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(Research Article)

Contribution of remote sensing and GIS and the analytical hierarchical process approach to identifying groundwater recharge in the Abacha watershed, Chad

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Abstract

Groundwater is a major source of water supply for various areas. However, over the last ten years, demographic growth and other changes have contributed to an increase in water demand. It is therefore essential to map groundwater recharge areas in order to use them to meet local consumption needs. The aim of this study is to map groundwater recharge areas in the Abacha watershed in eastern Chad using a combination of GIS and AHP. Seven different factors were used in this study: altitude, lineament density, drainage density, precipitation, lithology, slope, and land use/land cover. Pairwise comparison matrices were then used to assess the degree of importance of each factor in relation to the others. Next, the raster calculator tool was used to map and identify groundwater recharge zones (GWRZ) by categorizing the Abacha watershed into three zones (high, medium, and low). The northeastern areas have low recharge potential. The medium class occupies a significant part of the central watershed, while the southern areas have acceptable recharge potential. Finally, the high class occupies the southern part of the watershed, which is characterized by good groundwater recharge. This approach, GIS and AHP, is important for groundwater resource decision-makers in determining the ideal sites for new water infrastructure projects in the Abacha watershed.

Keywords: (GIS); (AHP); Recharge; Abeche watershed; Sahel; Chad

1. Introduction

Water resources are the most important elements on Earth. Their availability in good quality is essential for domestic, agricultural, and socioeconomic activities (1,2). It is estimated that around 70% of the world's groundwater resources are used for agriculture (3). More than 50% of the world's population depends on groundwater resources, which are widely used for irrigation to ensure food security in arid and semi-arid regions (4,5). However, problems have begun to emerge over the last decade, with groundwater being overexploited, significantly affecting its natural recharge. In general, in semi-arid regions, surface water is not available in sufficient quantities throughout the year; therefore, the demand for groundwater increases to meet needs (6,7). Groundwater recharge is influenced by anthropogenic activities and natural factors, such as climate, precipitation, lineament density, topography, and lithology, all of which affect the location and movement of groundwater (8,9). Recharge is a water resource management tool that plays an important role in balancing water demand and supply for development, particularly in semi-arid and arid regions (10,11). Therefore, understanding and characterizing recharge requires accurate quantitative assessment of multiple parameters, based on a combination of scientific principles and modern geospatial analytical techniques (12,13). Indeed, recharge is a key element in the development of water supply in semi-arid and arid areas, in balancing water demand and water resource management (14,15). Recently, remote sensing has been used as a tool for exploration groundwater, planning, and water resource management (16–18). Numerous geoscience studies have made extensive use of AHP in various fields (19–23). Many researchers in different geographical contexts have used various techniques

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to identify potential groundwater recharge areas, for example frequency ratio (24,25), random forest model (26,27), decision tree model (28), logistic regression model techniques (29), and artificial neural network (30). However, few studies have been conducted on remote sensing and GIS combined with the AHP approach to identify potential groundwater recharge areas. Some researchers who have delineated potential groundwater recharge areas using the integrated AHP method, combined with remote sensing and GIS, have obtained satisfactory results for example, (31–34). The main objective of this study is to identify groundwater recharge areas using geospatial technology and the AHP approach.

The results of this research will provide information for sustainable groundwater management and determine suitable locations for drilling. In addition, this study will help decision-makers implement a strategy for the sustainable management and use of groundwater resources in the Abacha watershed.

1.1. Study area

The Abacha watershed, located in northeastern Chad between 15°N and 13°N latitude and 20 ° E and 22°E longitude, covers an area of 2.634km² and encompasses two provinces, Wadai and Wadi-Fira (Fig. 1). The basin's terrain consists of mountainous and hilly landscapes, with maximum altitudes reaching 980 m and minimum altitudes of 450 m. The watershed is located in a semi-arid zone, characterized by an eight-month dry season and a four-month rainy season, from June to September. Annual rainfall varies irregularly between 400 and 600 mm, with temperatures ranging from 23°C to 37°C and an annual average of 30°C.

