# Delineation of Groundwater Potential Zone in Hard Rock Terrain, using Remote Sensing, GIS, and Analytical Hierarchy Process (AHP): A Case of Suleja Local Government Area, North-Central Nigeria

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Groundwater exploration using integrated approaches such as remote sensing data, geographic information system (GIS), and Multi-criteria decision-making techniques has recently become a breakthrough in groundwater exploration. Suleja, a suburb underlain by Basement complex rocks, has in recent times recorded a reasonable number of abortive boreholes, largely due to poor exploration techniques and lateral discontinuity of the hard rock lithologies. This research aims to delineate possible groundwater potential zones (GPZ) by integrating remote sensing, GIS, and electrical resistivity data. Geophysical data were obtained using the electrical resistivity method through vertical electrical sounding (VES), and the interpreted data were used to produce the study area map. Thematic layers such as geology, depth to bedrock, drainage density, elevation, land use/land cover, and the lineament density were generated from conventional maps, remote sensing data, and geophysical investigation. The data were processed into readable maps in the GIS environment using IDW interpolation techniques. The generated maps were subjected to weighted overlay analysis to obtain the groundwater potential zones. The weights for the various layers were generated using the multi-criteria decision-making technique called the analytical hierarchy process (AHP), which allows the pairwise comparison of criteria influencing the Groundwater potential zone. Using the overlay analysis technique, the thematic maps were integrated to produce the GPZ map of the study area. The map displays five groundwater potential zones, namely very high, high, moderate, low, and very low potential zones. The results of the study revealed that the very high potential zone occupies 0.01% (0.006 $km^2$), high 10.04% (11.92 $km^2$), moderate 61.46 % (72.98 $km^2$), low 28.34% (33.66 $km^2$), and very low 0.15% (0.1 $km^2$), of the study area respectively. The map generated from this research agrees reasonably with field conditions.
**Keywords:** Analytical Hierarchy Process, Electrical Resistivity, GIS, Groundwater Potential Zone, Remote Sensing

## Introduction

The ability to improve groundwater exploration accuracy by integrating geophysical exploration techniques with remote sensing (RS) and geographic information system (GIS) approaches is apparent. Groundwater has become the major source of potable water in urban as well as rural areas in Nigeria owing to the infrastructural decay of the public water supply systems and the lack of will or inadequate commitment to address these persistent challenges over the years (Isukuru *et al.,* 2024). As one of the earth's most vital resources and a requirement for continued survival, water plays a significant part in man's physiological and socioeconomic activities (United Nations Educational, Scientific and Cultural Organizations (UNESCO, 2023)). Aquifers are water-bearing structures in the earth's crust. They serve as both water reservoirs and transmission channels. Their identification and delineation are carried out through indirect investigation of some apparent terrain elements, such as geology and geomorphic landforms, and their hydrologic properties (Prasad *et al.,* 2008).

Basement complex terrain is one of the challenging environments in groundwater exploration and development because its aquifers are discontinuous and often limited in lateral and depth extent (Wright, 1992). The occurrence and movement of groundwater in basement complex terrain is controlled by geological factors. The crystalline basement rocks are characterized by secondary porosity arising from joints, fissures/fractures, and intergranular porosity (Amadi, & Olasehinde, 2010). Secondary porosities caused by these joints/fractures/faults significantly increased storage capacity in fractured basement aquifers. The weathered basement aquifer is porous but has poor permeability due to its clayey composition, yet its storage capacity can be large because of its relatively high porosity (Abiola *et al.,* 2009). Low to moderate groundwater potential rating is often associated with the weathered aquifer because its groundwater-yielding capacity is limited (Olorunfemi, & Fasuyi, 1993). Groundwater yield is often substantial where both weathered and cracked basement aquifers are present (Olorunfemi, & Fasuyi, 1993).

Exploration for groundwater requires a clear understanding of the study area's surface and subsurface features (Mogaji *et al.,* 2011). The incorporation of various data, such as terrain characteristics derived from hydrogeological data, remote sensing images, and hydrogeomorphic details, will aid in generating groundwater potential zone maps, which, when accompanied by geophysical data, will facilitate effective groundwater exploration (Yadav & Singh, 2007).

Integrating remote sensing and electrical resistivity methods has been considered two important methods for groundwater exploration and mapping in hard rock terrain; several works have been published on the use of these methods in groundwater investigation where the GIS platform provides a suitable unifying environment for geospatial integration and analysis (Akinluyi, 2012; Goki *et al.,* 2010). Despite successes recorded in applying the two methods independently in groundwater investigations, combining the two methods proves to be more reliable (Srivastava & Bharadwaj, 2012).

The electrical resistivity approach using vertical electrical sounding (VES) is commonly employed to find aquifers in basement complex environments. The technique is frequently preceded by horizontal profiling or electromagnetic profiling as a reconnaissance approach to mapping areas with deep weathered layers (overburden) and/or discontinuities caused by faults and fractured zones (Afolayan *et al.,* 2004). Satellite data has also played an important part in geological applications over the years, assisting in the resolution of geological problems such as finding a good aquifer for sustainable groundwater supply in basement complex terrain (Krishnamurthy *et al.,* 2000). Several researchers have employed satellite imagery for lineaments mapping in the hunt for acceptable locations for boreholes that will provide economically feasible yields of groundwater and mineral exploration and prospecting in Nigeria's hard rock terrain in recent years (Akinwumiju *et al.,* 2016; Mogaji *et al.,* 2011).

**Study Area**

The study area covers an area of 136.33 km$^2$ and is a major satellite town close to the Federal Capital Territory (FCT), Abuja (Figure 1). It is generally accessible through major highways, including the Abuja – Kaduna highway. It is a densely populated town with a population growth rate of 3.2% ((National Population Commission (NPC, 2006)), which can be attributed to its strategic position as a central hub for commuters and trade. The rapid population growth and other related factors have increased the dependence of the inhabitants of this ancient town on groundwater for both domestic and industrial use (Ejaro & Abdullahi, 2013).

Suleja and its environs are underlain by crystalline basement rocks whose hydraulic properties are characterized by thrilling variations over short distances; these characteristics often limit groundwater development to low-yielding Boreholes (Akinwumiju & Olorunfemi, 2016). The drainage system, which is part of the Niger River basin, exhibits a dendritic pattern primarily influenced by the rugged rock terrain. Its rivers and tributaries are seasonal; prominent among them is the Kantoma (Maje) river. Aquifers in the permeable zones and low-lying areas in Suleja are often recharged by rainfall during the rainy season (Akano *et al.,* 2016). The study area can be topographically described as undulating, comprising alternating rugged hills and valleys.

