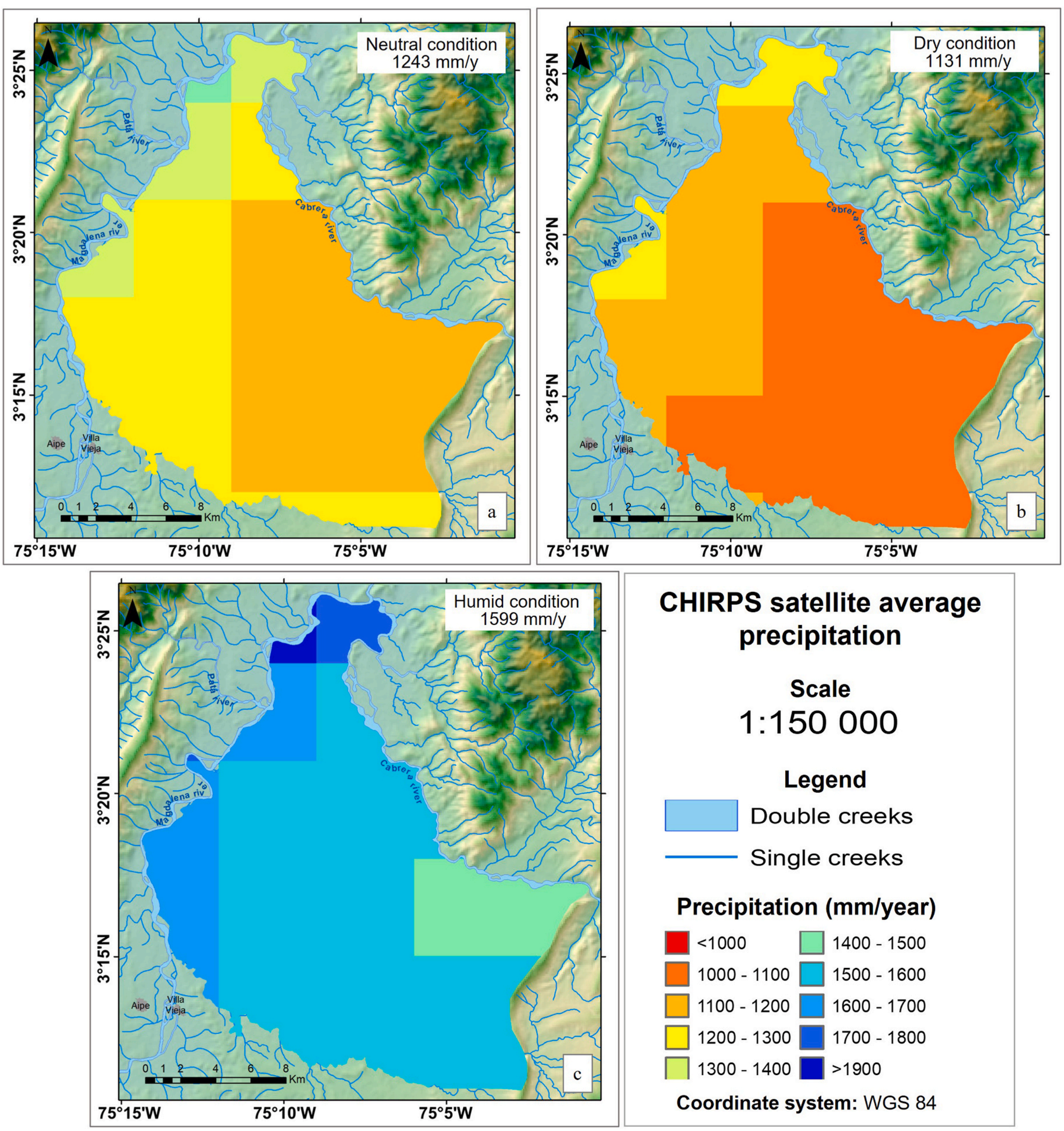

Fig. 2. Precipitation maps for neutral, dry, and humid conditions in La Tatacoa Desert: a) Neutral condition, b) Dry condition, c) Humid condition.

