ADVANCES IN GEOMATICS

VOLUME 02 • ISSUE 01 • APRIL 2024
e-ISSN: 3023-4980

ORIGINAL ARTICLE

Submission: 09/03/2024
Accepted: 23/04/2024

AN INTEGRATED APPROACH OF REMOTE SENSING AND GIS FOR MAPPING GROUNDWATER RESOURCES IN MUBI REGION OF ADAMAWA STATE, NIGERIA

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ABSTRACT

This study employs multi-criteria decision analysis based on Saaty's analytical hierarchy processing technique to establish groundwater potentiality in the study area. The technique weighted and ranked seven hydrogeological parameters: geomorphology, lineament density, drainage density, soil type, slope, rainfall, and land use/land cover based on their relative contribution to groundwater occurrence. The derived normalized weight, and rank of the hydrogeological parameters were further integrated using the overlay tool in the ArcGIS software to delineate the groundwater potential zone of the study area. The groundwater potentiality map generated consists of five groundwater potential classes: very high, high, moderate, low, and very low. The map shows that the study area generally has moderate groundwater potentiality (76.35 %). The very high and high potential classes occupy 2.2% and 12.75 % of the study area, respectively.

Keywords: Analytical Hierarchy Process (AHP), Multi-criteria, Groundwater, Weightage overlay, GIS.

Cited As:

Ndatuwong, L. G., Ezekiel, K., & Peter, Y. (2024). An integrated approach of remote sensing and GIS for mapping groundwater resources in Mubi region of Adamawa State, Nigeria, Advances in Geomatics, 2(1), 1-16. https://doi.org/10.5281/zenodo.11313768

INTRODUCTION

Water is considered as the main constituent of the Earth's hydrosphere and as one of the most precious natural resources for the survival of living things on the planet Earth. Groundwater is a form of water held under the ground in the saturated zone that fills all the pore spaces of soils and geologic formations. It is formed by the infiltration of rainwater through the soil into the underlying rocks (Bank and Robins, 2007). It is a hidden and replenishable resource whose occurrence and distribution varies spatially according to local and regional geology, soil type, amount of rainfall, drainage network, slope, and, to an extent, the nature of human activities on the land. In basement complex terrain, the occurrence of groundwater is hosted within the weathered and fractured zones, which are often not continuous in vertical and horizontal extends (Idris et. al., 2018). This form of water is limited in nature and is an essential source of potable water for domestic, agriculture, and industrial needs.

The identification and location of groundwater potential zones are based on indirect analysis of some observable terrain features that can be used to decipher significant indicators of groundwater investigation. Such features can be extracted from RS imagery, Landsat data, and other ancillary maps.

Remote sensing involves the acquisition of information about the Earth surface using sensors mounted on aircraft or satellites. It provides valuable data on land cover, topography, and vegetation indices, which are essential for groundwater dynamics.

Geographic Information Systems (GIS) provide a powerful framework for integrating and analyzing diverse datasets in a spatial context. GIS allows the creation of detailed maps, visualization of spatial patterns, and performance of complex spatial analysis.

The conventional approach of groundwater exploration using geophysical methods is expensive because of the high cost of drilling and time-consuming investigation. Furthermore, these surveys do not always account for the different factors that control the occurrence and movement of groundwater (Oh et. al., 2011). The remote sensing technique provides the advantage of having access to large coverage, even in inaccessible areas. Satellite images are widely used for groundwater exploration because of their ability to identify various ground features, which may serve as an indicator of groundwater presence. The peculiar attributes of the remote sensing technique include its advantages of spatial spectral and temporal availability of data covering large and inaccessible areas within a short time.

Multi-Criteria Decision Analysis (MCDA) is a comprehensive decision-making framework that evaluates multiple conflicting criteria in decision making. It is particularly useful in scenarios where decisions are complex and involve various quantitative and qualitative factors. In the context of groundwater potential mapping, MCDA facilitates the integration of diverse geological, hydrological, and environmental criteria to identify areas with high potential for groundwater resources.

