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TRESEARCH

HYDROGEOPHYSICAL DELINEATION OF GROUNDWATER POTENTIAL IN DOHO, GOMBE STATE, NIGERIA: INTEGRATION OF GEO-ELECTRICAL RESISTIVITY AND LITHOLOGICAL CONSTRAINTS FOR SUSTAINABLE WATER RESOURCE MANAGEMENT.

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ABSTRACT

The weathered and fractured aquifers in Doho (Gombe State, Nigeria) are heterogeneous, but the spatial variation of aquifer thickness, permeability, and protective capacity is only poorly constrained, which does not allow for reliable borehole siting and sustainable groundwater management. Manual and computer-assisted curve matching was used to interpret 10 vertical electrical soundings (VES) that were acquired to define 3-5 geo-electric layers per site. The layer resistivity and thickness were used to calculate the following petrophysical parameters: Dar Zarrouk parameters (longitudinal conductance, transverse resistance, formation factor, anisotropy ratios, and petrophysically inferred hydraulic conductivity (K) and transmissivity. Geostatistical tools such as descriptive statistics, correlation analysis, and spatial interpolation were used to map the hydrogeological properties and to identify potential drill sites. The interpreted resistivities were between 9.7 and 9,454.8 Ω·m, and the thicknesses of the various layers lay between 0.5 and 114.4 m. The range of inferred K was 3.75 to 322.17 m/day (median ≈66–80 m/day), and the range of point transmissivity was ≈1.8 to 9,665 m2/day with several values outside this range being flagged for validation. The VES02, VES05, and VES06 results indicated very high transverse resistivities (5,828–6,516 $\Omega.m^2$) and moderate–high S values (0.118–1.202 mhos) with good transmissivity and protection capacity while the results of VES07 and VES08 showed very low conductance and negligible aquifer thickness. The integration of VES-derived resistivity, Dar Zarruk parameters, and robust statistics provided a defensible ranking of groundwater prospects, identifying targets appropriate for sustainable borehole development (VES02, VES05, and VES06), and areas of low prospect (VES07 and VES08). These results contribute to SDG 6 (clean water and sanitation) in the sense that informed decisions can be made to explore groundwater resources cost effectively, with awareness of risk, and prioritize groundwater borehole testing and aquifer protection.

KEYWORDS: Groundwater, Hydrogeophysical, Unconfined Aquifers, and Geoelectric Resistivity

HIGHLIGHTS

- Geophysical mapping shows that the unconfined aquifers of Doho contain high storage capacity and transmissibility, resulting in the sustainability of the groundwater in domestic and farm areas.
- Selected resistivity mapping indicates that the properties of aquifers vary greatly throughout the area, and proper pre-drilling geophysical investigations are essential to decreasing dry boreholes.
- The research identifies the promising locations like VES 02, 05, and 06, which have thick, highly transmissive aquifers that can be tapped to provide a dependable water supply, enhancing water security in the region.
- Synthesizing geoelectric data and hydrogeological analysis will give relevant information to policy makers and drilling agencies to maximize the utilization of groundwater and promote socio-economic growth of water-depleted regions.

1. INTRODUCTION

Groundwater is one of the most significant freshwater resources for domestic use, irrigation, and rural development, particularly in semi-arid and drought-prone areas where surface water is not reliable. Development of groundwater in many parts of sub-Saharan Africa today relies heavily on cost-effective geophysical methods that can minimize the risk of dry boreholes and increase the success of borehole siting; the Schlumberger vertical electrical sounding (VES) method is particularly popular and is non-invasive, relatively cheap, and successful in resolving subsurface layering. Groundwater prospecting is especially critical in sedimentary terrains because of the lithologic heterogeneity and structural control that can cause productivity, vulnerability, and transmissivity of the aquifers to change rapidly over short distances. Access to groundwater is a development issue in addition to being a concern of hydrogeology, as it is in the Doho community of Gombe State, where access to water directly influences access to food and health. Considerable efforts have been made demonstrating the capability of VES based interpretation in deducing aquifer geometry and groundwater potential in conjunction with Dar-Zarrouk parameters like longitudinal conductance and transverse resistance. For instance, aquifer parameters in Osogbo and other parts of Nigeria were estimated from Schlumberger sounding, curve matching, and layered-earth inversion; and it was found that estimates of transmissivity and protective capacity could be made by using resistivity and thickness, but interpretation was found to be sensitive to lithologic ambiguity and model non-uniqueness. Moderate to high groundwater potential was generally reported in the weathered or fractured zones, whilst the aquifer in the resistive basement dominated zones had low potential, many studies indicated that the limitation of VES is not sufficient to separate thin layers, and aquifer properties could not be confirmed without borehole validation. The results demonstrate the usefulness of electrical resistivity methods, but they also indicate that site-specific calibration is important due to the possible variability in geologic and saturation conditions that can produce similar resistivities for different materials.

The groundwater occurrence in the Gongola Basin and the Upper Benue Trough is closely related to the stratigraphic features of the Gombe Formation and to the structural and weathering features at the local scale. There is previous work that suggests the formation could receive groundwater locally, especially at the point where the sandstones are weathered or fractured, but that the hydrogeologic behavior of the formation depends on lateral facies change, ferruginization, and the interbedded shale and siltstone horizons that can create both productive and restricting zones. This implies that aquifer potential in the area is not likely to be uniform and that the use of point based assessment methods will be required to identify favourable drilling locations from those where the aquifer potential is low. One of the drawbacks of previous regional studies is that they tended to be generalised and lacked adequate spatial variability for borehole targeting at a community scale.

The analysis of Dar-Zarrouk can help in bridging this gap as it relates the geoelectric layer resistivity and thickness to aquifer protection, transmissivity, and storage potential. Recent Nigerian studies have indicated that a higher transverse resistance may be correlated with thicker and more transmissive aquifer units, and a higher longitudinal conductance may be correlated with better natural protective capacity as a result of the thickness of the clayey overburden or the weathered cover. However, these are all indirect estimates, and may be affected by the presence of outlier values, extreme transmissivity estimates, inversion uncertainty, and by the presence of clay content and salinity, and should therefore be treated carefully and with caution and substantiated by other means. The literature thus reinforces the idea of combined use of the geoelectric layering, hydrogeologic reasoning, and the Dar-Zarrouk parameters, but it also reminds the user that local studies are necessary to create operationally useful groundwater maps by combining all three. The background of this, the present work has been carried out to evaluate the groundwater potential of the Doho and its environs, Kwami Local Government Area, Gombe state, employing the Schlumberger-array VES approach at ten sounding sites. The work includes the interpretation of subsurface resistivity structures, estimation of hydraulic conductivity and transmissivity, calculation of the Dar-Zarrouk parameters, and classification of the aquifer potential throughout the study area. The study is based on a Gombe Formation scenario where lithologic heterogeneity is known to exist and addresses a real problem in rural groundwater exploration in northeastern Nigeria, where drilling uncertainty is a problem for potential borehole sites, and there is an urge to make the most cost-effective use of borehole resources.

Groundwater stands as one of the most vital natural resources, essential for the survival and socio-economic development of communities worldwide. In the semi-arid regions of Northern Nigeria, including Gombe State, the reliance on groundwater has intensified due to the ephemeral nature of surface water bodies and the increasing demand from a growing population (Arabi et al., 2022). Doho, located within the Kwami Local Government Area, is situated in a geologically complex region where water scarcity is a perennial challenge. The study area lies within the Gongola Arm of the Northern Benue Trough, a major rift basin filled with a thick sequence of Cretaceous and Tertiary sedimentary rocks. The hydrogeology of this region is primarily dictated by the Gombe Sandstone and the overlying Kerri-Kerri Formation. The Gombe Sandstone, a Campano-Maastrichtian deposit, consists of a sequence of sandstones, siltstones, and shales. It is generally divided into three members: a lower sandstone-shale member, a middle silty-clay member, and an upper massive sandstone member (Nur and Ayuni 2003). While the upper sandstone member often serves as an aquifer, its productivity is frequently limited by high clay content and ferruginous cementation, which significantly reduces primary porosity and permeability (Abubakar et al., 2011). To mitigate these risks, geoelectrical methods, specifically Vertical Electrical Sounding (VES), have become indispensable tools in hydrogeological exploration. The VES technique utilizes the Schlumberger array to measure the electrical resistivity of subsurface formations at varying depths. Because different earth materials, such as saturated sand, dry sand, clay, and shale, exhibit distinct resistivity values, this method allows geophysicists to "see" the subsurface without digging. By interpreting the resulting geoelectric layers, it is possible to

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delineate the depth to the water table, the thickness of the aquiferous zone, and the potential yield of a site (Alabi et al., 2016). Despite its location within a sedimentary basin, Doho and the surrounding settlements in Kwami L.G.A. suffer from acute water shortages, particularly during the dry season when surface ponds and shallow wells dry up. Many existing boreholes in the area have failed or reached their "end-of-life" prematurely due to a lack of detailed scientific data on the local aquifer system. The problem is compounded by the Gombe Formation's internal complexity, where clay-rich "aquitards" can easily be mistaken for water-bearing layers during drilling if not properly delineated. Without a systematic geoelectrical investigation to map the subsurface resistivity and identify the most productive fracture zones or thick sandstone beds, the community continues to face economic losses from failed water projects and the health risks associated with inadequate water supply.

About one-third of the Bagh region has high groundwater potential, and the map showed good predictive performance with an AUC of 0.796. The approach worked well overall, but 1D geophysical data, expert weighting, and limited uncertainty analysis reduce confidence in the results; 3D imaging and machine learning could improve future mapping. (Basharat et al., 2025). The overburden thickness is generally good, and the resistivity values are low, reflecting generally good groundwater potential except for the extreme eastern part of the area, where the aquifer capacity is moderate to high. The zones of resistivity less than 100 Ωm are associated with higher porosity and thicker overburden, which is conducive to sustainable groundwater development, but the interpretation is reduced by a lack of significance testing and uncertainty analysis. Reliability is limited by the fact that this study is based on 1-D resistivity surveys, which can introduce some lateral non-uniqueness and/or hidden features into the study of the heterogeneity, particularly in basement terrain. The high-resistivity outliers are probably due to local variations in geology and/or measurement error. 3D imaging and integrating hydrogeological data would help increase resolution and reduce uncertainty in future work. (Fajanah 2020). The 33 VES measurements suggest mainly horizontally layered subsurface conditions, with the mean value 1.27 and a range of values from 1.05 to 1.48. The uncertainty of the 1D inversion approach is added to the above 1.4, which is probably due to local heterogeneity, facies changes, or structural features. The pattern suggests anisotropy is an important control on fluid flow and reservoir behavior in the Upper Benue. Higher resolution surveys, borehole information, and 3D resistivity imaging will be needed to improve the validation. (Mohammed et al., 2021).