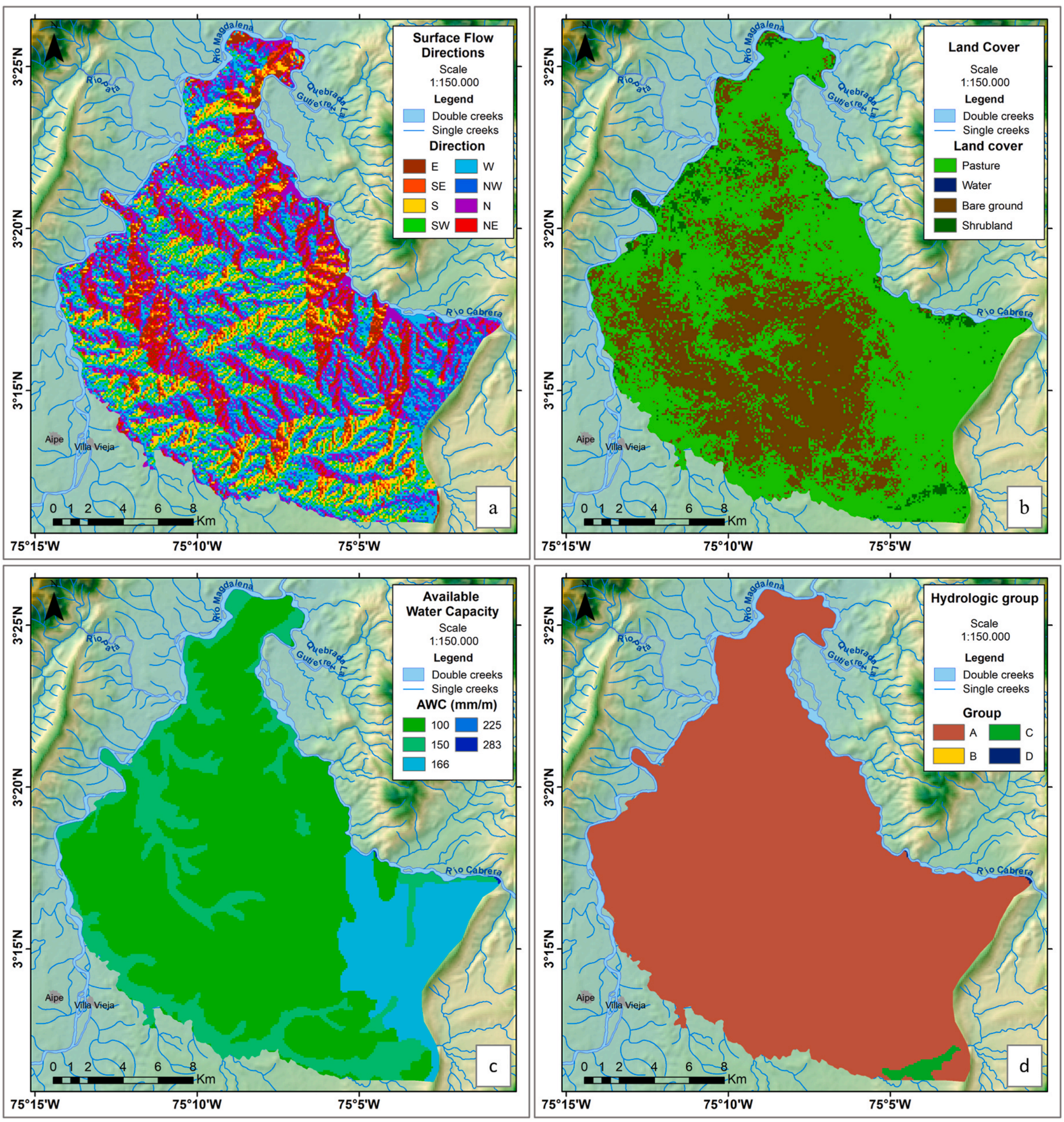

Fig. 3. Thematic maps: a) Surface flow directions; b) Landcover; c) Soil water retention capacity; d) Hydrologic group.

