Estimation of groundwater recharge potential using MIF techniques in the Tatacoa desert, Huila, Colombia

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Abstract

The Tatacoa desert, in the department of Huila, Colombia, is located between the Magdalena River and the Eastern Mountain Range. It is an arid zone, with a lot of erosion, classified as a tropical dry forest with maximum temperatures of 40 °C. The climatic and hydrogeological conditions produce problems related to water resources in the area, since, during the summer, 90 % of the streams dry up, causing a problem of drought in the municipality of Villavieja; however, there is underground water, but it is exploited in an empirical and not scientific way. The little hydrogeological knowledge comes from the Institute of Hydrology, Meteorology and Environmental Studies (IDEAM) studies, where it is made clear that the area belongs to the Neiva-Tatacoa-Garzon aquifer system, but there is not enough information to develop studies that allow the sustainable use of groundwater resources.

For this reason, it was decided to carry out this study, which is part of a larger project of the EAFIT University, which seeks to expand the hydrogeological knowledge of this aquifer system. The objective of this work was to make a map of potential groundwater recharge zones, using geographic information data and satellite images of six geological factors: lithology, drainage density, slope gradient, land use/cover (LULC), guidelines and type of soil; these were chosen by the work team. The thematic layers of the factors were also transformed into raster and reclassified, according to a weight calculated from the multiple influence factor (MIF) methodology. The groundwater recharge potential (GWRpot) map obtained was divided into five categories: *very poor*, *poor*, *moderate*, *high* and *very high*. Finally, the results indicate that 83 % of the study area has moderate to very high potential and it is mainly located between the western and central zones.

Resumen

El desierto de la Tatacoa, en el departamento del Huila, Colombia, se encuentra ubicado entre el Río Magdalena y la Cordillera Oriental; es una zona árida, con mucha erosión, catalogada como bosque seco tropical con temperaturas máximas de 40 °C. Las condiciones climáticas e hidrogeológicas producen problemas relacionados con el recurso hídrico en la zona, pues, en tiempos de verano, el 90 % de las quebradas se secan, lo que ocasiona un problema de sequía en el municipio de Villavieja; sin embargo, existe agua subterránea, pero esta es explotada de manera empírica y no científica. El poco conocimiento hidrogeológico proviene de los estudios del Instituto de Hidrología, Meteorología y Estudios Ambientales (IDEAM), en donde se deja claro que el área pertenece al sistema acuífero Neiva-Tatacoa-Garzón, pero no se cuenta con información suficiente para desarrollar estudios que permitan el aprovechamiento sostenible del recurso hídrico subterráneo.

Por esta razón, se decidió hacer el presente estudio, que forma parte de un proyecto más grande de la Universidad EAFIT, el cual busca ampliar el conocimiento hidrogeológico de este sistema acuífero. El objetivo de este trabajo fue realizar un mapa de zonas potenciales de recarga de agua subterránea, con la utilización de datos de información geográfica e imágenes satelitales de seis factores geológicos: litología, densidad de drenaje, gradiente de pendiente, uso de suelo/cobertura, lineamientos y tipo de suelo; estos fueron escogidos por el equipo de trabajo. Las capas temáticas de los factores también fueron transformadas en ráster y reclasificadas según un peso calculado a partir de la metodología de factor de influencia múltiple (FIM). El mapa obtenido de potencial de recarga subterránea fue dividido en cinco categorías: *muy pobre*, *pobre*, *moderado*, *alto* y *muy alto*. Finalmente, los resultados indicaron que el 83 % del área de estudio tiene un potencial de moderado a muy alto, y se encuentra principalmente entre la zona occidental y central.

Keywords: groundwater potential zones, Tatacoa desert, GIS, MIF technique.

1 Introduction

The groundwater is a vital natural resource for the reliable and economic provision of potable water supply in both urban and rural environments, it contributes around 34 % of the total annual supply and it is an important fresh water supply. Magesh et al. (2012) integrated the remote sensing data and the geographical information system (GIS) for the exploration of groundwater resources, and it has become a breakthrough in the field of groundwater recharge, which assists in assessing, monitoring and conserving groundwater resources.

In this study, we are going to apply the MIF methodology to create the map of the GWRpot. Some examples of other authors implementing this technique are Saraf et al. (2004), Solomon and Quiel (2006), Chenini et al. (2010), Hammouri et al. (2012), Kaliraj et al. (2014), Patil and Mohite (2014), Thapa et al. (2017), Shaban et al. (2006), Singh et al. (2018), Magesh et al. (2012), and Yeh et al. (2016).

On the other hand, the background that led to the realization of the project is that the zone of the Tatacoa desert has become an important place for tourism. This desert is located in the department of Huila, Colombia, and it suffers whenever tourists come to visit, because they have potable water problems due to the arid condition of the zone. Taking this in mind, a previous study from Ballesteros and González (2020) was done, in order to define if the precipitation was the main source of groundwater recharge, with the intention of expanding the knowledge on the aquifer systems of the zone to have a better view on how to explode this natural resource. They found out that the precipitation was not the main source of recharge. Therefore, the objective of this work is to find out in which part of the zone is the recharge most effective, in order to define which is the main source of the groundwater recharge.

