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Integrated Geological Mapping, Remote sensing, and Geoelectrical Investigation for Groundwater Potential Assessment of Parts of Minna Sheet 164NE, North Central Nigeria

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Abstract

Groundwater is an essential freshwater resource that sustains domestic, agricultural, and industrial activities, particularly within crystalline Basement Complex terrains, where groundwater occurrence is primarily controlled by weathering processes and geological structures. This research assessed the groundwater potential of selected areas within Minna Sheet 164NE, North-Central Nigeria, by integrating geological mapping, hydrogeological observations, electrical resistivity surveys, remote sensing, and Geographic Information System (GIS) analyses. Geological field investigations were undertaken to characterize the lithological units and structural elements, while hydrogeological data were obtained from 60 hand-dug wells. Additionally, 48 Vertical Electrical Sounding (VES) measurements were carried out using the Schlumberger electrode array to evaluate subsurface geoelectrical conditions. The interpreted resistivity data revealed weathered layer thicknesses ranging from 1 to 33 m, weathered layer resistivity values between 10 and 800 Ωm, depths to fresh basement of 2–45 m, and basement resistivity values ranging from approximately 1,000 Ωm to over 28,000 Ωm. Geological, hydrogeological, geophysical, slope, drainage density, and lineament density datasets were integrated in a GIS platform using a weighted overlay technique to generate a groundwater potential map. The analysis identified areas with high groundwater potential where thick weathered overburden, fractured basement rocks, high lineament density, gentle terrain, and favorable resistivity characteristics occur together. Conversely, zones characterised by shallow basement, thin weathered profiles, and highly resistive crystalline rocks exhibit relatively poor groundwater prospects. The results demonstrate that the integration of multiple datasets provides a reliable and effective framework for groundwater exploration, thereby supporting informed groundwater resource development within the Nigerian Basement Complex.

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1. Introduction

Groundwater is among the most dependable freshwater resources and plays a vital role in satisfying domestic, agricultural, industrial, and environmental water demands. In many developing nations, including Nigeria, rapid population growth, urbanisation, climate variability, and increasing stress on surface water resources have heightened dependence on groundwater for potable water supply. Within the Precambrian Basement Complex of Nigeria, groundwater serves as a critical water resource because perennial surface water is scarce in many areas, making it the principal source of water for both rural and urban populations (Khilchevskyi and Karamushka, 2021; Dinka, 2018).

Unlike sedimentary formations, where groundwater is stored within interconnected pore spaces, crystalline Basement Complex rocks are characterised by very low primary porosity and permeability. Consequently, groundwater availability in these terrains is controlled mainly by secondary geological structures formed through weathering and tectonic deformation. Productive aquifers are therefore commonly associated with thick weathered overburden, fractured basement rocks, joints, faults, and other structural discontinuities that enhance groundwater storage and movement (Rahaman, 1988).

Groundwater occurrence and spatial distribution within Basement Complex terrains are governed by the interaction of several factors, including lithology, structural characteristics, topography, drainage conditions, weathering intensity, and basement morphology. Because these controlling factors vary considerably over short distances, relying on a single exploration technique often results in inconsistent groundwater predictions. Therefore, integrated approaches combining geological, hydrogeological, geophysical, remote sensing, and Geographic Information System (GIS) techniques have become widely accepted for groundwater exploration and resource assessment.

Remote sensing provides valuable spatial information for identifying geomorphological and structural features that control groundwater occurrence. Variables such as slope, elevation, drainage density, and lineament density can be extracted from satellite imagery and applied to groundwater potential assessment. Likewise, electrical resistivity investigations, particularly the Vertical Electrical Sounding (VES) technique employing the Schlumberger electrode array, provide an effective means of characterizing subsurface conditions, estimating weathered layer thickness, determining basement depth, and delineating fractured zones that may function as productive aquifers.

The present investigation focuses on parts of Minna Sheet 164NE located within Bosso and Chanchaga Local Government Areas of Niger State, North-Central Nigeria. The area has experienced increasing demand for groundwater owing to population growth, agricultural activities, and urban expansion. Despite widespread reliance on groundwater, variations in lithology, weathering depth, and structural complexity have resulted in inconsistent borehole

yields across the study area. This highlights the necessity for a comprehensive assessment of groundwater potential using complementary investigation techniques.

Accordingly, this study integrates geological mapping, hydrogeological investigations, remote sensing analysis, geoelectrical surveys, and GIS-based spatial modeling to evaluate groundwater potential across the study area. The findings are expected to enhance groundwater exploration, optimize borehole siting, and support sustainable groundwater resource management within the Nigerian Basement Complex. The study area is situated within Minna Sheet 164NE, covering parts of Bosso and Chanchaga Local Government Areas of Niger State, North-Central Nigeria. It extends between latitudes 9°33′00″N and 9°36′00″N and longitudes 6°32′00″E and 6°35′00″E, covering approximately 30 km² (Figure 1).

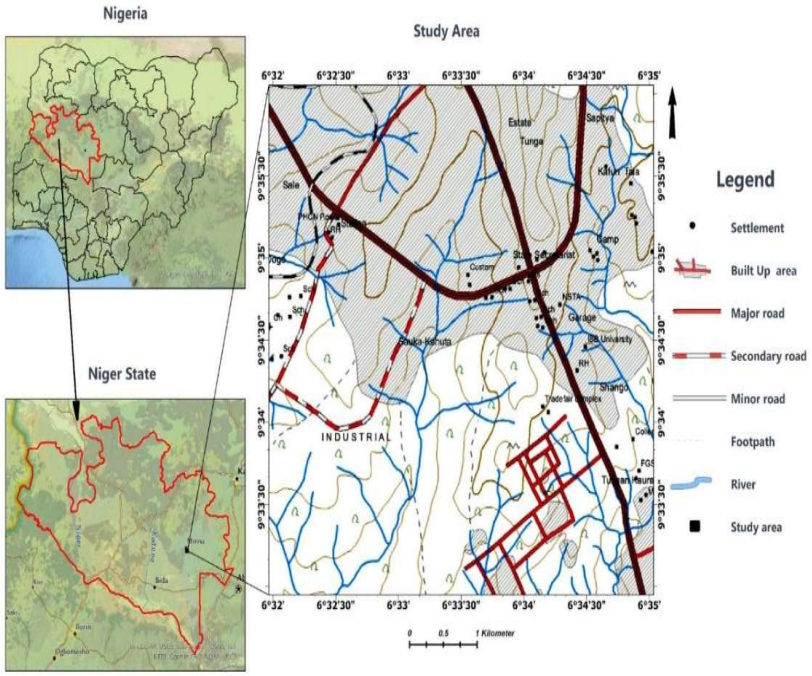


Figure 1: Location map of the study area

Geologically, the study area forms part of the Nigerian Precambrian Basement Complex, a crystalline terrain composed predominantly of migmatite, granite gneiss, granite, and quartzofeldspathic veins. These rocks are characterised by extremely low primary porosity; consequently, groundwater occurrence is controlled mainly by secondary structures such as fractures, joints, faults, together with the thickness of the weathered overburden. Differences in weathering intensity and structural deformation have produced considerable variations in aquifer characteristics throughout the study area.