The Analytical Hierarchy Process (AHP) is a specific MCDA method that structures complex decision problems by organizing criteria into a hierarchical structure. This study innovatively integrates them with Geographic Information System (GIS) tools, specifically ArcGIS, to assess groundwater potential. This integration allows for spatial analysis and visualization, which enhances the understanding of groundwater distribution.

In this study, an integrated approach of remote sensing imagery and conventional maps was used to delineate the groundwater potential zone of the study area. This method offers a cost-effective approach by optimizing the use of available data before conducting extensive field investigations. It enhances the accuracy and reliability of groundwater assessments by integrating different data sources and models, leading to more informed decision-making. The aim of this work is to use multi-criteria analysis of the analytical hierarchy process to assign weight to hydrogeological parameters and combine the maps in GIS environment for delineating the potential zones of groundwater resource in Mubi region.

Many researchers have delineated the groundwater potentiality of an area by integrating different hydrological parameters that influence groundwater occurrences with the weighted overlay tool in ArcGIS software after assigning suitable weights to these factors based on experts opinion and existing literature available (Adiat et al., 2013; Agarwal et al. 2013; Ndatuwong and Yadav, 2014; Chowdhury et al. 2018; Ghosh et.al., 2020; Kumar et.al., 2022; Yossa et.al., 2022). The most common groundwater storage controlling parameters considered in these prior studies includes lineament, slope, soil, drainage network, lithology, and rainfall.

The review of literature revealed that an integrated remote sensing and GIS-based Multi-Criteria Decision Analysis (MCDA) approach using Analytic Hierarchy Process (AHP) technique has facilitated drastic improvement in groundwater potential zonation (eg. Jhariya et.al., 2016; Singh et.al., 2018; Ajayi et.al., 2022; Farhat et.al., 2023; Magina and Alexanda, 2023; Driba et.al., 2024).

1. STUDY AREA

The study area is the Mubi North and Mubi South Local Government Areas in the northeastern state of Adamawa State, Nigeria. It covers an area of about 1249.5sqkm and located between latitudes 10° 11 ‘30” and 10° 22’ 30”N and between longitudes 13° 13’ 00” and 13° 30’ 00” ‘E (figure 1). The area is drained by the Yadzaram River, which is one of the major rivers that drain into Lake Chad. It is located within the Pracambrian Basement Complex in the northern Part of Adamawa State and occupies a landmass of approximately 506,440 square kilometers. The rocks in the area are Granite Migmatite Gneisses, and Older Granites (Obiefuna, 1999). The climate of the area is characterized by a typical wet and dry season. The dry season spans for five months (November to March), whereas the wet season lasts between April and October each year. The annual rainfall ranges from 700-1,050 mm (Adebayo, 2004).

Mubi area falls within the Hawal Precambrian basement terrain where groundwater occurs within the overburden, fractures and weathered basement. The area is covered by hard rock formations, and faces acute water scarcity problem both with respect to irrigation as well as drinking purposes. In this area a lot of boreholes were drilled and failed (Lazarus et.al., 2020; Kasidi et.al., 2023).