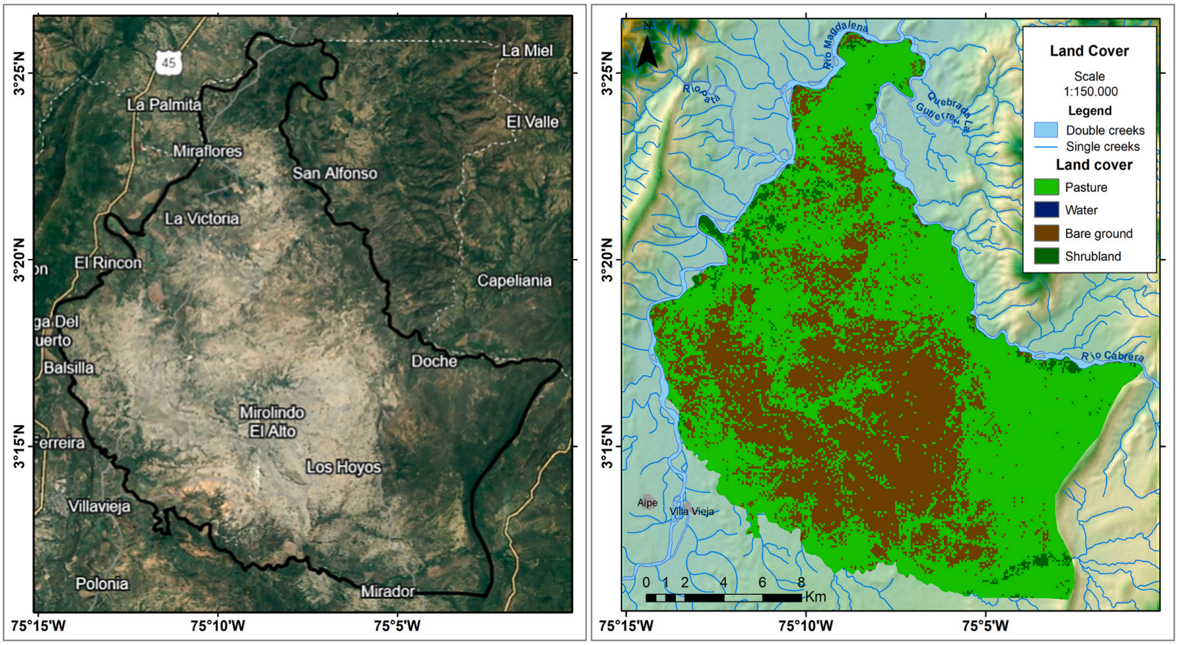

Fig. 4. Validation of the results of the NDVI methodology (right) by comparing with a recent satellite image of the area (left).

The average for neutral conditions is 158 mm/year, corresponding to 13% of the precipitation for the same condition. The average for dry conditions is 114 mm/year, accounting for around 10% of the precipitation during that same period. Finally, the average recharge for humid conditions is 378 mm/year, representing almost 23% of the precipitation (Table 5).

4.4. Actual evapotranspiration maps for the three climatic conditions

Actual evapotranspiration (AET) for neutral conditions is between 900 and 1200 mm/year (Fig. 6a), with an average value of 1056 mm/year, corresponding to 85% of the precipitation for this climatic condition (Table 5). As for AET for dry conditions, the values are primarily between 900 and 1050 mm/year (Fig. 6b), with an average value of 1024 mm/year, corresponding to 90% of the precipitation for these conditions. Finally, for humid climatic conditions, AET presents values above 1050 mm/year (Fig. 6c) and the highest average values of all conditions (1178 mm/year), representing 73% of the precipitation (the lowest percentage of the three conditions).

Finally, the difference in recharge values for the different climatic conditions based on neutral conditions shows that recharge increases by 128% in humid conditions and decreases by 30% in dry conditions (Table 5).