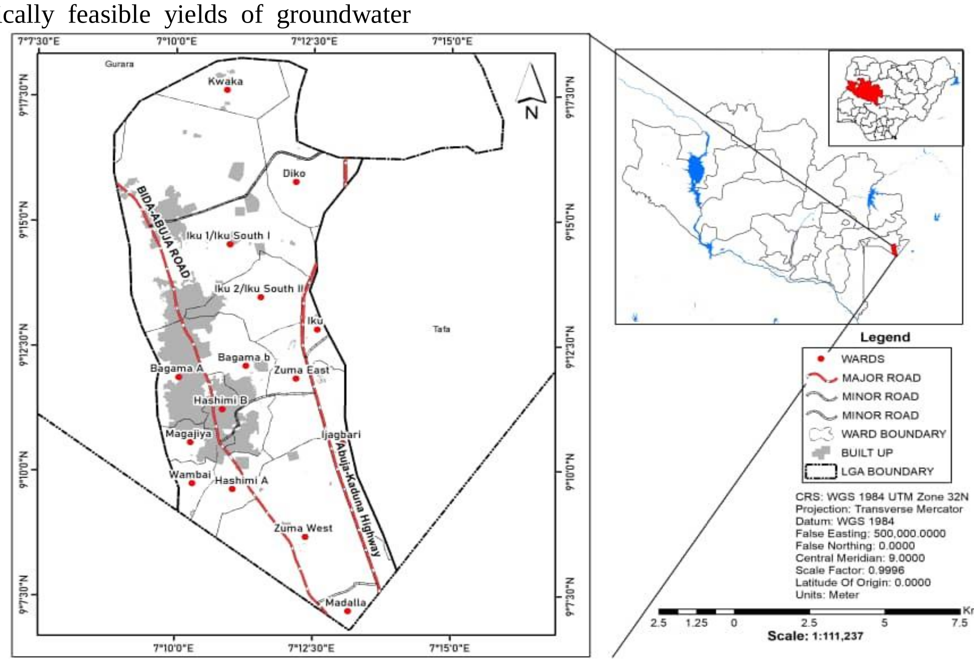


**Figure 1: Location map of the study area**

**Methods and Approach**

**Thematic map generation**

The methods employed for this research are multidisciplinary. A data-driven multi-criteria analysis was carried out using the Analytical Hierarchy Process (AHP) method, integrating several parameters (thematic layers) relevant to groundwater exploration in the region. These include local geology, topography, drainage density, land use and land cover (LULC), lineament density, and depth to bedrock (Figure 2). These factors play a vital role in evaluating groundwater potential and movement in the study area, as outlined below.

*Geology*

Groundwater accumulation, quantity, and quality are influenced by the geology of an area (Rahmati *et al.,* 2015a). The geological map of the study area was clipped out from the Geological Map of Nigeria (1:2,000,000 scale), produced by the Nigerian Geological Survey Agency (NGSA). The extracted image was transferred to the ArcGIS environment for geo-processing where it was georeferenced to align the map with the geographic coordinates of the study area. The georeferenced map was subsequently projected for geospatial analysis. Using the digitizing tool in ArcGIS, the geological boundaries in the projected image were then digitized. To validate the mapped boundaries and evaluate the structural element in the field a geological reconnaissance survey was carried out in the study area. Transitions between different rock units at different locations and the interface between regolith and basement rock in the field, especially where there is exposure, were confirmed through field observations. The inclination and orientation of lineaments were measured using a geological compass, and their respective coordinates were captured using GPS, which gives a clear understanding of the structural geological setup of Suleja. Using the information collected in the field and the existing geological map, an updated geological map of the study area was created in the ArcGIS environment (Figure 4).

*Drainage density*

The degree of infiltration in a region is determined by how well the environment is drained. When the drainage density is very high, the runoff is very high, and the infiltration rate is relatively low. Conversely, as drainage density decreases, runoff decreases, and infiltration increases (Ibrahim-Bathis & Ahmed, 2016). Drainage density (DD) was created using the ASTER Digital Elevation Model (DEM), and the data was acquired from the USGS Earth Explorer website. The drainage density map was produced in the ArcGIS environment using the spatial analyzer tool (Arc Hydro tool in ArcGIS 10.8). Real-time Google Earth pictures and Landsat 8 data were used to update extracted drainages. The raw DEM data was first transformed into a Fil > > Flow direction > > accumulation raster. The watershed hydrological pattern was then delineated by calculating the effective drainage area using the drainage density index Equation below (Mogaji *et al.,* 2015).

$$D = \sum_{i=1}^{i=n} \frac{D_i}{A} \ (km^{-1}) \quad (1)$$

Where:

$\sum D_i$ = Total length of all streams in the mesh $i$ (km) and

A = Area of the grid ($km^2$).

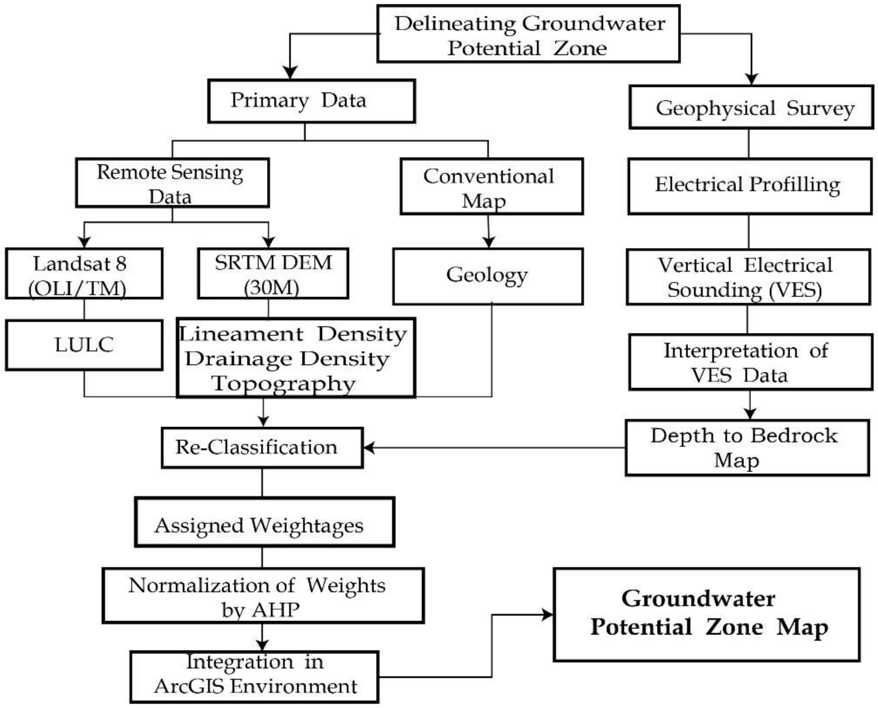


**Figure 2: Methodology flowchart for this Research**

*Lineament density*

Lineament is the surface expression of structurally regulated subsurface structures like fractures (faults and/or Joints). In satellite photographs, they are typically portrayed as linear features. Lineaments are important in the transport and storage of groundwater. Lineaments act as conduits for surface runoff to seep into the subsurface, increasing groundwater storage. The lineament density of an area can directly reveal the groundwater potential since the presence of lineaments usually denotes a permeable zone (Sitender & Rajeshwari, 2011).