Hydrogeologically, groundwater is hosted mainly within the weathered regolith and fractured basement aquifers. Borehole productivity is therefore influenced by the thickness of the weathered zone, the depth to competent basement, and the degree of rock fracturing. Locations where thick weathered materials coincide with fractured crystalline bedrock generally provide the most favorable conditions for groundwater storage and abstraction.

2. Methodology

2.1 Research Design

This investigation adopted an integrated methodology combining geological field mapping, hydrogeological observations, electrical resistivity surveying, remote sensing, and Geographic Information System (GIS) analysis to assess groundwater potential within parts of Minna Sheet 164NE. The methodology was designed to evaluate both surface and subsurface factors controlling groundwater occurrence in the crystalline Basement Complex terrain.

2.2 Geological Investigation

Geological field mapping was conducted at a scale of 1:25,000 to delineate lithological units and structural features across the study area. Field observations focused on rock types, geological contacts, weathering characteristics, joints, fractures, foliations, and quartz veins. Geographic coordinates of observation points were acquired using a handheld Global Positioning System (GPS), while structural measurements were obtained with a geological compass. Representative rock samples collected during fieldwork were used to verify lithological interpretations and support preparation of the geological map.

2.3 Hydrogeological Investigation

Hydrogeological information was obtained from 60 existing hand-dug wells distributed throughout the study area. At each location, measurements were taken for total well depth, static water level, water column thickness, and ground elevation. Geographic coordinates were also recorded to facilitate spatial analysis.

2.4 Remote Sensing and GIS Analysis

Spatial datasets required for groundwater potential assessment were generated from Shuttle Radar Topography Mission (SRTM) Digital Elevation Model (DEM) data processed using ArcGIS software. The DEM was pre-processed to remove spurious depressions before hydrological analysis.

Terrain variables including elevation, slope, drainage network, and drainage density were extracted from the processed DEM. Geological lineaments were identified from enhanced satellite imagery and digitized to produce a lineament map. A lineament density map was subsequently generated to evaluate the spatial distribution of structural features that influence groundwater occurrence.

Before spatial analysis, all thematic layers were transformed into a common coordinate reference system and converted into compatible raster datasets. Each groundwater-conditioning factor was then reclassified according to its relative contribution to groundwater occurrence using geological knowledge and information obtained from field investigations.

2.5 Electrical Resistivity Survey

Subsurface investigations were performed using the Vertical Electrical Sounding (VES) method using the Schlumberger electrode array. A total of 48 VES stations were established throughout the study area to examine variations in subsurface resistivity associated with weathered layers, fractured basement zones, and fresh crystalline bedrock.

Electrical current was injected into the subsurface through a pair of outer current electrodes, while the resulting potential difference was recorded using two inner potential electrodes. During data acquisition, the spacing between the current electrodes was progressively expanded to probe greater investigation depths, whereas the spacing of the potential electrodes was adjusted whenever necessary to ensure reliable measurements. The maximum half-current electrode spacing (AB/2) used during the survey was 100 m, providing sufficient penetration to investigate the targeted aquifer zones.

2.5.1 Generation of Geoelectrical Parameter Maps

The interpreted resistivity parameters from the VES analysis were exported into ArcGIS for spatial interpolation. Continuous distribution maps of weathered layer thickness, weathered layer resistivity, basement resistivity, and depth to fresh basement were generated using the Inverse Distance Weighting (IDW) interpolation technique. These thematic maps were subsequently used in assessing groundwater potential across the study area.

2.6 Groundwater Potential Modeling

Groundwater potential zones were delineated by integrating geological, hydrogeological, remote sensing, and geoelectrical datasets within a Geographic Information System (GIS) framework. The thematic layers incorporated into the analysis included lithology, slope, drainage density, lineament density, weathered layer thickness, weathered layer resistivity, basement resistivity, and depth to fresh basement.

Each thematic layer was assigned an appropriate rank according to its influence on groundwater occurrence, while weights were allocated to reflect their relative importance in groundwater potential assessment. The weighted thematic layers were integrated using the Weighted Overlay Analysis tool in ArcGIS to generate a groundwater potential index for the study area. The resulting index was subsequently classified into five groundwater potential categories: very low, low, moderate, high, and very high.

The groundwater-potential model was developed by integrating the thematic datasets according to their relative influence on groundwater occurrence and storage. Each thematic layer was first standardised and reclassified into suitability classes, with higher ranks assigned to conditions considered more favourable for groundwater recharge, storage, and movement. The principal parameters included lithology, slope, drainage density, lineament density, overburden thickness, weathered-layer resistivity, and bedrock resistivity. The geoelectrical parameters derived from VES interpretation were converted into spatial thematic layers and combined with the geological and remotely sensed datasets within ArcGIS. The ranked layers were subsequently integrated using the Weighted Overlay tool, allowing the contribution of each

parameter to the final groundwater-potential index to be considered simultaneously. The resulting composite index was used to delineate areas of relatively low to high groundwater potential, while available borehole and well information provided field-based evidence for assessing the reliability of the resulting groundwater-potential map.

2.7 Validation of the Groundwater Potential Model

The reliability of the groundwater potential map was assessed by comparing the predicted groundwater potential zones with field observations obtained during geological mapping, hydrogeological investigations, and interpretation of the geoelectrical data. The level of agreement between the predicted favorable zones and the observed groundwater conditions was then used to evaluate the performance of the integrated modeling approach.