The Obudu Basement Complex has demonstrated high heterogeneity in both the electrical and hydrogeological properties, having wide variations in terms of transverse resistance, longitudinal conductance, and anisotropy. The empirical groundwater models correlate well with these geophysical parameters, which are also found to be correlated with transmissivity and hydraulic conductivity; thus, they seem to be suitable for a fast, cheap assessment in fractured basement terrains. Limited by the 1D resistivity assumptions, which can be incomplete and introduce uncertainty about lateral variability. Future work should involve using 3D resistivity imaging and borehole-based joint inversion to better estimate the hydraulic properties and to delineate groundwater boundaries, as these outliers may be true geological complexity or may be measurement effects (Ebong et al., 2023). The dataset of 33 VES points in the Niger Delta predominantly shows moderate horizontal anisotropy ratios (λ) around 1.27, indicating a general prevalence of layered stratification with limited extreme deviations. High anisotropy ratios (>1.3) are associated with significant horizontal layering. The observed values suggest that horizontal stratification influences subsurface flow, which is critical for hydrocarbon and groundwater exploration, as it constrains vertical fluid migration pathways. However, several outliers exceeding 1.4 highlight localized geological heterogeneities, potentially reflecting fracture networks or structural features. The reliance on 1D inversion assumptions introduces uncertainties, especially given the complex deltaic environment and limited spatial sampling. Future work should incorporate higher-resolution 3D imaging methods, such as ERT, combined with geological data to better resolve anisotropic zones and improve subsurface characterization for resource management and environmental planning (Mbiimbe et al., 2010). Integrated 2D resistivity imaging, magnetic profiling, and VES effectively delineate fractures and weathered zones controlling groundwater in basement terrains. The strong agreement between VES results and borehole yields (≈96% correlation) confirms their reliability for identifying productive aquifers. While interpretation is limited by VES assumptions, inversion non-uniqueness, and sampling density, observed anomalies indicate subsurface heterogeneity and complex fracture networks. Future integration of 3D imaging with detailed lithological and hydraulic data is recommended to improve subsurface characterization and optimize sustainable groundwater development (Olorunfemi et al., 2019).

The final processed high-resolution aeromagnetic data with the aid of Regional-Residual Separation (RRS), Fast Fourier Transform (FFT) spectral processing, Analytic Signal, and Lineament extraction, well delineated subsurface structures that control groundwater and mineralization in the study area of Jada, northeastern Nigeria. The predominant NE-SW trend of the lineaments is indicative of tectonic control of structurally controlled aquifers and mineralized zones. The magnetic source depths vary from 0.530–1.960 km, with the shallow source depth (0.423–0.622 km) indicating the presence of good groundwater and mineral exploration targets. The integrated depth estimation and lineament analysis is an effective method for the groundwater assessment and mineral exploration in crystalline basement terrains (Ezikiel et al., 2026). A significant spatial variability in groundwater quality across Kano is influenced by both natural hydrogeological processes and anthropogenic activities. Integrated multivariate hydrochemical analyses (PCA, correlation, Piper diagrams, GIS, and geostatistical methods) effectively identified geochemical processes and contamination hotspots. Groundwater quality varied widely, with TDS ranging from 0–4,917 mg/L and pH from 5.6–8.7. The combined statistical and geospatial approach provides a robust framework for groundwater quality assessment and supports sustainable groundwater resource management. (Mohammed et al., 2026).

Quasi-3D pole–pole and dipole inversions, performed over a 17-year repeat ERT campaign at BCCT, document shallow increases at depth, largely interpreted as surface/saturation changes, and deeper increases at the leading edge, which are primarily attributed to the recharge and its associated downward flow of ions (notably nitrate), with some anthropogenic changes; the study highlights the need for improving ERT resolution for deeper leading edge increases and calls for integrating time-lapse ERT with transport modeling to better constrain the vadose zone fluxes (Johnson and Wellman 2023). They propose new reduction coefficients for FAO-56 (based on SWC) and demonstrate through lab calibration and time-lapse ERT on a maize plot field, that spatially resolved Kr and Ks (and cumulative ET from ΔSWC) can be derived, and show a good correlation of spatial patterns obtained from TDR. They discuss limitations imposed by the data (heterogeneity, transferability from calibration, smoothing of inversion, temporal sampling) and recommend more dense ERT surveys for ET estimation (Chou et al., 2021). In Gwalior, the vertical electrical sounding (VES) technique was employed to map sub surface geo-electrical layers and a major water bearing layer was located at a depth of 30-45 m below the surface. The shallow, alluvial/weathered part of the aquifer was found to be relatively suitable for artificial recharge while the hard, compact shale was found to be a poor aquifer. The information can be used to enhance the management of water in the region and the overlying unsaturated zone may be suitable for artificial recharge (Raj 2017). Vertical Electrical Sounding (VES) for determining the hydrogeological conditions of the subsurface in an urban area characterized by limited groundwater availability. They found 3-4 separate geoelectric layers, one of which is the main water-bearing layer at a depth of 30-45 m. The study determined that the shallow, alluvial/weathered zone is favorable for artificial recharge while the hard, shale zone is not. The technique used included Schlumberger resistivity survey, complemented with litholog correlation and data interpretation using partial curve matching and WINSEV 6 software. The study overcomes the limitations of site-specific aquifer parameters and offers insights for groundwater management in environments similar to that of the study area. The results can be directly applied to research related to aquifer characterization, groundwater recharge planning, and sustainable groundwater development in semi-arid or hard rock environments (Farid and Bakhsh 2015). LS-SVM and PC-FIS machine learning models to forecast groundwater quality indices in fractured aquifers within an arid region in Tunisia. The models exhibited high accuracy, with R^2 values above 0.90, indicating their robustness for groundwater quality assessment. Their approach effectively addresses the limitations of conventional, laborious methods, providing a cost-effective alternative for predicting water quality parameters critical for sustainable irrigation (Mohammed at al., 2023).

Understanding the hydrogeological properties of the aquifer system in the Malam Sidi area is essential for assessing its potential to store and transmit groundwater. Hydraulic conductivity, porosity, and transmissivity are key properties that influence how water moves through the subsurface. These properties vary based on lithology, grain size, and geological structures.

2. STUDY AREA AND BACKGROUND

Doho is a prominent settlement located within the Kwami Local Government Area (LGA) of Gombe State, North-Eastern Nigeria. Geographically, the area falls within the Sudan Savanna ecological zone. The environs of Doho typically refer to the surrounding rural hinterlands, including neighboring settlements such as Malleri and Jurara, which share similar geomorphological and anthropogenic characteristics. This report outlines the physical setting, geological attributes, and land use patterns that define the region (Fig 1).

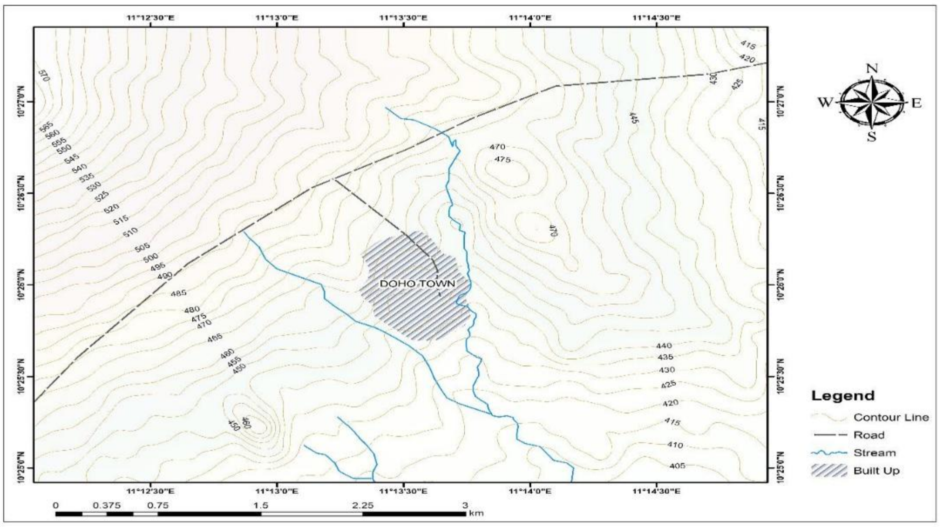

Figure 1: Topographical map of the study area

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The study area of Doho, situated within the Kwami Local Government Area of Gombe State, lies geologically within the Gongola Sub-basin of the Upper Benue Trough. The locality is primarily underlain by the Gombe Formation, a Maastrichtian-aged sedimentary sequence that represents the final phase of Cretaceous sedimentation in this region. This formation is characterized by a lithology of fine-to-medium grained, often ferruginized Sandstones intercalated with Siltstones and Shales. These sediments reflect a transitional depositional environment, shifting from continental fluvial systems to marginal marine conditions. Structurally, the area is influenced by the Gombe Inlier, where sedimentary beds typically exhibit gentle dips, although localized fracturing and folding are common due to the proximity of major regional fault lines. From a hydrogeological perspective, the porous sandstone units within the Gombe Formation serve as the primary aquifers for the Doho community, though the groundwater often exhibits high iron concentrations consistent with the ferruginous nature of the host rock (Fig 2).

