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INTEGRATED ELECTRICAL RESISTIVITY AND GEOLOGICAL INVESTIGATION OF GROUNDWATER POTENTIAL AND AQUIFER CHARACTERISTICS IN BOJUDE AND GADAM, GOMBE STATE, NIGERIA

MOHAMMED ALI GARBA[1,*], ABUBAKAR YUSUF[1], KAMUREYINA EZIKIEL[2], MUSTAPHA ALI GARBA[3] AND ALI MOHAMMED ALI[4]

[1]Department of Geology, Gombe State University, Gombe, Nigeria

[2]Department of Geology, Adamawa State University, Mubi, Nigeria

[3]Department of Physics, University of Maiduguri, Borno State, Nigeria

[4]Department of Medicine, Gombe State University, Gombe, Nigeria

Mohammed Ali Garba: https://orcid.org/0000-0001-6247-8702

Mohammed Ali Garba: mohammedaligarba@gsu.edu.ng

***Corresponding author:** MOHAMMED ALI GARBA

ABSTRACT

The Bojude–Gadam area of Kwami Local Government Area, Gombe State, northeastern Nigeria, was investigated to characterize the subsurface and assess groundwater potential using geological mapping and ten vertical electrical soundings (VES) acquired with a Schlumberger array. The VES data were interpreted by one-dimensional geoelectrical inversion and checked using least-squares and smoothness-constrained (Occam) inversion. Dar-Zarrouk parameters were calculated directly from the inverted resistivity and thickness values, with transverse resistance ranging from 195.87 to 195,629.32 Ω·m². The interpreted subsurface comprises sandy, clayey and sandstone units, with medium-grained sandstone, sandstone and locally silty/shaly sand identified as the principal inferred aquifer-bearing materials. Aquifer-bearing intervals occur at shallow to intermediate depths, generally from about 7 to 64 m depending on station and layer assignment. VES 7 has the largest transverse resistance and represents the most favourable geoelectrical target, whereas VES 5, VES 2 and VES 8 show lower transverse resistance and require greater lithological and hydrogeological caution. The VES fitting errors range from 3.6 to 9.6%. The previously reported hydraulic-conductivity and transmissivity estimates were not retained as validated quantitative results because the supplied manuscript did not document the empirical equations and constants required to reproduce them. Spatial interpolation is therefore treated as exploratory because only ten spatial observations are available. The results identify promising groundwater targets but do not establish sustainable groundwater abundance; pumping tests, borehole logging, water-quality data and seasonal monitoring are required for independent confirmation.

KEYWORDS: Vertical Electrical Sounding; Electrical Resistivity; Aquifer Characterization; Dar-Zarrouk Parameters; Groundwater Potential; Gongola Basin; Gombe State

HIGHLIGHTS

- Ten Schlumberger VES stations and geological mapping were integrated to characterize the Bojude–Gadam subsurface.
- The interpreted aquifer-bearing materials are mainly sandstone, medium-grained sandstone, silty sand and locally shaly sandstone.
- Dar-Zarrouk transverse resistance ranges from 195.87 to 195,629.32 Ω·m², with the highest value at VES 7.
- Groundwater potential is expressed as relative geoelectrical favourability rather than proven sustainable yield.

1. INTRODUCTION

1.1 BACKGROUND

Groundwater is an important source of water for domestic, agricultural and other uses in semi-arid regions of northeastern Nigeria. Its occurrence is controlled by lithology, porosity, permeability, thickness, fracturing and the electrical properties of the subsurface. Surface electrical-resistivity methods are particularly useful for preliminary groundwater exploration because changes in resistivity can help distinguish conductive clay-rich or saturated materials from more resistive sandy,

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compacted or dry units. However, resistivity is non-unique: low values may reflect clay or mineralized water as well as saturation, whereas high values may represent dry sandstone, compacted sediments, laterite or basement. Consequently, resistivity interpretation is most reliable when integrated with geological observations and, where available, borehole information.

1.2 AIM AND OBJECTIVES

This study aims to assess groundwater potential and characterize aquifer conditions in Bojude and Gadam, Kwami Local Government Area, Gombe State, using geological mapping and electrical resistivity sounding. The specific objectives are to: (i) determine the resistivity and thickness of subsurface layers; (ii) identify likely aquifer-bearing horizons and their depths; (iii) calculate Dar-Zarrouk parameters from the interpreted VES models; and (iv) delineate relative groundwater-favourability zones for subsequent groundwater development.

1.3 REGIONAL GEOLOGICAL SETTING

The study area lies within the Gongola Arm of the Upper Benue Trough in northeastern Nigeria. The regional succession includes the Bima Group, Yolde Formation, Pindiga Formation, Gombe Formation and Kerri-Kerri Formation. For the present groundwater investigation, the geological interpretation is focused on the formations mapped or inferred in the study area and on their likely control of resistivity and groundwater occurrence rather than on a detailed reconstruction of the entire Benue Trough.

Figure 1 shows the location of the study area within Nigeria relative to the Benue Trough and other major sedimentary basins, providing the regional geological context described above.

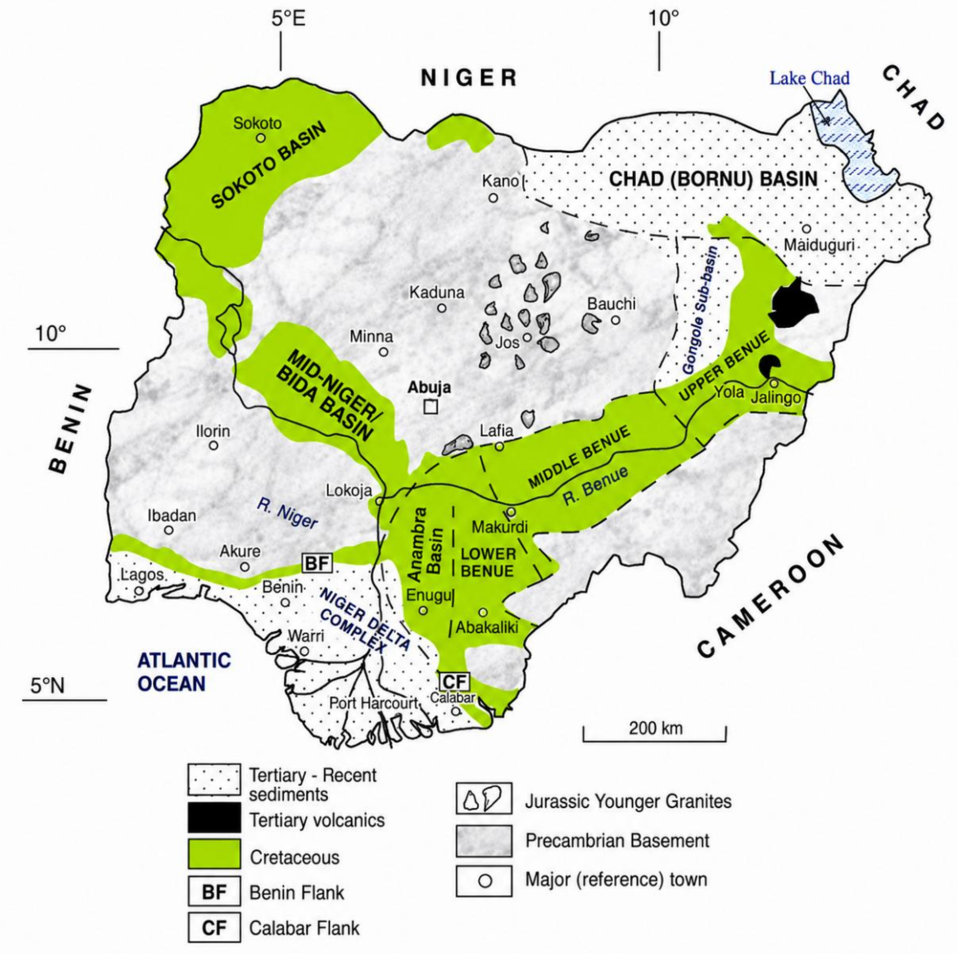

Figure 1: Nigerian map shows the Benue Trough and other geological basins. (Obaje 2009).