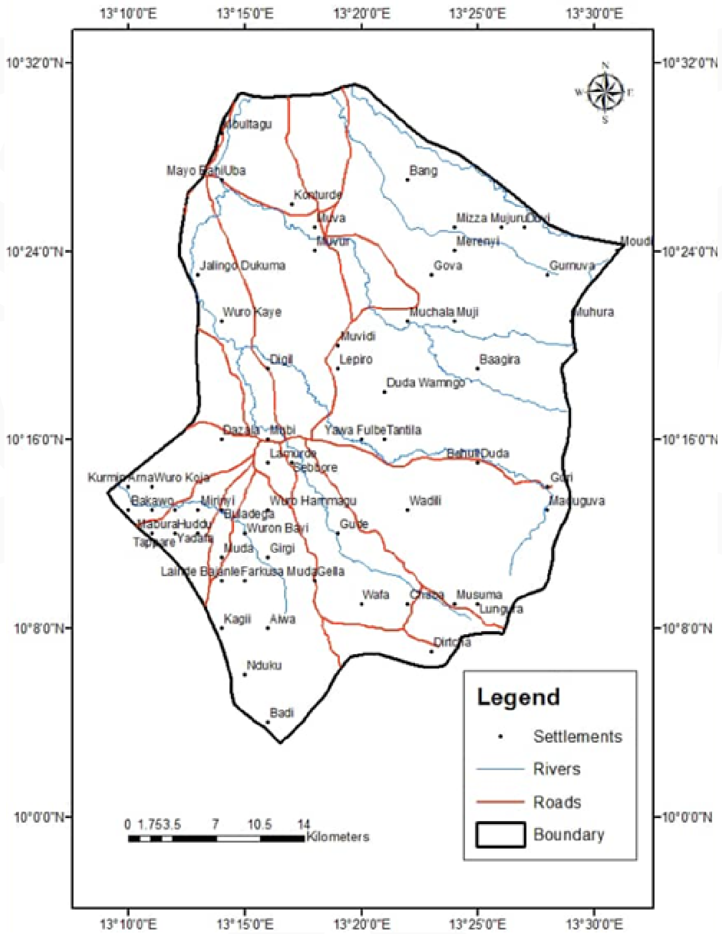


Figure 1. Map of study area.

2. MATERIALS AND METHODS

Images from remote sensing and auxiliary data were used in the investigation. The ancillary data include the following: the Nigerian dominant soil map from the FAO/UNESCO/IS-RIC website, the geomorphology map of Northeastern Nigeria from the Geological Survey of Nigeria (GSN), and the annual precipitation data for Nigeria from 2011 to 2020 from the Climatic Research Unit (CRU) website. The remote sensing images include the Shuttle Radar Topography Mission – Digital Elevation Model (SRTM- DEM) data and Landsat 8 satellite image, both acquired from the United States Geological Survey (USGS) official website.

A total of seven different thematic layers (geomorphology, land use and land cover (LULC), soil, drainage density, slope, rainfall, and lineament density) perceived to be controlling factors in groundwater flow and storage were produced from the ancillary data and remote sensing images and used in this study. The association of these factors is weighted according to their influence or contribution to groundwater occurrence based on a review of past studies and the researchers' opinions. The process involves the use of ArcGIS 10.3 software to create the thematic maps. The information obtained from the different thematic maps was analyzed using the AHP template works in Excel by Goepel (2013) to, determine the weight and influence of each feature of the thematic map. Finally, a final potential zonation map is prepared using a weighted overlay technique in a GIS environment.

2.1. Assigning Weight to Each Feature

In this study, the weighting of various criteria was conducted through a combination of field experiences and literature review. The primary steps for determining the system's normalized weight and consistency ratio (CR) were as follows:

(i) Experts' knowledge and existing research informed the creation of a pairwise comparison matrix. This matrix used a scale of 1-9 developed by Saaty (1980) to compare seven factors crucial for identifying groundwater potential.

(ii) Each factor's score was divided by the sum of scores in its column, resulting in a normalized matrix.

(iii) The average of each normalized row was calculated, representing the priority score for each factor.

The consistency of criterion ratings across the pairwise comparison cells and the derived priority scores was assessed to optimize the priority scale and reduce subjectivity among the groundwater factors (Jha et al. 2010). This was achieved in three stages as follows:

(i) A mathematical technique (eigenvector method) was used to assess the consistency of expert judgments within the pairwise comparison matrix. This involved calculating the principal eigenvalue ($\lambda \max$).

(ii) Equation (1) would be used to calculate the consistency index (CI) based on the consistency measure ($\lambda \max$).

$$CI = \frac{\lambda \max - n}{n-1} \tag{1}$$

where n is the number of groundwater factors

(iii) By dividing the CI by the average random consistency index for a 7x7 matrix (a specific value based on matrix size), the consistency ratio (CR) would be obtained using Eq. 2:

$$CR = \frac{CI}{RCI} \tag{2}$$

The resulting final criteria weights are considered as the normalized values as long as the consistency ratio lies within the expected limit. For a consistent normalization, the value of CR is expected to fall within 0.01 to 0.09, otherwise, the priority scores have to be re-evaluated (Alonso and Lamata, 2006). Upon determining the weights for each theme, their classes were ranked on the basis of their respective influences within the particular thematic layer.