Utilizing data from Landsat 8 OLI images with a spatial resolution of 30m x 30m, linear structures such as joints and fractures in the study area were mapped using a manual lineament extraction technique. An enhanced band combination of SWIR1-NIR-Red was used to expose the structural patterns in the images in addition to the image enhancement techniques such as contrast stretching, and edge recognition employed for image processing. The structural features were manually digitized in an ArcGIS environment. The identified structures were then verified and refined by cross-referencing them with DEMs and the geological map of the study area. Lineament Density was produced from the lineament map using the grid cells method expressed in Eq. 2 (Rahmati *et al.,* 2015b). The lineament direction was visualized by plotting its rose diagram (Figure 7a).

$$LD = \sum_{i=1}^{i=n} \left(\frac{L_i}{A}\right) (km^{-1}) \qquad (2)$$

Where:

$LD$ = Lineament density,

$L_i$ = Sum of the length of all the lineaments (km),

$i$ = Linear feature in the study area,

$A$ = Effective area of lineament cell grids ($km^2$).

*Topography*

The Topographic map was created using the Shuttle Radar Topography Mission (SRTM) Digital Elevation Model (DEM) data in the ArcGIS environment. To represent the variation in elevation and capture the terrain features such as valleys, slopes and ridges, contour lines were generated at specified intervals. Subsequently, a Hillshade raster was created to improve terrain visualization, The topographic map was resampled and reclassified for easy integration into the Analytical Hierarchy Process (AHP) model.

*Land uselLand cover (LU/LC)*

The Land cover variations map (LU/LC Map) was delineated using Landsat 8 OLI (30 X 30m) satellite data. To correct the spectral distortion and reflectance quality of the images downloaded, the images were first subjected to radiometric and atmospheric correction before the LU/LC analysis. This was followed by the generation of composite bands (1 to 7) used for spectral analysis. Using the Earth Resources Data Analysis System (ERDAS Imagine) software, supervised classification was done on the corrected data using the Maximum Likelihood Classification (MLC) algorithm. Using confusion matrix and Kappa coefficient accuracy assessment was performed on the classified image. The land use/land cover in the study area was categorized into built-up area, bare land, forest, impervious surface, and grassland. Further processing, including filtering and reclassification of the classified map, was done in the ArcGIS 10.8 environment.

*Depth to bedrock*

To estimate the aquifer thickness and determine the depth to bedrock in the study area Vertical electrical sounding (VES) data were used. Using the Inverse Distance Weighting (IDW) technique in ArcGIS environment, the spatial distribution of depth to bedrock in the study area was established using interpolation techniques. The VES data points with their respective coordinates were imported into the GIS environment where the IDW algorithm was subsequently applied. Using the IDW approach greater weights are assigned to known data points (Sampled location) and the depth values of unsampled locations are calculated using the inverse of their distance from known points.

$$Z(x) = \frac{\sum_{i=1}^{n} \frac{Z_i}{(d_i)^n}}{\sum_{i=1}^{n} \frac{1}{(d_i)^n}} \quad (3)$$

Where:

*Z(x)*= Interpolated value at location x.

$Z_i$= Measured value at point i.

$d_i$= Distance between points i and x.

$n$ = Power parameter controlling the influence of distance (commonly set to 2)

The IDW method works on the principle that sample points at locations in close proximity have similar characteristics compared to those farther apart. The resulting depth to bedrock map illustrates the spatial variation of the aquifer thickness across the study area, which provides insight into the subsurface conditions.

**Geophysical investigation**

The Geophysical investigation was carried out using the Electrical Resistivity Method to determine the depth-to-bedrock (overburden thickness) within the study area. Four-electrode arrays were used at the surface, one pair introduced the current into the earth, and the second pair measured the potential difference established in the earth by the current flow.

Fifty (50) vertical electrical soundings (VES) using the Schlumberger array were conducted across the study area (Figure 3), with a maximum electrode spacing of 100m. The survey was carried out by progressively increasing the electrode spacing around a stationary point of the configuration. The electrode spread of AB/2 varied from 1 m to a maximum of 100m. To obtain the apparent resistivity values in Ohm-meter (Ω-m), the ground resistance (Ω) value was multiplied by the relevant geometric factor (K) for each electrode separation. The data obtained using were interpreted using IP2Win software which presents the VES data as depth-sounding curves with the apparent resistivity $\rho$ (Ωm) on the ordinance (Y-axis) against the electrode spacing AB/2 (m) on the abscissa (X-axis).

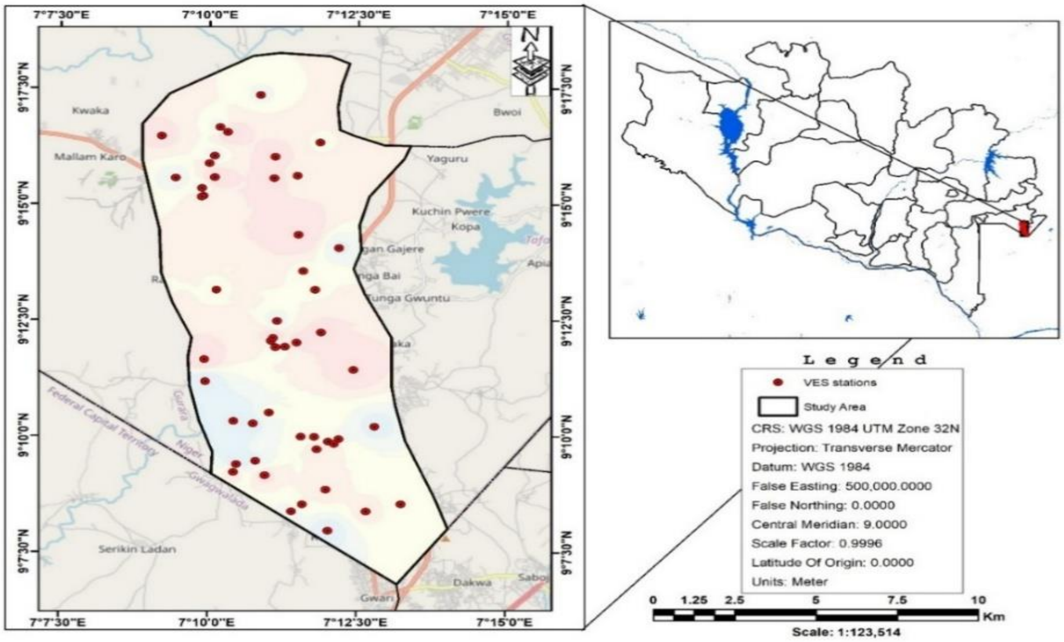


**Figure 3: Study area map showing the vertical electrical Sounding (VES) Stations**

**Analytical hierarchy process (AHP)**

For this research, the Analytic Hierarchy Process (AHP) developed by Saaty (1994), a form of Multi-Criteria Decision Analysis Technique (MCDA) was applied. Elevation, Geology, Lineament Density, Drainage Density, Depth to Bedrock, and Land use/Land cover were identified as factors influencing groundwater potential in the study area. The relative value of each unique theme's (factor's) attributes to groundwater potential was calculated intuitively. The approach of (Fashae *et al.,* 2014; Singh *et al.,* 2013) was used to create a matrix comparing features within each theme based on their importance to groundwater potential (Table 1).