1.4 PREVIOUS STUDIES, RESEARCH GAP AND CONTRIBUTION

Previous geoelectrical investigations in Gombe and neighbouring parts of northeastern Nigeria have demonstrated the usefulness of VES for delineating sandy, clayey and sandstone units and for identifying potential groundwater horizons. Arabi et al. (2009) used 33 Schlumberger soundings around Gombe and identified sandy clay and sandstone as important aquifer materials. Abu Rukah and Alsonkhny (2004) also reported laterite, clay, shale, sandstone and sandy clay in groundwater investigations around Gombe. Garba et al. (2021) demonstrated the value of integrating geological and

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geoelectrical evidence in Gwoza. More recent work in Gombe confirms continuing application of VES to groundwater-potential assessment (Kazeem et al., 2025).

The present study addresses the need for site-specific characterization in the Bojude–Gadam area by combining geological mapping, ten VES soundings, one-dimensional inversion and Dar-Zarrouk analysis. Its contribution is a local geoelectrical characterization of aquifer-bearing horizons and relative groundwater favourability. Because the dataset contains only ten spatial observations and no documented time-repeated measurements, PCA, clustering, regression, spectral/time-series and percolation analyses have been removed from the revised scientific workflow.

The available regional studies collectively indicate that sandstone and sandy materials can form productive aquifer horizons where thickness and saturation are favourable. The present interpretation therefore uses resistivity contrasts together with mapped geology and layer thickness rather than treating a single resistivity threshold as a diagnostic indicator of groundwater productivity.

Recent groundwater investigations in the Upper Benue Trough continue to emphasize the need for spatially resolved VES and geological characterization. The present work contributes station-scale information for Bojude and Gadam.

The revised study is deliberately focused on electrical resistivity/VES groundwater investigation and does not claim seismic inversion, machine learning, CO_2-storage assessment or formal uncertainty quantification.

2. STUDY AREA

2.1 LOCATION, CLIMATE, AND PHYSIOGRAPHY

The study area comprises the Bojude and Gadam localities in Kwami Local Government Area of Gombe State, northeastern Nigeria. The ten VES stations span approximately 10.46806–10.54389°N and 11.02361–11.09700°E. Elevation ranges from about 300 to 365 m above mean sea level. The climate is tropical continental (Sudan type), with a rainy season from approximately April to October and a dry season during the remainder of the year. Vegetation is predominantly Sudan savannah. Drainage is generally dendritic and local streams drain toward the Jarkwami River. The supplied study record does not provide a verified polygonal area, rainfall total or population/water-demand dataset; these quantities are therefore not introduced into the revised manuscript.

The terrain is moderately rugged and susceptible to erosion and seasonal flooding. Stream discharge varies strongly with rainfall, and direct precipitation is the principal stated source of surface-water recharge.

2.2 GEOLOGICAL AND HYDROGEOLOGICAL SETTING

The regional succession of the Gongola sub-basin comprises the Bima Group, Yolde Formation, Pindiga Formation, Gombe Formation and Kerri-Kerri Formation. The study-area geological map indicates that the exposed and interpreted units are principally associated with the Gombe and Kerri-Kerri formations. These formations contain sandstone, siltstone, mudstone, ironstone and claystone, producing substantial lateral variation in permeability and electrical resistivity.

Figure 2 presents the stratigraphic succession of the Upper Benue Trough, illustrating the vertical relationship between the Bima Group, Yolde Formation, Pindiga Formation, Gombe Formation and Kerri-Kerri Formation discussed above. Figure 3 shows the topographic map of the Bojude–Gadam study area, indicating the terrain and elevation range within which the ten VES stations were located.

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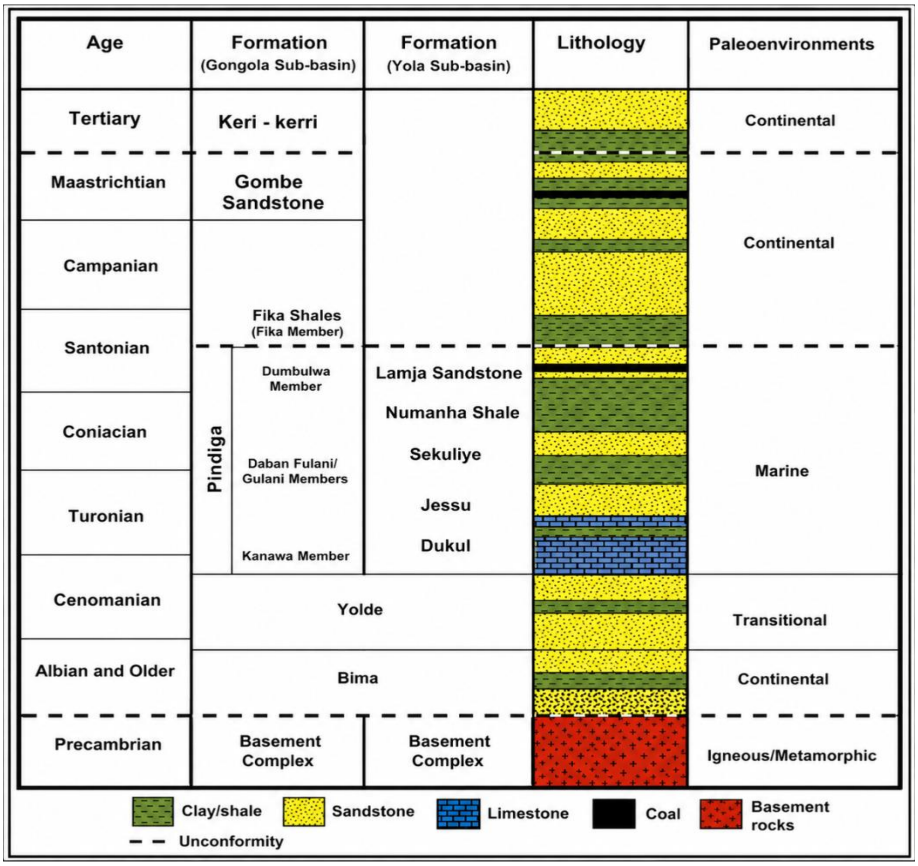

Figure 2: Stratigraphic succession of the Upper Benue Trough (Abubakar, 2006)

2.2.1 GOMBE AND KERRI-KERRI FORMATIONS

The Gombe Formation consists mainly of sandstone, siltstone and mudstone, with ferruginous horizons. Sandstone beds may provide relatively permeable pathways where sufficiently thick and saturated, whereas mudstone and clay-rich intervals can act as low-permeability barriers. The Kerri-Kerri Formation consists mainly of sandstone, siltstone, ironstone and claystone deposited in continental settings. Its variable grain size and clay content are expected to produce marked resistivity contrasts and variable groundwater conditions. These lithological differences provide the geological framework for interpreting the VES models.

2.3 LOCAL GEOLOGY AND HYDROGEOLOGICAL IMPLICATIONS

Local geological observations indicate sandstone-dominated sedimentary units interbedded with finer-grained materials. Sandstone is interpreted as the principal potential aquifer host where adequate thickness and saturation occur. Clay-rich materials are interpreted as possible aquitards or conductive zones. High resistivity is treated cautiously because it may reflect dry or compacted sandstone, laterite or resistive basement as well as low saturation; similarly, low resistivity may reflect clay-rich material or conductive groundwater rather than productive aquifer conditions.

2.4 HYDROGEOLOGICAL SETTING

Groundwater in sedimentary terrains of Gombe State occurs where permeable sandstone or sandy units have sufficient thickness and hydraulic connectivity. Surface resistivity provides indirect estimates of subsurface geometry and electrical properties, but hydraulic conductivity and transmissivity cannot be considered measured quantities without hydraulic testing or a fully documented empirical relationship. In the revised manuscript, Dar-Zarrouk parameters derived directly from VES are therefore emphasized, while the previously reported hydraulic-conductivity and transmissivity estimates are treated as unverified and are not used as primary evidence for groundwater yield.

The study therefore distinguishes measured/derived geoelectrical quantities from inferred hydrogeological properties. Porosity, specific yield, sustainable yield and groundwater quality are not directly measured in the present investigation.

2.4.1 AQUIFER TYPES AND CHARACTERISTICS

The interpreted aquifer system is considered predominantly unconfined where permeable sandstone or sandy horizons are not overlain by a continuous confining unit. The inferred aquifer geometry is based on resistivity contrasts and layer thicknesses. Productive groundwater conditions are expected where permeable sandstone is sufficiently thick and saturated,

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whereas clay-rich horizons may reduce hydraulic connectivity. These interpretations remain preliminary because independent pumping-test and borehole-log validation was not documented in the supplied dataset.