5. Discussion

We used the SWB model to quantify direct recharge in La Tatacoa Dessert (LTD). The results showed a recharge between 10% and 13% of the average precipitation for neutral and dry (El Niño) climatic conditions, which validates the hypothesis that, despite having higher precipitation than arid and semiarid areas, recharge values are similar to those found by other authors in semiarid regions (Gee and Hillel, 1988; Scanlon et al., 2006; Yeh et al., 2007; Alvarez et al., 2013; Demlie, 2015; Dash et al., 2016; Hou et al., 2016; Coelho et al., 2017). On the other hand, recharge values for humid conditions (La Niña) are outside the ranges for semiarid zones and doubled and tripled those for neutral and dry conditions, respectively. The high temporal variability of recharge values in LTD correlates with the temporal variability reported in other studies conducted in semiarid regions (Gee and Hillel, 1988; Souza et al., 2018; Baalousha et al., 2018). Vries and Simmers (2002) and Baalousha et al. (2018) stated that direct recharge occurs even in arid and semiarid regions; however, as aridity increases, indirect recharge becomes more critical in these areas. This opens the possibility of indirect recharge sources to the aquifer in La Tatacoa, probably from permanent streams such as the Magdalena and Cabrera rivers.

Besides precipitation, evapotranspiration is another essential element to estimate recharge, which, for the SWB model, is calculated using the Hargraves and Samani equation (Westenbroek et al., 2010). This approach can be a limitation because such an equation only considers temperature information. Therefore, the percentage of evapotranspiration obtained in this study (for neutral conditions, 85% of the precipitation; for dry conditions, 91%; and for humid conditions, 74%) should be validated with other evapotranspiration estimation methods, such as those that use energy balance (for example the METRIC model), or local measurements. In this way, the influence of evapotranspiration on the recharge estimates could be evaluated to determine whether this is the control variable for dry areas, as other authors suggest.

Regarding the spatial variability of recharge, the eastern zone presented the lowest recharge values for the three climate scenarios, probably due to the high water retention capacity in the soil that hinders the percolation of water to the aquifer. On the other hand, the highest recharge values were located mainly in the northern and southwestern zones of the study area, where the vegetation is grassland, and the water retention capacity is low (100 mm/m or 1.2 in/ft). According to Gee and Hillel (1988) and (Vries and Simmers, 2002), little or no vegetation cover is conducive to groundwater recharge. In La Tatacoa, the vegetation cover is sparse, mainly grasses, bare soil, shrubs, and water bodies; therefore, the vegetation cover's characteristics are conducive to