**Table 1: Pairwise comparison matrix between all criteria for the AHP model**

| Criteria | Geology | LULC | Drainage Density | Depth to bedrock | Topography | Lineament Density | Weight |
|---|---|---|---|---|---|---|---|
| Geology | 0.10 | 0.33 | 0.66 | 0.05 | 0.12 | 0.04 | 0.22 |
| LULC | 0.01 | 0.04 | 0.02 | 0.4 | 0.18 | 0.04 | 0.12 |
| Drainage Density | 0.03 | 0.33 | 0.16 | 0.2 | 0.29 | 0.54 | 0.26 |
| Depth to bedrock | 0.10 | 0.01 | 0.04 | 0.05 | 0.06 | 0.05 | 0.05 |
| Elevation | 0.05 | 0.01 | 0.03 | 0.05 | 0.06 | 0.05 | 0.04 |
| Lineament Density | 0.71 | 0.29 | 0.08 | 0.25 | 0.29 | 0.27 | 0.32 |
| Sum | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |

**Assigning rank and weight**

Six (6) thematic layers were used in this research and assigned weights based on their distinctive effects on groundwater prospects to achieve the outlined objective. The thematic layers were first converted into raster form using 100m cell width to realize substantial accuracy. The layers were

then reclassified and assigned weightage. Each factor was given a weight using AHP and a priority-based scale (Table 2). Weights were allocated using ArcGIS's "extAHP20" extension following the AHP method (ESRI, 2018). The knowledge-based approach for groundwater potential indexing used in this study was based on the environmental and hydrogeological characteristics of the study area; a thematic layer with low weight has little effect on groundwater potential, whereas a thematic layer with high weight has a significant impact on the groundwater prospect.

**Table 2: Normalized pairwise comparison matrix and weights of each criterion**

| Criteria | Geology | LULC | Drainage Density | Depth to bedrock | Topography | Lineament Density |
|---|---|---|---|---|---|---|
| Geology | 1 | 8 | 4 | 1 | 2 | 1/7 |
| LULC | 1/7 | 1 | 1/8 | 8 | 3 | 1/7 |
| Drainage Density | 1/4 | 8 | 1 | 4 | 5 | 2 |
| Depth to bedrock | 1 | 1/8 | 1/4 | 1 | 1 | 1/5 |
| Elevation | 1/2 | 1/3 | 1/5 | 1 | 1 | 1/5 |
| Lineament Density | 7 | 7 | 1/2 | 5 | 5 | 1 |

**Groundwater potential zone delineation**

Employing the weighted overlay method (the spatial analyst tool) in ArcGIS to overlap all the thematic layers after assigning weights to each and ranking each sub-class of the thematic layers by means of the AHP technique, the groundwater potential zones were characterized. Based on the index value calculated using the equation below, five distinctive groundwater potential zones were identified using a natural break classification system (very high, high, moderate, low, and very low). This classification system was developed by (Macdonald *et al.,* 2009), and has been employed by many authors due to its efficacy (Nampak *et al.,* 2014; Rahmati *et al.,* 2015c).

$$GPZ = \sum_{i=1}^{n} G_w G_r + DD_w DD_r \dots\dots + DB_W\, DB_r \qquad (4)$$

Where:

G is the geology; DD is drainage density; LD is lineament density; E is elevation; LL is Land use land cover; DB is depth to bedrock; w is the weight, and *r* is the rank.

**Results and Discussion**

**Factors influencing groundwater potential**

*Geology*

Geologically, the study area is made up of basement complex rocks of the North - Central Nigeria. The exposed lithological units consist of banded gneiss, biotite, hornblende granite, and migmatites (Figure 4). About 50% of the study area is dominated by Migmatitic Gneiss manifesting as low-lying flat terrains. They exhibit generally dark colour and are commonly characterized by felsic bands. Visible in most of the rock bodies are the quartzofeldsapathic veins, displayed in diverse sizes and orientations. They are commonly covered by thin soil (regolith) with vegetation cover, especially in the rainy season. The second dominant rock is the coarse porphyritic biotite and hornblende granites, which occupy roughly 35%. A small portion of the area about 15% is made up of undifferentiated granite, migmatite and granite gneiss.

Linear alignment of minerals was observed on the gneissic rocks, which indicates the rock's gneissosity. Most of the granites are coarse-grained and appear to have intruded into the gneiss complex. In most locations visited, the rocks exhibit various degrees of weathering and structural elements. The rocks are commonly rich in feldspar, which could be attributed to high-weathering activities observed in the rocks because felspathic minerals are very vulnerable to chemical weathering. The weathering effect could be responsible for the relatively deep overburden observed in some locations. Deep overburden supports groundwater storage.

Structurally, the rocks are jointed and display two prominent trending directions, NW-SE and NE-SW, with the NW-SE dominating the study area. They seem relatively foliated, and the structural elements trend NS and NE-SW and are more visible among the banded gneiss. The rock group in the study area are said to have been formed about 2.5 billion years ago (Rahaman, 1988). The migmatization of these paleo-Proterozoic rocks occurred around 600 years ago during the pan-African Orogeny (Rahaman, 1988).