2.2. Overlay Analysis

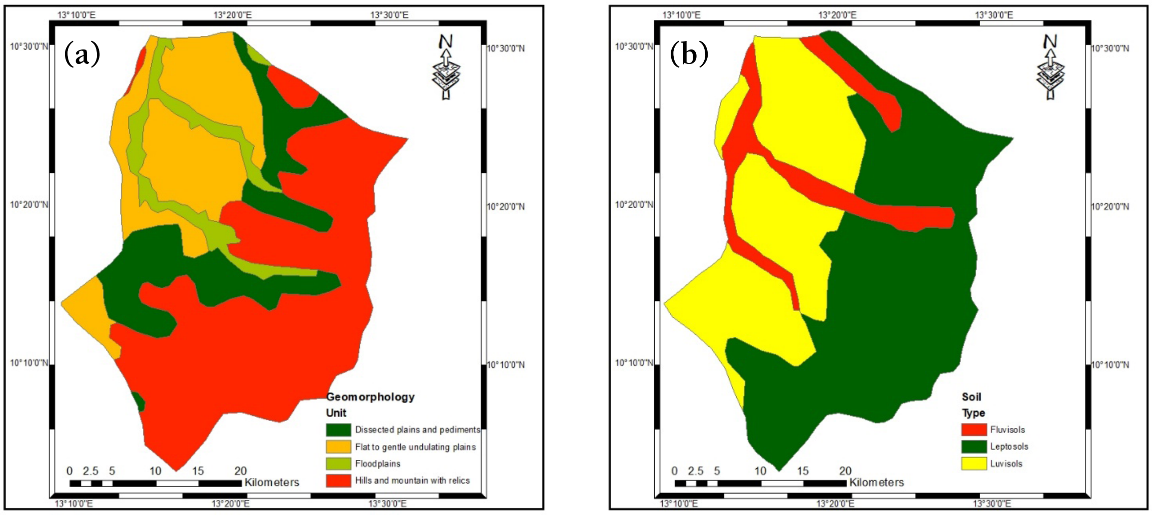
This technique combines the individual thematic maps using the weighted overlay tool in the Analysis toolbox in the ArcGIS environment, considering the weights assigned to each map. The groundwater potential map of the study area was generated by integrating all relevant parameters based on the percentage weights determined and the assigned ranks using the following equation:

$$\sum_{i=1}^{7} WiRi \tag{3}$$

Wi is the normalized weight for each thematic layer, Ri is the ranking of each class of the layer, and i denotes each of the seven influencing factors with serial numbers from 1 to 7.

3. RESULTS AND DISCUSSION

The results obtained for various aspects, namely geomorphology, soil, rainfall, slope lineament density, drainage density, and land use land cover, are discussed below.