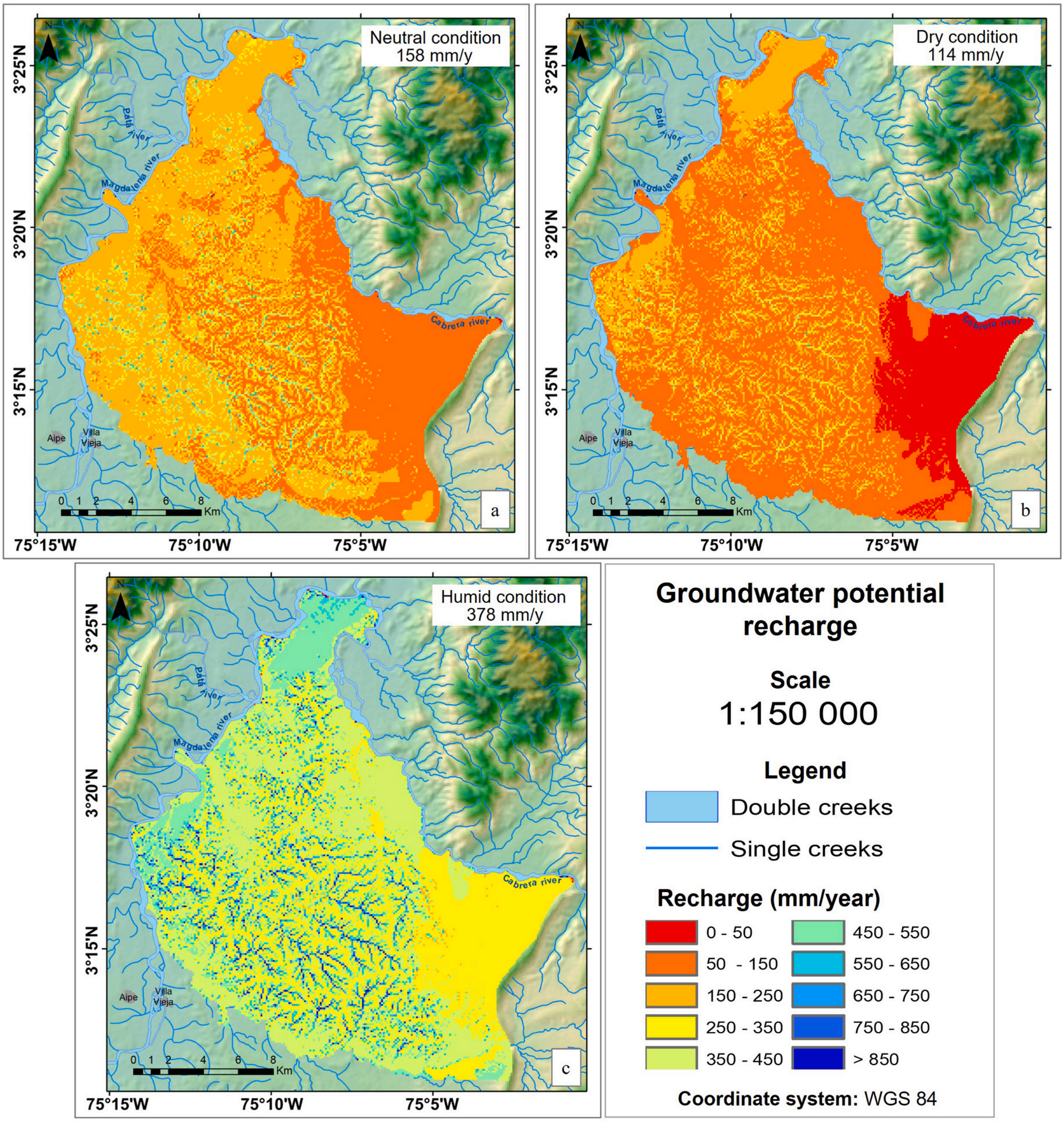

Fig. 5. Potential Recharge maps of groundwater for neutral (a), dry (b), and humid (c) conditions in La Tatacoa Desert.

Table 5
Summary of average precipitation, recharge, and evapotranspiration.

Climate condition	Precipitation (mm/year)	Recharge (mm/year)	Actual Evapotranspiration (mm/year)	% Precipitation converted in recharge	% Precipitation converted in evapotranspiration
Neutral	1243	158.6	1056.8	12.8	85.0
Dry	1131	114.5	1024.0	10.1	90.5
Humid	1599	378.7	1178.1	23.7	73.7

groundwater recharge. It is essential to highlight that due to some limitations of the SWB, the vegetation cover information is considered a constant file during the entire recharge simulation. Therefore, considering the importance of this variable in the recharge estimation results of this project, we recommend that further studies use physically based methods such as the TETIS model (Francés et al., 2007), which allows for the variability in vegetation cover implementation. Despite the limitations, Dripps and Bradbury (2007) argue that the SWB model balances accuracy and complexity; in addition to being a simple method to apply, it provides spatial and temporal estimates of precipitation recharge of groundwater. Furthermore, these models can generate reasonable recharge estimates at monthly and annual scales (Westenbroek et al., 2010).

Vries and Simmers (2002) state that groundwater recharge in semi-arid areas is much more susceptible to near-surface conditions. According to the results of this project, recharge is directly affected by precipitation rates, and El Niño Southern Oscillation (ENSO) tends to modify precipitation regimes (Poveda and Mesa, 1996; Puertas-Orozco