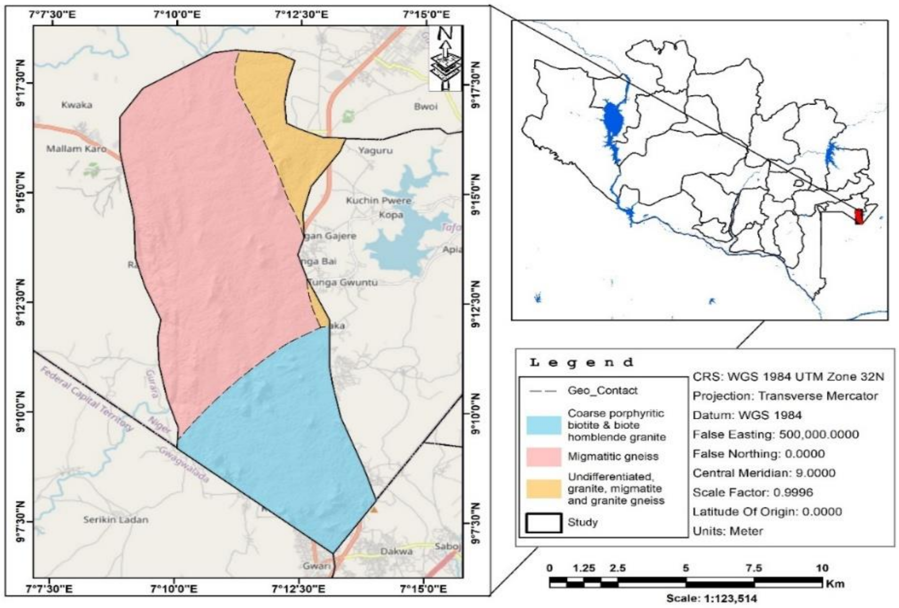


**Figure 4: Geological map of the study area**

**Land use/land cover (LU/LC)**

Water infiltration into the earth is influenced by land use/land cover features. The study area's LU/LC was evaluated for suitability for groundwater potential evaluation. It comprises the distribution of developed land, forestland, agricultural land, and impervious surface (Figure 5). Despite its continuous decline over the years, owing mainly to human activities in the study area, Vegetation in the form of shrubs and Bareland still maintains its lead with large area coverage. This indicates that groundwater recharge, an important component of the hydrological cycle in the study area, is not hindered by land use or anthropogenic effects.

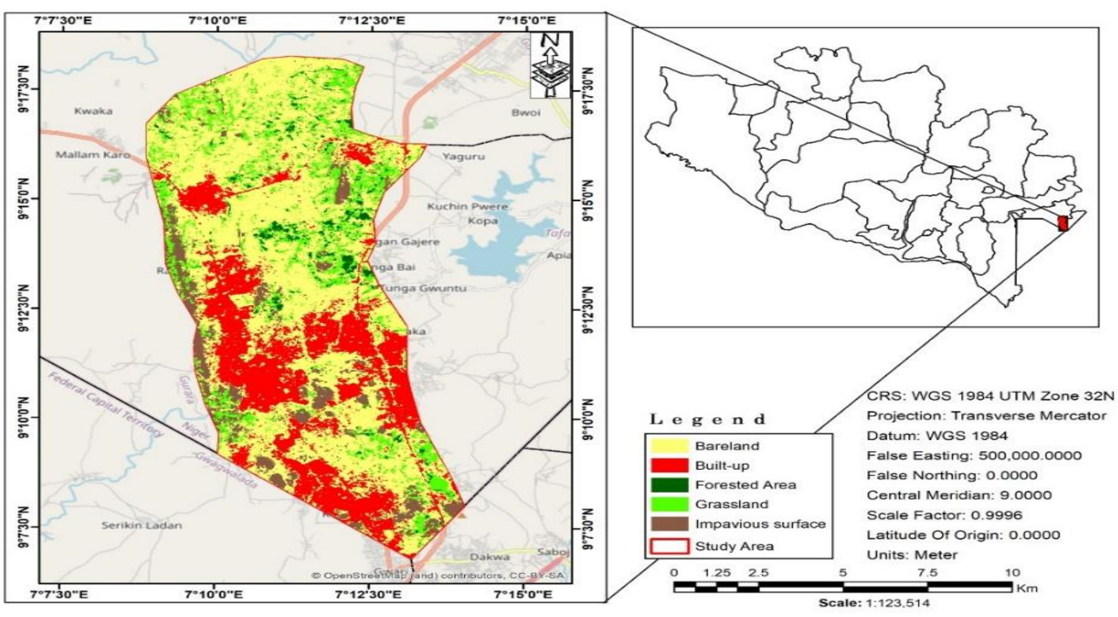


**Figure 5: Land use/ Land cover map of the study area**

**Drainage density**

The drainage pattern of the study area is dendritic, reflecting the topographic influence of the area (Figure 6). Suleja is a relatively high-drained town; hence, it is predicted to have a relatively low level of infiltration. The drainage density influences runoff and quantity of infiltration into the ground (Ibrahim-Bathis & Ahmed, 2016). The drainage density of the study area varies between 0 and 8.18 km$^2$ (Figure 6).

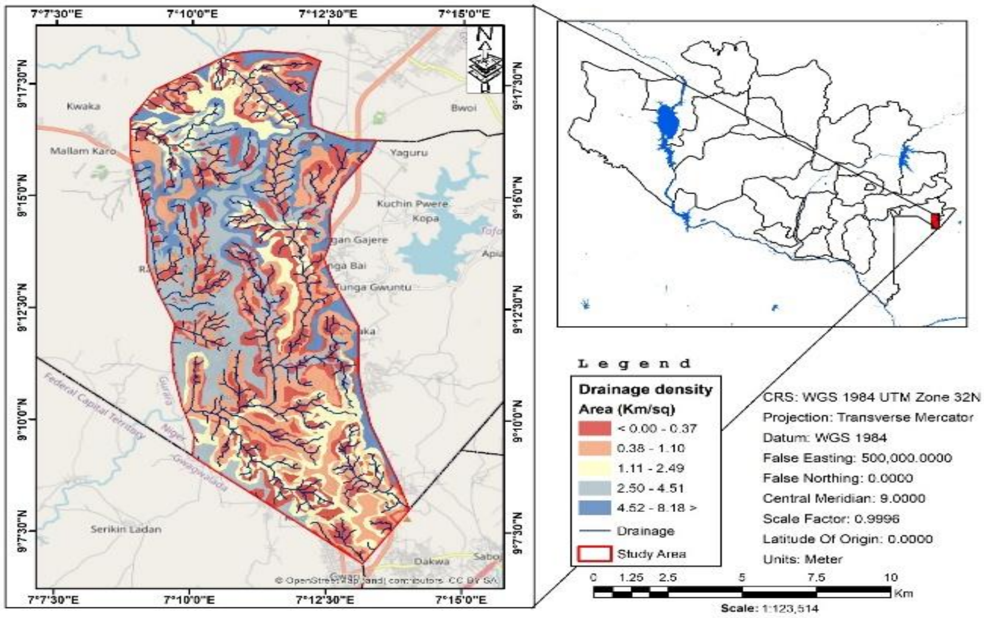


**Figure 6: Drainage Density map of the study area**

**Lineament density**

Suleja is relatively dense in lineament, with denser lineaments predominant in the western part of the study area. The lineaments primarily trend NNE-SSW, with a few moving about NE-SW and others trending NW-SE (Figure 7a). Lineaments act as conduits for surface runoff to infiltrate into the subsurface, increasing groundwater storage. This is evidenced in the Suleja lineament density map which indicates a good groundwater storage potential.

The study area's lineament density varied from 0 to 58.90 km$^2$ and was categorized into five classes for the convenience of assigning weights. The highest value of lineament density indicates the highest potential for groundwater recharge; hence, the highest rating of 0.51 was assigned to regions with 4.54 – 58.90 km$^2$ of lineament density (Figure 7b).