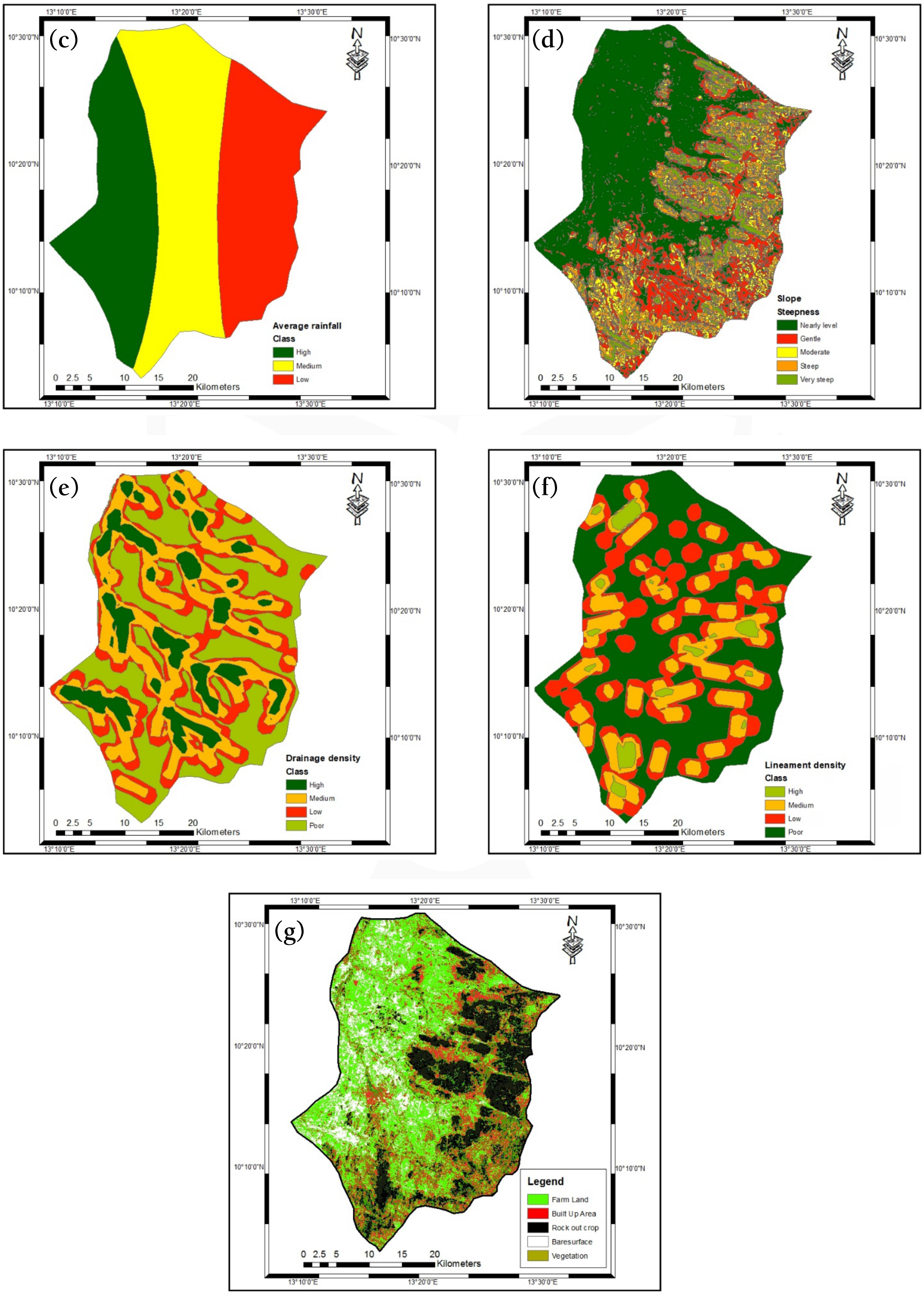


Figure 2. a) Geomorphology, b) Soil, c) Rainfall, d) Slope, e) Drainage density, f) Lineament density, and g) Land use land cover maps of the study area.

3.1. Geomorphology

Geomorphologic units are different landforms and structural units created by the natural forces such as erosion, deposition, and tectonic activity. These units can significantly impact the occurrence and distribution of groundwater resources (.Jaiswal et. al., 2003). The geomorphologic units of the study area are classified into dissected plains or pediments, flat to gently undulating plains, flood plains, hills and mountains with relics as show in Figure 2a.

Dissected plains or pediments are gently sloping surface formed by the erosion of hills or mountains. They are often composed of permeable rocks, such as sandstone or limestone. This makes them good aquifers for groundwater storage.

Flat to gently undulating plains often have low relief and minimal topographic variation. These areas may support groundwater recharge by allowing rainfall and surface water to percolate into the subsurface more uniformly. Their contribution to groundwater recharge varies depending on the nature of the surface materials.

Flood plains are low-lying areas that are composed of sediments that have been deposited by rivers. They are excellent sites for groundwater recharge because of their proximity to surface water sources.