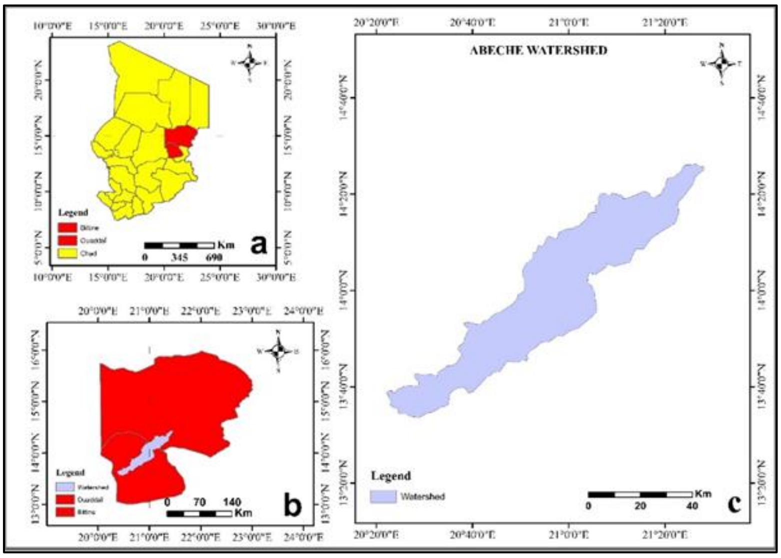

Figure 1 Location map of the study area

2. Geology and Hydrogeology setting

The geology is dominated by calc-alkaline granite formations, which form the primary bedrock of the basin figure 2 (18). Weathering products have contributed to the formation of fluvial-lacustrine alluvial deposits, abundant along rivers, which are generally homogeneous and, in some cases, aligned parallel to the east-west direction. These deposits are the result of prolonged erosion, facilitating the development of fluvial-lacustrine alluvial deposits, which are abundant along rivers and are generally homogeneous and, in some cases, aligned parallel to the east-west flow direction. These deposits are the result of prolonged erosion, facilitating the development of the local hydrographic network.

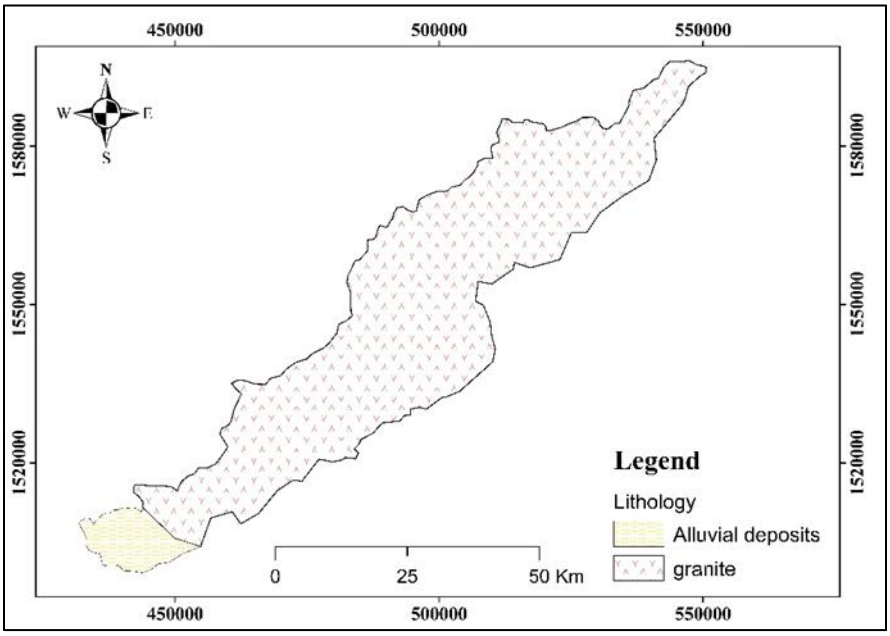

Figure 2 Lithological map of the Watershed

3. Materials and methods

Geospatial identification of artificial groundwater recharge areas based on several parameters using the hierarchical analytical process.

3.1. Methodology

The aim of this study was to identify areas conducive to groundwater recharge. To do this, we used GIS (geographic information system) tools and the analytic hierarchy process (AHP) to define potential groundwater recharge areas in the Abacha watershed in Chad. Seven thematic layers were developed, taking into account factors such as precipitation, elevation, lineament density, drainage density, slope, lithology, and land use. All data collected were processed using ArcGIS 10.8.1 software. The methodology used in this study is explained in Figure 3.