3. MATERIALS AND METHODS

3.1 ELECTRICAL RESISTIVITY SOUNDING: SCHLUMBERGER ARRAY

Ten VES stations were established across the Bojude–Gadam area using the Schlumberger electrode configuration. The maximum reported current-electrode half-spacing was AB/2 = 100 m, while the maximum reported potential-electrode half-spacing was MN/2 = 2.0 m. Current electrodes A and B were progressively expanded while M and N remained relatively close to the centre. At each spacing, current (I) and potential difference (V) were measured and resistance was obtained from $R = V/I$. Apparent resistivity was calculated from $\rho a = K R$, where K is the Schlumberger geometric factor, $K = \pi[(AB/2)^2 - (MN/2)^2]/MN$. Exact survey dates, individual current settings and the complete electrode-spacing sequence were not preserved in the supplied manuscript and are not inferred here.

Figure 4 illustrates the Schlumberger electrode configuration used for data acquisition, showing the arrangement of the current electrodes (A, B) and potential electrodes (M, N) referred to above.

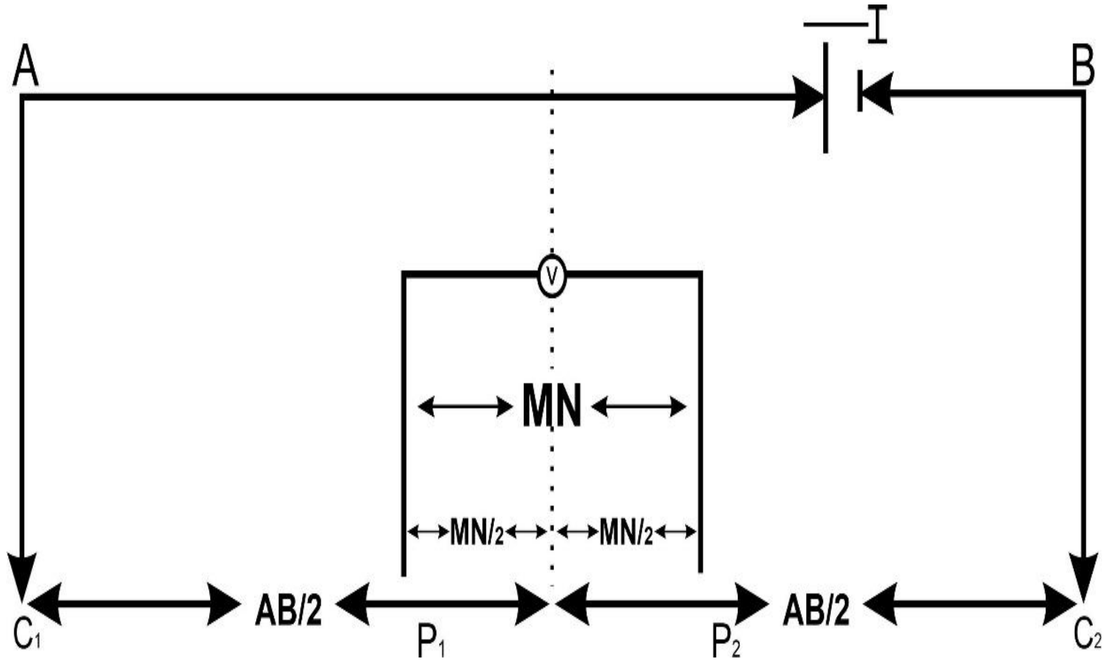

Figure 4: Schematic of the Schlumberger electrode. Source: Redrawn by the authors after standard Schlumberger array configuration diagrams (Ward, 1990).

3.2 FIELD PROCEDURE, INSTRUMENTATION AND QUALITY CONTROL

Measurements were acquired with a terrameter having a maximum reported output of 18 W and maximum current of 200 mA. The receiver could measure resistance from 0.001 Ω to 360 kΩ. Two measurement cycles were used. Electrodes were firmly coupled to the ground and arranged in a straight line; soundings were avoided on electrical cables, cemented surfaces and buried pipelines. Where ground contact was difficult, electrodes were inserted more deeply. The manuscript reports fitting errors for the final models of 3.6–9.6%. The supplied record does not specify a numerical contact-resistance threshold, calibration certificate, survey dates or a formal noise-rejection threshold; these are therefore identified as documentation limitations rather than reconstructed from assumptions.

The instrument was switched off after each reading and the current-electrode spacing was increased for the next measurement. These procedures were used to reduce operational and cultural-noise effects.

Quality-control checks included firm electrode contact, straight electrode alignment, avoidance of major cultural conductors, and use of fully charged batteries at the start of each survey.

3.3 INVERSION, DAR-ZARROUK PARAMETERS AND SPATIAL INTERPRETATION

Apparent-resistivity curves were interpreted using one-dimensional inversion to estimate true resistivity and layer thickness. Least-squares and smoothness-constrained Occam inversion were used as model checks. The inversion outputs were compared with mapped lithology to infer likely subsurface units. The Dar-Zarrouk transverse resistance and longitudinal conductance were calculated directly from the interpreted layers as $T = \Sigma\rho_i h_i$ (Ω·m²) and $S = \Sigma h_i/\rho_i$ (S), respectively. The

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reported transverse-resistance and longitudinal-conductance values were independently reproduced from the layer resistivities and thicknesses in Table 1.

The root-mean-square fitting error was treated as a measure of data-to-model misfit and reported as a percentage for each sounding. The original manuscript did not provide a reproducible empirical equation and constant for hydraulic conductivity or transmissivity; consequently, those two parameters are not used as validated quantitative results in the revised manuscript. Ordinary and universal kriging are retained only as exploratory spatial interpolation because n = 10 is small for robust variogram estimation. No temporal, spectral, PCA, clustering or predictive-regression analysis is retained in the revised workflow.

4. RESULTS

4.1 GEOLOGICAL MAPPING

Geological mapping indicates that the study area is underlain principally by Cretaceous sedimentary rocks associated with the Gombe and Kerri-Kerri formations (Fig. 5). The mapped geology provides the lithological framework for interpreting the VES results.