Using the MIF methodology, we chose five factors: lithology, slope, drainage density, lineament density, LULC, and soil); these are the most relevant ones in the process of groundwater recharge, according to our teamwork and previous authors. The five factors chosen affect the occurrence and movement of groundwater, so it is necessary to consider all of the above to understand the GWRpot (Yeh et al., 2008). The MIF method is a faster and more cost-efficient alternative than the traditional methods, as it is based on the use of remote sensing techniques, such as satellite images and GIS information (Singh et al., 2017).

This method defines which factor has a stronger influence on the other ones, which depends on the larger weight (Shaban et al., 2006; Magesh et al., 2012); the relationship between the factors and the further procedures are best explained in the methodology. To summarize, the present study focuses on the identification of groundwater potential zones in the Tatacoa desert using the technology of remote sensing, MIF and GIS for the management of groundwater resources.

2 Generalities

2.1 Research question

Does the Tatacoa desert have a good potential for groundwater recharge? If so, where are these located?

2.2 Hypothesis

The characteristics of the zone indicate that there could be a good GWRpot because, in most of the area, there are outcrop rocks of sedimentary origin and the slope gradient is low.

2.3 General objective

Make the map of potential groundwater recharge zones in the La Tatacoa desert using the MIF methodology (multivariate influence factor).

2.4 Specific objectives

- Compile and analyze secondary information of the methodology to be used and select the influencing factors proposed by the work team.
- Obtain the relative weights of each influence factor through the MIF method.
- Process in GIS the thematic maps of the selected factors (Polygon to raster) and reclassify them according to the value assigned for the degree of influence.
- Elaborar el mapa de potencial de recarga de agua subterránea utilizando el álgebra de mapas de ArcGis.

3 Study zone

This study took place in the Tatacoa desert, located in the municipality of Villavieja, in the northern part of the Huila department, in Colombia (Figure 1, A). The length of the study area is of 355 Km2 the zone limits to the west with the Magdalena River and to the east with the Cabrera River. It is important to notice that, even if the name of the zone is called "desert", it is not really a desert, because the characteristics of the zone are not right for this classification because it is actually a tropical dry forest, located between the Magdalena River and the Cordillera Oriental, it is an arid zone with lots of erosion with maximum temperatures of 40°C; the climatic and hydrogeological conditions produce problems related to water resources in the area, since in summer times 90% of the streams dries up, causing a problem of drought in the municipality of Villavieja. Such zone is located in the higher hydrogeological province of Magdalena (Figure 2), and it is part of the aquifer system of Neiva-Tatacoa-Garzon (Figure 2), composed by free, semi-confined and confined aquifers (IDEAM, 2015). Figure 1B is a drainage network map that also shows the cisterns and springs of the zone, which checks the existence of groundwater resources.

A B

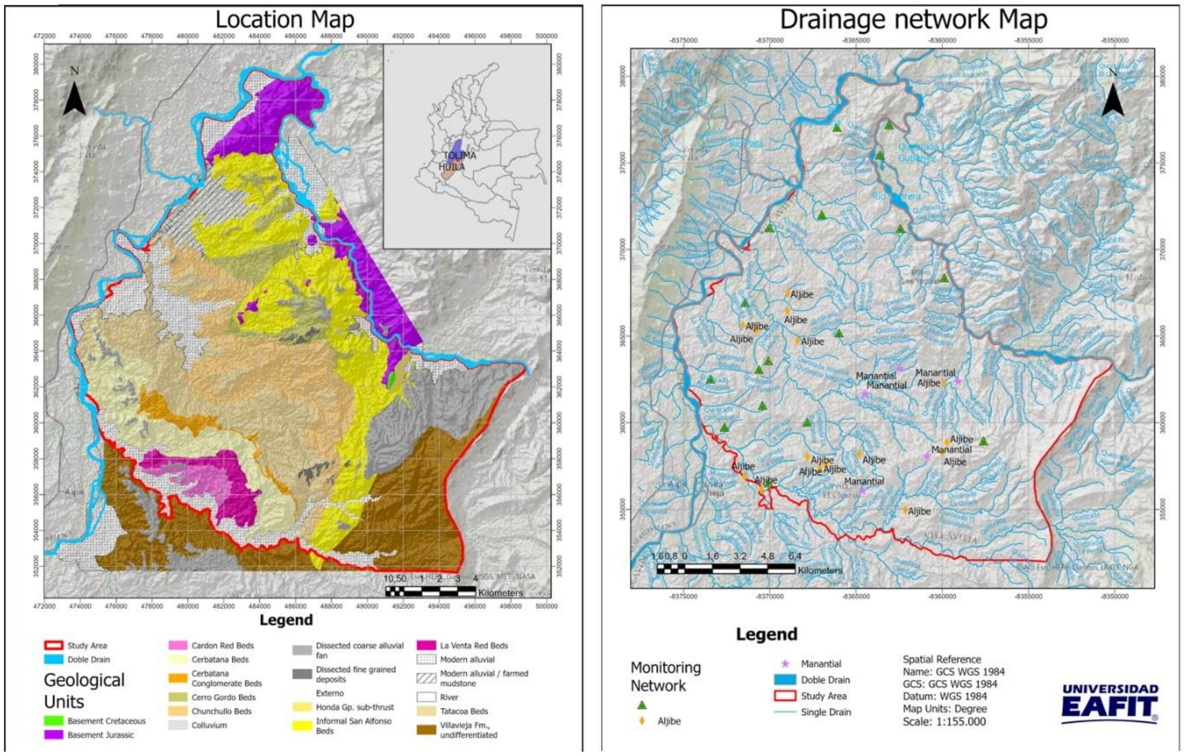


Figure 1. A) Localization map of the study zone with the geological units that outcrop. B) Drainage network map

Taken and adapted from Montes et al. (2021).