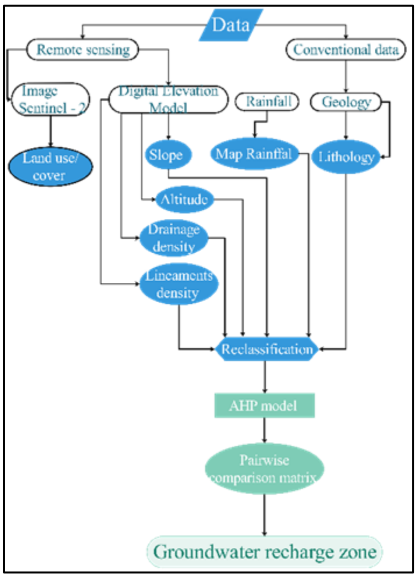

Figure 3 Flow chart methodology adopted in the study area

3.2. Data collection

Seven parameters were used to prepare the geospatial database. These parameters are geology, slope, land cover, lineament density, hydrographic network density, precipitation, and altitude. These various data were projected using the UTM zone 34N-WGS 84.

3.3. Thematic maps

Preparation of multiparametric maps to delineate groundwater recharge areas in the Abéché watershed. Thematic maps representing the variables influencing groundwater recharge were generated to visualize their spatial distribution in a GIS environment. In this study, seven (7) spatial parameters such as geology, slope, land use and land cover, lineament density, hydrographic network density, altitude, and precipitation were analyzed using the AHP approach, including the calculation of the geometric mean and normalized weight, in order to explore the potential groundwater recharge area.

3.4. Preparation of thematic maps

3.4.1. Geology

The geological map was georeferenced and digitized in order to extract the Abéché watershed. Two different types of rock influence recharge processes in different ways depending on their intrinsic properties, such as permeability and porosity, which determine the rate and efficiency of groundwater infiltration.

3.4.2. Slope

Slope has a significant impact on the rate and amount of water infiltration (35,36). On steeper slopes, surface runoff velocity increases, reducing the amount of time water remains in contact with the soil. This decrease in contact time limits the amount of water that infiltrates the soil

3.4.3. Drainage density

Drainage density influences the indicator of suitable locations for recharge by indirectly indicating the permeability and porosity of the terrain in relation to surface runoff (37).

3.4.4. Altitude

Altitude plays an important role in groundwater recharge by influencing both the amount of water available and the dynamics of its infiltration. Altitude also directly affects precipitation and its nature, which are the primary sources of recharge.

3.4.5. lineaments density

Lineaments indicate areas of faults, fractures, and joints, which significantly influence the movement, accumulation, and recharge of groundwater (16,38). Proper mapping and analysis of lineaments is essential for effective groundwater resource management, particularly in bedrock areas.

3.4.6. Land use/cover

Land use/ cover (LULC) significantly affect groundwater recharge by altering surface runoff, infiltration capacity, and evapotranspiration rates (39).

Natural vegetation, such as forests and grasslands, generally promotes greater infiltration and recharge through improved soil structure and reduced surface impermeability.

3.4.7. Rainfall

Rainfall is an important hydrological factor and the main source of recharge. It determines the amount of water available to infiltrate an area.

3.4.8. Analytical hierarchical Processus

GIS and AHP were used to delineate potential groundwater recharge areas. This approach was proposed by Saaty (1980). The AHP method allows us to assign weights to thematic maps. In order to evaluate the thematic maps, pairwise comparisons were made to rank the factors, ensuring reliable decision-making while taking into account the uncertainty of the assessment. In addition, AHP is one of the multi-criteria approaches widely used in the field of groundwater exploration (19,40,41).

3.4.9. Thematic weightings

Since the beginning of the 21st century, AHP has become an essential tool in problem structures at various levels. This powerful structure enables managers, decision-makers, and consultants among project stakeholders to make decisions. To this end, AHP ranks and prioritizes criteria relative to each other in a pairwise comparison matrix to analyze different factors. Saaty proposed a scale of values ranging from 1 to 9 (Table 1).

3.5. The process for determining weightings consists of three steps:

- Step I: constructing the AHP approach requires an analysis in which the various parameters must be clearly defined in order to form a model.
- Step II: pairwise comparison including the various thematic layers taken from this study, based on Saaty's 1-9 scale (Table 1)
- Step III: Determination of the different weights of the coefficients by calculating the consistency ratio (CR) for consistency control.

Table 1 A scale for pairwise comparisons and their definitions

Scale	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
Importance	Equal	Weak	Moderate	Moderate plus	Strong	Strong plus	Very strong	Very strong	Extreme

3.6. Consistency validation

The consistency of the matrix was analyzed based on the different rankings of the criteria. The consistency index (CI) is calculated using equation (1).

$$CI = \frac{\lambda \max - N}{N-1}$$

Where λ max is the significant eigenvalue of the pairwise comparison matrix, and "N" represents the number of classes.