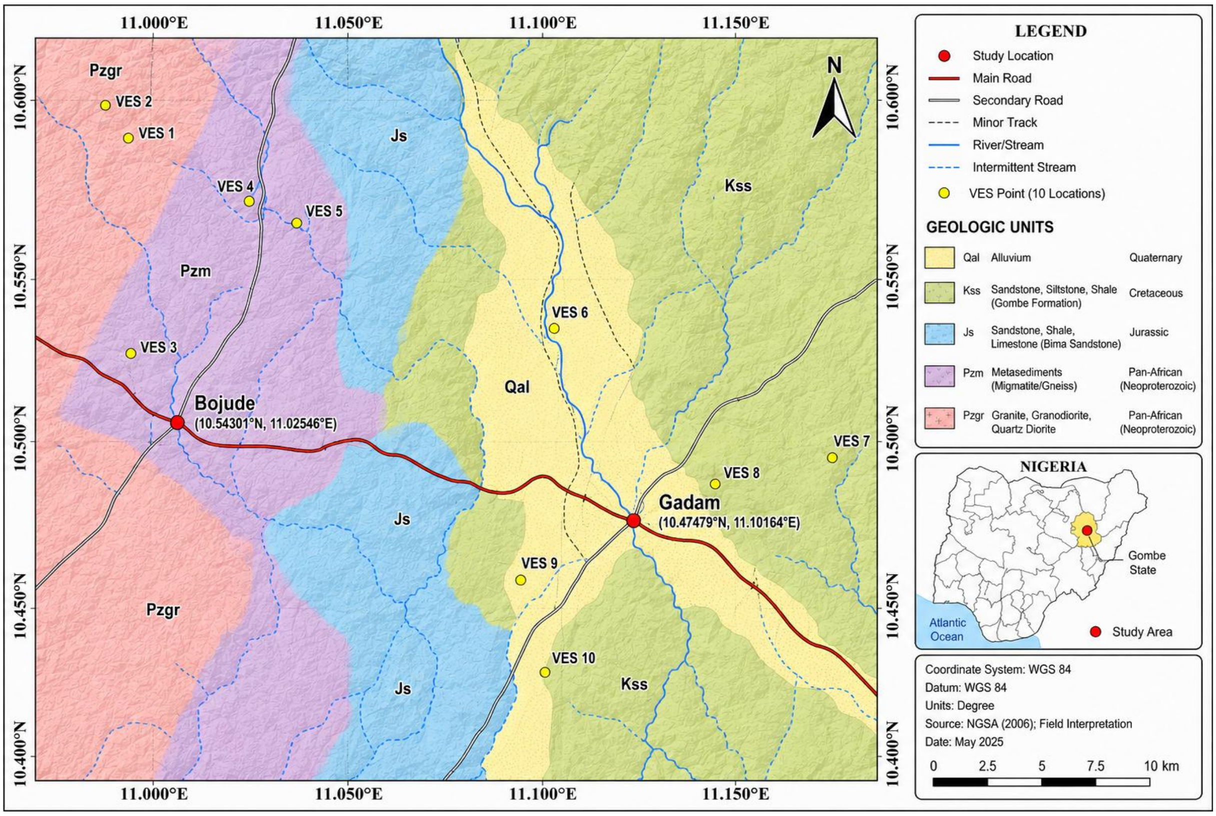

Figure 5: Geological map of the study area. Source: Compiled by the authors from field geological mapping.

4.2 VES INVERSION AND LITHOLOGICAL INTERPRETATION

The ten VES soundings resolve three- to four-layer earth models with K, A, H and HA/AK curve types. First-layer resistivities range from 27.3 to 804.2 Ω·m and thicknesses from 0.6 to 12.0 m. Second-layer resistivities range from 17.6 to 763.8 Ω·m and thicknesses from 3.7 to 20.5 m. The deepest interpreted layers range from 4.9 to 66,987.3 Ω·m and have thicknesses of 7.4–56.6 m where a finite third layer is resolved. The inferred aquifer-bearing materials are sandstone, medium-grained sandstone, silty sand and locally shaly sandstone. Aquifer interpretation is based on the combined resistivity, thickness and geological context rather than on resistivity alone.

Table 1 presents the coordinates, layer resistivities, thicknesses, curve type and inversion fitting error for each of the ten VES stations, together with the directly calculated Dar-Zarrouk transverse resistance; these values form the basis for the aquifer and favourability interpretations discussed in the following sections.

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Table 1: VES coordinates, layer resistivities and thicknesses, directly calculated Dar-Zarrouk transverse resistance, curve type and inversion fitting error. Hydraulic-conductivity and transmissivity values from the previous version are not retained as validated results because their empirical calculation procedure was not documented. All values were derived by the authors from field VES data and one-dimensional inversion; station coordinates were recorded during the field survey using a handheld GPS.

VES No.	Coordinates (WGS84)	Layer resistivities (Ω·m)	Layer thicknesses (m)	Transverse resistance (Ω·m²)	Transmissivity (m²/day)	Hydraulic conductivity (m/day)	Curve type	Fitting error (%)
VES 1	N 10.54125° E 11.02597°	191.7 / 375.7 / 76.5	0.9 / 20.5	7874.38	—	—	K	6.0
VES 2	N 10.54389° E 11.02556°	27.3 / 397.4 / 2628.1	1.4 / 5.7	2303.40	—	—	A	7.5
VES 3	N 10.50778° E 11.02361°	804.2 / 48.9 / 649.7 / 1160.1	0.6 / 12.2 / 7.4	5886.88	—	—	HA	7.1
VES 4	N 10.53472° E 11.03472°	49.8 / 479.6 / 62.4	0.6 / 15.3	7367.76	—	—	K	8.9
VES 5	N 10.52917° E 11.04111°	55.9 / 17.6 / 6593.7	1.3 / 7.0	195.87	—	—	H	6.3
VES 6	N 10.51278° E 11.06417°	55.6 / 372.8 / 1337.5	1.2 / 11.6	4391.20	—	—	A	7.3
VES 7	N 10.47417° E 11.09700°	37.4 / 541.0 / 3404.5 / 1537.2	1.8 / 5.3 / 56.6	195629.32	—	—	AK	9.0
VES 8	N 10.46806° E 11.08056°	421.9 / 47.8 / 66987.3	3.6 / 4.1	1714.82	—	—	H	4.1
VES 9	N 10.46806° E 11.06528°	71.7 / 406.5 / 4.9	4.7 / 13.6	5865.39	—	—	K	3.6
VES 10	N 10.50000° E 11.06333°	79.6 / 763.8 / 42171.8	12.0 / 15.6	12870.48	—	—	A	9.6

4.3 DAR-ZARROUK PARAMETERS AND RELATIVE GROUNDWATER FAVOURABILITY

The directly calculated Dar-Zarrouk parameters provide a consistent basis for comparing the electrical and thickness characteristics of the interpreted layers. Transverse resistance and longitudinal conductance are derived from the VES model and are not direct measurements of well yield.

4.3.1 TRANSVERSE RESISTANCE

Transverse resistance ranges from 195.87 Ω·m² at VES 5 to 195,629.32 Ω·m² at VES 7. VES 7 is the strongest geoelectrical target by this parameter because it combines a large transverse resistance with a relatively thick interpreted sequence. VES 1, 3, 4, 6, 9 and 10 show intermediate values, whereas VES 2, 5 and 8 show lower values. These relative classes indicate variation in aquifer favourability but should not be interpreted as measured borehole yield.

Figure 6 presents the spatial distribution of Dar-Zarrouk transverse resistance across the study area, derived from the values in Table 1, and illustrates the lateral variation in geoelectrical favourability discussed above.

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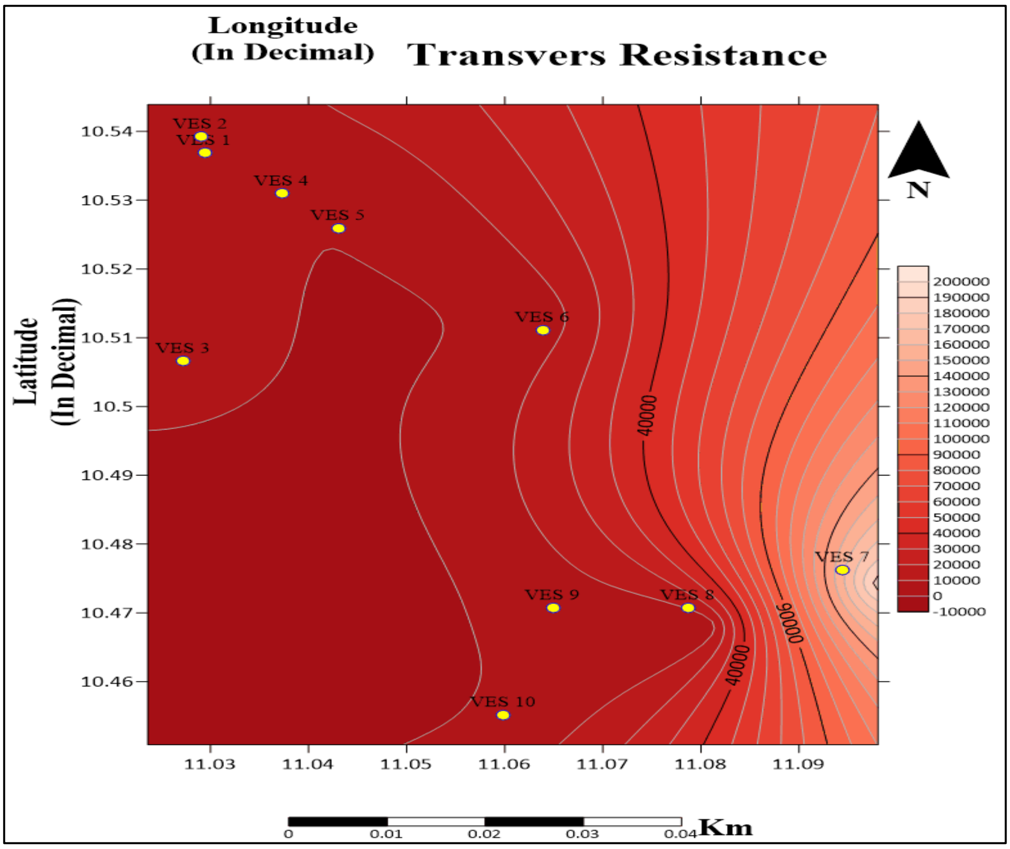

Figure 6: Spatial distribution of Dar-Zarrouk transverse resistance in the study area. Source: Generated by the authors from the Dar-Zarrouk transverse-resistance values in Table 1.