Hills and mountains with relics are typically older, weathered landforms that have undergone significant erosion and modification over time. The contribution of these features to groundwater recharge can be substantial, especially if they consist of permeable rocks and are well-fractured.

3.2. Soil Type

The type of soil found in an area plays a significant role in groundwater recharge and water holding capacity of the area (Kumar et. al., 2016). Consequently, it could be considered as one of the important factors for the delineation of groundwater potential zones. The major soils found in the study area are luvisols, leptosols, and fluvisols with loam, sandy loam, and clay texture, as presented in Figure 2b.

Luvisols are clay-rich soils with a deep profile and a well-developed argillic horizon, which is a layer of clay that has accumulated over time. This clay layer helps to store water and prevents it from draining away too quickly. Luvisols are therefore good aquifers, or sources of groundwater.

Leptosols are shallow soils formed on rock or other hard substrates. They do not have a well-developed profile and therefore have a limited capacity to store water. However, they can be important sources of groundwater in areas with no other type of soil.

Fluvisols are soils formed from alluvial deposits, such as river sediments. They are typically young and have shallow profile. However, they can be good aquifers if the alluvial deposits are thick and permeable.

Luvisols can contribute to groundwater formation through the accumulation of water above impermeable clay layers, Fluvisols provide pathways for water to percolate into the ground because of their high permeability, and Leptosols play a role in the rapid infiltration of water into the soil, especially in areas with steep slopes or rocky terrain.

3.3. Rainfall

Rainfall plays a crucial role in groundwater formation. It is considered the primary source of groundwater recharge and has a direct relationship with groundwater resources. Adequate rainfall is essential for maintaining groundwater levels and sustaining the overall hydrological balance in the basement complex. The average annual rainfall map of the study area classified into four classes is presented in Figure 2c. Region with high rainfall rates increase the availability of water for infiltration and recharge.

3.4. Slope

Slope is defined as the ratio of the altitude change to the horizontal distance between any two points on the line (Adewumi and Anifowose, 2017). It plays a significant role in groundwater formation by affecting the direction and speed of water movement. The slope of the study area is classified into nearly level, gentle, moderate, and steep slopes as presented in Figure 2d. Steep slopes can accelerate surface runoff, limiting water infiltration and recharge. Conversely, gentle slopes allow for slower movement of water, increasing the opportunity for infiltration and groundwater recharge.

3.5. Drainage density

Drainage network, refers to the concentration and pattern of streams and rivers in a particular area. It is determined by the underlying geology, topography, and climate of the area. The drainage network of the study area was used to produce a drainage density map, which measures of the number of stream channels per unit area of land. The drainage density map of the study area is classified into poor, low, medium, and high drainage density as shown in Figure 2e.

The drainage density has an inverse relationship with the groundwater prospect. The higher the drainage density, the lower the probability of a groundwater potential zone. (Melese and Belay, 2021). Poor to low drainage density areas provide less surface water run-off, as such favors high infiltration and recharge to groundwater, which act as a good groundwater prospect zone. On the other hand, the high drainage density area permits low infiltration because of high surface run-off, which makes it a poor zone for groundwater prospecting.

3.6. Lineament density

Lineament refers to the linear geological features such as faults, fractures, and joints found in the subsurface. They act as pathways for groundwater movement and can significantly influence the formation and flow of groundwater particularly in the basement complex. The lineament density map produced is shown in Figure 2f. It is classified into poor, low, moderate, and high-density area. A region of high-density lineament provides more pathways for water infiltration and can enhance the storage and movement of groundwater. In contrast, the region with lower lineament density are associated with poor groundwater potential.

3.7. Land use land cover (LU LC)

Land use land cover is an important factor that determines groundwater occurrence, recharge, and availability (Ghosh et al.2016; Badamasi et al.2016). The LULC cover classes in the study area are vegetation, farmland, bare surface, built-up, and outcrops as, shown in Figure 2g. Vegetation and farmland occupied about 60% of the study area with a total area of approximately 964.9 square kilometers. Built-up area and bare land comprise of about 252.7 square kilometers of the total study area, while the least is the rock outcrop, which is mostly found around the eastern axis of the study area just occupying about 33.5 square kilometers.