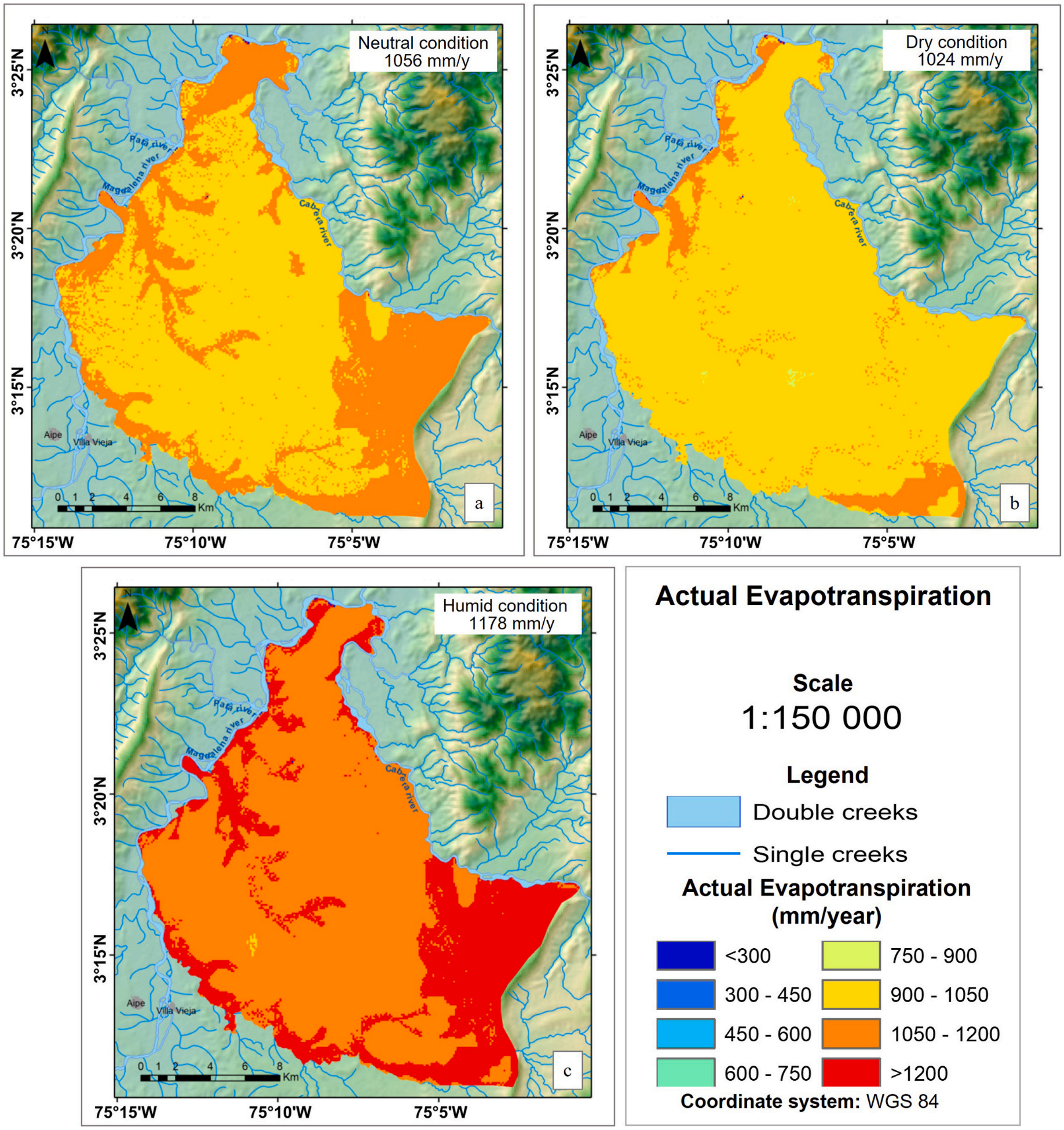

Fig. 6. Evapotranspiration maps of groundwater for neutral (a), dry (b), and humid (c) conditions in La Tatacoa Desert.

and Carvajal-Escobar, 2008). Considering the influence that precipitation has on groundwater recharge in La Tatacoa and the groundwater supply role in this region, studies are recommended, such as those by Abdulla et al. (2008), Chen (2013), Pulido-Velazquez et al., 2014, Jyrkama and Sykes (2007), where the effect of climate change in precipitation and temperature on recharge was evaluated.

One of the region's main problems is water resources due to dry climatic conditions and elevated levels of desertification (Alcaldía de Villavieja, 2016). The local desertification condition is such that it was one of the areas most affected by the 1998 El Niño phenomenon, even " … endangering the existence of the inhabitants … " (Alcaldía de Villavieja, 2016). Moreover, despite the potential of groundwater to supply the demand (totally or partially) for domestic, livestock, and agricultural use, few specialized studies have been conducted in La Tatacoa.