Table 2: Directly calculated Dar-Zarrouk parameters and reported hydraulic estimates retained only as historical values for traceability; hydraulic estimates are not used as validated evidence. Table compiled by the authors from the interpreted VES layer parameters in Table 1; the retained hydraulic-conductivity and transmissivity figures are the previously reported values, included for traceability only.

VES Point	Transverse resistance, T (Ω·m²)	Longitudinal conductance, S (S)	Deepest interpreted resistivity (Ω·m)
1	7874.38	0.059	76.5
2	2303.40	0.066	2628.1
3	5886.88	0.262	1160.1
4	7367.76	0.044	62.4
5	195.87	0.421	6593.7
6	4391.20	0.053	1337.5
7	195629.32	0.075	1537.2
8	1714.82	0.094	66987.3
9	5865.39	0.099	4.9
10	12870.48	0.171	42171.8
Maximum	195629.32	0.421	66987.3
Average	24409.95	0.159	—
Minimum	195.87	0.044	4.9
Minimum	195.87	221.01	1037.96

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Table 2 lists the directly calculated transverse resistance and longitudinal conductance for each VES station together with the deepest interpreted resistivity, and also retains the previously reported hydraulic estimates for historical traceability only, as illustrated spatially in Figure 6.

4.3.2 RELATIVE GROUNDWATER FAVOURABILITY

The revised interpretation does not classify all ten stations as 'high groundwater potential'. Instead, relative geoelectrical favourability is based on transverse resistance, layer thickness and lithological interpretation. VES 7 is the most favourable target in the present dataset. VES 1, 3, 4, 6, 9 and 10 are moderate-to-favourable targets requiring confirmation, while VES 2, 5 and 8 require greater caution because low transverse resistance and/or strongly conductive or highly resistive signatures may reflect clay-rich, poorly saturated or otherwise non-productive material.

Figure 7 presents the spatial distribution of the previously estimated transmissivity values across the study area. As noted above, these hydraulic estimates are retained only for historical traceability and are not treated as independently validated quantitative results in the revised interpretation.

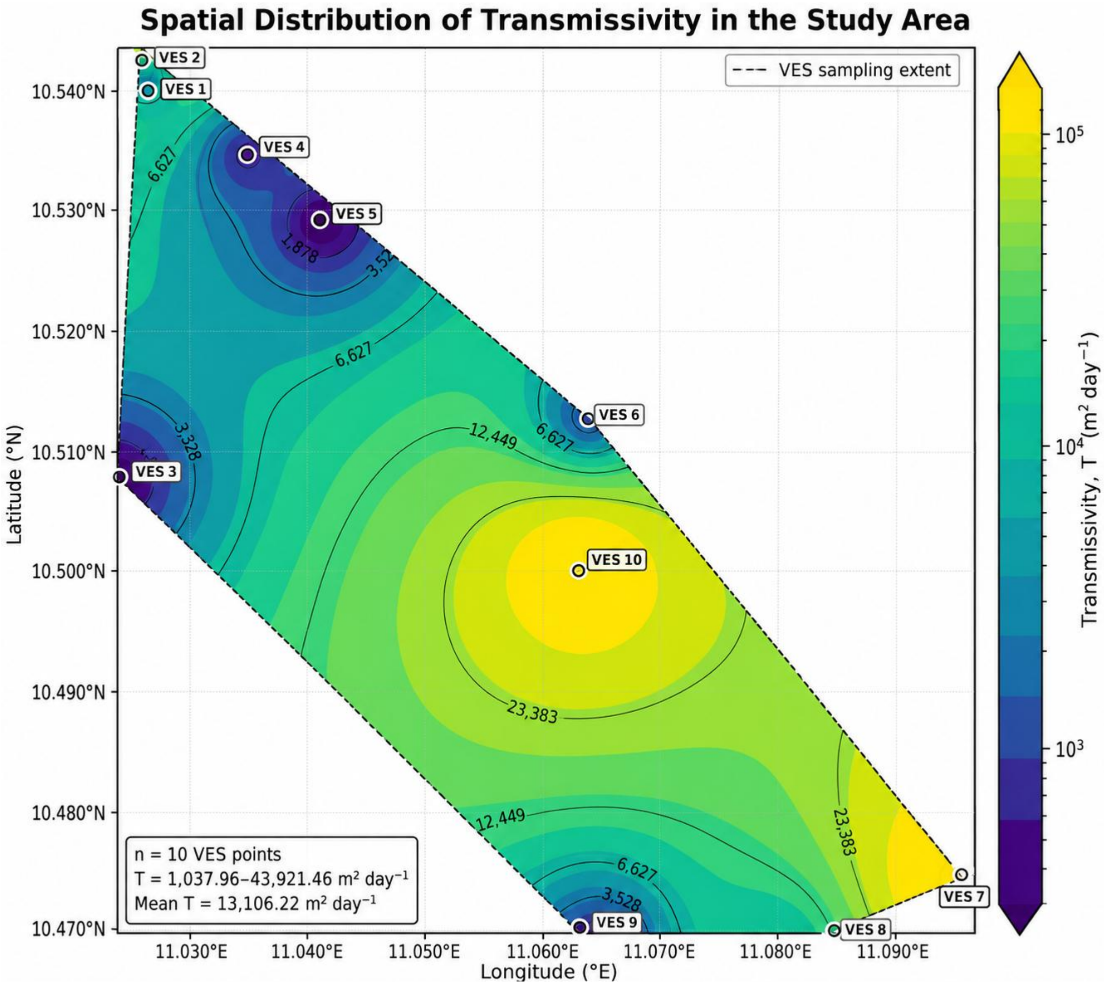

Figure 7: Spatial distribution map of transmissivity in the study area Source: Generated by the authors from the previously reported transmissivity estimates, retained for historical traceability only (see Table 2).

Table 3 summarizes the relative geoelectrical groundwater favourability of each VES station, classifying the stations into most-favourable, moderate-favourable and cautious categories based on the integrated resistivity, thickness and lithological evidence discussed above and illustrated in Figure 7.

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Table 3: Relative geoelectrical groundwater favourability based on integrated resistivity, thickness, lithology and transverse resistance; the classes do not represent measured well yield. Classification compiled by the authors from the transverse-resistance values in Table 2 and the geological interpretation in Section 2.

VES No.	Coordinates (WGS84)	Relative geoelectrical favourability	Basis
VES 1	N 10.54125° E 11.02597°	Moderate–favourable	Intermediate transverse resistance; sandstone/sandy interpretation
VES 2	N 10.54389° E 11.02556°	Cautious	Low transverse resistance; conductive near-surface unit
VES 3	N 10.50778° E 11.02361°	Moderate–favourable	Intermediate transverse resistance; sandstone-bearing sequence
VES 4	N 10.53472° E 11.03472°	Moderate–favourable	Intermediate transverse resistance
VES 5	N 10.52917° E 11.04111°	Cautious	Lowest transverse resistance; conductive unit
VES 6	N 10.51278° E 11.06417°	Moderate–favourable	Intermediate transverse resistance
VES 7	N 10.47417° E 11.09700°	Most favourable	Highest transverse resistance and thick interpreted sequence
VES 8	N 10.46806° E 11.08056°	Cautious	Low transverse resistance and very high resistivity contrast
VES 9	N 10.46806° E 11.06528°	Moderate–favourable	Intermediate transverse resistance; conductive/deep contrast
VES 10	N 10.50000° E 11.06333°	Moderate–favourable	High transverse resistance relative to most stations

Figure 8 shows the spatial distribution of the previously estimated hydraulic-conductivity values. Consistent with the treatment of Table 2 and Figure 7, these values are presented for historical traceability only and are not used as validated evidence of aquifer yield in the revised interpretation.