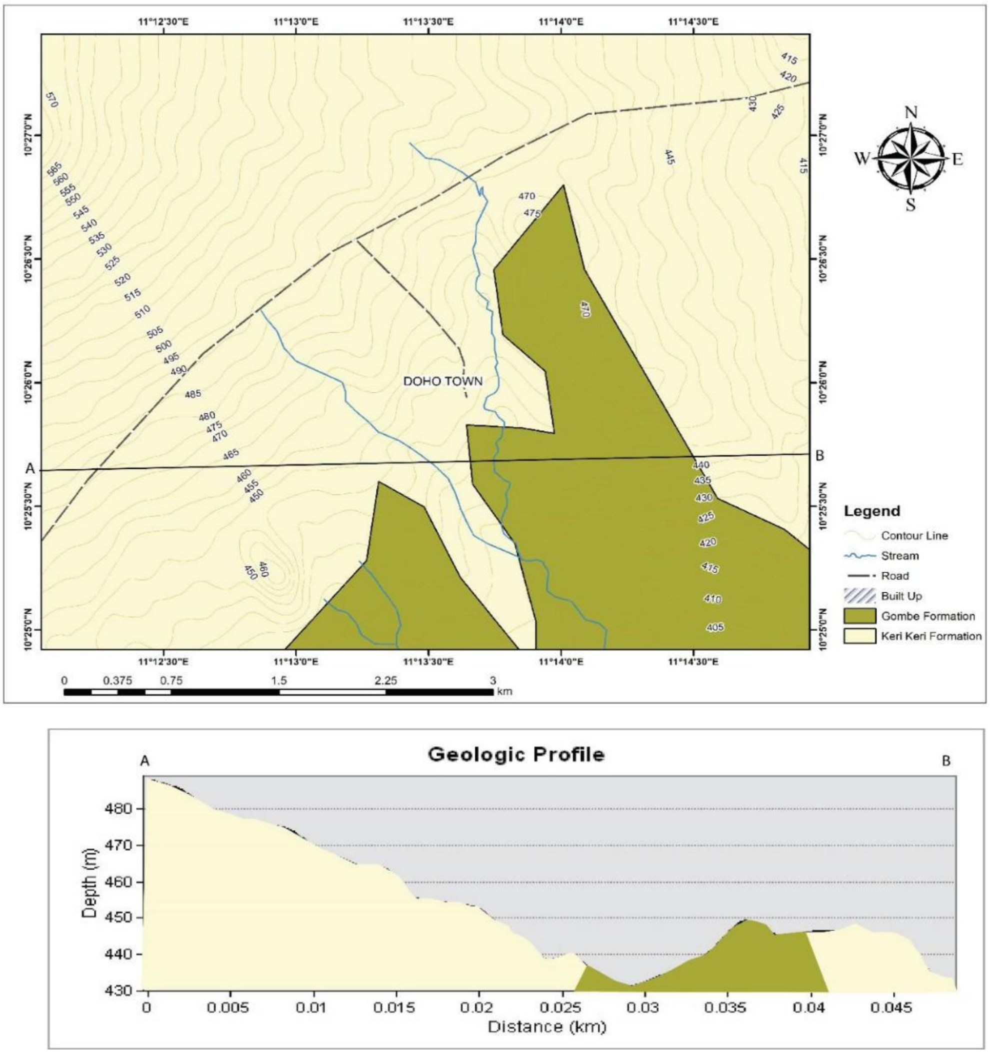

Figure 2: Geological map of the study area

This research will serve the main objective of having a complete picture of the subsurface geology and hydrogeology of the Doho region, through integration of surface geological mapping, Vertical Electrical Sounding (VES) surveys, and analysis of geophysical data. The detailed aims will be to map the land geological units and structural features, conduct VES surveys to sample the subsurface geoelectric layers, define the thickness and resistivity of the potential aquifer systems, and create geoelectric sections and maps to define the most promising places to develop sustainable boreholes, and eventually guide exploration and management of groundwater resources in the region.

3. DATA

3.1 GEO-ELECTRIC DATA ACQUISITION AND LAYER PARAMETERS

Delineated subsurface hydrogeological units using vertical electrical sounding (VES), identifying 3–5 geo-electric layers with resistivity ranging from 9.7–9,454.8 Ωm and thicknesses from 0.5–114.4 m, revealing heterogeneous aquifer characteristics across the study area. Ten (10) VES stations were surveyed using Schlumberger array configuration, with geo-electric parameters (resistivity, thickness, curve type) interpreted through manual and computer-assisted curve matching to classify layer sequences (KH, QQ, KQ, HAK, HK, AA types Table 1).

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Table 1: Summary of the geo-electric parameters, inferred Lithology, and curve models for VES points

VES No	Coordinate	Layers No	Resistivity (Ω)	Thickness (m)	CurveType
VES 01	10°26'27"N 11°13'25"E	1	9.7	1.1	KH
		2	50.0	7.2	
		3	25.3	23.9	
		4	88.8	----	
VES 02	10°26'59"N 11°12'57"E	1	15.2	1.4	KH
		2	614.1	6.6	
		3	72.8	24.1	
		4	539.8	-----	
VES 03	10°25'59"N 11°13'33"E	1	557.3	2.2	QQ
		2	270.8	0.6	
		3	21.9	0.8	
		4	15.7	-----	
VES 04	10°25'23"N 11°13'33"E	1	471.3	1.7	KQ
		2	826.9	5.0	
		3	300.2	2.9	
		4	140.0	----	
VES 05	10°26'07"N 11°13'53"E	1	143.2	0.9	KH
		2	772.9	3.1	
		3	181.8	19.6	
		4	330.5	----	
VES 06	10°25'50"N 11°12'71"E	1	13.5	3.6	HAK
		2	9.7	3.3	
		3	37.7	3.5	
		4	237.9	26.5	
		5	87.9	----	
VES 07	10°26'91"N 11°14'02"E	1	580.4	8.6	HK
		2	392.4	12.6	
		3	9454.8	114.4	
		4	454.7	----	
VES 08	10°25'50"N 11°13'31"E	1	51.7	1.2	KH
		2	533.1	9.4	
		3	526.3	24.7	
		4	911.1	----	
VES 09	10°26'05"N 11°13'40"E	1	193.3	0.6	KH
		2	2284.6	1.7	
		3	181.1	7.6	
		4	9175.8	----	
VES 10	10°26'11"N 11°13'22"E	1	22.3	0.5	AA
		2	138.4	20.6	
		3	586.4	11.0	
		4	3822.0	----	

3.2 COMPUTATION OF DAR-ZARROUK PARAMETERS

Dar-Zarrouk parameters were computed from the layer resistivity–thickness pairs at each VES to characterize aquifer protective capacity and transmissive potential. Total longitudinal conductance and total transverse resistance were calculated for each sounding using standard layer-sum formulations:

3.2.1 TRANSVERSE RESISTANCE

Transverse resistance, also known as lateral or transverse electrical resistance, refers to the opposition to electrical current flow perpendicular to the primary direction of conduction within a material or device. It is a critical parameter in the study of anisotropic materials and layered structures, where electrical conductivity varies with direction. Transverse resistance is influenced by the material's intrinsic properties, such as resistivity and geometry, as well as external factors like temperature

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and magnetic fields. Accurate measurement of transverse resistance provides insights into the anisotropic behavior of materials, which is essential in designing electronic devices, sensors, and understanding their electrical characteristics. Its SI unit is the ohm (Ω).

$$T_{r} = K_{z} \times b \quad (1)$$

Where

T_r = Transverse resistance

K_z = Resistivity of the layer (Ω·m) [Note to authors: the equation object above still shows the symbol "Kz" — please update it in Word to "ρ" (resistivity) to match this corrected definition; transverse resistance is the sum of resistivity × thickness, not hydraulic conductivity × thickness]

b = Thickness of the formation (L)

3.2.2 LONGITUDINAL CONDUCTANCE

Longitudinal Conductance refers to the ability of a material or a device to conduct electric current along its primary axis or length. It is an important parameter in electrical and electronic systems, especially in the analysis of layered or segmented structures, where it indicates how effectively current can flow through the material in the direction of its length. Longitudinal conductance depends on the material's conductivity, geometry, and the presence of any conductive pathways or interfaces. Higher longitudinal conductance implies better electrical connectivity along the length, which is crucial in applications such as cables, electrodes, and conductive coatings. Its SI unit is Siemens (S).

$$S = \frac{b}{\rho} \quad (2)$$

where

S The Longitudinal conductance

b The thickness of the layer (m)

ρ Resistivity of the layer (Ω.m)

3.3 PETROPHYSICAL PARAMETERS: FORMATION FACTOR AND ANISOTROPY

3.3.1 FORMATION FACTOR

The formation factor is a dimensionless parameter that characterizes the ease with which a fluid can flow through a porous medium, reflecting the relationship between the apparent electrical conductivity of the saturated rock and that of the pore fluid. It is an important parameter in petrophysics and hydrogeology, used to estimate porosity and permeability from electrical measurements. The formation factor depends on the pore structure, mineral composition, and connectivity within the rock matrix.

$$F = \frac{\rho_{rock}}{\rho_{water}} \quad (3)$$

where

F = Formation factor (dimensionless)

ρ_{rock} Electrical resistivity of saturated rock (Ω.m)

ρ_{water} Electrical resistivity of formation water (Ω.m)

3.3.2 ANISOTROPY

Anisotropy is the property of a material or medium where its physical characteristics, such as electrical conductivity, permeability, or strength, vary depending on the direction in which they are measured.

$$A_r = \frac{K_{max}}{K_{min}} \quad (4)$$

where

A_r Anisotropy

K_{max} = Hydraulic conductivity in the direction of maximum flow (m/s)

K_{min} = Hydraulic conductivity in the direction of minimum flow (m/s)

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3.4 HYDRAULIC CONDUCTIVITY AND TRANSMISSIVITY ESTIMATION

3.4.1 HYDRAULIC CONDUCTIVITY

Hydraulic conductivity is a property of a porous medium that measures its ability to transmit water under a hydraulic gradient, typically expressed in units of length per time (e.g., m/day).

$$K = \frac{Q \, x \, L}{A \, x \, \Delta h} \tag{5}$$

where

K = Hydraulic conductivity (m/s)

Q = Volumetric flow rate (m^3/s)

L = Length of the specimen or Length of flow path (m)

A = Cross-sectional area through which flow occurs (m^2)

Δh = Hydraulic head difference across specimen (m)

3.4.2 TRANSMISSIVITY ESTIMATION

Transmissivity is the rate at which groundwater flows through a unit width of an aquifer under a unit hydraulic gradient. It is the product of the aquifer's hydraulic conductivity and its thickness.

$$T = K \, x \, b \tag{6}$$

T = Transmissivity (m^2/s)

K = Hydraulic conductivity (m/s)

b = Thickness of the aquifer or saturated zone (m)

Table 2: Hydraulic Conductivity and Transmissivity

S/No	VES	HYDRAULIC CONDUCTIVITY (m/day)	TRANSMISSIVITY (m^2/day)
1	VES1	8.82	9.70
2	VES2	10.86	15.20
3	VES3	253.32	577.33
4	VES4	277.23	471.20
5	VES5	158.89	143.00
6	VES6	3.75	13.50
7	VES7	67.44	579.98
8	VES8	43.08	51.70
9	VES9	322.17	193.30
10	VES10	44.6	22.30

3.5 SPATIAL AND STATISTICAL ANALYSIS

Descriptive statistics (median, interquartile range, skewness) were computed for hydraulic conductivity, transmissivity, anisotropy, and Dar-Zarrouk parameters to assess central tendency, dispersion, and outliers. Spatial interpolation (e.g. inverse distance weighting or geostatistical methods, as applicable) was applied to map the distribution of key parameters (hydraulic conductivity, transmissivity, longitudinal conductance, transverse resistance) and to visualize lateral variability in groundwater potential across the survey area. Correlation analysis was undertaken between geoelectric-derived parameters (e.g. resistivity, S, T, and anisotropy) and hydrogeological indices (K, T,and inferred groundwater potential) to identify statistically meaningful relationships.