3.8. Derived weight and ranks

The weightage of individual theme and feature ranks was established using the AHP model within the context of multi-criteria decision analysis (MCDA). During this process, a consistency ratio (CR) of 0.0063, which is less than 0.1 was obtained, suggesting a sufficient level of consistency. This analysis supports the acceptability of the result. The eigenvalue ($\lambda \max$) of 7.508, consistency index (CI) of 0.37, and random consistency index (RCI) of 0.23 was obtained.

The thematic layer features were then ranked based on their influence on groundwater potential within each parameter along with its spatial area extent. The highest ranking was assigned to the feature with the greatest groundwater potentiality, whereas the lowest potential feature received the minimum ranking. The results are presented in Table 1.

3.9. Groundwater Potential Mapping

Groundwater potential map of the study area generated through analytical hierarchy processing, which involves ranking, assigning weight to all the various results of the hydrogeology parameters, and overlaying them using ArcGIS 9.3 software. Spatial analysis and modeling involves integration of the generated thematic layers using equation 1. The output map was classified into five zones of groundwater occurrence potentiality: high, moderate, low, and poor (Fig. 3). The map shows that most of the study area is occupied by the moderate potential zone (76.35 %), followed by the high potential zone (12.75 %), low potential zone (6.85 %), very high potential zone (2.2 %), and very low potential zone (1.85 %).

Table 2. Class ranking and percentage weight of thematic layers.

	Classes	Feature Rank (Ri)	Normalized weight (Wi)	Spatial Area (Sqkm)
Rainfall (mm)	Low	1	19 %	386.04
	Medium	2		491.52
	High	3		371.97
Drainage density (km/km²)	Poor	4	15 %	467.49
	Low	3		293.13
	Medium	2		299.16
	High	1		189.70
GM	Dissected plains or pediments	3	15 %	236.86
	Flat to gently undulating plains	2		302.80
	Flood plains	4		89.14
	Hills and mountains with relics	1		620.70
Lineament density (km/km²)	Poor	1	15 %	593.42
	Low	2		343.52
	Medium	3		270.36
	High	4		42.17
LU/LC	Built-up area	2	13 %	34.73
	Bare surface	2		85.83
	Outcrops	1		175.78
	Farm land	3		667.35
	Vegetation	4		285.76
Soil type	Fluvisols	3	13 %	138.53
	Leptosols	2		664.34
	Luvisols	1		446.62
Slope (Steepness)	Gentle	5	10 %	269.48
	Nearly level	4		587.43
	Moderate	3		154.46
	Steep	2		154.00
	Very steep	1		84.10