Table 1: Summary of Datasets Used in the Study

S/N	Dataset	Source	Purpose
1.	Geological field data	Field mapping	Lithological map
2.	GPS Coordinate	Field survey	Location of sampling points
3.	Hand-dug well data	Field Measurements	Hydrogeological assessment
4.	SRTM DEM	Remote sensing	Slope, Drainage, Elevation
5.	VES data (48 stations)	Electrical Resistivity	Subsurface characterization
6.	ArcGIS	GIS Processing	Spatial analysis and groundwater modeling
7.	IPI2Win	Geophysical Interpretation	Layer resistivity and thickness estimation

The integration of the geological, hydrogeological, remote-sensing, and geoelectrical datasets was undertaken within a common GIS framework to ensure spatial compatibility among the thematic layers. This approach enabled the groundwater-conditioning factors to be evaluated collectively rather than independently, thereby providing a basis for delineating areas with relatively favourable or unfavourable groundwater potential.

3. Results

3.1 Geological Characteristics

Field mapping identified migmatite, granite gneiss, granite, and quartzo-feldspathic veins as the principal lithological units underlying the study area (Figure 2). Among these, migmatite is the most widespread rock type, while granite gneiss and granitic intrusions occur in discrete portions of the area. Quartzo-feldspathic veins were observed cutting across the older basement rocks, indicating multiple phases of tectonic activity.

Structural observations revealed numerous joints, fractures, foliations, and quartz veins. These discontinuities vary in orientation and density across the study area and are considered significant because they improve secondary permeability within the otherwise impermeable crystalline rocks. Consequently, groundwater occurrence is expected to be greatest where these structures coincide with sufficiently weathered basement materials.

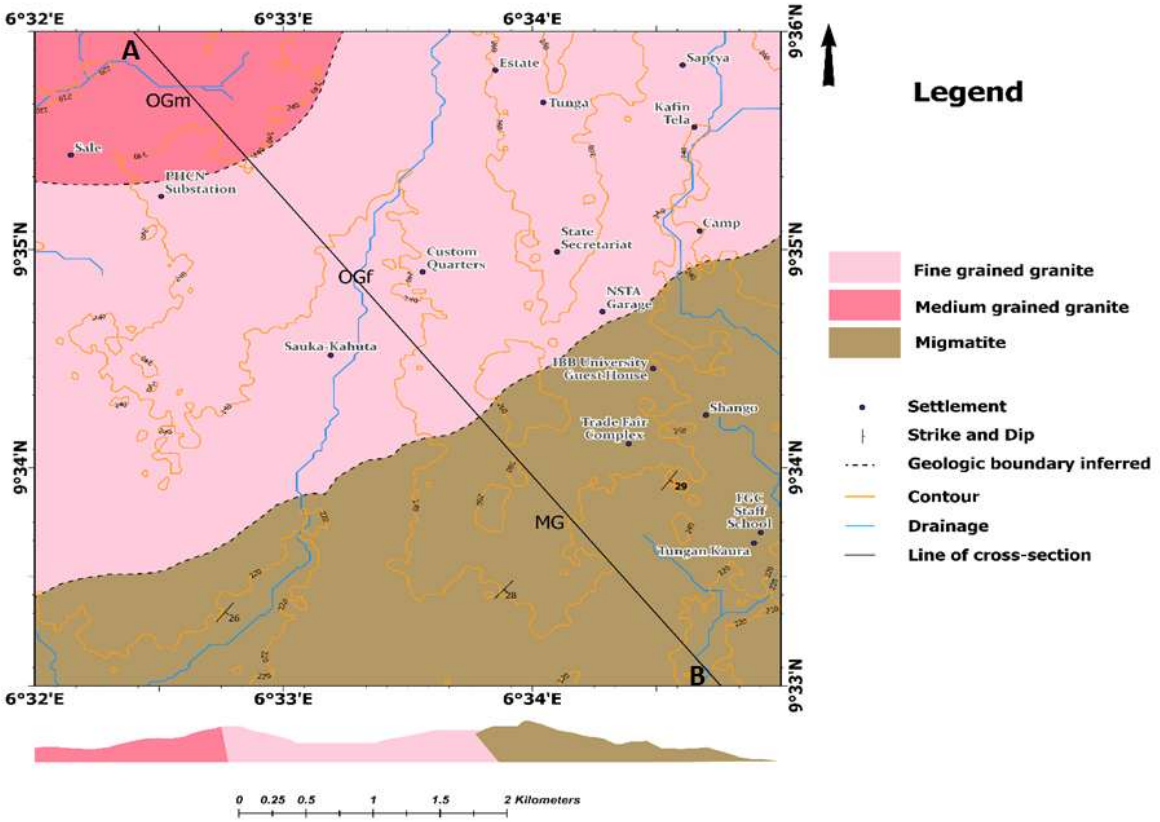


Figure 2: Geological map illustrating the spatial distribution of the major lithological units within the study area

Field observations further identified several structural elements, including joints, fractures, foliations, and quartz veins. These geological structures enhance secondary porosity and permeability, thereby providing favorable pathways for groundwater recharge and subsurface flow within the otherwise low permeability crystalline basement rocks. Joints and fracture readings are presented in Table 2 while the rose diagram is in Figure 3. The exposed rocks within the study area have experienced multiple phases of deformation, as demonstrated by the orientations of the observed structural elements (Rahaman, 1988; Ajibade *et al.,* 1987; Macledo *et al.,* 1971; Leblanc, 1981).

Table 2: Joints readings

Joint Values						
124	182	20	298	316	24	212
134	184	328	310	220	168	213
310	168	302	212	45	120	20
154	20	290	200	38	211	42
168	40	82	30	32	184	294
187	296	100	186	140	184	180
300	300	300	45	200	194	82
144	316	300	28	182	156	225
210	210	130	184	220	210	290
192	212	44	38	218	310	124

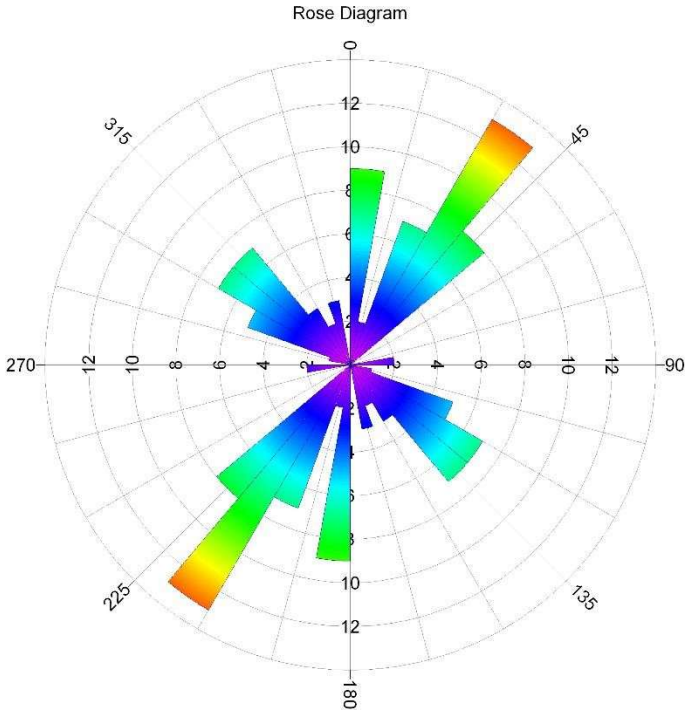


Figure 3: Generalised Rose Plot showing trends of joints on exposed rock surfaces in the study area