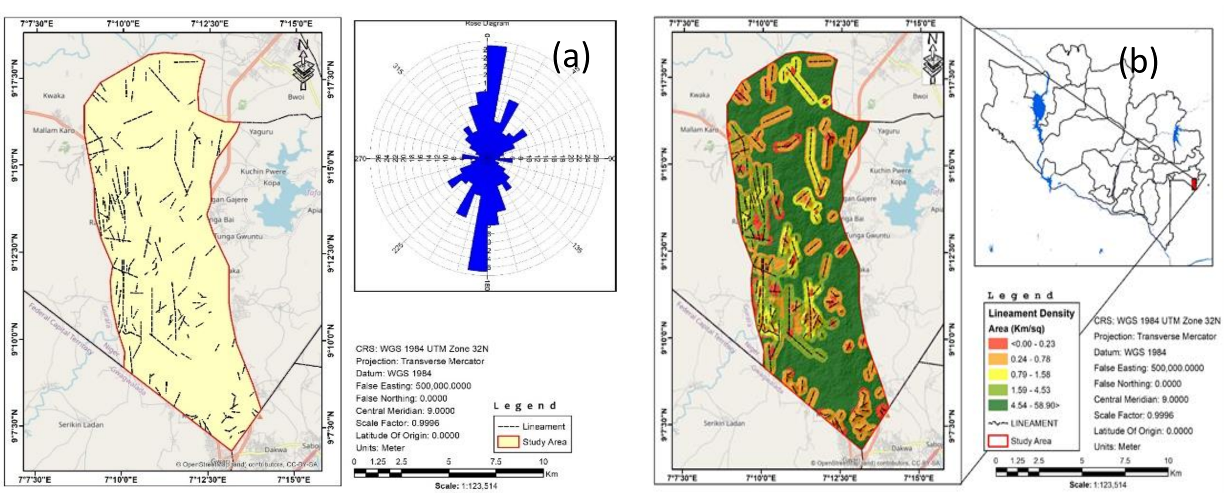


**Figure 7: (a) Lineament map (b) Lineament density map**

**Depth to bedrock**

The overburden map (Figure 8) shows that areas with the thickest overburden are sparsely distributed and are commonly observed in the northern and central parts of the area. In Suleja, the overburden thickness ranges from 3 to 28 m. The average thickness of overburden in the area is 15m. Areas with heavy overburden and a low percentage of clay, with noticeable inter-granular flow, are known to have high groundwater potential, particularly in basement complex terrain (Olorunfemi & Fasuyi, 1993).

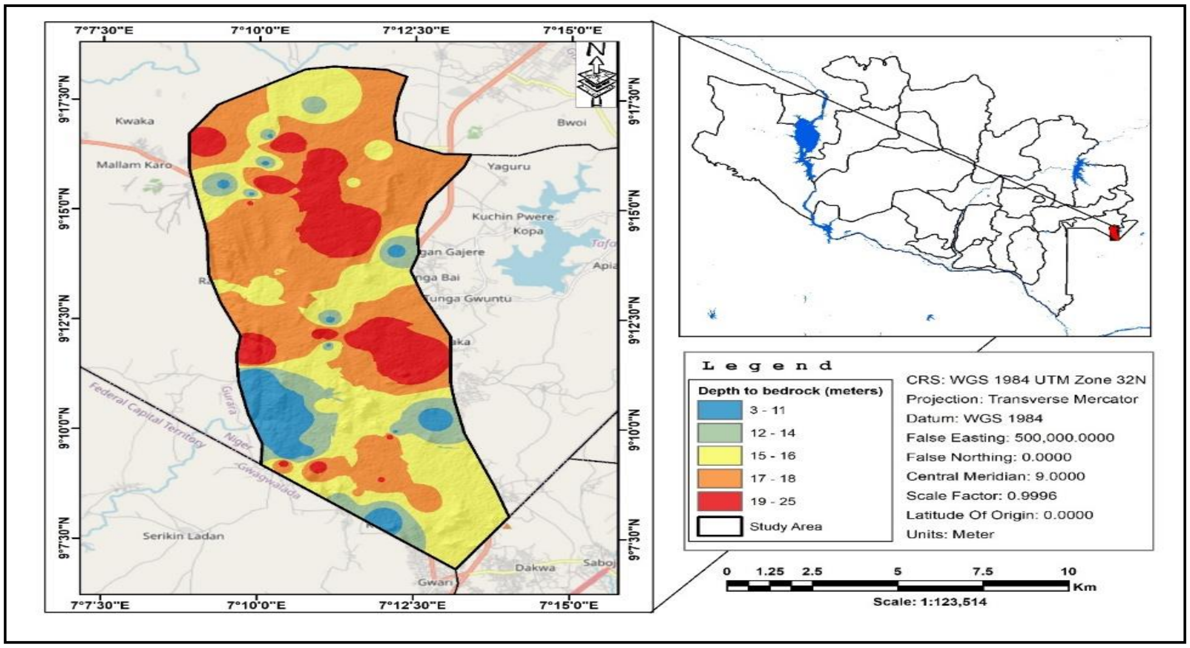


**Figure 8: Depth to Bedrock map of the study area**

**Topography**

The rate of groundwater recharge and the nature of precipitation are influenced by altitude (Moeck *et al.,* 2020). The elevation of the study area ranges from 299 to 560m above mean sea level. A two-dimensional perspective model of the study area was created using DEM to better understand the impact of surface reservoirs and their topographic positions in affecting groundwater conditions (Figure 9).