The results of this study will be helpful for future research to identify the primary source of recharge for the aquifers of La Tatacoa Desert. Since precipitation recharge values are like those of arid and semiarid zones, it is possible that, as reported in the literature, indirect recharge has a more significant contribution to aquifer recharge. At the same time, it will help to improve the knowledge of groundwater resources in the area, directly impacting the population for whom groundwater becomes, in many cases, the only supply option.

Recharge estimations are crucial for any groundwater management, but they become essential in arid or economically fast-growing regions, such as La Tatacoa. However, in developing countries, the availability of data that allows a precise determination of groundwater offer is limited, and generic assessments such as the one used for this research are needed, mainly because they open the door to more studies. In the case of La Tatacoa Desert, the main question remains about the primary source of recharge, and a new question arises: How will climate change affect groundwater availability? Until we know the answers to these questions, the research must continue, and hopefully, the government will join in the efforts.

6. Conclusions

This paper presents the results of estimating direct groundwater recharge for La Tatacoa Desert, Colombia's second-most arid region and one that attracts more tourists every year. The method used was the soil water balance (SWB) developed by the USGS, and annual recharge maps were generated for average hydroclimatological conditions and the dry and humid phases of the ENSO (El Niño and La Niña, respectively).

The results obtained in this research for percentages of precipitation recharged (12.8% for average conditions, 10% for El Niño, and 23.7% for La Niña) are similar to those of semiarid zones reported by several authors. The low values might suggest sources of indirect recharge in the area, possibly from the main perennial rivers, the Magdalena and the Cabrera. Isotope studies should be conducted to evaluate this hypothesis and determine the primary recharge source, which is essential to manage and protect the groundwater resources in the region adequately.

Although precipitation is essential for estimating direct recharge, other factors such as evapotranspiration, vegetation cover, and soil texture must be considered. Therefore, the quality and resolution of these data should be continuously improved, variations in vegetation cover should be implemented, and soil texture information should be updated with newly reported evidence. Finally, studies must be conducted to evaluate climate change's effects on precipitation and temperature in this area, as those are the two main variables controlling direct recharge.

Research on groundwater recharge in La Tatacoa Desert highlights the need for adaptative water management, especially in contexts of climate variability. For sustainable management, it is suggested that high rainfall periods be taken advantage of for water capture and storage, and soil and vegetation conservation practices that enhance infiltration should be adopted. Planning should consider both the spatial variability of recharge and the interactions between surface and groundwater, integrating complementary assessment methods to obtain a more complete picture of the hydrological cycle. These findings can inform public policy and conservation strategies, underlining the importance of incorporating climate change adaptation into water resources management.

Few studies on the hydrogeology of La Tatacoa Desert have been conducted; therefore, the current information needs to be more comprehensive to generate an accurate conceptual hydrogeological model that would allow integrated management of water resources. It is necessary to review and collect more geological and geophysical data that would enable the definition of the geometry of the aquifer and the possible hydraulic connection among the hydrogeological units to determine other potential indirect sources of recharge. Also, instrumentation of the aquifer with observation wells is needed to monitor piezometric levels so a groundwater flow model of the aquifer can be implemented and calibrated, and the decision-makers in the region can have a robust tool that allows them to sustainably manage the water in the short, medium, and long term.

Funding

This reserach was funded by EAFIT University, Medellin, Colombia, South America.

CRediT authorship contribution statement

Ballesteros-Buitrago Karen: Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Conceptualization. **Jaramillo Marcela:** Writing – review & editing, Supervision, Project administration, Funding acquisition, Conceptualization. **Vergara-Bechará Santiago:** Writing – review & editing, Supervision, Software, Methodology, Conceptualization. **González-Jiménez Lauren:** Writing – review & editing, Methodology, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

We want to thank EAFIT University for funding this research and express our gratitude to the Undergraduate Groundwater Research Group (SIAS by its Spanish acronym) of the Geology program at the School of Applied Sciences and Engineering of EAFIT University.

Data availability

Data will be made available on request.

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