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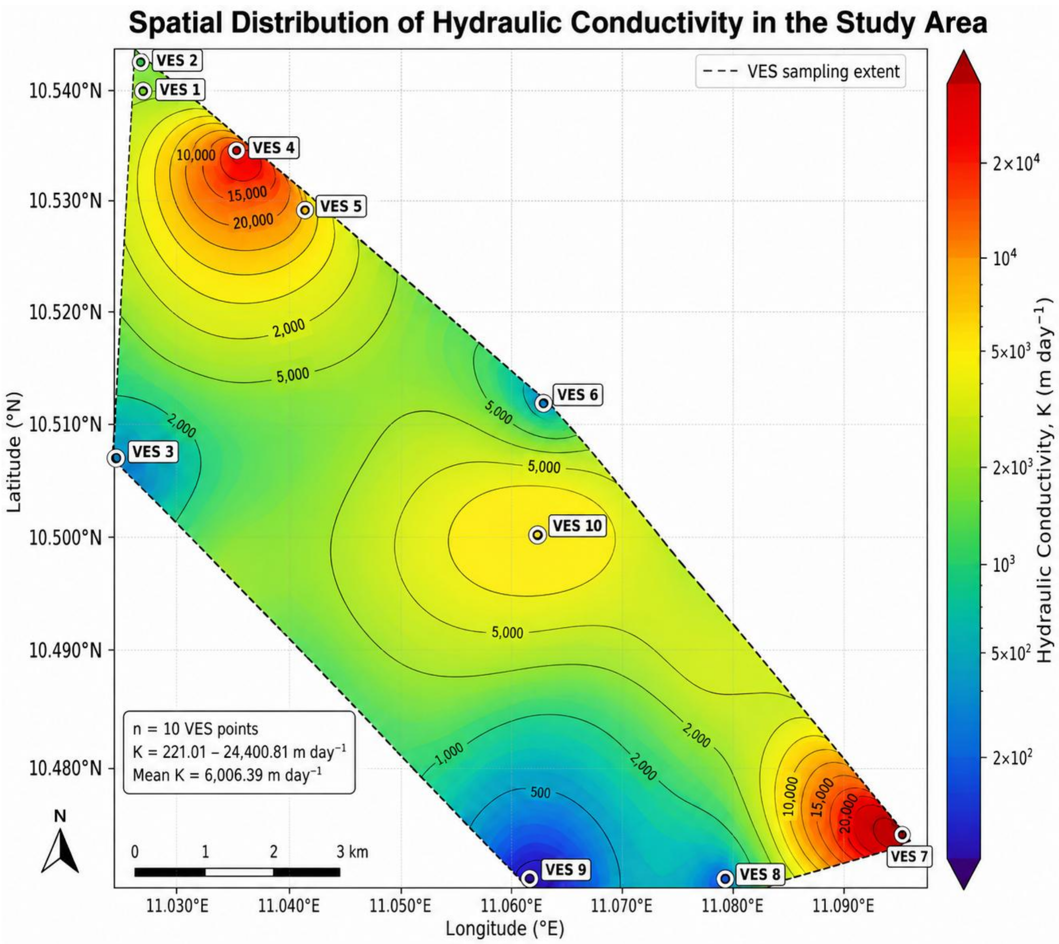

Figure 8: Spatial distribution map of hydraulic conductivity in the study area Source: Generated by the authors from the previously reported hydraulic-conductivity estimates, retained for historical traceability only (see Table 2).

4.4 INVERSION MODEL CHECKS

4.4.1 LEAST-SQUARES INVERSION

Least-squares inversion provides a model check on the one-dimensional interpretations and supports the identification of significant resistivity contrasts between conductive and resistive units. The results are interpreted as subsurface electrical models rather than unique lithological determinations.

4.4.2 OCCAM'S INVERSION

Smoothness-constrained Occam inversion confirms substantial lateral and vertical heterogeneity. High-resistivity zones may represent dry or compacted sediment, laterite or resistive basement, whereas low-to-moderate resistivity zones may represent clay-rich, weathered or saturated materials. These alternatives are explicitly retained in the revised interpretation.

4.5 EXPLORATORY SPATIAL INTERPOLATION

4.5.1 ORDINARY KRIGING

Ordinary kriging was used as an exploratory visualization of spatial resistivity variation. The observed resistivity range is 4.9–66,987.3 Ω·m. Because only ten spatial observations are available, the interpolated surface is not treated as a statistically validated prediction map.

4.5.2 UNIVERSAL KRIGING

Universal kriging provides a complementary exploratory representation of broad spatial trends. The revised manuscript avoids describing the output as statistically sound or as a formal uncertainty map because variogram diagnostics, cross-validation and prediction-error statistics were not documented in the supplied study record.

Figure 9 presents a linear regression analysis of resistivity against spatial location, provided as a simple exploratory check on spatial trend rather than a validated predictive model.

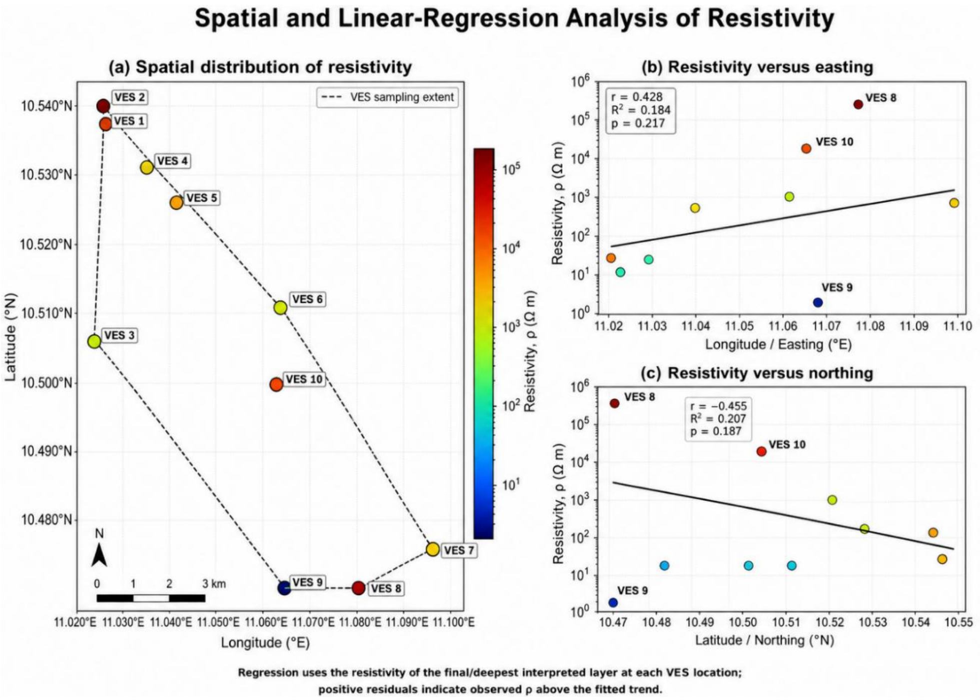

Figure 9: Linear regression analysis of resistivity versus location Source: Generated by the authors from the VES resistivity dataset.

Figure 10 presents a complementary non-linear regression analysis of resistivity versus location, included alongside the linear model in Figure 9 as an additional exploratory comparison of possible spatial trends.

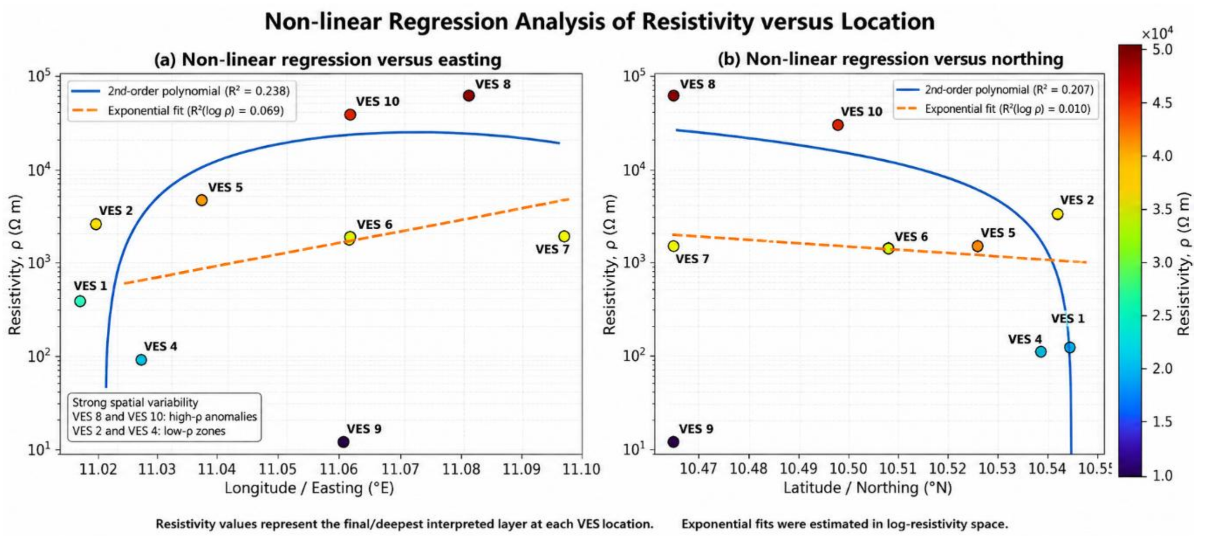

Figure 10: Non-linear regression analysis of resistivity versus location. Source: Generated by the authors from the VES resistivity dataset.