The CR is calculated as the ratio between the CI and the random index (RI). This step allows for checking the consistency of the analysis and evaluation of the scale. The CR is calculated using the following equation:

CR= CI/RI

Table 1 Pairwise comparison matrix for the AHP process

	Alt	**Dd**	**LD**	**Lt**	**Rf**	**Slope**	**LULC**
Alt	1	3	3	3	3	1	1/5
Dd	3	1	1	3	5	3	3
LD	3	1	1	1/3	7	3	3
Lt	5	5	3	1	3	5	1/3
Rf	3	3	5	3	1	7	7
Slope	1	1/3	1/3	1/3	1/7	1	1/5
LULC	5	1/3	1/3	3	1/7	5	1
Total	21.00	13.66	14	13.66	19.29	25	14.73

3.7. Weights of thematic

3.7.1. Aggregation of criteria

The seven thematic maps were integrated into ArcMap using the weighted overlay analysis technique. Each layer was entered into the weighted overlay tool, with scale values and normalized influence levels assigned based on previous studies in areas similar to our study area. For the sake of impartial evaluation, equal weights were assigned to all layers, meaning that each parameter was considered a significant parameter in the groundwater recharge process.

Table 2 Determining the normalized weights for thematic layers

	Alt	Dd	LD	Lt	Rf	Si	LULC	Weight
Alt	0,05	0,22	0,22	0,22	0,16	0,04	0,01	0,13
Dd	0,14	0,07	0,07	0,22	0,26	0,12	0,20	0,16
LD	0,14	0,07	0,07	0,02	0,36	0,12	0,20	0,14
Lt	0,24	0,37	0,22	0,07	0,16	0,20	0,02	0,18
Rf	0,14	0,22	0,37	0,22	0,05	0,28	0,48	0,25
Slope	0,05	0,02	0,02	0,02	0,01	0,04	0,01	0,03
LULC	0,24	0,02	0,02	0,22	0,01	0,20	0,07	0,11

4. Results and discussions

Areas likely to recharge groundwater were explored based on various parameters such as altitude, drainage density, lineament density, lithology, rainfall, slope and land use land cover.

4.1. Altitude

The altitude map was created from SRTM using ArcMap's Surface tool. The watershed is classified into three categories (good, poor, and mediocre). The area represented by elevations between 444 and 622 m is favorable for groundwater recharge. This is explained by the low hydraulic gradient of low-altitude sites and their spatial correlation with unconsolidated sediments. While the area represented by low elevations (622–800 m) is moderately favorable for groundwater recharge, and the area represented by high elevations has been found to be unfavorable for groundwater recharge, areas at relatively low altitudes (800–979 m) have been found to be favorable for the presence of groundwater figure 4.

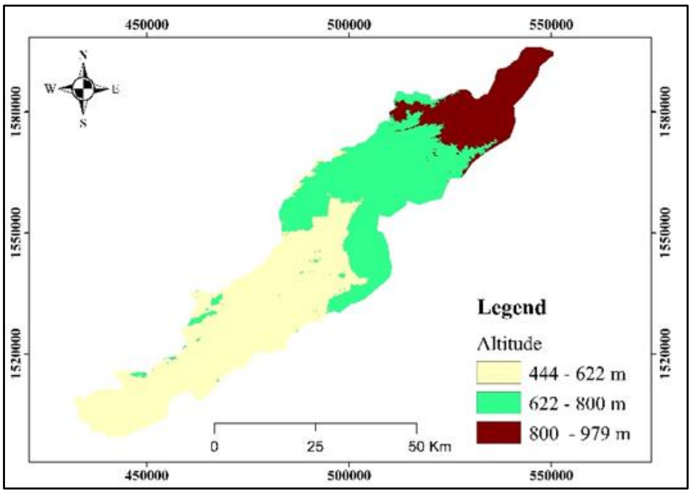

Figure 4 Altitude

4.2. Drainage density

Drainage density (Dd) is a crucial factor to consider when evaluating a region's groundwater recharge potential. In the Abacha watershed, hydrographic networks were extracted from the SRTM using the Arc Hydro tool. These hydrographic networks were processed using the ArcGIS 10.8 Statistical Focus tool to produce the Dd map. The Dd map was classified into four categories using the ArcMap 10.3 classification tool (Fig. 5). The four drainage density classes are “very high, high, medium, and low.” Determining the drainage density of a watershed provides an idea of infiltration and runoff behavior (surface runoff and permeability). In the Abacha watershed, the density of lineaments varies from 0.06 to 1.9 km/km^2. The very high class (0.06 to 0.7) is defined as the most suitable for water recharge and infiltration. The high class (0.7 to 1) is considered a suitable area for water infiltration and recharge. The medium class (1 to 1.3) is considered a transition zone between surface runoff and water infiltration. Finally, the low class (1.3 to 1.9) is considered a zone that promotes runoff and is not suitable for groundwater recharge (Table 2).