4. METHODS

The Schlumberger array methodology would use a special electrode arrangement to perform vertical electrical sounding, in which the current electrodes (A and B) are separated by significantly greater distances than the potential electrodes (M and N), and in which current is introduced into the ground by electrodes (A and B) and the potential difference is measured by electrodes (M and N). Normally, during field work, the current electrodes are continually spaced out as the potential electrodes are held relatively constant, enabling probing of various depths into the subsurface. The Schlumberger array is similar in form to the Wenner array, except that the potential electrodes have a fixed distance a and the current electrodes have a greater distance nai, with n being a factor of the target depth and size. The benefits of this arrangement include high signal-to-noise ratio, good horizontal layer resolution, and improved depth sensitivity (Fig 3).

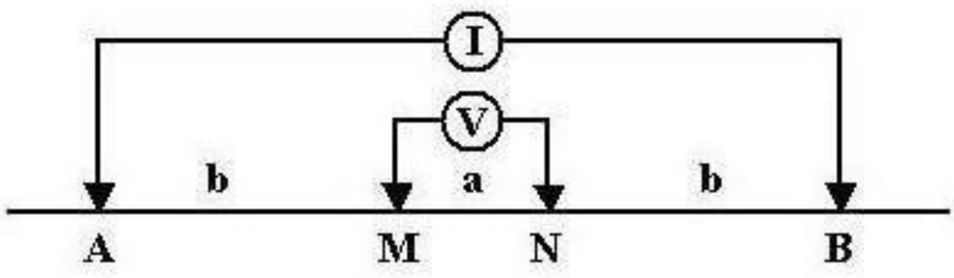

Figure 3: Schlumberger Array

The procedure entailed determining ten vertical electrical sounding (VES) points at various positions, and potential electrodes were attached to a resistivity meter. Proposed Schlumberger configuration attached the electrodes on the arrangement, and the electrode space (MN) was half of AB, which was slowly extended to a limit of 320 meters per point. The resistivity meter was adjusted to a cycle of two to enable the current to go through the ground twice, maximizing time and power saving. The current was applied through the current electrode, and the potential difference across the potential electrodes was measured. The meter automatically determined resistance (R) in ohms-meters, and at the end of each run, the meter was switched off, and the distance between electrodes was increased to make the next run. The apparent resistivity was calculated using the data at different electrode separations to give subsurface resistivity profiles at each VES point.

5. RESULTS

5.1 HYDRAULIC CONDUCTIVITY

Hydraulic conductivity ranges widely between the lowest value of 3.75 at VES6 and the highest of 322.17 at VES9; the median is between 66 and 80, which is an area of high heterogeneity throughout the survey area. Notably, three sites (VES3, VES4, VES9) have anomalously high conductivities, suggesting high permeability and coarse grained zones, and VES6 has an unusually low conductivity, which may indicate low permeability or confining zones. The rest are between about 8.8 and 159, with a large range and skewness suggesting that they are not Gaussian distributed, and therefore it is recommended to use median and interquartile ranges rather than mean and standard deviation. There are several sources of uncertainty, such as petrophysical assumptions, lithological variability, clay content, salinity effects, and measurement limitations that can introduce a bias into the resistivity-to-hydraulic conductivity conversion. These estimates need to be confirmed through cross-validation with independent hydrogeological tests and lithological data. The high K values in the high K areas suggest strong flow pathways, and the low K at VES6 suggests possible barriers, highlighting the significance of spatial heterogeneity and anisotropy in aquifer modelling. The use of probabilistic inversion techniques, combining multi-physics data, and targeted field validation at outlier sites is recommended to enhance the reliability of hydrogeological parameters used in regional flow assessments that better represent and connect the hydrogeological parameters to the flow conditions (Table 2 and Fig 4).

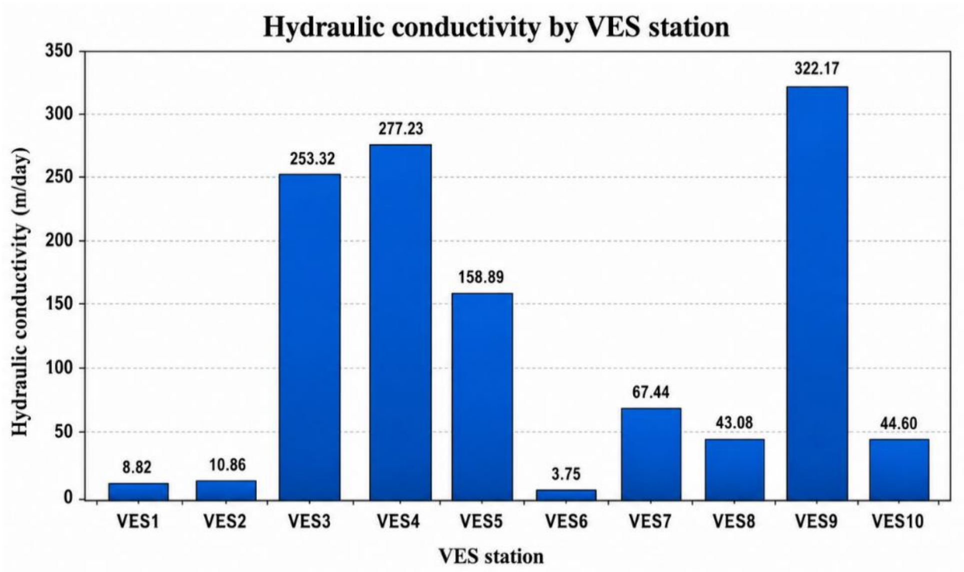

Figure 4: Hydraulic conductivity of the study area

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5.2 TRANSMISSIVITY

The estimated transmissivity for the ten sites (VES1 to VES10) based on VES data shows significant spatial variation, ranging from 1.76 to 9,665.10 m²/day, and with some extreme outliers that need careful review of the methodology used. The data is very skewed and non-Gaussian, and so the median and IQR are better measures of central tendency than the mean and SD. Statistical analysis, such as log transformations and outlier detection, identified VES3, VES4, VES6, and VES9 as possible outliers that may need independent validation. Uncertainties in hydraulic conductivity, saturated thickness, and inversion non-uniqueness are amongst the major sources of error and can lead to large bias in the calculation of transmissivity. For such evidently extreme values, it is crucial to conduct cross-validation using aquifer tests, borehole lithology, and regional data to ensure plausibility. These point estimates are not suitable for use in regional models or well placement due to the diversity and possible inaccuracies. Propagation of uncertainties using probabilistic approaches, incorporation of several geophysical datasets, incorporation of borehole information to better constrain saturated thickness, and focus on field validation at outlier sites to improve the reliability of transmissivity estimation derived from VES interpretations are recommended(Table 2 and Fig 5).

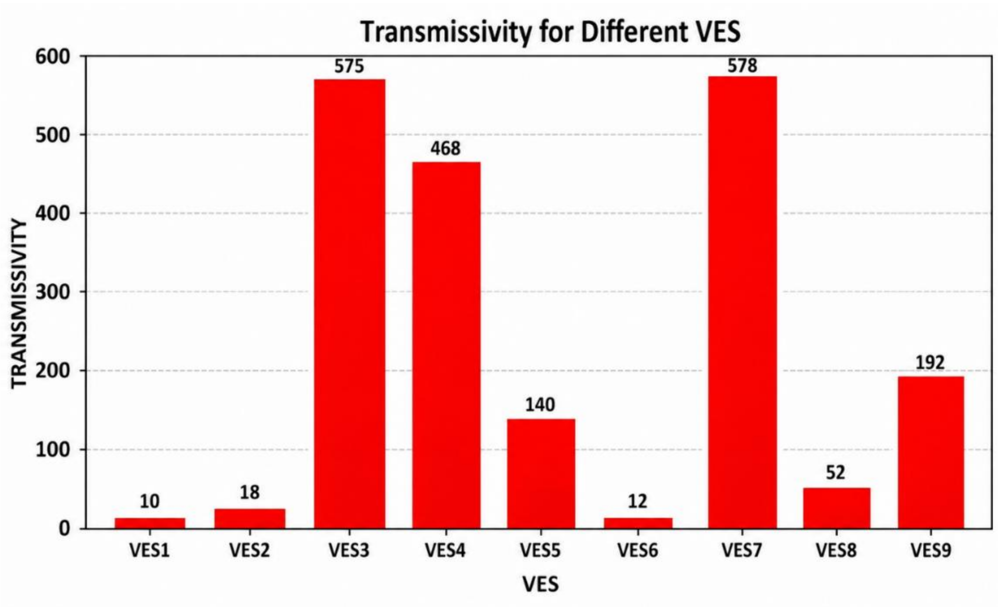
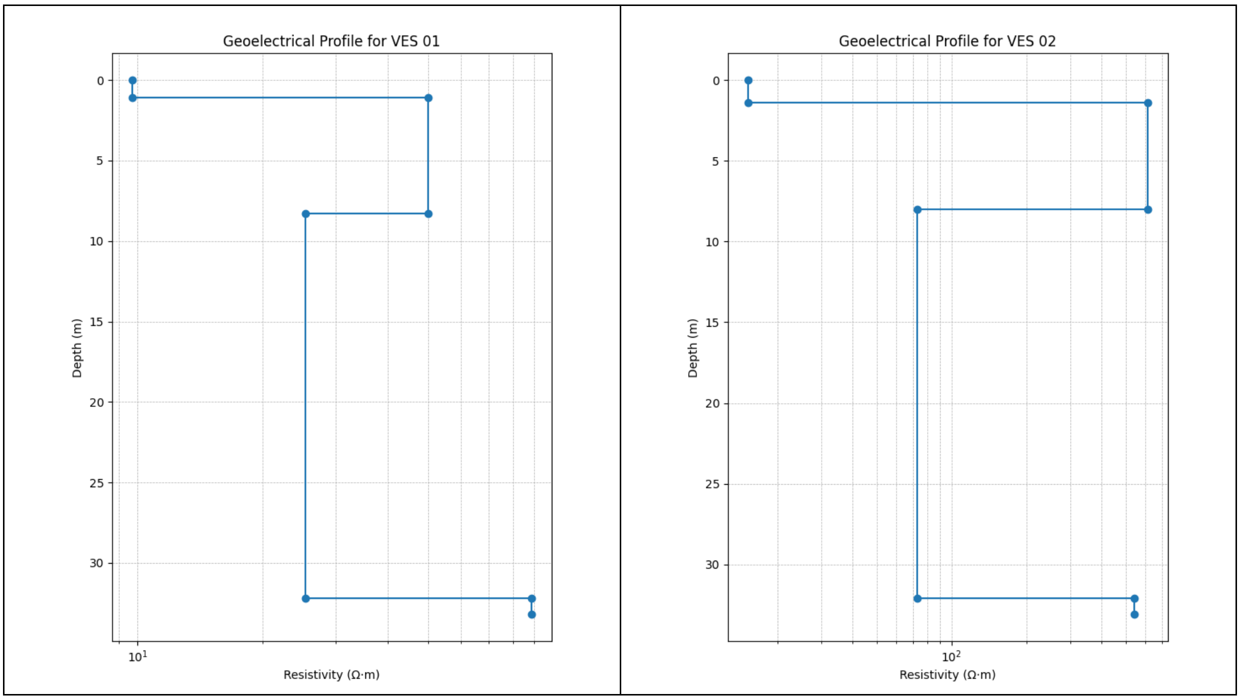