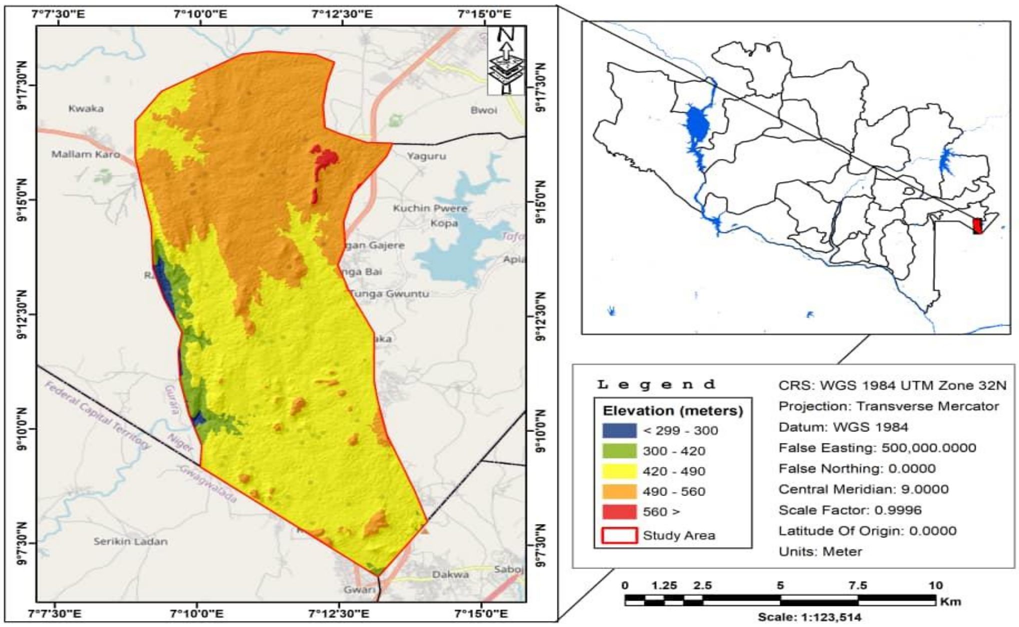


**Figure 9: Topographic map of the study area**

**Interpretation of vertical electrical sounding (VES)**

The VES data are presented as sounding curve plots of apparent resistivity ($\rho_a$) against electrode spacing AB/2 on a log-log graph sheet. For this research, Computer-aided interpretation (Ip2win software) was used to interpret the VES data. The software is based on an algorithm that employs digital linear filters for the fast computation of resistivity function for a given set of layer parameters. The electrical resistivity curves generated using computer-aided interpretation of the field data are displayed in the form of graphs and numerals. Eleven curve types were observed in the study area: H, HA, HKH, KH, KHQ, A, AA, HKHKH, KHA, KHKH, and QH. The KH, H, and HKH curves are the predominant curve types, accounting for 32%, 21%, and 10%, respectively. The degree of variation in curve types confirms the heterogeneity of the geology of a typical basement complex (Figure 10).

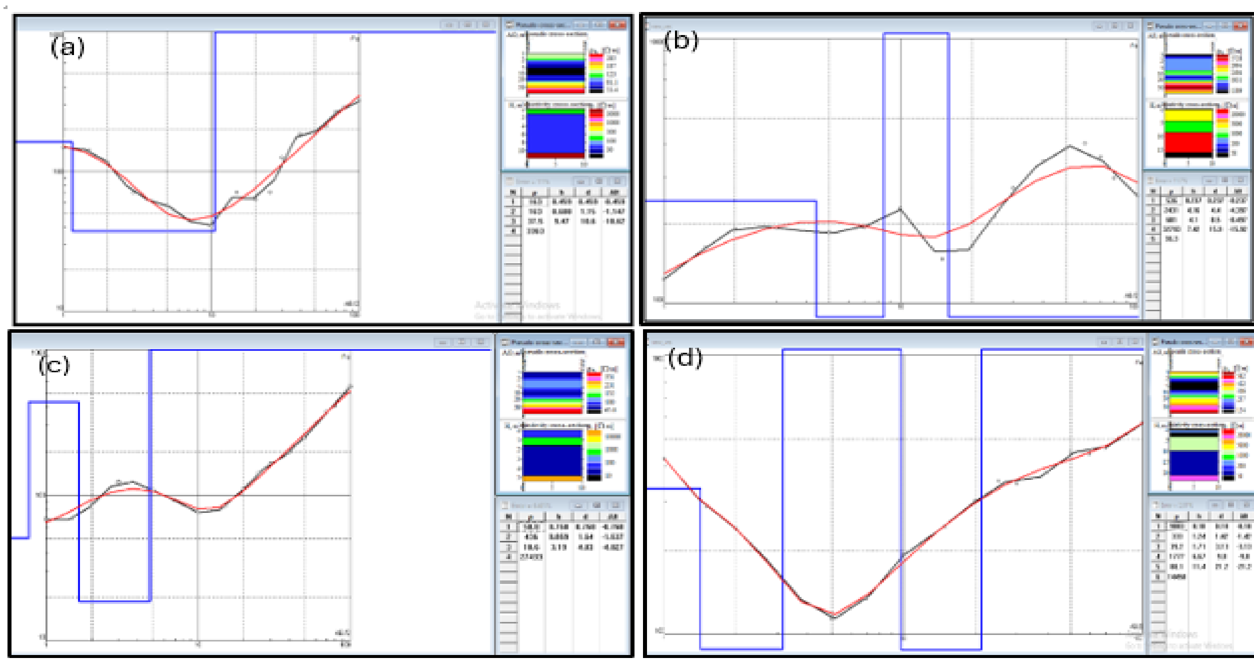


**Figure 10: A Typical VES interpretation Curve of the study area (a) H-Type, (b) KHQ-Type, (c) KH-Type, (d) HA-Type**

**Aquifer resistivity**

Aquifer resistivity is a crucial factor in assessing groundwater potential in Suleja. Groundwater potential zones are characterized by low resistivity, this is confirmed by several studies in the basement complex terrain of Nigeria. Field experience, drilling records and logs revealed that the weathered layer is the primary aquifer unit in the research area, while the fractured basements are categorized as secondary aquifers. The area's aquifer resistivity typically ranges from 15 to 1200Ωm; this variation in resistivity reveals the subsurface characteristics, where lower resistivity values often correspond to higher groundwater potential. Aquifers in basement complexes are characterized qualitatively as weathered fractured basement aquifers or partly weathered or fractured basement aquifers, and these classes are related to the subsurface layer's resistivity.

The aquifers in the research area are partly weathered, weathered/fractured basement, and fresh fractured basement. The resistivity ranges of weathered layers are 150 - 350Ωm, partly weathered/fractured basement aquifer resistivity is 350 - 600Ω, and fresh basement aquifer resistivity is 600 – 1200 Ωm.

**Groundwater potential zone**

Using the AHP techniques on the weighted thematic layers has allowed the mapping of the groundwater potential zones of the study area in raster format in the ArcGIS environment (Figure 11). The lineament density has the highest weightage of 31.53% from the analysis of the normalized weights of the thematic layers. Rocks in the study area are rich in felspathic minerals, which are susceptible to weathering; the high lineament density could be attributed to the chemical weathering activities on the rock. In Basement Complex environment lineament serves as the pathway for groundwater recharge. Drainage density has the second highest weightage of 25.90%, which can be ascribed to the dendritic pattern of the drainage system of Suleja and the undulatory nature of its topography, these factors over the years have contributed to the groundwater potential of the area. Another significant factor is geology with the weightage of 21.55%. The role played by geology can be attributed to the mineral composition of the rocks which allows the creation of both primary (Regolith) and secondary (Fractured Basements) aquifers in the study area (Table 3). The final groundwater potential map of Suleja highlights five distinct areas (Figure 10). The very high potential category covers about 0.006km$^2$ of the total area, the high potential for groundwater covers about 11.92km$^2$, while the moderate zones occupy about 72.98km$^2$. The low and very-low categories of the potential zone dominate 33.66km$^2$ and 0.17km$^2$ of the total area, respectively. The graphical representation of the result indicates that the dominant groundwater potential zone in the area is moderate potential (Figure 12).