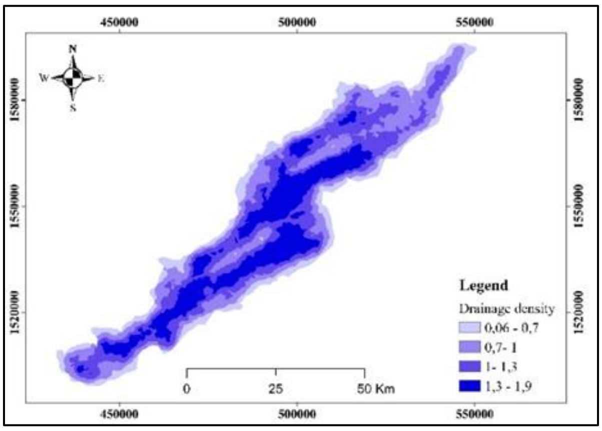

Figure 5 Drainage Density

4.3. Lineament Density

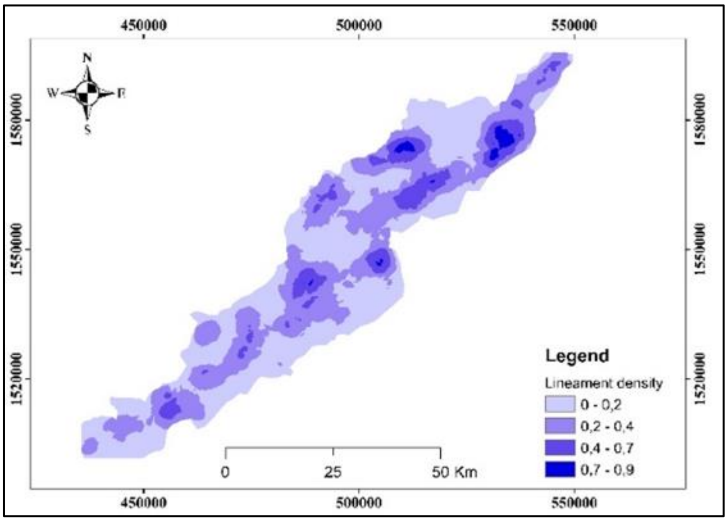

Figure 6 Lineament Density

Lineaments are linearly fractured areas in the geological structure of an area, such as faults and dikes. They can also provide information on water flow and infiltration through their openings, depending on the type of rock (42). The high density of lineaments provides information on lithological types: the higher the density, the more this area consists of hard rocks, whereas a low density indicates a predominance of soft/sedimentary rocks. The map of the watershed's lineaments was created using Landsat 8 OLI imagery. Based on density values, the watershed is classified into four classes: low, medium, high, and very high. In the Abacha watershed, the density of lineaments varies from 0.06 to 1.9 km/km^2. The low class (0.06 to 0.7) is considered an area that promotes runoff and is not suitable for groundwater recharge. The medium class (0.7 to 1) is considered a transition zone between surface runoff and water infiltration. The high class (1 to 1.3) is considered a zone suitable for water infiltration and recharge. Finally, the very high class of 1.3

to 1.9 is defined as the area most suitable for water recharge and infiltration (Fig. 6). High densities of lineaments are considered a good indicator of groundwater storage potential.

4.4. Lithology

Lithology is an important factor that determines the quantity and quality of groundwater in a region. It describes the different lithological units in a region. In terms of lithology, the Abacha watershed is characterized by two types of formations: granite and alluvium. In terms of permeability and fractures, the Abacha watershed is classified into two categories in order to assess the potential for groundwater recharge. The alluvial formation is characterized by very high permeability, which further promotes groundwater infiltration, while the calc-alkaline granite formation is mediocre and has very low permeability, which promotes less infiltration, resulting in low groundwater recharge potential (Figure 7).