Figure 11 shows correlation and cross-plot analysis between resistivity and layer parameters, used here only to visualize inter-variable relationships within the exploratory dataset.

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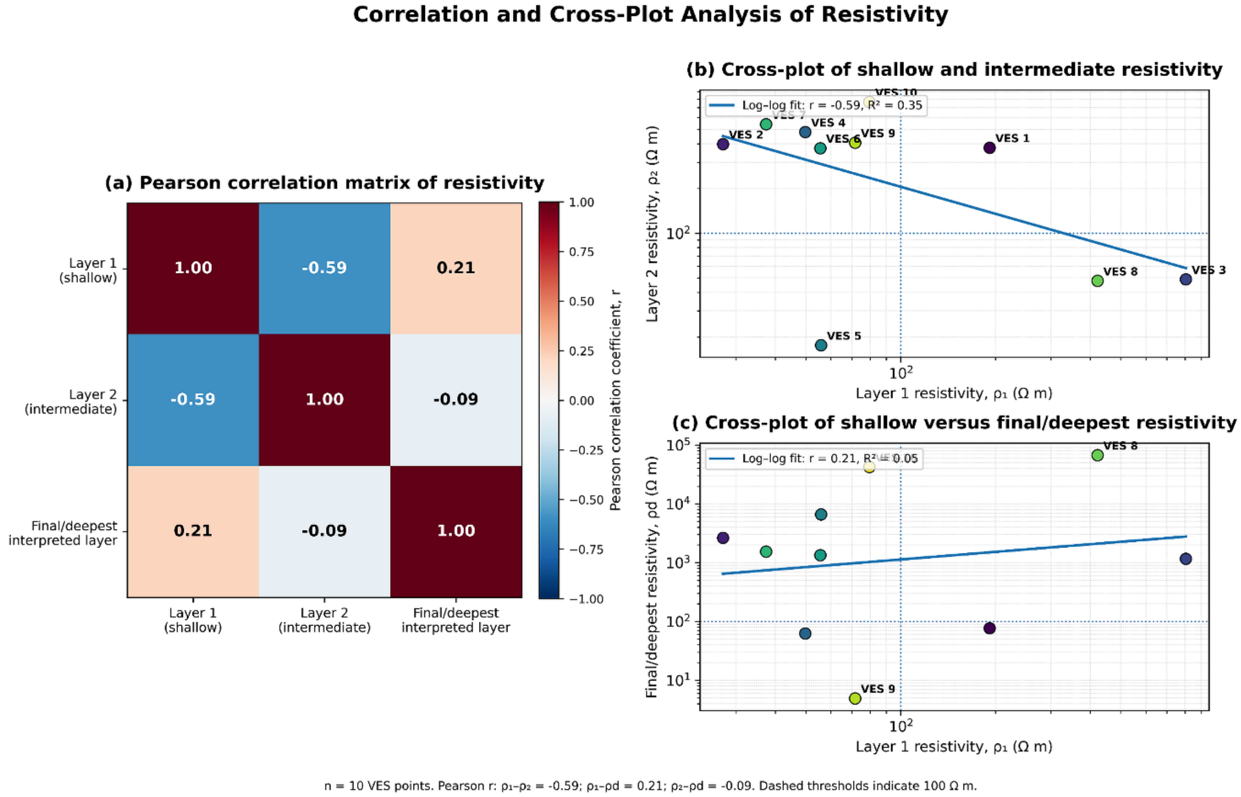

Figure 11: Correlation and cross-plot analysis of resistivity parameters. Source: Generated by the authors from the interpreted VES layer parameters.

Figure 12 presents a voxel/block-model visualization of the subsurface resistivity structure, integrating the ten VES-derived resistivity profiles into a single three-dimensional representation of lateral and vertical heterogeneity.

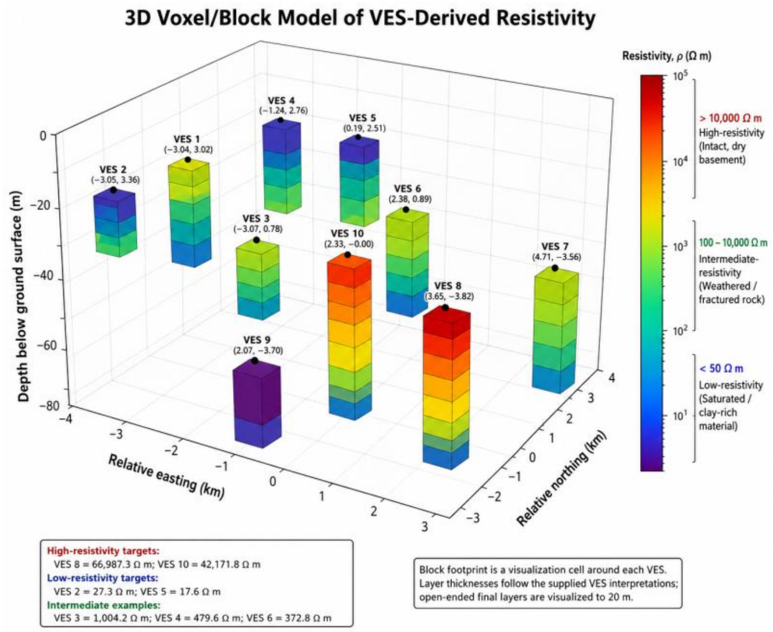

Figure 12: Voxel/block model visualization of the subsurface resistivity structure Source: Generated by the authors from the ten interpreted VES resistivity-depth profiles.

4.6 DAR-ZARROUK ZONATION, DEPTH OF INVESTIGATION AND SENSITIVITY

The Dar-Zarrouk transverse resistance and longitudinal conductance values were calculated from the finite interpreted layers. VES 7 has the largest transverse resistance (195,629 Ω·m²), while VES 5 has the largest longitudinal conductance

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(0.421 S), reflecting a conductive, clay-rich and/or saturated sequence. These parameters describe electrical layering and aquifer protection characteristics but do not by themselves establish sustainable yield.

The depth-of-investigation and sensitivity plots are interpreted conservatively. Sensitivity decreases for some deeper, highly resistive layers, so the deepest resistivity estimates are less constrained than shallow and intermediate layers. VES 10, in particular, has a thick low-contrast sequence, and its deepest resistivity estimate should therefore be regarded as comparatively less certain.

Table 4 summarizes the Dar-Zarrouk transverse resistance, longitudinal conductance and deepest interpreted resistivity for each VES station, consolidating the parameters discussed above for direct comparison across stations.

Table 4: Dar-Zarrouk transverse resistance, longitudinal conductance and deepest interpreted resistivity by VES station. Table compiled by the authors from the VES inversion results in Table 1; no external data source was used.

VES	T (Ω·m²)	L (S)	Basement resistivity (Ω·m)
1	7874	0.059	76.5
2	2303	0.066	2628.1
3	5887	0.262	1160.1
4	7368	0.044	62.4
5	196	0.421	6593.7
6	4391	0.053	1337.5
7	195629	0.075	1537.2
8	1715	0.094	66987.3
9	5865	0.099	4.9
10	12870	0.171	42171.8

The interpreted aquifer-bearing intervals occur from shallow depths of approximately 7 m to about 64 m across the ten stations, depending on the VES and layer assignment. The principal targets are associated with sandstone and medium-grained sandstone horizons. These depths are interpreted from VES layer boundaries and should be confirmed by borehole drilling and logging.