3.2 Hydrogeological Characteristics

Measurements obtained from the 60 hand-dug wells indicate spatial variation in groundwater conditions throughout the study area. Differences in well depth, static water level, and groundwater elevation reflect the combined influence of lithology, topography, and structural

controls on groundwater occurrence. Interpolation of groundwater elevations suggests that groundwater generally migrates from relatively elevated northern and northeastern areas towards lower-lying southwestern portions of the study area (Figure 4). Local deviations in flow direction are interpreted to result from variations in basement topography and fracture

distribution

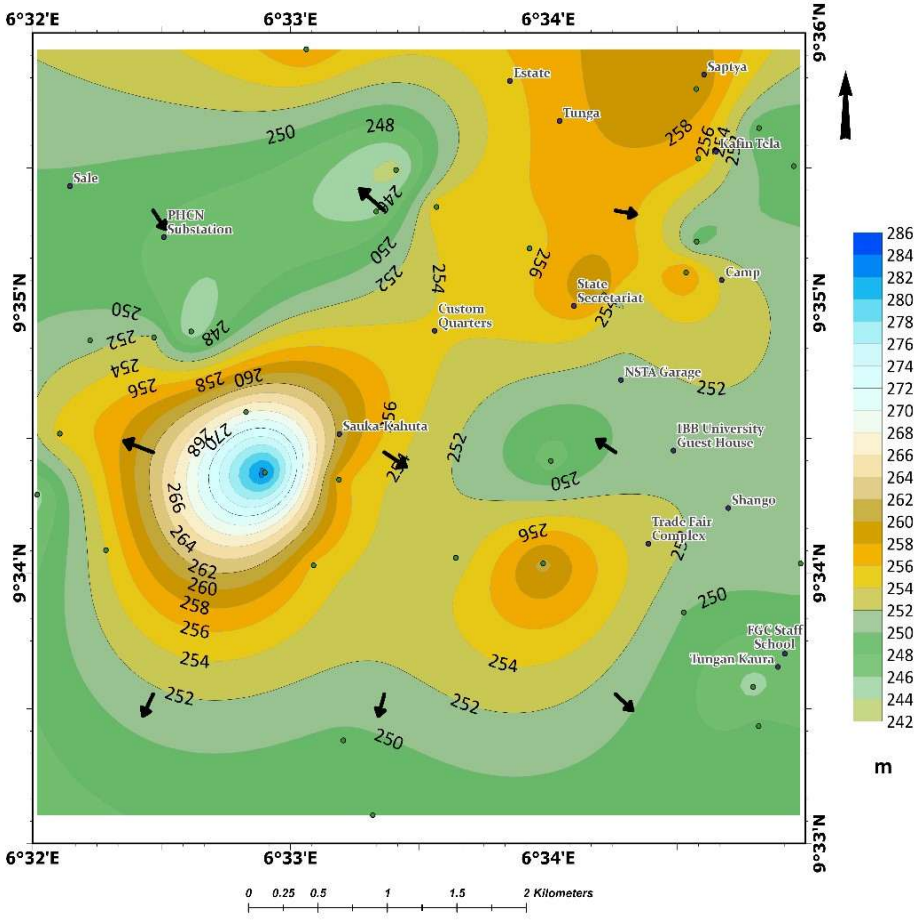


Figure 4: Groundwater level contour map of the study area

3.3 Terrain and Structural Parameters

3.3.1 Slope

The slope map (Figure 5) shows that gentle to moderate slopes dominate most parts of the study area, whereas relatively steep slopes are concentrated mainly around resistant granitic outcrops. The spatial distribution of slope classes indicates variation in terrain gradient across the study area.

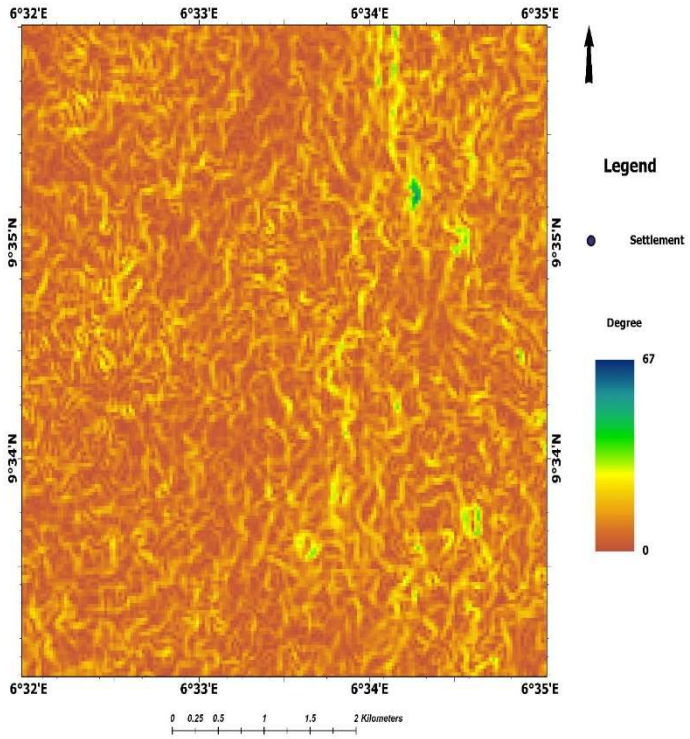


Figure 5: Slope map of the study area

3.3.2 Drainage Density

The drainage-density map (Figure 6) shows noticeable spatial variation across the study area, with relatively sparse drainage networks occurring in some sectors and more closely spaced drainage channels concentrated in others. The distribution reflects spatial differences in surface drainage development across the study area.