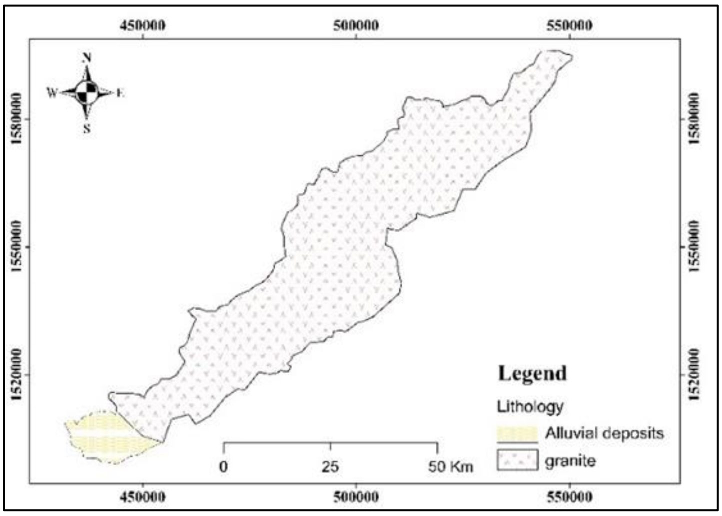

Figure 7 Lithology

4.5. Rainfall

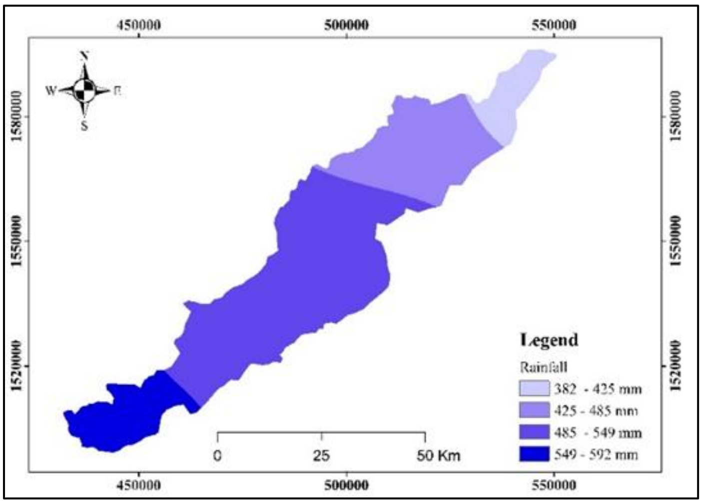

Figure 8 Rainfall

Rainfall is an important hydrological factor and the main source of recharge. It determines the amount of water available to infiltrate an area. Given the importance of this parameter, we used it in mapping groundwater recharge. The map was produced from meteorological data for the watershed using the interpolation method to obtain the precipitation distribution map (Figure 8). Due to the uneven distribution of precipitation, the Abacha watershed was classified into four intervals using the ArcMap classification tool. According to Figure 8, the upper part of the watershed is characterized by very low precipitation (342–425 mm), while the northern and central parts of the watershed are characterized by low precipitation (425–485 mm). The southern and central parts of the Abacha watershed are characterized by average precipitation (485–549 mm), and finally, the high class is characterized by higher precipitation downstream of the Abacha watershed (549–592 mm).

4.6. Slope

The slope of an area plays an important role in the behavior of groundwater flow and infiltration. Therefore, areas with low slope are considered very good for infiltration (high), areas with moderate slope are considered "good," while areas with high slope are classified as "low" due to rapid runoff of precipitation and low water infiltration (43). The slope map was created from the ASTER DEM image using ArcGIS software, thanks to the spatial analysis tool in ArcMap 10.8. The watershed slope map was classified into six slope classes, namely 0–5°, 5–10°, 10–15°, 15–25°, 25–35°, and greater than 35° (very low, low, medium, poor, high, and very high) (36) (Fig. 9). Areas with a very low to low slope percentage (0–5%, 5–10%) are considered "very good to good" for groundwater recharge potential, while areas with a slope of 10–15° are considered moderate, while areas with a slope of 15–25° are considered poor for groundwater recharge potential, and finally, areas with a slope of 25–35° and greater than 35° are considered "bad and very bad" for groundwater recharge potential.