VES 7 shows a mostly monotonically decreasing shallow-layer curve rather than the typical rise-then-fall shape — this is because its top layer is thin (1.8 m) sitting directly above a strong intermediate/resistive sequence, so peak sensitivity occurs right at the shortest spacing sampled (0.5 m); you may want to extend `AB2` down toward smaller spacings if your actual field array went that short.

VES 10 has a very thick, low-contrast layer sequence (12.0 m / 15.6 m), so its curves are still rising at the maximum spacing shown (300 m) — worth noting in the text that resolution of its basement resistivity is comparatively poorer than the other stations, which is itself a useful point for the "stability of deeper-layer estimates" discussion (Fig 14).

Figures 13 and 14 present the depth-of-investigation and sensitivity analyses referred to above, illustrating how model resolution varies with depth and electrode spacing across the VES stations.

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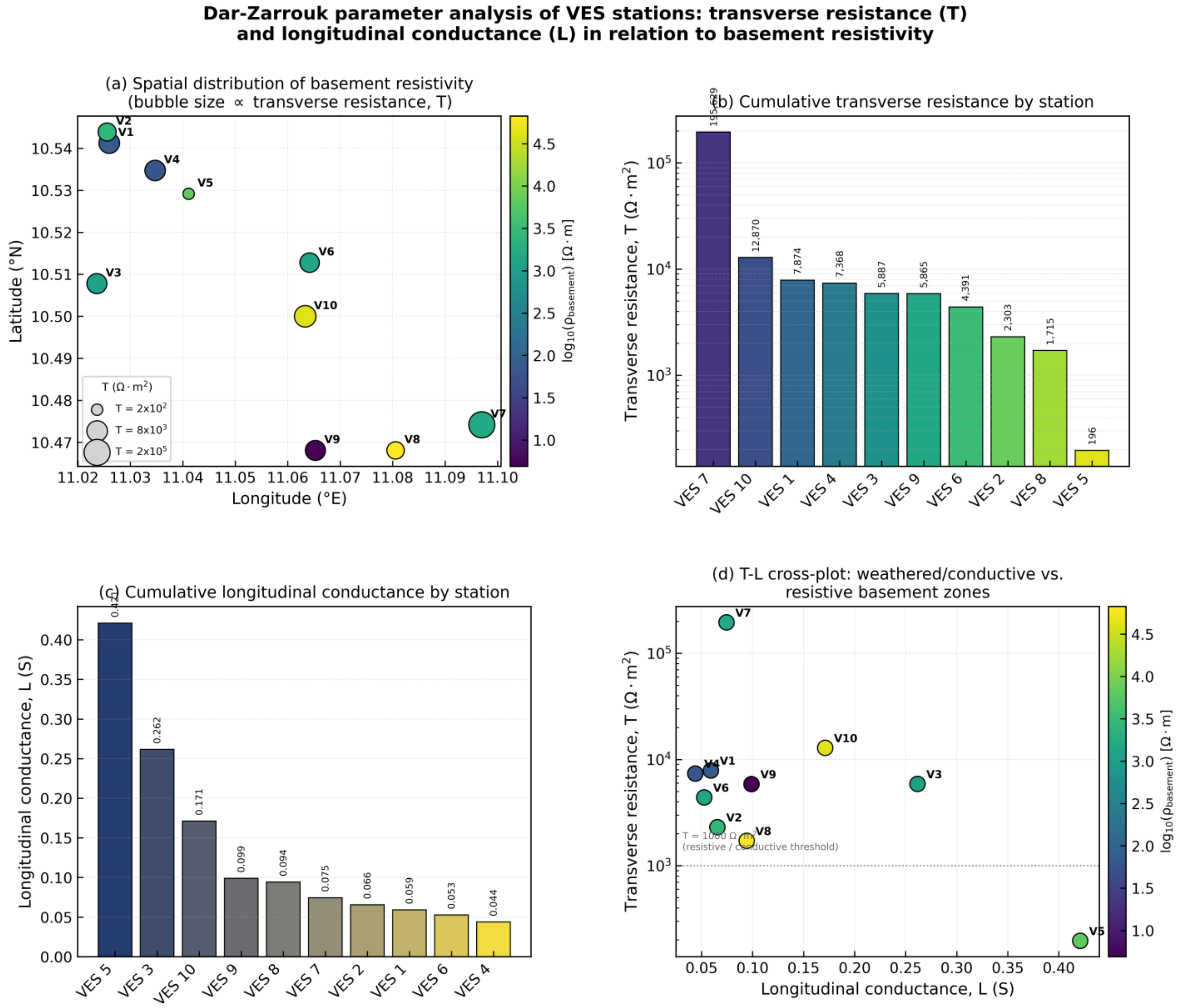

Figure 13: Depth-of-investigation analysis Source: Generated by the authors from the VES inversion models.

5. DISCUSSION

The revised results indicate a heterogeneous sedimentary aquifer system in which sandstone and medium-grained sandstone form the principal inferred groundwater-bearing materials. The resistivity structure is consistent with alternating permeable and finer-grained units, explaining the strong lateral variation between the VES stations. The interpretation is consistent with previous groundwater studies in Gombe and the Upper Benue Trough that identify sandstone and sandy materials as important aquifer hosts.

The Dar-Zarrouk results provide a more defensible basis for comparing stations than the previously reported hydraulic-conductivity and transmissivity values. Transverse resistance varies by more than three orders of magnitude, with the maximum at VES 7 and the minimum at VES 5. This variability reflects differences in resistivity and thickness and indicates that groundwater favourability is not uniform across the study area. High resistivity is not automatically interpreted as basement or dry rock, because dry sandstone, compacted sediments and other resistive materials can produce similar responses; similarly, very low resistivity may indicate clay-rich material or conductive groundwater.

The ten-station dataset is appropriate for reconnaissance-scale interpretation but is small for robust statistical modelling. For this reason, the revised manuscript removes PCA, clustering, regression, spectral/time-series and percolation-threshold analyses that were not adequately documented or validated. Kriging is retained only as an exploratory spatial visualization. No independent borehole or pumping-test dataset is documented in the supplied manuscript, so the revised paper does not claim quantitative validation. The principal limitation is therefore the non-uniqueness of resistivity interpretation and the absence of independent hydraulic confirmation.

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6. CONCLUSION

Geological mapping and ten Schlumberger VES soundings characterize a heterogeneous sedimentary subsurface in the Bojude–Gadam area, principally associated with the Gombe and Kerri-Kerri formations. The VES models contain three to four layers with resistivities from 4.9 to 66,987.3 Ω·m. Sandstone, medium-grained sandstone, silty sand and locally shaly sandstone constitute the principal inferred aquifer-bearing materials, with interpreted aquifer intervals occurring at approximately 7–64 m depth depending on station. Directly calculated transverse resistance ranges from 195.87 to 195,629.32 Ω·m², with VES 7 providing the most favourable geoelectrical target and VES 5 showing the least favourable transverse-resistance response. The revised study does not regard the previously reported hydraulic-conductivity and transmissivity values as independently validated because their empirical equations and constants were not documented. The findings therefore identify promising groundwater targets rather than proving sustainable groundwater abundance.

The principal limitations are the small number of VES stations, the non-uniqueness of resistivity-to-lithology interpretation and the absence of documented pumping-test, borehole-log and water-quality validation. The results provide a reconnaissance-scale basis for borehole targeting, with independent hydrogeological testing required before development decisions are made.

7. RECOMMENDATIONS

Future groundwater development in Bojude and Gadam should prioritize the most favourable VES targets, particularly VES 7, while treating VES 1, 3, 4, 6, 9 and 10 as secondary targets requiring confirmation. Before drilling decisions are finalized, additional VES or two-dimensional/three-dimensional electrical-resistivity tomography should be used to refine lateral and vertical geometry. Borehole drilling should be accompanied by lithological/geophysical logging and pumping tests to determine hydraulic conductivity, transmissivity and sustainable yield directly. Groundwater-quality assessment and seasonal water-level monitoring should also be undertaken to evaluate suitability and long-term availability.

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