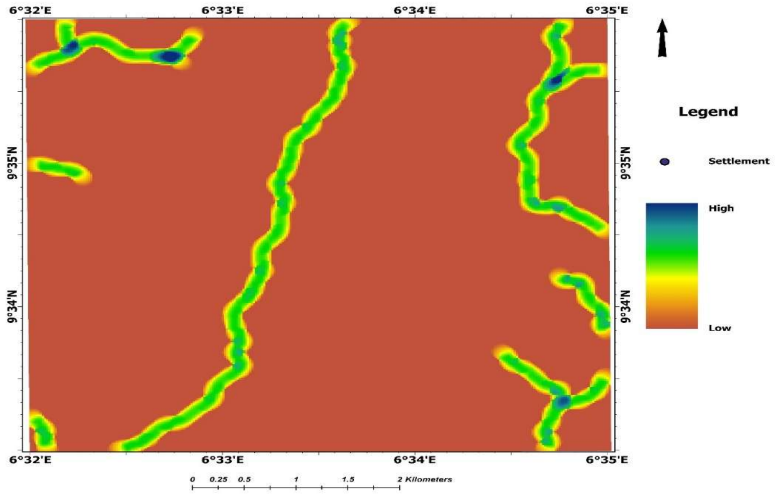


Figure 6: Drainage density map of the study area

3.3.3 Lineament Density

The lineament-density map (Figure 7) illustrates the spatial distribution of structural lineaments across the study area. Higher concentrations occur mainly in the northern and central sectors, whereas relatively lower lineament densities occur in the southeastern part of the study area.

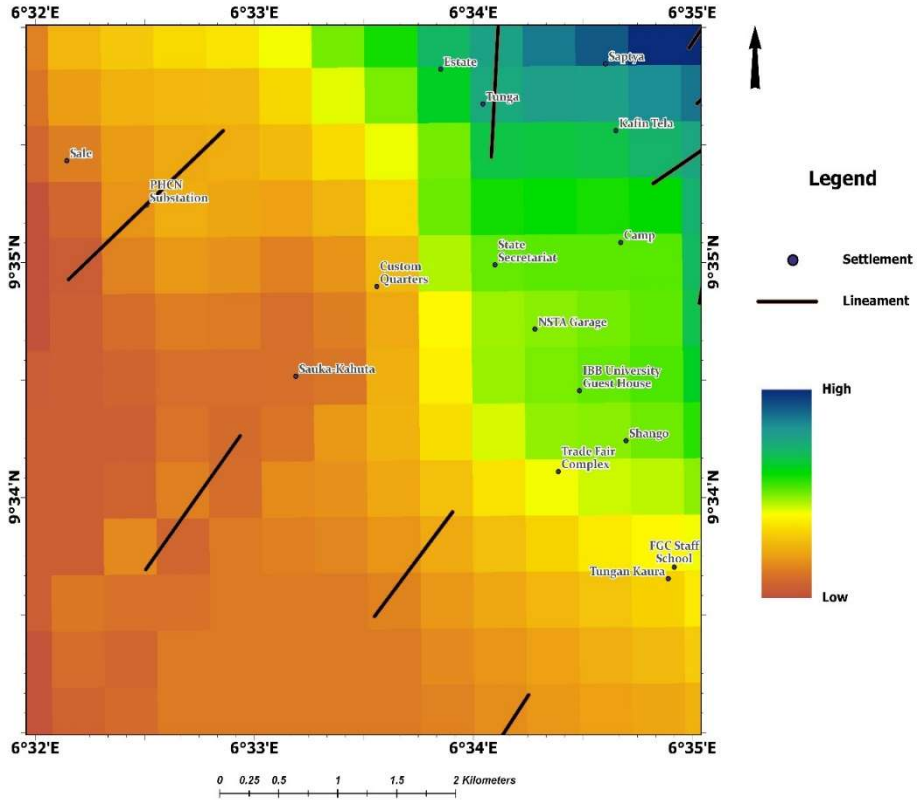


Figure 7: Lineament Density map of the study area

3.4 Geoelectrical Characteristics

3.4.1 Weathered Layer Thickness

Interpretation of the resistivity sounding data indicates that the weathered-layer thickness ranges from 1 to 33 m (Figure 8). Thicker weathered overburden is predominantly developed in the northern and southwestern parts of the study area, whereas comparatively thinner weathered materials occur mainly in the western and southeastern sectors.

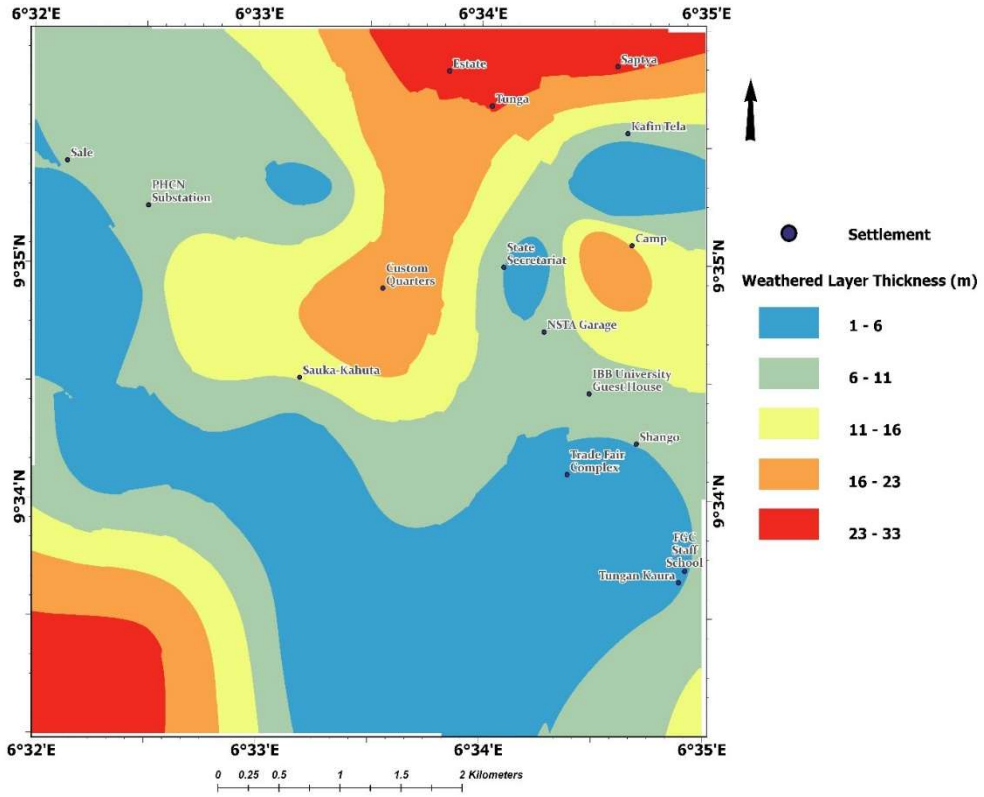


Figure 8: Iso-thickness map of the weathered layer across the study area

3.4.2 Weathered Layer Resistivity

The interpreted resistivity values of the weathered layer range from 10 to 800 Ωm (Figure 9). The spatial distribution shows considerable variation in weathered-layer resistivity across the study area, with zones of relatively low, intermediate, and high resistivity.