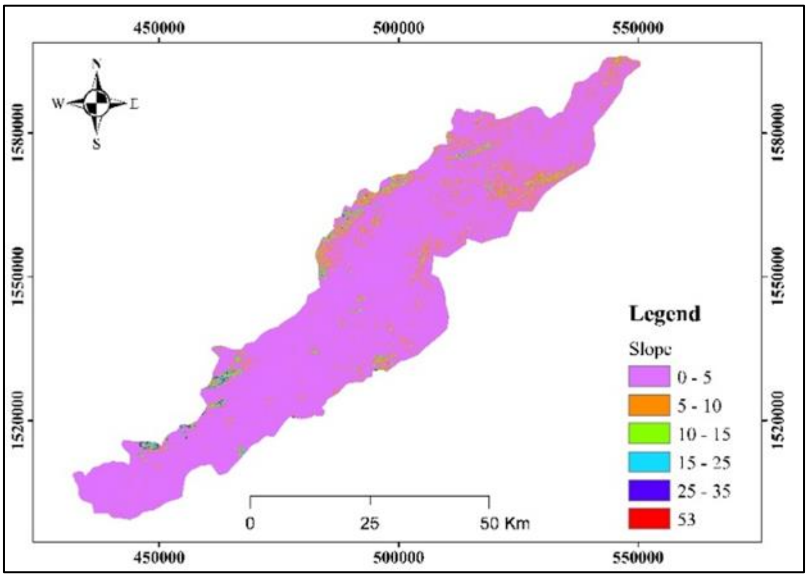

Figure 9 Slope

4.7. Land use/land cover

The development of a thematic map of land use in a region is a factor to be taken into account when exploring groundwater. It is also a good indicator for quantifying recharge, runoff, and infiltration. This map was downloaded from the website https://gee-community-catalog.org/projects/esrilc2020/. The identified components of land use/land cover in the watershed are watercourses, agricultural land, buildings, forests, and soils (Fig. 10). Based on their infiltration and runoff capacities, we classified them into six categories (very high, high, medium, low, very low, and poor). Watercourses represent the (very high) class as a source of groundwater recharge. While agricultural land and forests represent the two classes (high and medium), these two classes (high and medium) are significantly more conducive to infiltration than runoff. Finally, buildings and soils represent the two classes (low and very low) that favor runoff over infiltration of stormwater.

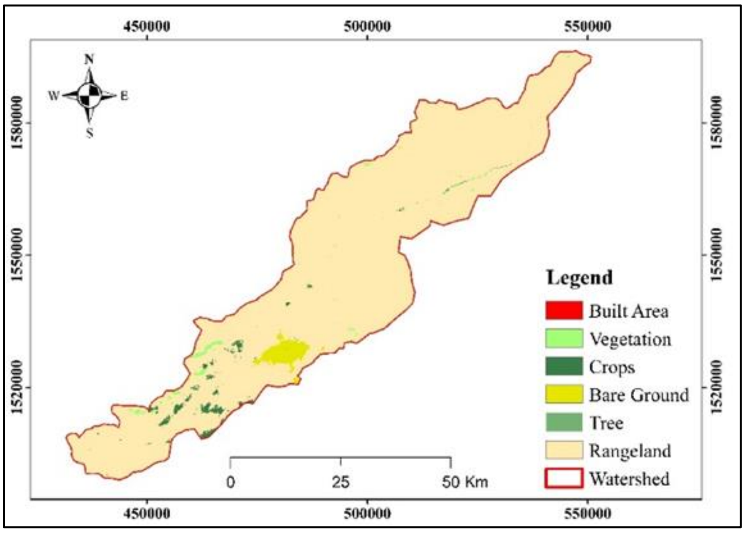

Figure 10 Land use/land cover

4.8. Groundwater recharge zone

The groundwater recharge potential map (GWRZ) was produced by assigning weights to seven thematic maps and their internal components, drawing on previous studies that aimed to develop a groundwater recharge map. The thematic vector layers were converted to raster format. The thematic maps were reclassified using the raster calculator module in the ArcGIS 10.8 environment. Based on this concept, the normalized weighted raster was classified into zones. However, the zone classifications reflect the judgment of researchers. Referring to the AHP approach, the final groundwater recharge map of the Abacha watershed is classified into three categories: good, medium, and poor (Table 4, Fig. 11).

The GWRZ areas were calculated (Table 3) using the following formula:

∑ = (GWRZ) = ALTWI * ALTR+ DDWI * DDR +LDWI * LDR+ RFWI*RFR +LTWI * LTR + SWI* SR + LULCWI*LCR

where Alt is altitude, Dd is drainage density, LD is lineament density, Rf is rainfall, Lt is lithology, S is slope, and LLC is land use/land cover. The indices “Wi” and “r” indicate the normalized weight of the thematic maps and their internal components, respectively. Figure 9 shows that groundwater recharge areas are unevenly distributed in the Abacha watershed. The northern part is considered to be an area with low recharge potential in the watershed. This is explained by a steep slope and a density of lineaments and impermeable to semi-permeable lithology, while the area considered to be average occupies a significant place in the center of the watershed. This can be explained by significant permeability, good drainage density, good lineament density, and average slopes. Finally, the area considered good for groundwater recharge is located downstream of the watershed. It should be noted that the delimitation of these areas, mainly those with good, medium, and low recharge potential, could help decision-makers define recharge areas for the implementation of hydraulic infrastructure.