4 Methodology

To analyze the GWRpot in this study, we first assigned weights for the different factors influencing the recharge, using the MIF methodology applied by Shaban et al. (2006), Singh et al. (2018), Magesh et al. (2012), and Yeh et al. (2016), among other authors. This methodology helps to integrate remote sensing data and geographical information of the factors chosen (lithology, LULC, lineaments, drainage, slope, and soil); then, the GIS information of each factor is transformed to raster data using the “feature to raster” converting tool in ArcGIS Pro. The raster maps of the factors are allocated in a fixed score and weight computed from the MIF technique; and, for the assignation of the weight, two different “families of weights” were considered. The first one comes from the discussion and field experience of each member of the teamwork, and the second is taken from weights of similar previous studies mentioned. The average between these two families leads to a final weight score, which is the one used for all the calculus in this project. The interaction and further calculus mentioned are going to be explained later on.

In other words, the weighed raster maps are thematic layers, statically computed to get groundwater potential zones, and these last were divided into five categories: *very poor*, *poor*, *moderate*, *good* and *very good*.

4.1 Establishment of the groundwater recharge factors and sources of information

1. **Lithology:** lithology has an evident influence on percolation of water and on the GWRpot (Singh et al., 2019). The classification of the factor lithology was done according to the permeability of the rock in the Tatacoa desert. Shaban et al. (2006) pointed out that the type of rock exposed on the surface significantly affects groundwater recharge by controlling the percolation of water flow. The reason why this factor was chosen was because of its highly influence in the recharge. Also, the GIS information of this factor was obtained from the geodatabase of 302 and 303 Colombian geological service (SGC) and the geodatabase given by Montes et al. (2020).
2. **LULC:** this plays an important role in groundwater recharge. It includes the type of soil deposits and the distribution of residential areas and vegetation cover (Yeh et al., 2016). But, in this study, this factor is not going to consider the type of soil deposits. Another important reason to support the election of this factor is that LULC affects evapotranspiration, run-off and recharge of the groundwater system (Leduc et al., 2001). These GIS data was interpretable from satellite image and LULC maps obtained by the national geodatabase of the biological resources research institute Alexander von Humboldt.
3. **Drainage:** the structural analysis of a drainage network helps asses the characteristics of a groundwater recharge zone. The quality of a drainage network depends on lithology, which provides an index of the percolation rate (Yeh et al., 2016). Therefore, a high drainage density is associated with a highly permeable lithology and a high GWRpot (Sener et al., 2005). The GIS layers were obtained from the same resources of the factor lithology.
4. **Slope:** the slope governs the partition of precipitation into run-off and infiltration and, hence, it is considered as an important factor for run-off generation. A higher slope

results in rapid run-off and less recharge (Abdalla, 2012; Magesh et al., 2012). Larger slopes produce a smaller recharge because water flows rapidly down a steep slope during rainfall, so it doesn't have sufficient time to infiltrate the surface and recharge the saturated zone (Yeh et al., 2016). The GIS layers were obtained from the same resources of the factor lithology.

5. **Lineaments:** lineaments represent the zones of faulting and fracturing resulting in increased secondary porosity and permeability; these factors are hydro-geologically important, as they provide the path ways for groundwater movement (Magesh et al., 2012). Since the presence of lineaments usually denotes permeable zones, areas with high lineament density are good for groundwater potential zone (Haridas et al., 1998). The GIS layer of this factor was obtained by the interpretation of satellite images. It is also important to mention that, after the interpretation of the images, only lineaments associated to the drainage were seen; this is the reason why in this project only this kind of lineaments are taken for the analysis, despite the fact that other tectonic studies were also considered.
6. **Soil:** the soil type has a significant impact on infiltration of precipitation according to its characteristics (Singh et al., 2018). The GIS layer was obtained from the geodatabase given by Montes et al. (2021).

In order to develop the methodology, a conceptual map that shows the relationship between the influencing factors was drawn first (Figure 3). The map has two types of arrows, continuous arrows mean a major influence (A) of one factor over another, with a value of 1; and dashed arrows mean a minor influence (B) on the other factor, with a value of 0,5. In order to quantify the weight factor (WF), the points have to be added. For example: two solid arrows point out from the “slope” to “soil”, and “LULC”, and one dashed arrow points out from “slope” to “lineaments”. Thus, there are two solid lines going out, it means a value of 2 points; and one dashed line going out means 0,5 points; then, the WF = 1 point + 1 point + 0,5 points, which implies that the WF of the slope is 2,5 points. All the processes and the weight for each individual factor are shown in tables 1 and 2, by using the following formula:

$$\left[\frac{(A+B)}{\sum(A+B)}\right] X\ 100$$

Formula taken from *Magesh et al. (2012)*

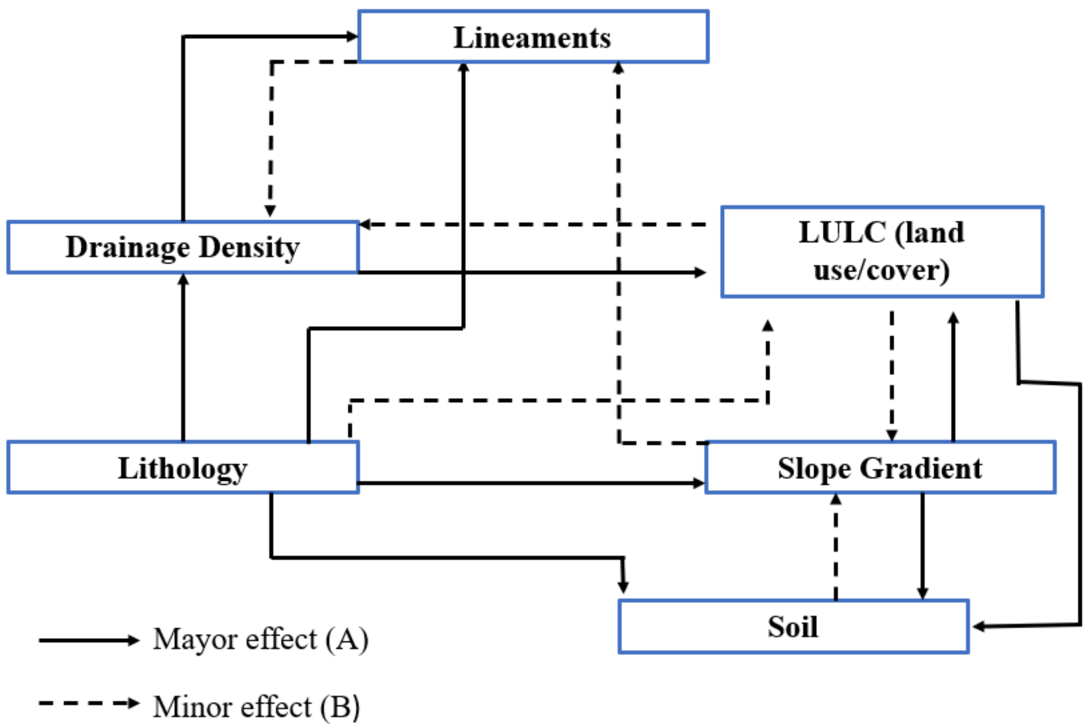


Figure 2. Schematic sketch showing the interactive influence of the factors. The relationship between these factors shows which one has a major grade of influence over the other. The relationships were established by the teamwork

As mentioned before, three different families of weights are going to be considered for the analysis. The first one (WF) was obtained after applying the MIF method, according to the relative weights of the factors established by the teamwork (Table 1, A); the second one (literature weight) comes from the average of 10 similar studies carried out previously by Shaban et al. (2006), Yeh et al. (2008), Yeh et al. (2016), Senanayake et al. (2016), Patil and Mohite (2014), Magesh et al. (2012), Sener et al. (2005), Hammouri et al. (2012), Solomon and Quiel (2006), and Krishnamurthy et al. (1996), as shown in Table 1, B. In order to reduce the error, a third family (final weight) was considered, this was obtained by combining and averaging the families one and two. Moreover, in Table 1, a summary of the three families of weights is shown: the first one was obtained by the teamwork; the second one was obtained and modified by Shaban et al. (2018); and the third one corresponds to the average between families 1 and 2.

Table 1. A) Table showing all the factors with their relative weights and process to find the final weight. B) Relative weights of the same factors but from other authors

A)

Factor	Mayor effect (A) (x * 1)	Minor effect (B) (x * 0,5)	Proposed relative rates (rr) (A + B)	Proposed score/weight (Wf) 100 * (rr / 12)	Literature weight	Final Weight
Lineaments	0	0,5	0,5	4,2	18	11,1
Drainage	2	0	2	16,5	13,5	15
Lithology	4	0,5	4,5	37,5	22	29,7
Slope	2	0,5	2,5	21	17	19
LULC	1	1	2	16,5	19,5	18
Soil	0	0,5	0,5	4,2	14,5	9.3
			Σ 12	Σ 100		

B)

Table 2
Relative weightage values of other studies with a similar methodology.

Factor	Shaban et al. (2006)	Yeh et al. (2009)	Yeh et al. (2016)	Senanayake et al. (2016)	Patil and Mohite (2014)	Magesh et al. (2012)	Sener et al. (2005)	Hammouri et al. (2012)	Solomon and Quiel (2006)	Krishnamurthy et al. (1996)
Litho-logy	0.28	0.29	0.29	0.15		0.25	0.17	0.10	0.25	0.18
Land cover/ land use	0.17	0.24	0.24	0.10	0.25	0.22	0.14			
Drai-nage density	0.17	0.14	0.14	0.10	0.05	0.09	0.12	0.22		0.18
Slope		0.14	0.14	0.11	0.20	0.16	0.12	0.22	0.25	0.18
Soil				0.14	0.20	0.06				0.18

Source: taken from Singh et al. (2018)

The weight of a factor represents the proportion of its value in the potential recharge scale; the higher the recharge weight, the larger the influence of the factor in the GWRpot (Yeh et al., 2016).