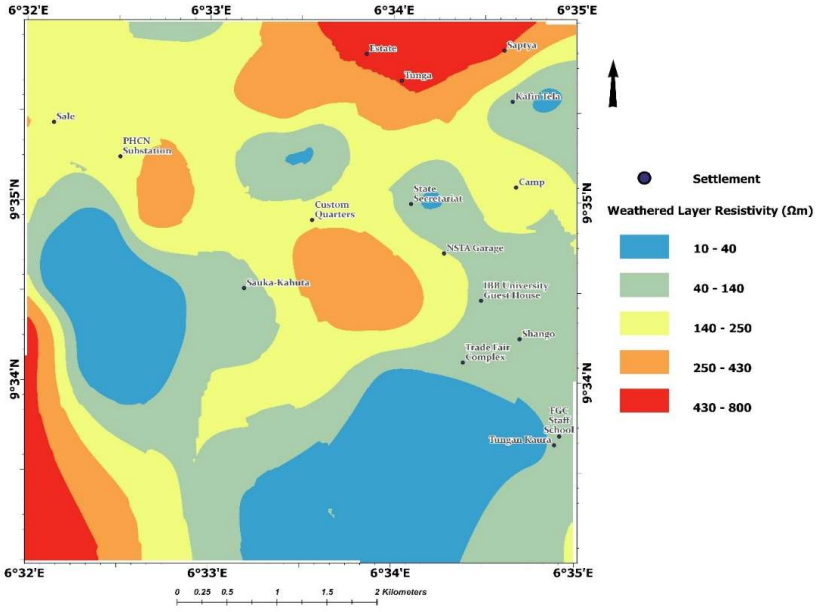


Figure 9: Weathered layer iso-resistivity map

3.4.3 Depth to Fresh Basement

The estimated depth to fresh basement ranges from 2 to 45 m (Figure 10). Deeper basement conditions are mainly concentrated in the northern and southwestern parts of the study area, whereas relatively shallow basement occurs in the southeastern and western sectors.

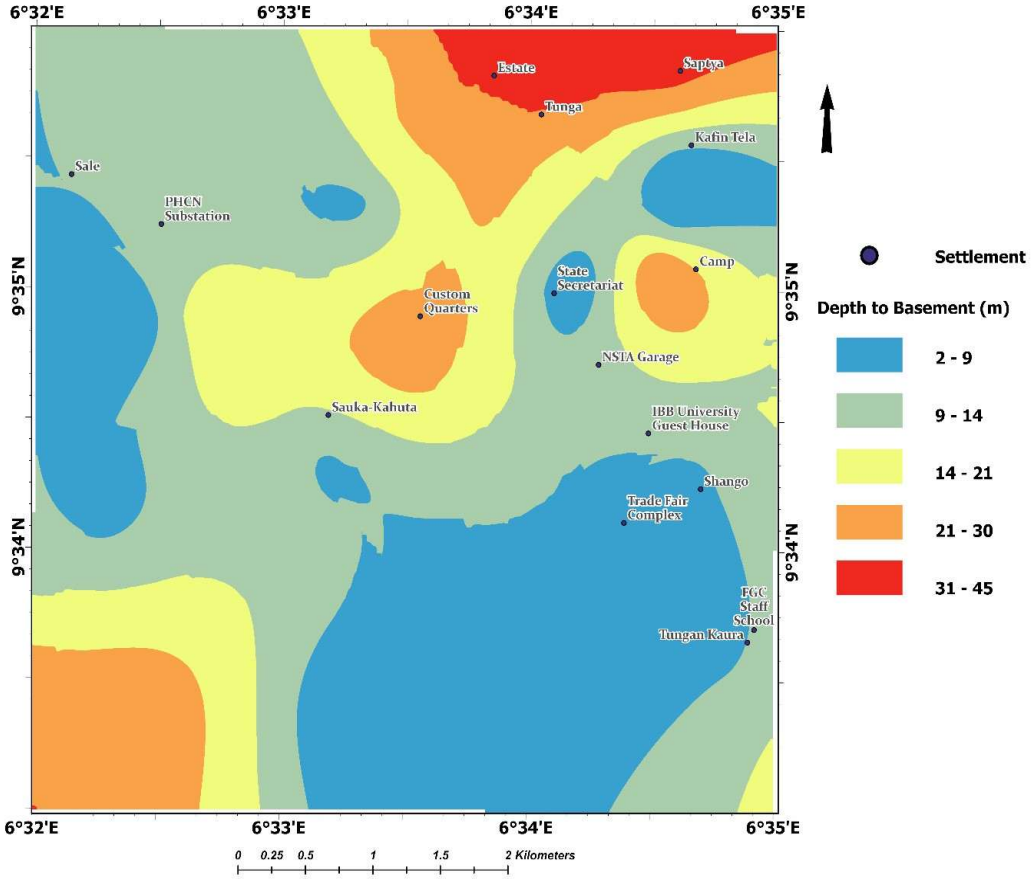


Figure 10: Depth to basement map of the study area

3.4.4 Basement Resistivity

Fresh-basement resistivity values range from approximately 1,000 Ωm to over 28,000 Ωm (Figure 11). The spatial distribution indicates substantial variation in basement resistivity across the study area, with relatively lower values occurring in some sectors and markedly higher values in others.