Table 4 Factor weights and classes of different features of seven factor for groundwater recharge

Factor	Weight	Classes	Recharge	Assigned rank	Feature normalized weight
Altitude (m)	21	444 - 622	Good	7	0.5
		622 - 800	poor	5	0.357
		800 - 979	Mediocre	2	0.142
Dd(km/km^2)	13.66	0.06 - 0.7	Very high	9	0.45
		0.7 - 1	High	7	0.35
		1 - 1.3	Medium	3	0.15
		1.3 - 1.9	Low	1	0.05

Ld(km/km²)	14	0 - 0.2	Low	1	0.062
		0.2 - 0.4	Medium	3	0.187
		0.4 - 0.7	High	5	0.312
		0.7 - 0.9	Very high	7	0.437
Lt	13.66	Alluvial deposits	High	9	0.818
		Granite	Low	2	0.181
					0.687
Rf (mm)	19.28		Very high	7	0.437
			High	5	0.312
			Medium	3	0.187
			Low	1	0.062
Slope (degree)	25	0 – 5	Very low	9	0.333
		5– 10	Low	7	0.259
		10 –15	Medium	5	0.185
		15 – 25	Poor	3	0.111
		25 – 35	High	2	0.074
		> 35	Ver high	1	0.037
Land use/ cover	14.73			9	0.333
			High	7	0.259
			Medium	5	0.185
			Low	3	0.111
			Very low	2	0.074
			Mediocre	1	0.037

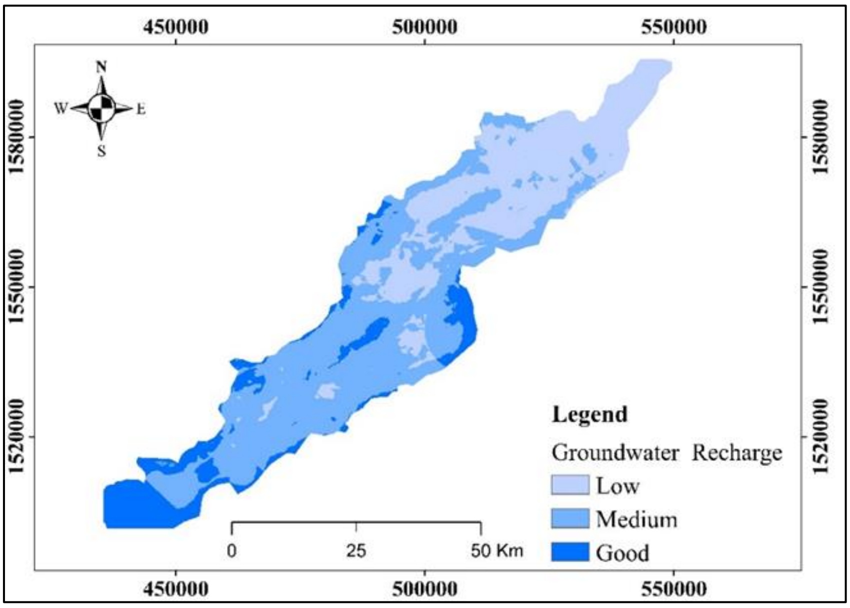

Figure 11 Groundwater recharge zone

5. Conclusion

The use of GIS integrated with AHP has become a preliminary tool in identifying potential groundwater recharge areas in the Abacha watershed. This approach effectively saves time, energy, and money. This study maps potential groundwater recharge areas by analyzing various factors. The potential groundwater recharge map was mapped using seven thematic layers: elevation, lineament density, drainage density, precipitation, lithology, slope, and land use/land cover. The results reveal that the northern part of the watershed has been classified as an area with low groundwater recharge potential. The center of the watershed has medium potential for groundwater recharge. However, downstream of the watershed, the southern part is classified as good. This area is characterized by alluvial deposits and a very gentle slope, making it ideal for groundwater recharge. The results of this study show that the adapted methodology is effective for exploring and mapping recharge areas. It also provides decision-makers with a tool for their future activities in the Abacha watershed in terms of water resource planning and management.

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