After getting the final weight, the layer information of the factors needs to be rasterized and reclassified with spatial analyst tools in the software ArcGIS Pro. For such reclassification, five major descriptive levels were given, ranging from very high to very low, where the highest values have a large influence on the potential groundwater recharge and are represented in red color, while the lowest value is the opposite and is represented with the blue color. The weights for each factor were added together, in order to obtain the recharge potential factor. In this study, satellite images were used to analyze the digital map and to set appropriate influential scores according to the influential factors. To rasterize the information, different methods were used, according to each factor:

- Lineaments: the tool “create line” was used in order to create the GIS information after a process of satellite images interpretation.
- Drainage and slope: these were rasterized using the DEM with the tool “line density”.

- Lithology: LULC and soil were rasterized after creating polygons with the tool "rasterize" from spatial analyst tools.

The final step is to calculate the final value of the GWRpot by doing an algebra of maps and adding all the individual maps of each factor already rasterized and reclassified. This final value was calculated as:

GWRpot = Lir x Liw + LUr x LUw + DDr x DDw + SLr x SLw + Lr x Lw + SOr x Sow

Where Li is lithology, LU is LULC, DD is drainage, SL is slope, L is lineaments, and SO is soil. The subscripts "r" and "w" refer to the reclassified value and the weight respectively. All this procedure was done after applying the methodology explained by Singh et al. (2018) with our own data regarding the area of study. The representation of the process can be seen in Figure 3.

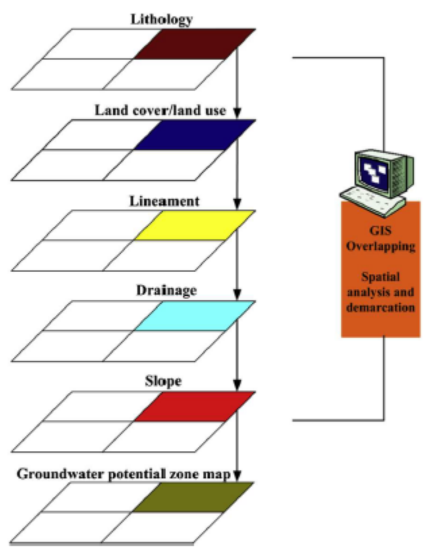


Figure 3. Process of superposition principle for integrating relevant factors with an algebra of maps to derive GWRpot zone maps

Taken from Yeh et al. (2016).

5 Results

Table 2 shows, for each influencing factor, the weights and respective reclassified values. These last were used to create the maps of each factor (figures 3 to 9), using the "reclassify" tool of spatial analysis tools. After calculating the final weights of the factors, the obtained values were reclassified into five different levels, in order to put the information in the ArcGIS to create the map.

Table 2. Classification of WF influencing the potential zones

Factor	Value Range	Weightage	Reclassified value	Influence con the GWRpot	Color
Lithology	*Basement*	*< 6*	*1*	*Very low*	*Blue*
	Mudstones	*6 - 12*	*2*	*Low*	*Green*
	Clay Sandstone	*12 - 18*	*3*	*Moderate*	*Yellow*
	Sandstones and conglomerates	*18 - 24*	*4*	*High*	*Orange*
	Alluvial sedimentary deposits	*> 24*	*5*	*Very high*	*Red*
Slope gradient	*0 -10*	*< 3,8*	*1*	*Very low*	*Blue*
	10 - 20	*3,8 - 7,6*	*2*	*Low*	*Green*
	20 - 35	*7,6 - 11,4*	*3*	*Moderate*	*Yellow*
	35 - 60	*11,4 - 15,2*	*4*	*High*	*Orange*
	> 60	*> 15,2*	*5*	*Very high*	*Red*
Drainage (km/km2)	*0 -2*	*< 3*	*1*	*Very low*	*Blue*
	2 - 4	*3 - 6*	*2*	*Low*	*Green*
	4 - 6	*6 - 9*	*3*	*Moderate*	*Yellow*
	6 - 8	*9 -12*	*4*	*High*	*Orange*
	8 - 10	*> 12*	*5*	*Very high*	*Red*
LULC	*Human settlements*	*< 3,6*	*1*	*Very low*	*Blue*
	Dense grassland	*3,6 - 7,2*	*2*	*Low*	*Green*
	Open bushland	*7,2 - 10,8*	*3*	*Moderate*	*Yellow*
	Open areas with no vegetation	*10,8 - 14,4*	*4*	*High*	*Orange*
	River	*> 14,4*	*5*	*Very high*	*Red*
Soil	*Shale*	*< 1,86*	*1*	*Very low*	*Blue*
	Claystone	*1,86 - 3,72*	*2*	*Low*	*Green*
	Sandstones	*3,72 - 5,58*	*3*	*Moderate*	*Yellow*
	Fine to medium alluvial deposit	*5,58 - 7,44*	*4*	*High*	*Orange*
	Alluvial deposit	*> 7,44*	*5*	*Very high*	*Red*
Lineaments (km/km2)	*No presence of lineaments*	*< 5,5*	*1*	*Low*	*Blue*
	Precense of lineaments	*> 5,5*	*5*	*High*	*Red*

This table shows the intervals of the factors with their value range. The reclassified value means the level of importance in the GWRpot, where 5 implies that the influence is very high; and 1, that the influence is very low.