Figure 5: Transmissivity of the study area



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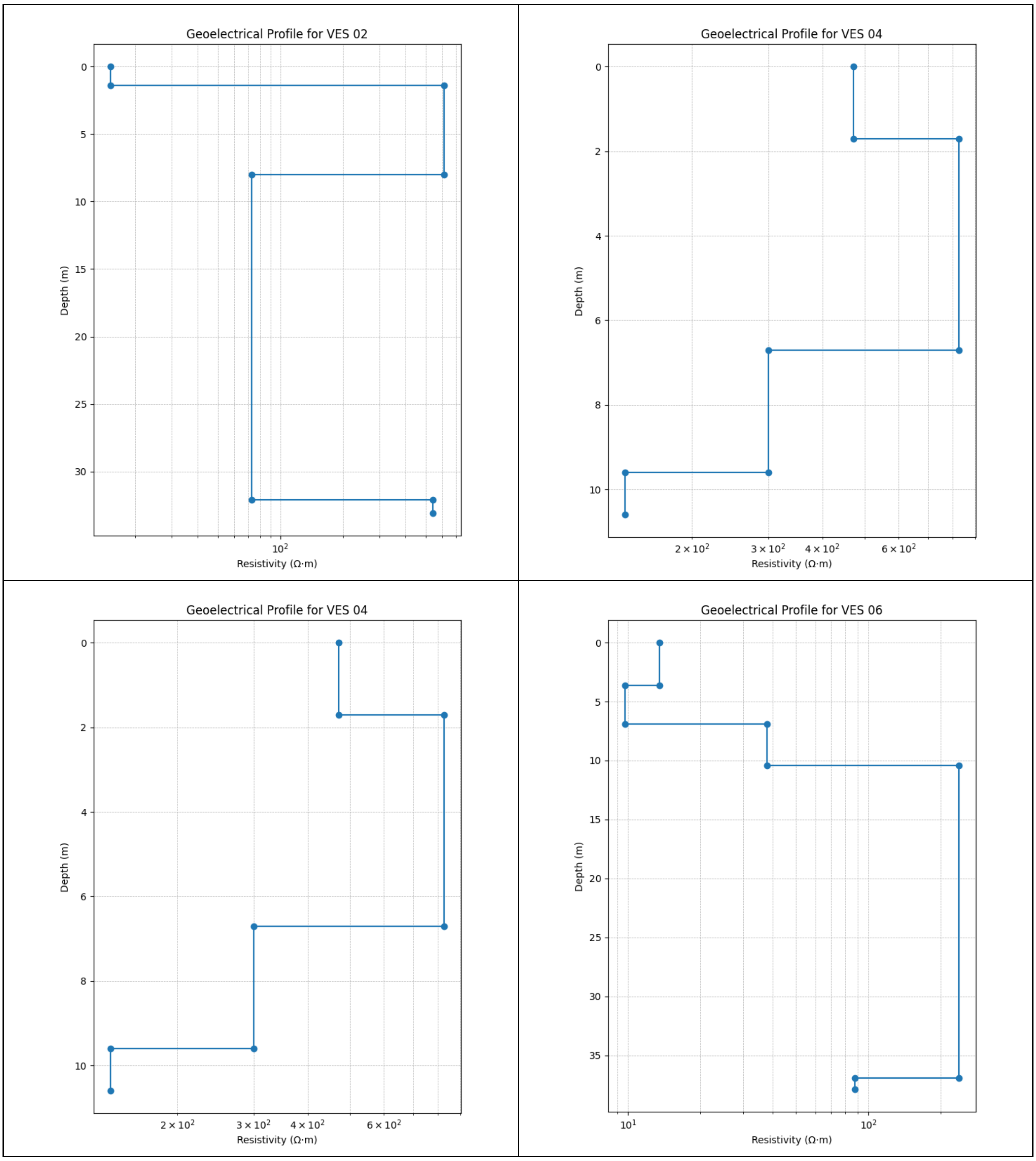

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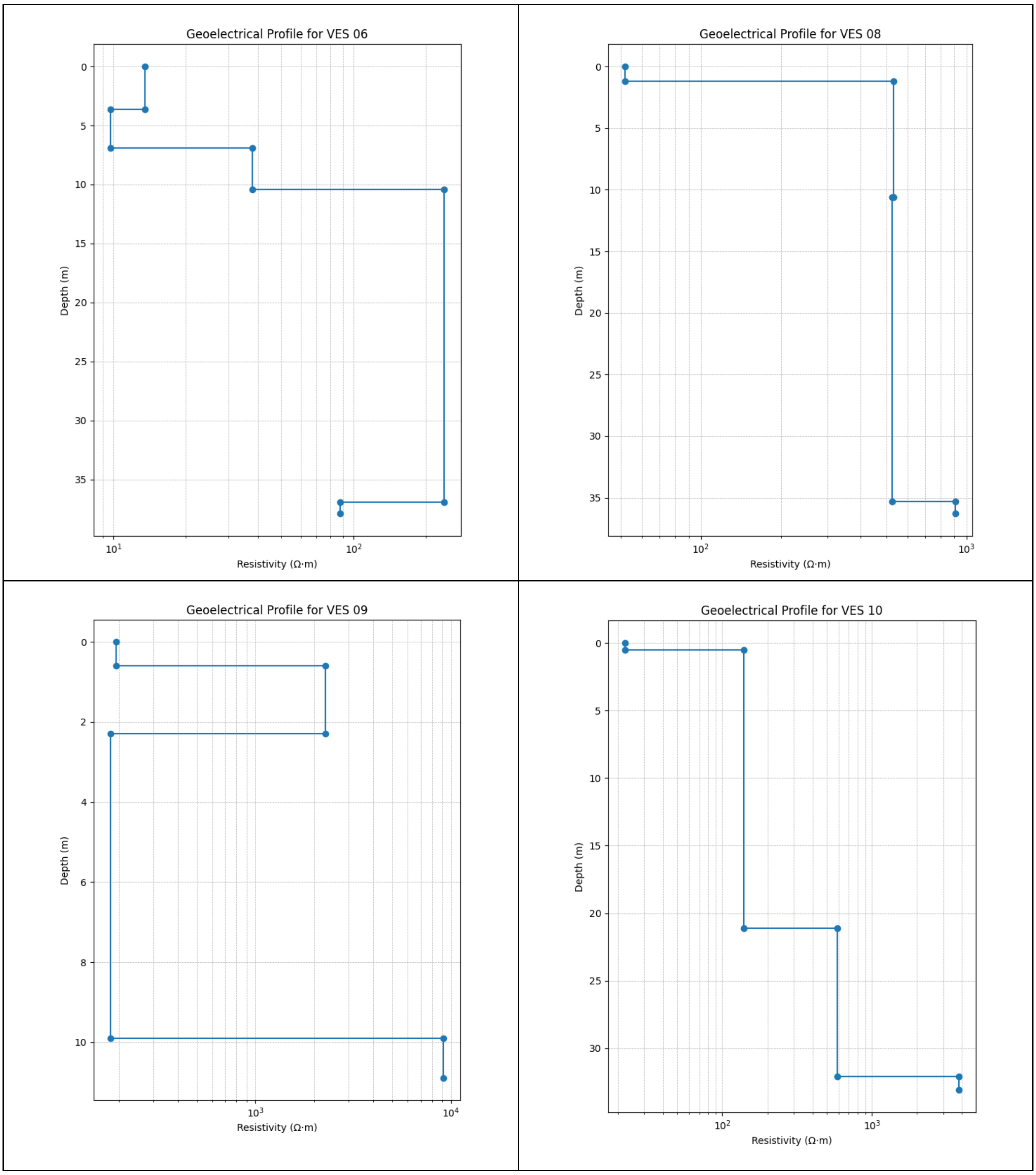

Figure 6: Resistivity profiles of the VES

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TRESEARCH

5.3 DAR-ZARROUK PARAMETERS

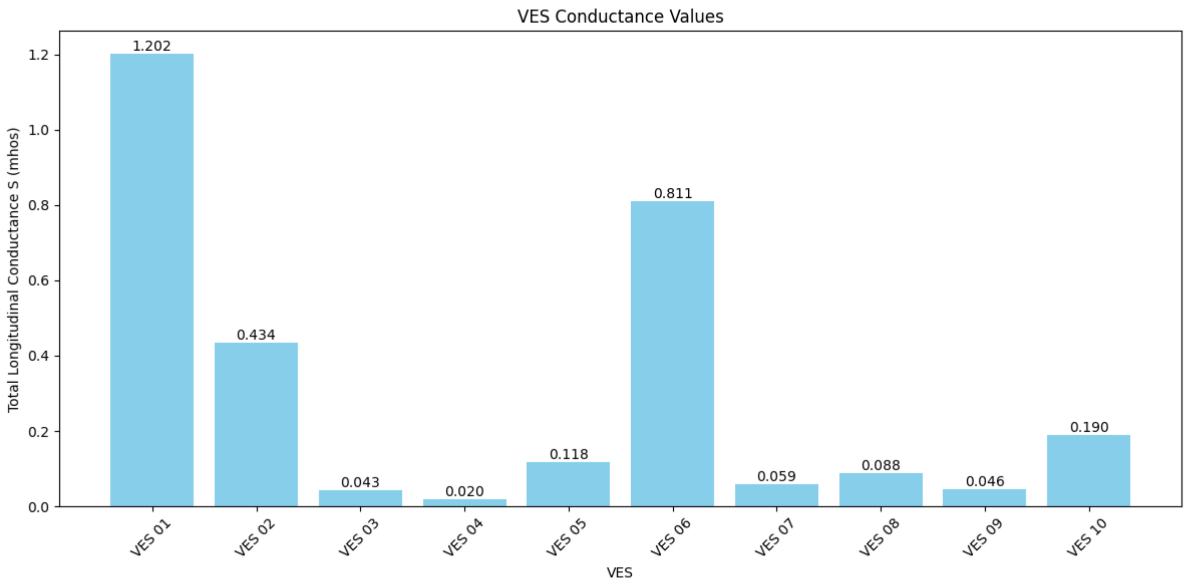
Dar-Zarrouk parameters were computed to further assess aquifer protective capacity and transmissivity.