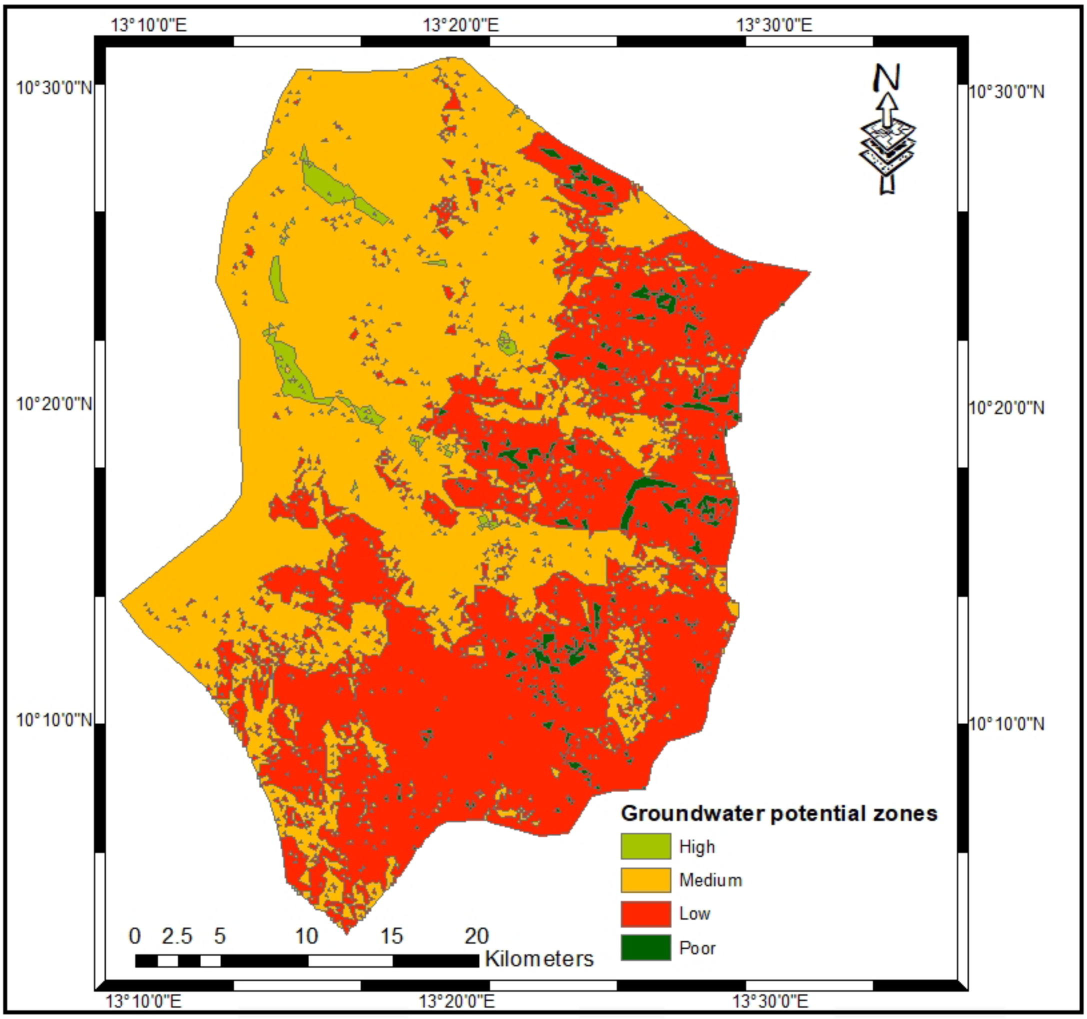


Figure 3. Groundwater potential map of the study area.

CONCLUSIONS

The study delineated very low, low, moderate, and high groundwater potential zones. Groundwater resources in basement terrain are limited and commonly restricted to diastrophic features. Groundwater exploration in the terrain requires precise determination of the attributes of these features. The remote sensing–GIS approach would serve as the preliminary inventory method to understand the groundwater potential index and facilitate the delineation of zones adjudged suitable for further hydrogeophysical investigations.

Remote sensing and GIS techniques proved to be a valuable tools for exploring groundwater resources in basement complex terrain in such a way that time and cost can be saved. Lineament density, geomorphology, drainage density, soil type, slope, and annual rainfall were the parameters used as indicators in deciphering groundwater conditions in this work.

The groundwater potential distribution map generated is a crucial resource for future development, particularly in the planning and site selection for establishments with high or low water demands within the studied area. It also offer valuable information for identifying regions suitable for groundwater development to mitigate deficiencies in the public water supply where needed. By leveraging this data, decision-makers can ensure sustainable and equitable use of groundwater resources, and supporting long-term development.

A correlation of the groundwater potential map with the existing boreholes data in the study area is recommended for future study. This will validate the efficacy of the method in mapping potential site for groundwater exploration.

Acknowledgements: The authors acknowledge the financial support from TETFUND's Institutional Base Research (IBR) Fund, which enabled this research. We are particularly grateful to the anonymous reviewers and editor for their insightful comments, which helped us strengthen the paper's arguments. We also appreciate the ongoing support of the Director of Research and Innovation at Adamawa State University, Mubi.

Conflict of interest: The authors declare no conflict of interest.

Author's contribution: All the authors contributed meaningfully to the actualization of the work.

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