Lithology: the lithology map (Figure 4, A) shows that in the study area most of the rocks (> 95 %) are of sedimentary origin. The highest values were assigned to the alluvial deposits and sandstones and were expressed with the color orange, while the lowest value that contributes to the recharge of groundwater is the basement, with blue color. According to this factor, the majority of the study zone has a high potential for the recharge of groundwater, especially in the western zone.

Drainage density: the drainage density map (Figure 5, B) shows that less than the 54 % of the study area has a high potential for the groundwater recharge. The reason for this is that the weather in the zone is hot (~ 33 °C) and dry (low rate of raining), and these characteristics don't allow the drainage to have a continuous flow. The zones with higher values for the recharge potential are in the central and south parts, where the tributary Quebrada Las Lajas flows.

Slope gradient: the slope map (Figure 5, C) shows that the majority of the zone has a low slope gradient (0-10), which favors the GWRpot.

LULC: the LULC map (Figure 5, D) shows that most of the space corresponds to open areas with no vegetation (> 85 %). The northwest zone is the one with the highest recharge potential.

Lineaments: after doing the analysis of satellite images of the zone, only four lineaments were spotted; these can be seen on Figure 4, E, because they don't correspond to structural lineaments, which are the ones that have a major influence in the recharge potential. The lineaments in the zone are associated to the drainage network and correspond to primary drainages.

Soil: the soil map (Figure 5, F) shows that the zones with the greatest potential for the GWRpot correspond to alluvial sediments (85 % of the area). However, the other zones have textures that also favor the groundwater recharge and sandstones. According to this factor, there are no zones with a low recharge potential.