Table 3: Dar-Zarrouk Parameters for All VES Locations

VES	No of Layers	Aquifer Unit	Total Longitudinal Conductance S (mhos)	Total Transverse Resistance T (Ωm^2)	Groundwater Potential
VES 01	Layer 3	Saturated clay shale	1.202	975.54	Moderate
VES 02	Layer 3	Weathered fractured zone	0.434	5828.42	Moderate to High
VES 03	Layer 3&4	Saturated clay shale	0.043	1406.06	Low
VES 04	Layer 4	Saturated shale weathered basement	0.020	5986.29	Moderate
VES 05	Layer 3	Weathered fractured sandstone	0.118	6088.15	Moderate
VES 06	Layer 3&4	Weathered fractured basement	0.811	6516.91	High
VES 07	Layer 2	Sandstone	0.059	10,924.76	Very Low
VES 08	Layer 3	Sandstone	0.088	18,082.79	Very Low
VES 09	Layer 3	Weathered fractured sandstone	0.046	5376.16	Moderate
VES 10	Layer 2	Sandstone	0.190	9312.59	Low

The Dar-Zarrouk parameters reveal marked spatial variability in both protective capacity and transmissivity potential across the survey area (Table 3, Fig. 7). Total longitudinal conductance ranges from very low to high values, reflecting variations in overburden thickness, clay content, and degree of weathering. High conductance at VES 1, 2, and 6 indicates thick, conductive overburden with good protective capacity against surface contamination, making these locales favourable for groundwater development. In contrast, VES 3, 4, 7, and 8 show low conductance, implying weak protective capacity and higher vulnerability to contamination, particularly a resistive basement dominates (e.g., VES 7 and 8).

Transverse resistance values identify VES 2, 5, 6, and 9 as locations with more favourable combinations of aquifer thickness and transmissivity; among these, VES 6 stands out due to both high transverse resistance and high protective capacity. Overall, groundwater potential is generally moderate at the scale of the study area, but with distinct zones of high potential (e.g., VES 2, 5, 6) and very low potential in areas largely underlain by resistive basement rocks (Table 3, Fig. 7).



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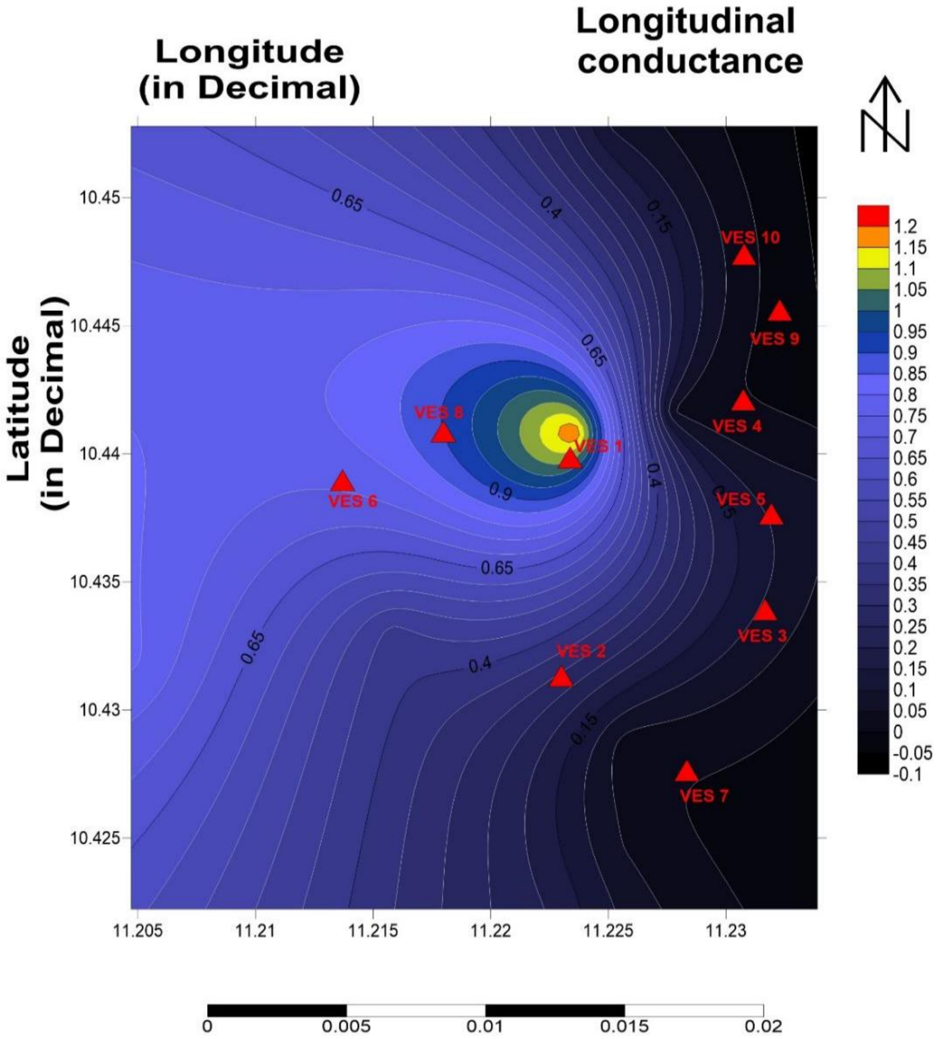
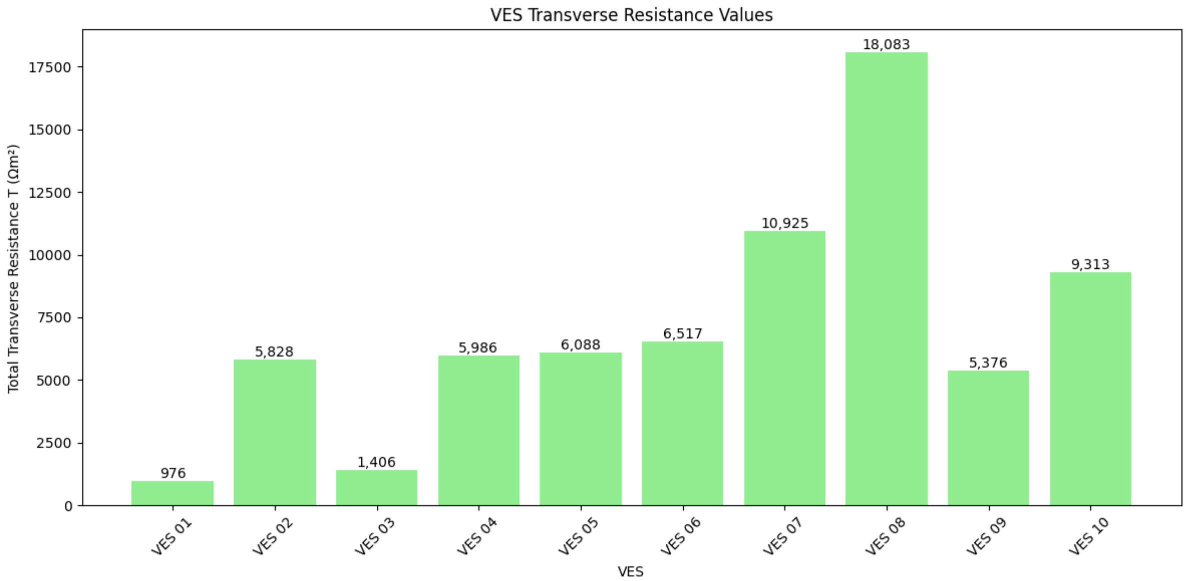


(a)



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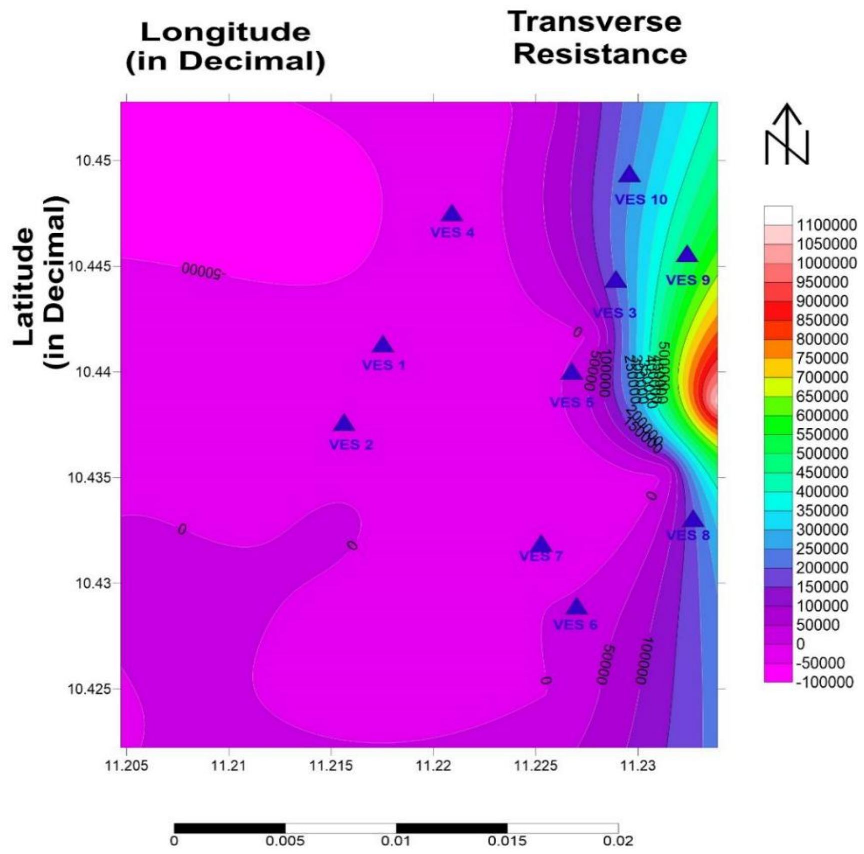

(b)

Figure 7: (a) Longitudinal Conductance (b) transverse Resistance

5.4 GROUNDWATER POTENTIAL EVALUATION

The VES curve characteristics, the parameters of the geoelectric layers, and the indices of Dar Zarrouk revealed a clear spatial discrimination in the groundwater potential (Table 4, Figs. 8–9). VES 1, 5 and 6 are good examples of sites that have deeper weathered and fractured aquifers, moderate resistivities, high transverse resistance, and high longitudinal conductance, which result in good storage, transmissivity, and protective capacity and make them highly promising for sustainable groundwater abstraction. On the other hand, VES 7 and 8, having very high resistivities and low conductance values of the layers overlying the massive basement and/or dry fractured layers, show very low groundwater potential.