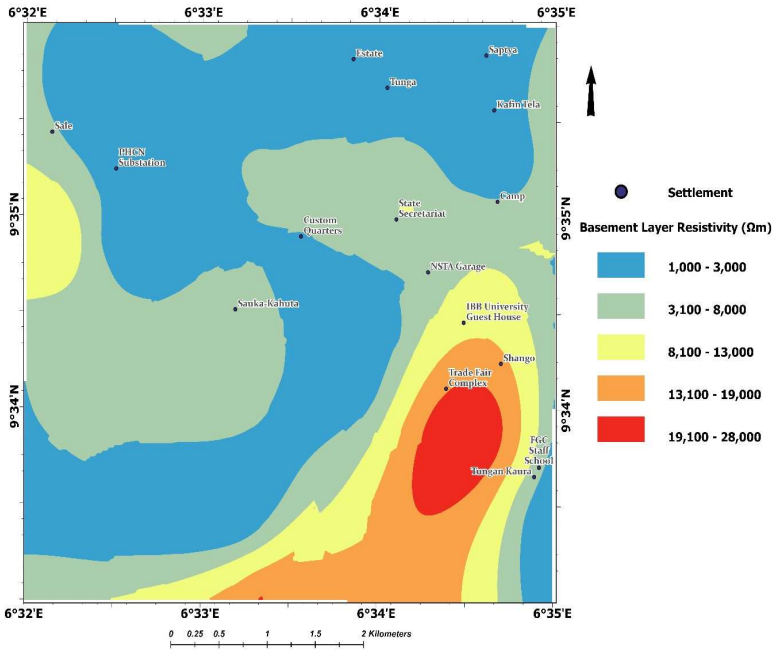


Figure 11: Basement layer iso-resistivity map

3.5 Groundwater Potential Assessment

The integration of all groundwater-conditioning factors resulted in the groundwater potential map presented in Figure 12. Based on the model output, the study area was categorized into five groundwater potential classes: very low, low, moderate, high, and very high.

The resulting groundwater-potential map shows that the five classes are spatially associated with variations in the geological, terrain, structural, and geoelectrical conditions described above. Areas classified as high to very high potential generally coincide with more favourable combinations of these parameters, whereas low-potential zones correspond to less favourable conditions.

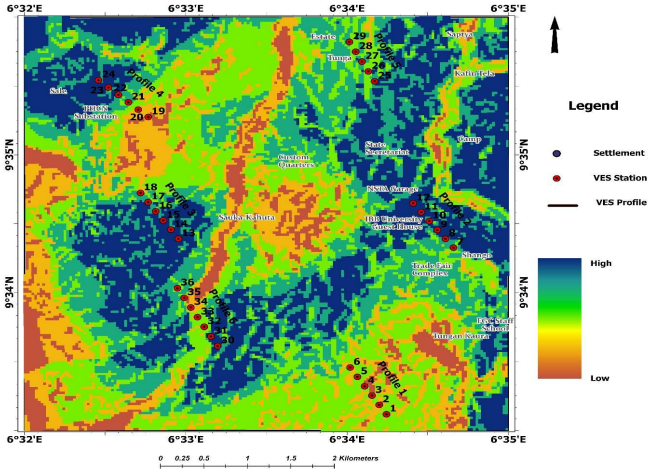


Figure 12: Groundwater potential zonation map of the north-western sector of the study area

4. Discussion and Limitations

4.1 Geological and Structural Controls on Groundwater Occurrence

The geological framework of the study area exerts a significant influence on groundwater occurrence and distribution. The mapped lithological units, comprising migmatite, granite gneiss, granite, and quartzo-feldspathic veins, are crystalline rocks characterised by negligible primary porosity. Consequently, groundwater storage depends largely on secondary features developed through prolonged weathering and tectonic deformation. Field observations indicate that joints, fractures, foliations, and quartz veins are widespread across the study area and collectively enhance secondary permeability by creating interconnected pathways for groundwater recharge and movement.

In crystalline Basement Complex terrain, the relationship between weathering and structural deformation is particularly important because primary porosity is generally negligible. Weathering increases the thickness and storage capacity of the regolith, while fractures and joints provide secondary permeability through which groundwater can migrate between the weathered zone and the underlying basement. Consequently, locations where sufficiently thick weathered materials coincide with interconnected fractures are expected to have greater groundwater storage and transmission potential than areas dominated by shallow, fresh, and relatively unfractured basement.

The predominance of groundwater within weathered and fractured basement rocks observed in this study is consistent with the hydrogeological behavior of Precambrian Basement Complex terrains reported by Rahaman (1988) and Olorunfemi & Okhue 1992; Dan-Hassan et al., 2012. These findings reinforce the importance of geological structures in groundwater exploration within crystalline environments.

4.2 Significance of Terrain and Structural Parameters

The terrain and structural datasets provide complementary information on the two principal processes governing groundwater occurrence in the study area: recharge and subsurface transmission. Slope primarily influences the partitioning of rainfall between surface runoff and infiltration, whereas drainage density provides an indirect indication of the efficiency of surface drainage and infiltration. Lineament density, in contrast, provides information on the distribution of structural discontinuities that may enhance secondary permeability within the crystalline basement.

The predominance of gentle to moderate slopes across much of the study area suggests that portions of the terrain provide relatively favourable conditions for rainfall infiltration, particularly where surface drainage is comparatively sparse. Steeper terrain is expected to favour more rapid runoff and therefore provide less opportunity for infiltration. However, slope alone cannot determine groundwater potential because infiltration ultimately depends on the permeability of the underlying weathered material and the presence of subsurface pathways.

The relationship between drainage density and groundwater recharge should likewise be interpreted in conjunction with lithology and slope. Areas of low drainage density may indicate greater infiltration opportunities, whereas closely spaced drainage channels can reflect increased runoff. In this study, the structural control of some drainage channels is particularly significant because drainage alignment along mapped lineaments indicates a possible relationship between surface drainage and subsurface structural discontinuities.

Lineament density provides the strongest structural component of this interpretation. In crystalline basement terrain, fractures and joints can provide secondary permeability where they are sufficiently open and interconnected. Consequently, areas where high lineament density coincides with favourable weathering and terrain conditions are more likely to support groundwater movement than areas where lineaments are sparse. The observed relationship is consistent with the established role of fractures and weathered zones as principal groundwater-bearing features in crystalline Basement Complex terrains (Rahaman, 1988; Olorunfemi & Okhue, 1992; Dan-Hassan et al., 2012).

The combined interpretation therefore suggests that terrain and structural parameters should not be considered independently. Their hydrogeological significance increases where favourable recharge conditions coincide with structural pathways and sufficient weathered materials, providing a conceptual basis for their integration in the groundwater-potential model.