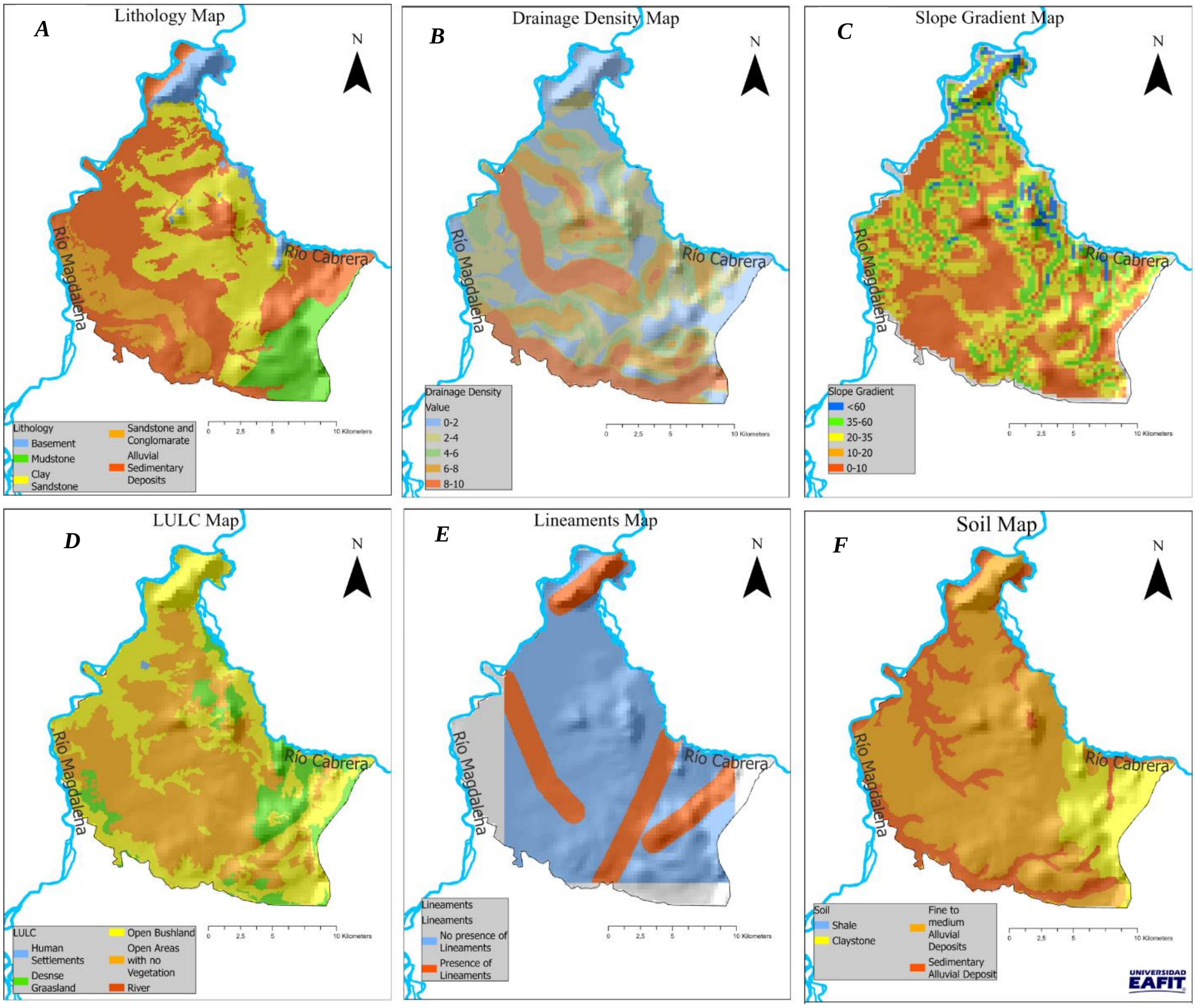


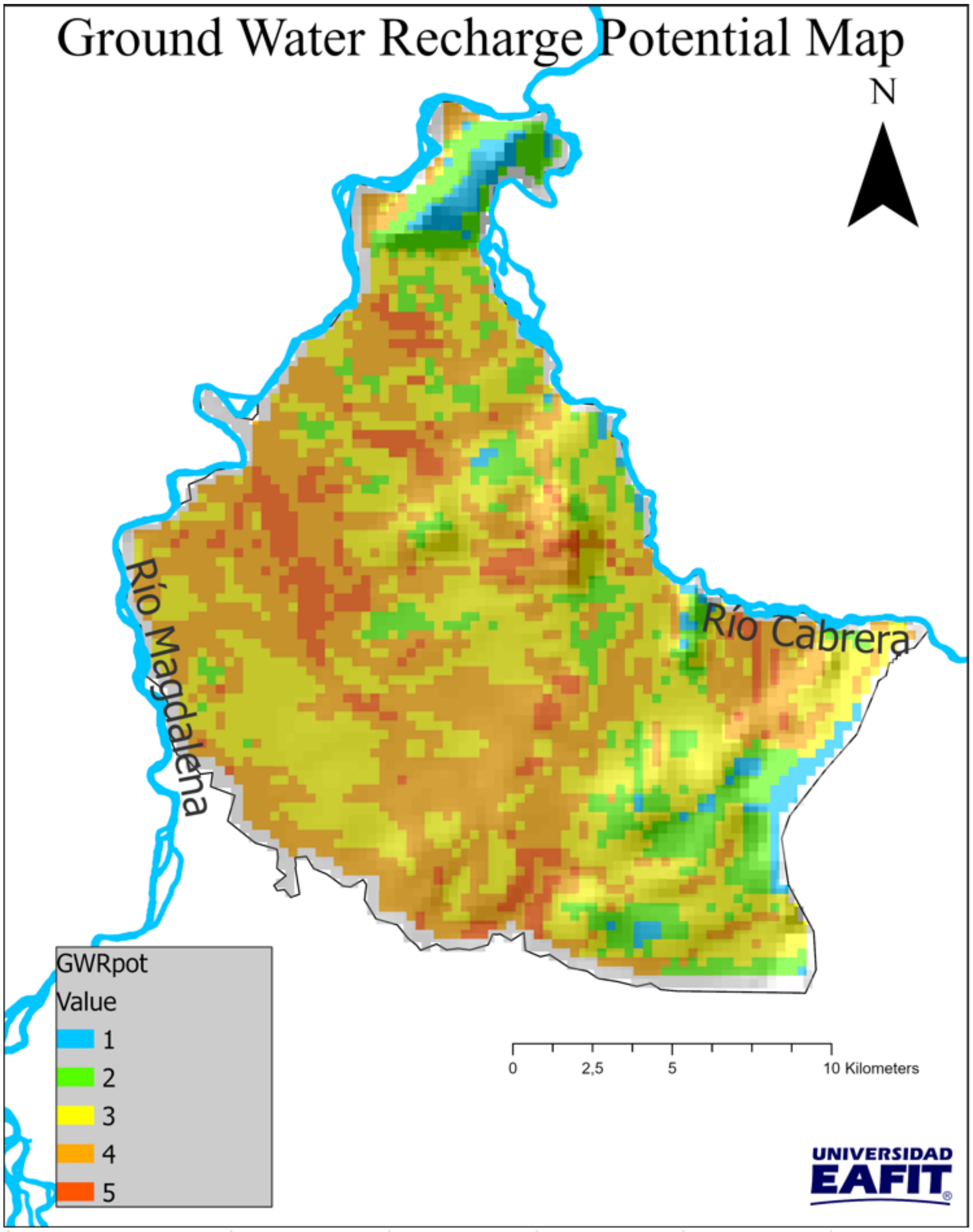
Figure 4. Maps of the factor according to their relative importance to the groundwater recharge. A) Lithology map. B) Drainage map. C) Slope gradient map. D) LULC map. E) Lineaments map. F) Soil map

Additionally, Table 3 shows all the factors with their reclassfied vaue, the influence on the GWRpot and the percentage of area that they occupy.