Sites with a thin or low-permeability aquifer (such as VES 3, 4, 9 and 10) have low to moderate potential and may be more sensitive to contamination or changes in water levels. Overall, the data suggest that VES 2, 5, and 6 are most promising areas for groundwater development, with the VES 7 and 8 areas being low priority. These results highlight the importance of using both geophysical and petrophysical data for the best groundwater exploration in a heterogeneous basement and deltaic areas (Table 4 and Figs). 8–9).

Table 4: Comparative Hydrogeological Characteristics of All VES Locations

VES Location	Curve Type	Layer	Aquifer Depth (m)	Aquifer Thickness (m)	Groundwater Potential
VES 01	KH	Layer 3	~8–32	>23	Moderate–High
VES 02	KH	Layer 3	~10–34	>24	High
VES 03	QQ	Layer 3–4	>5	Thin	Low
VES 04	KQ	Layer 4	>10	Moderate	Moderate
VES 05	KH	Layer 3	~6–26	>19	High
VES 06	HAK	Layer 2–3	~3–30	>26	High
VES 07	HK	Layer 2	—	Negligible	Very Low
VES 08	KH	Layer 3	—	Negligible	Low
VES 09	KH	Layer 3	~8–16	Thin	Low–Moderate
VES 10	AA	Layer 2	~5–25	Moderate	Moderate

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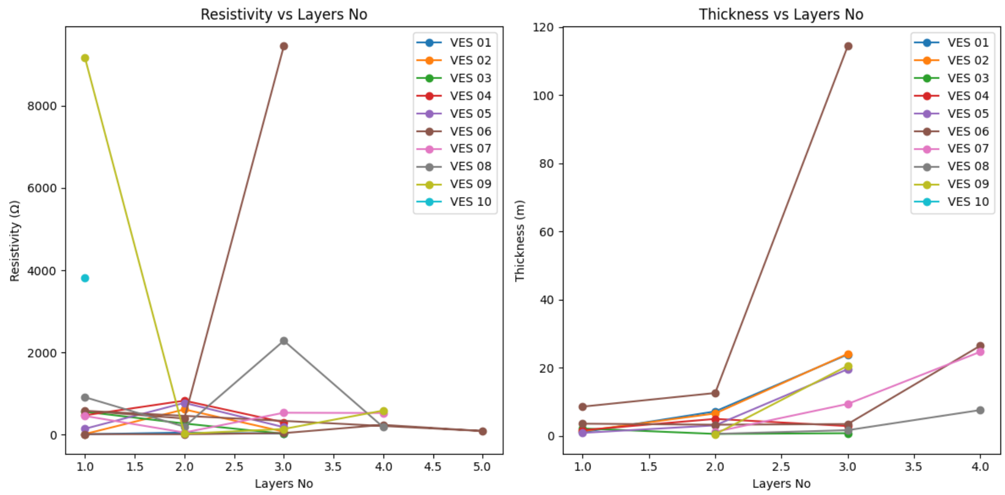

Figure 8: Variation in Resistivity

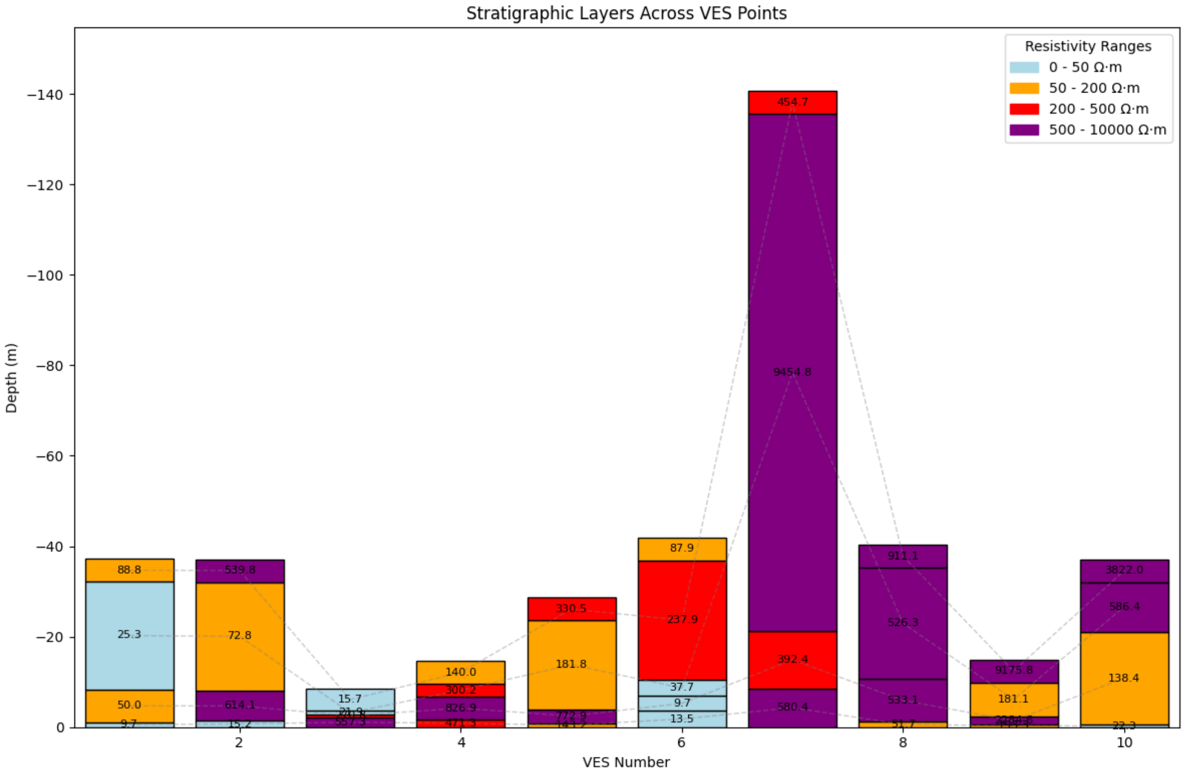

Figure 9: Geo-electrical stratigraphic section

5.5 DESCRIPTIVE STATISTICS AND ANISOTROPY

The horizontal anisotropy ratio of the VES points is around 1.27, with most values remaining moderate and very few above 1.4. This pattern suggests a controlled layering of the subsurface with fewer structurally disturbed/fractured zones that have higher anisotropy values. Higher resolution imaging is required within these outlier zones of fluid flow influence to better characterize their geometry and connectivity in order to have a better understanding of fluid flow pathways within these zones.

The overall distribution is consistent with a conceptual model where the horizontal stratification controls groundwater flow at a primary level, which is controlled by local anisotropic domains on top of this. These statistics can be used practically to define areas of lateral flow and/or areas of vertical migration, to inform the design of multi method geophysical surveys and groundwater monitoring networks. The use of 1D inversion in the context of lateral variations suggests the need for 2D/3D electrical imaging and incorporation of geological and borehole constraints to resolve anisotropic zones to a greater degree.

5.6 CORRELATION ANALYSIS

The results of correlation analysis showed that there is a positive correlation between the geoelectric parameters that were considered such as resistivity distributions, Dar Zarrouk indices, anisotropy, and groundwater potential. The moderate anisotropy ratios (around 1.27–1.4) are associated with generally layered strata, while those above 1.4 are associated with localized heterogeneities and structural complexity that explain the observed variation in hydraulic conductivity, transmissivity, and borehole yields. The productive zones are characterized by good geoelectric continuity, moderate resistivities, and good protective capacity, while the structurally complex or high-resistivity zones feature poor aquifer performance.

The relationships are used to discriminate high-yield aquifers from low yield aquifers in the deltaic and basement terrains based on the integrated geophysical and lithological information. The correlations, however, are still affected by the 1D inversion assumption, spatial sampling, and interpretational non-uniqueness. Future studies should apply formal statistical tests to assess the strength and significance of the correlation, as well as develop a higher resolution 3D imaging and apply borehole and hydraulic data to enhance quantitative relationships between geoelectrical attributes and groundwater productivity.

5.7 SPATIAL INTERPOLATION AND HETEROGENEITY

The spatial interpolation of hydraulic conductivity, transmissivity, and Dar Zarrouk parameter demonstrates that the lateral variability has a more significant influence on groundwater potential than the uniform aquifer conditions. A dominantly stratified environment with heterogeneities, which are fractures, structural anomalies, and perturbations that cause the lack of continuity of the hydraulic properties. These patterns illustrate that measuring regional flow regime by simple point based estimates is not an adequate approach and stress the importance of spatial heterogeneous interpolation techniques.

Geostatistic or surface-based mapping methods, which explicitly consider variability and anisotropy, are better than methods that either oversmooth or average over the data from a methodological perspective. The 1D resistivity modelling limitations in a laterally heterogeneous medium illustrate the need to combine higher resolution 3D resistivity data with borehole control to define interpolation surfaces. This will enhance aquifer property estimates, as well as more reliable delineation and management of groundwater in complex crystalline and deltaic environments.

5.8 VALIDATION OF RESULTS

A consistent interpretation is achieved with consistency in geo electrical layering, in hydrogeological parameters calculated from the Dar Zarrouk results, and in derived hydrogeological parameters, which is an internal validation of the interpretation and reinforces the geological plausibility of the interpretation. The areas of moderate to low resistivity, moderate to high thickness, high transverse resistance and favourable longitudinal conductance, particularly VES 2, 5, and 6, are identified as areas with thick aquifer units that are transmissive and well protected, further supporting identification of priority groundwater development areas. On the other hand, the low groundwater potential indications at VES 7 and 8 are also consistent with the dominant resistances observed in the basement and the limited aquifer thickness, which is consistent with the regional geology of the Gombe Formation.

The spatial patterns of K and T are not directly derived, but they are similar to the geoelectric and lithological interpretations and enhance confidence in the conceptual aquifer model. The overall consistency among the independent geophysical indications indicates that the interpretation obtained from the VES is internally consistent, hydrogeologically reasonable, and acceptable for purposes of borehole siting and groundwater development plan in the study area.