**Table 3: Classification of weight and Rank of influencing factors**

| CRITERIA | CLASS | RANK | WEIGHTAGE |
|---|---|---|---|
| Lineament Density | Very high | 5 | 31.53% |
| | High | 4 | |
| | Moderate | 3 | |
| | Low | 2 | |
| | Very low | 1 | |
| LULC | Bareland | 4 | 11.52% |
| | Built-up | 2 | |
| | Forested Area | 3 | |
| | Grassland | 5 | |
| | Impervious surface | 1 | |
| Drainage Density | Very high | 1 | 25.90% |
| | High | 2 | |
| | Moderate | 3 | |
| | Low | 4 | |
| | Very low | 5 | |
| Depth to bedrock | 3 - 11 | 1 | 5.17% |
| | 12 - 14 | 2 | |
| | 15 - 16 | 3 | |
| | 17 - 18 | 4 | |
| | 19 - 25 | 5 | |
| Topography | 299 - 300 | 5 | 4.34% |
| | 350 - 420 | 4 | |
| | 420 - 490 | 3 | |
| | 490 - 560 | 2 | |
| | 560 - 630 | 1 | |
| Geology | Coarse granite | 6 | 21.55% |
| | Migmatitic gneiss | 5 | |
| | Granite gneiss | 7 | |

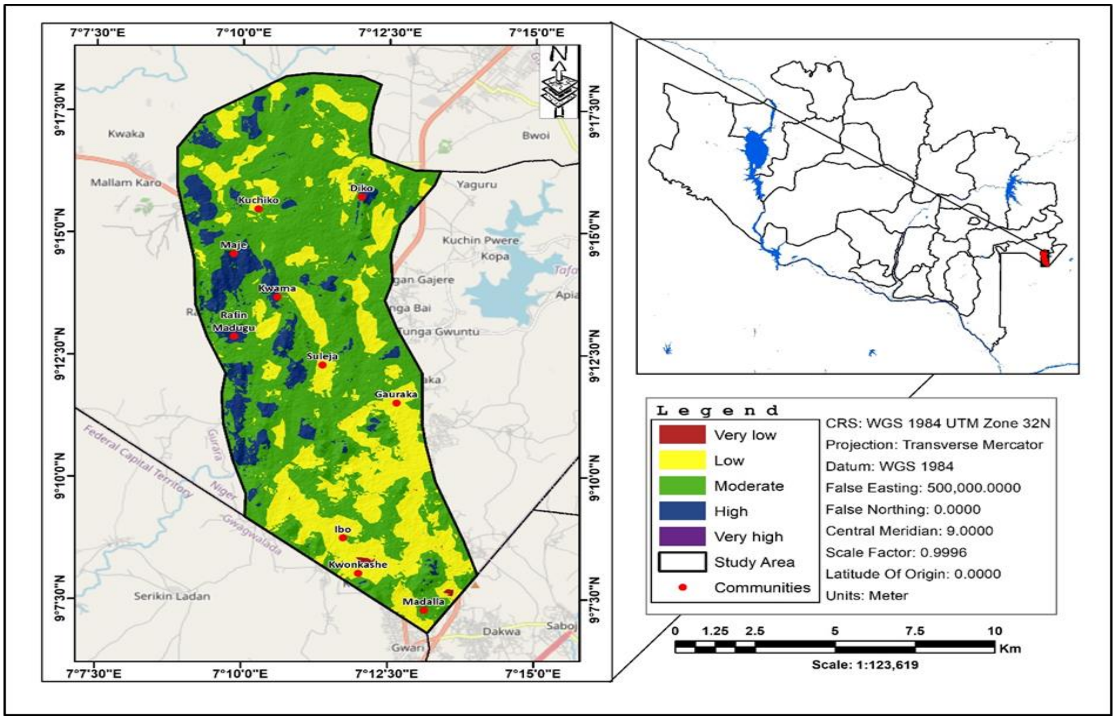


**Figure 11: Groundwater Potential Zone Map of the study area**

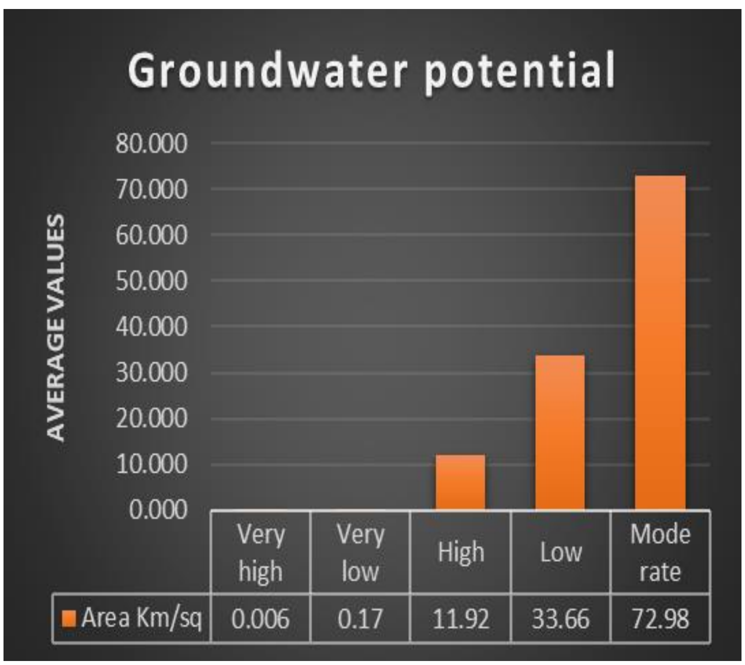


**Figure 12: Graphical representation of Groundwater potential zones in the study area**

**Conclusion**

Groundwater potential zones of Suleja were delineated using an integrated approach that includes the Electrical Resistivity Method, Remote Sensing Techniques, Geographic Information System and Analytic Hierarchy Process (AHP) model. Six thematic layers from multiple sources were selected as the groundwater influencing factors (geology, depth to bedrock, lineament density, Elevation, drainage density and land use). The Groundwater potential of the study area is majorly controlled by geology, depth to bedrock and lineament density, while other factors such as elevation, drainage density and land use are considered secondary factors. The groundwater potential map created using AHP model categorized the study area into five zones, very low which occupies 0.15% of the area, low 28.34%, moderate 61.46%, high 10.04% and very high 0.01% of the area. The geophysical investigation and reconnaissance fieldwork reveals that regions of low to moderate potential are characterized by thin overburden and slightly weathered/fractured basement aquifers; in contrast, zones of high to very high groundwater potential are characterized by thick overburden, composed of clayey sand, alluvial sand, fine sand, and partially weathered rock. This research reaffirms the efficacy of using the integrated approach and the AHP model in groundwater potential zone delineation, especially in the basement complex terrain of Nigeria. This study will also provide valuable information for decision-makers in planning sustainable groundwater development and management in the study area. The research findings will logically reduce the search area and minimize the risk of drilling abortive boreholes.

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