Table 3. Summarization of all the factors with their reclassified value, the influence on the GWRpot and percentage of area that occupies

Factor	Color	Reclassified value	Influence on the GWRpot	Area (%)
Lithology		1	Very low	5,27
		2	Low	9,94
		3	Moderate	27,98
		4	High	11,25
		5	Very high	45,55
Drainage Density		1	Very low	3,25
		2	Low	13,09
		3	Moderate	37,25
		4	High	39,79
		5	Very high	6,6
Slope Gradient		1	Very low	32
		2	Low	20
		3	Moderate	27,68
		4	High	16,32
		5	Very high	4
LULC		1	Very low	11,6
		2	Low	40
		3	Moderate	0,39
		4	High	47,7
		5	Very high	0,48
Lineaments		1	Very low	79,13
		2	Low	0
		3	Moderate	0
		4	High	0
		5	Very high	20,87
Soil		1	Very low	0
		2	Low	0
		3	Moderate	19,6
		4	High	66,66
		5	Very high	13,74

Groundwater potential zone map: the final map for the GWRpot (Figure 5) was done with an algebra map in ArcGIS Pro as it is explained in the methodology. This map shows with blue color the value of one of the zones with a very low GWRpot. This value goes up to 5 in red color, which means a very high GWRpot. Also, the zones with a low potential are located where the basement outcrops and slope gradients are high: while the highest potential is located in zones that correspond in their lithology and soil texture to alluvial sedimentary deposits and sandstones, where the slope gradient is low and the land is used for agriculture purposes.



GWRpot	Very high	High	Moderte	Low	Very low
Average (%)	6,78	38,22	38,22	13,44	3,34
Area extent (Km2)	21,67	122,22	122,22	42,98	10,69

Figure 5. Final map of the GWRpot in the Tatacoa desert

6 Discussion

We carry out this methodology with the purpose of expanding the hydrogeological knowledge of the study area and trying to confirm the hypothesis that there is a high potential for groundwater recharge in the area and that the highest potential is located in the western part where the Magdalena River passes. With the obtained results we can say that the hypothesis was partially validated, since the results effectively show that the area has a groundwater recharge potential that varies mostly from moderate to very high, in addition to this, the highest potentials are found between the western and central area, near the Magdalena River. However, the results obtained are not enough to say with certainty which is the main source of recharge because only superficial factors are taken into account and the development of the methodology is very subject to user interpretation.

The map of the GWRpot was done using GIS techniques, so it was necessary to overlap the layers of the geological factors, including lithology, slope gradient, drainage, LULC, soil and lineaments, which are important for the GWRpot. Three different approaches were used to determine the relative importance (weight) of each factor: and it is important to notice that the three weights don’t differ much between them, which indicates a low degree of uncertainty.

On the other hand, the GWRpot zones were classified into five descriptive classes: *very high*, *high*, *moderate*, *low* and *very low*. Most of the area of the Tatacoa desert (80 %) is classified between moderate to very high recharge potential, as can be seen in Figure 5. The results indicate that certain areas, where the basement outcrops and the slope gradient is high, have a low potential, while the areas with low slope gradient, where sedimentary rocks and alluvial deposits outcrop, have a good high potential for groundwater recharge. For the verification of the GWRpot, the field investigation must be developed. Moreover, after analyzing the data, the factor lineaments become of low importance to the groundwater recharge; this, because the lineaments spotted are associated to the drainage network and not to structural lineaments, which have more repercussions on the recharge of groundwater.

Comparing our results with studies from other authors applying the same methodology in areas with similar characteristics like altitude, soil type, weather and drainage density such as Yeh et al. (2016), Magesh et al. (2011), and Shaban et al. (2016), we realized that our results match and agree with the results of the other authors since the factors thar are most relevant to the recharge potential are always lithology and slope gradient.

The results of the factors lineaments and drainage density don’t match with the results of the other authors, the reason for this is that in the other studies the lineaments are structurally controlled which is a totally different scenario that ours, since the lineaments in the Tatacoa are mostly controlled by the drainage network. In the other hand the drainage density is not one of the most influential factors to the recharge because the flow of this streams is not continuous because it varies according to the season.

As mentioned before, the hypothesis was not fully tested due to limitations of the methodology, such as only taking into account superficial factors, subject to user interpretations, so it leaves a lot of room for subjectivity and uncertainty. However, it is recommended, as a first approximation to demarcate potential recharge zones and, thus, delimit sites for direct measurements. Finally, it is important to say that the western area, where the highest recharge potential is concentrated, corresponds to the limit with the Magdalena River. So, it is a good hypothesis for future studies whose main source of groundwater recharge is the product of an interaction between the river and the aquifer; however, this is outside the scope of this project.

7 Conclusion

- Less than 20 % of the study area (16,78 %) is classified as having a low recharge potential; therefore, more than 80 % of the Tatacoa desert area has suitable conditions for groundwater recharge.
- The lithology factors and the slope gradient are those that represent a greater degree of influence for groundwater recharge, since they resulted with a greater relative weight and this is evidenced in the results.
- This project provides a good basis for future work that tries to decipher the main source of groundwater recharge.
- The delineation of the GWRpot in the Tatacoa desert would be very expensive and would require a lot of time if it was done by field investigations; therefore, the MIF methodology integrating the GIS technology is a very efficient method that saves time and money.

- The methodology has some limitations: it only takes into account superficial factors and it is subject to user interpretation, so it leaves a lot of room for subjectivity and uncertainty. However, it is recommended, as a first approximation, to demarcate potential recharge zones and, thus, delimit sites for direct measurements.

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