4.3 Interpretation of Geoelectrical Characteristics

The geoelectrical results indicate substantial lateral variation in the weathered zone and basement configuration, reflecting spatial differences in weathering intensity and basement morphology. In the crystalline Basement Complex setting of the study area, these variations are hydrogeologically important because groundwater storage is commonly associated with the weathered mantle, while fractures within the underlying basement provide preferential pathways for groundwater movement.

The weathered-layer thickness of 1–33 m therefore represents an important control on groundwater storage. Thicker weathered profiles provide greater potential storage space, particularly where the weathered materials are sufficiently permeable and saturated. However, thickness alone does not guarantee groundwater productivity because the lithological composition of the weathered zone also determines its hydraulic properties.

The weathered-layer resistivity range of 10–800 Ωm further demonstrates the heterogeneous nature of the subsurface. Very low resistivity may reflect clay-rich or highly conductive materials, which can retain water but may have relatively low hydraulic conductivity. Conversely, very high resistivity may indicate relatively dry, coarse, or poorly weathered materials. Moderate resistivity values, when associated with sufficient weathered-layer thickness, are therefore more meaningful as potential groundwater targets than resistivity magnitude considered in isolation.

The depth-to-basement distribution provides an additional indication of basement morphology. Deeper basement depressions can accommodate thicker weathered materials and may therefore

support greater groundwater storage than basement highs where the weathered profile is thin. The hydrogeological significance of these depressions is consequently enhanced where they coincide with favourable lithology, lineament density, and resistivity characteristics.

Similarly, relatively low basement resistivity zones may reflect fractured or altered basement where groundwater-filled fractures contribute to increased electrical conductivity. Nevertheless, resistivity alone cannot uniquely distinguish water-bearing fractures from other conductive materials; interpretation is therefore strengthened when the geoelectrical anomalies coincide spatially with mapped structural features and favourable weathered profiles.

Taken together, the geoelectrical results demonstrate that groundwater potential cannot be reliably assessed from a single subsurface parameter; interpretation is strengthened when the individual geoelectrical indicators are considered collectively. This provides the principal hydrogeological basis for integrating the geoelectrical layers with the geological, terrain, drainage, and lineament datasets in the final groundwater-potential model.

4.4 Effectiveness of the Integrated Groundwater Potential Model

The integrated groundwater-potential model synthesizes the surface and subsurface controls identified from the geological, hydrogeological, remote-sensing, and geoelectrical investigations. Its principal value lies in evaluating the spatial coincidence of complementary indicators rather than relying on any single parameter.

The correspondence between the modelled favourable zones and available field observations provides supporting evidence for the spatial interpretation. Existing productive groundwater points occur within areas characterised by relatively favourable geological and geoelectrical conditions, whereas areas with shallow basement and thinner weathered profiles generally show less favourable conditions. This agreement suggests that the integrated approach reduces the uncertainty associated with interpreting any individual groundwater-controlling parameter.

The resulting groundwater-potential map should therefore be regarded as a spatial decision-support tool for groundwater exploration rather than as a direct prediction of borehole yield. Final borehole siting should incorporate site-specific geophysical investigation and, where possible, subsequent drilling and pumping-test verification.

4.5 Implications for Groundwater Development

The findings of this study have practical implications for groundwater exploration and water resource planning within the Nigerian Basement Complex. The groundwater potential map provides a scientific basis for selecting suitable borehole locations and can help reduce the frequency of unsuccessful drilling programs. By identifying areas where favorable geological, structural, and geoelectrical conditions occur together, the study contributes to more efficient utilization of groundwater resources.

Furthermore, the integrated methodology adopted in this investigation is applicable to other Basement Complex regions with similar geological characteristics. The combined use of geological mapping, electrical resistivity surveying, remote sensing, and GIS analysis provides

a dependable framework for groundwater exploration and supports sustainable groundwater resource management.

4.6. Study Limitations

Although the integrated approach adopted in this study provides a comprehensive assessment of groundwater potential within the study area, certain limitations should be acknowledged. The geoelectrical investigation was based on 48 Vertical Electrical Sounding (VES) stations, which provide one-dimensional information about subsurface conditions. While the survey density was adequate for the objectives of this study, the inclusion of two-dimensional or three-dimensional electrical resistivity imaging could provide improved resolution of subsurface geological features and fracture systems.

In addition, groundwater potential evaluation was based primarily on geological, hydrogeological, geoelectrical, and remotely sensed datasets. Parameters such as pumping-test results, groundwater quality characteristics, aquifer transmissivity, and seasonal groundwater-level fluctuations were not incorporated because such data were not available during the study period. Integrating these datasets in future investigations would provide a more comprehensive understanding of aquifer performance and groundwater sustainability. Despite these limitations, the multidisciplinary approach adopted in this study provides a dependable framework for groundwater exploration within crystalline Basement Complex terrains.

Conclusions

Summarise the article and highlight the main takeaways, limitations, impact, and future work. This study demonstrates that groundwater occurrence within the investigated part of Minna Sheet 164NE is controlled by the combined influence of geological, structural, terrain, and subsurface conditions. Integration of geological mapping, hydrogeological observations, remote sensing, and geoelectrical data provided a more comprehensive basis for delineating groundwater potential than consideration of individual parameters alone.

The resulting groundwater-potential map identifies areas requiring priority consideration for further groundwater investigation and borehole siting. However, the map should be regarded as a regional decision-support tool, and site-specific geophysical verification, drilling, and pumping tests remain necessary before final borehole development decisions are made.

The study demonstrates the value of combining geological, hydrogeological, remote-sensing, and geoelectrical information for groundwater-potential assessment in crystalline Basement Complex terrain. The resulting groundwater-potential map provides a useful regional framework for prioritising areas for further groundwater investigation and borehole siting. However, site-specific geophysical verification, drilling, and pumping tests remain necessary before final borehole development decisions are made.

Conflict of Interest

The authors declare that they have no competing interests related to this publication

Author Contributions

Olaleye Emmanuel Adeyemi: Investigation and writing of original draft

Idris Nda Abdullahi: Supervision

Stephen Jude Ejepu: Data curation, editing and formatting of draft

Alayande Abdulmojeed Ololade: Fieldwork assistant

Abdullahi Abba Usman: ArcGIS assistant

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Ethical Statements

The investigation did not involve human participants, experimental animals, or the collection of sensitive personal information. All field activities were conducted in accordance with applicable institutional requirements and accepted scientific practices.

Data and Code Availability

The datasets generated and analysed during the present study are available from the corresponding author upon reasonable request.

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