6. DISCUSSION

The hydrogeophysical investigation shows lithological heterogeneity, aquifer thickness, and degree of weathering and fracturing of the Cretaceous sediments of the Gombe Formation are the dominant factors affecting groundwater occurrence within the Doho area. The ten Vertical Electrical Sounding (VES) stations were interpreted to show 3 to 5 geoelectric layers, comprising alternating sandstone, clay, shale and weathered sedimentary units, which implied high lateral variations in subsurface conditions. This is common for the Gombe Formation, and the hydraulic properties vary markedly over short distances due to the rapid facies changes and ferruginization. Thus, the occurrence of groundwater cannot be reliably predicted on the basis of regional geology alone, but should be carefully investigated through detailed hydrogeophysical studies prior to borehole development.

The resistivity distribution also shows that besides the resistivity value, the groundwater potential is additionally controlled by the interaction of aquifer thickness and lithology. Relatively thick horizons of sandstones have moderate resistivity values and are mostly regarded as saturated and permeable aquifer units that are capable of efficient storage and transmission of groundwater, whereas very high values of resistivity are generally associated with relatively thick horizons of sandstones that are compacted, poorly fractured, or may be unsaturated and have limited groundwater potential. Very low resistivity values, on the other hand, are interpreted as a clay-rich section that would contain water but have low hydraulic conductivities and thus would limit the productivity of the groundwater. These observations underscore the importance of considering resistivity data with the geological context and not as direct indicators of aquifer productivity. The most

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favorable hydrogeophysical characteristics observed for groundwater development were a consistent feature of VES02, VES05, and VES06 of the investigated sites. These sites have relatively thick aquifer horizons, moderate resistivity, high transverse resistance, and favorable longitudinal conductance, which indicate better protection from surface derived contaminants and good groundwater storage, transmissivity. VES07 and VES08 had very high resistivity values, very small aquifer thickness and very low aquifer longitudinal conductance, which suggests low groundwater storage capacity and usually poor groundwater prospects. The integrated interpretation thus shows that groundwater productivity in the study area is variable, and that the local lithological variations have a significant impact compared to regional geological variations.

The derived Dar-Zarrouk parameters gave more information about the aquifer protection capacity and hydraulic performance than the standard resistivity interpretation. The overlying materials' resistance to contaminant flow (transverse resistance) is closely related to aquifer transmissive capacity, while longitudinal conductance is a measure of the capacity of overlying materials to attenuate contaminant migration. Groundwater targets with relatively productive aquifers and with higher protection from surface contamination are the most favourable locations with both high longitudinal conductance and high transverse resistance. The integrated interpretation of groundwater is found to be useful for the evaluation of groundwater as compared to the only apparent resistivity value and is also an example of the use of multiple hydrogeophysical indicators for groundwater resource assessment.

Estimated values of hydraulic conductivity and transmissivity also show high spatial variability as a result of differences in lithology, grain size distribution, degree of consolidation, and effective aquifer thickness within the study area. The empirical relationships generated from electrical resistivity do yield good first order estimates of hydraulic properties, but an interpretation of these relationships should be taken with a grain of salt as several factors may interact to influence electrical resistivity: pore-water salinity, clay content, saturation and temperature. Therefore, derived hydraulic parameters can only be used as comparative values to rank groundwater potential and should not be considered as absolute measures of hydraulic parameters. Confidence in these estimates would be significantly increased by independent testing of the pumping-test or borehole hydraulic data. Spatial variations observed here agree well with many hydrogeophysical studies carried out in sedimentary areas across Nigeria and other semi-arid regions of the world. Previous studies have also indicated that moderately resistive sandstones with adequate saturated thickness and favorable hydraulic continuity tend to be the productive groundwater zones, while clay rich intervals or highly cemented sandstones tend to be less productive zones. The present study further expands these findings by comparing the Dar-Zarrouk parameters, derived hydraulic properties, anisotropy assessment, and lithological interpretation with those of conventional VES interpretation, thereby creating a more comprehensive framework for groundwater evaluation than conventional VES interpretation alone. This holistic approach minimizes uncertainty in borehole siting while taking into account the aquifer's productivity as well as protective capacity.

The moderate horizontal anisotropy ratios generally found at the stations of the VES suggest that groundwater flow is dominated by stratified sedimentary anisotropy and not pervasive structural deformation. However, locally higher anisotropies indicate the presence of these sedimentary discontinuities, differential weathering, or preferential groundwater flow routes that locally affect aquifer productivity. The results highlight that the groundwater flow in the Gombe Formation is influenced by both primary depositional structures and secondary geologic changes. A more detailed understanding of the lateral variation could be achieved by future investigations using 2-D or 3-D electrical resistivity tomography, which would help to characterize groundwater flow pathways. The present investigation is valuable in terms of understanding groundwater occurrence in the Doho area; however, there are a number of restrictions that should be noted. The interpretation is done based on 1D-VES inversion of the data, which assumes laterally uniform conditions for the subsurface within each sounding location. However, sedimentary formations often have complex lateral variations that are not easily solved using 1D models. In addition, the derived hydrogeological parameters were indirect estimates based on empirical relationships, which added to the uncertainty of the derived parameters. The conceptual hydrogeological model is well supported by the strong consistency of the lithological interpretation, the distribution of the electrical resistivity, the Dar-Zarrouk parameters, and the groundwater potential, but a more detailed hydrogeological model would be strengthened by the addition of borehole logs, pumping-test data, groundwater level observations, and high-resolution electrical resistivity tomography.

In general, the study shows that an integrated hydrogeophysical technique based on the use of electrical resistivity sounding, Dar-Zarrouk parameters, empirical estimation of hydraulic properties, anisotropy analysis, and spatial interpretation in the context of a heterogeneous sedimentary environment is a powerful tool for groundwater exploration. In addition to finding good borehole sites, the approach also considers aquifer productivity and the natural protection against contamination for groundwater management based on evidence. The results presented here offer useful recommendations for groundwater development in the Gombe Formation and a transferable model, which can be adapted to other parts of the same sedimentary basin or other semi-arid sedimentary basins where groundwater is the major source of domestic and agricultural water.

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7. SUMMARY

This is an all-encompassing research project that evaluates the ground water potential of Doho and environs in Kwami LGA, Gombe State, Nigeria based on geo-electrical resistivity surveys and geophysical studies. The study employs Vertical Electrical Sounding (VES) of the Schlumberger array at ten sites to map the lithology of the subsurface, the properties of the aquifer, and assess spatial changes in groundwater prospects. The geological mapping shows that the region is primarily covered with Cretaceous sediments of the Gombe Formation, which are a mix of ferruginized sandstones, siltstone, and shales, indicating transitional environments of deposition. The geoelectric data indicate that the subsurface has 3-4 layers, each consisting of sandy soils, clay, shale and sandstone, with low to very high resistivity values, which can be attributed to different lithologies and saturation conditions. Dar-Zarrouk parameter analysis reveals that there is a high heterogeneity in terms of aquifer properties. VES 02, 05 and 06 are the sites with high transverse resistance and longitudinal conductance, indicating the locations have a large aquifer thickness, high resistance to contamination and high transmissivity-making them the most favorable areas where groundwater can be extracted sustainably. On the other hand, locations such as VES 07 and 08 which have been found to be of high resistivity and low conductance because of the huge basement rocks depict very low groundwater potential. The depths of the aquifer to be evaluated are generally between 8 and 34 meters with the most promising sites having aquifer thicknesses of over 19 meters. The profiles of resistivity and stratigraphic sections are visualized which demonstrate the heterogeneity and lateral continuity of geological layers, which help to define prospective zones. The region has unconfined, moderately to highly transmissive aquifers that can be used by households and agricultural activities. Nevertheless, great spatial heterogeneity requires specific hydrogeophysical surveys before the drilling of the boreholes to reduce the risks of dry wells and guarantee the sustainable management of water resources. These results offer useful information to policy makers and drilling organizations that seek to increase access to groundwater in water-deprived communities.

The results of this VES based hydrogeological assessment directly add to the sustainable groundwater management and to the identification of spatially variable aquifer properties and groundwater potential zones in the study area which are essential for reliable groundwater supplies. It expands on the integrated geoelectric parameters, indices of Dar Zarrouk and derived hydraulic conductivity and transmissivity to delineate high potential, better protected aquifer zones (e.g. VES 2, 5, 6) in contrast to low yield, vulnerable zones (e.g. VES 7, 8) to guide borehole siting away from structurally constrained, contamination prone zones. The work highlights the importance of groundwater development strategies that are more robust, evidence-based, considering the heterogeneity and anisotropy of the studied areas, as well as the need to validate the results in the field, supporting SDG 6 (clean water and sanitation), ensuring the integrity of the ecosystem and increasing the resilience and prosperity of local communities relying on groundwater resources. The results of this study show that when considering sustainable groundwater development, it is important to explicitly consider spatial heterogeneity and anisotropy in aquifer properties, as this enables targeting of high yield, well protected zones (e.g. VES 2, 5, 6) and avoiding structurally constrained, contamination prone zones (e.g. VES 7, 8), leading to enhanced water security, reduced risk of drilling failure and supporting long term socio-economic resilience in alignment with SDG 6.

CONCLUSION

1. The application of groundwater potential zones within the Doho area was attained successfully using the integrated application of Vertical Electrical Sounding (VES), Dar–Zarrouk parameters and lithological interpretation.
2. The most promising zones for groundwater development were identified as VES02, VES05, and VES06, which have thick aquifer units, high transmissivity, favorable hydraulic conductivity, high transverse resistance and moderate to high longitudinal conductance.
3. The poor groundwater prospect areas (VES07 and VES08) were identified by high resistivity, thin aquifer, low longitudinal conductance and dominant basement rock conditions.
4. The aquifer protective capacity and transmissivity were readily represented by the computed "Dar–Zarrouk parameters" indicating their usefulness for groundwater potential assessment.
5. Spatial interpolation and correlation analyses showed that lateral lithological heterogeneity, weathering and structures had the greatest control on groundwater occurrence over uniform regional geological conditions.
6. The moderate anisotropy values suggest mostly layered subsurface conditions, with localized higher anisotropy values suggesting structural complexity that may affect groundwater flow pathways.
7. The integrated hydrogeophysical approach ensures a safe basis for borehole location prioritization, the reduction of borehole failure, and an efficient groundwater exploration process.
8. The study shows that the integration of geo-electrical resistivity with lithological data provides a desirable tool for sustainable groundwater resource management in the heterogeneous sedimentary environment of Gombe Formation.
9. It is recommended that the findings will enable evidence-based groundwater planning, enhanced groundwater security and sustainable borehole development in other semi-arid sedimentary environments like Doho.
10. Overall, this work shows that integration of hydrogeophysical characterization is a viable and scientifically sound method for groundwater prospect evaluation and that has potential for use in a wide variety of heterogeneous sedimentary basins where delineation of the groundwater aquifers is critical to long-term sustainability of groundwater resources.

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APPENDIX

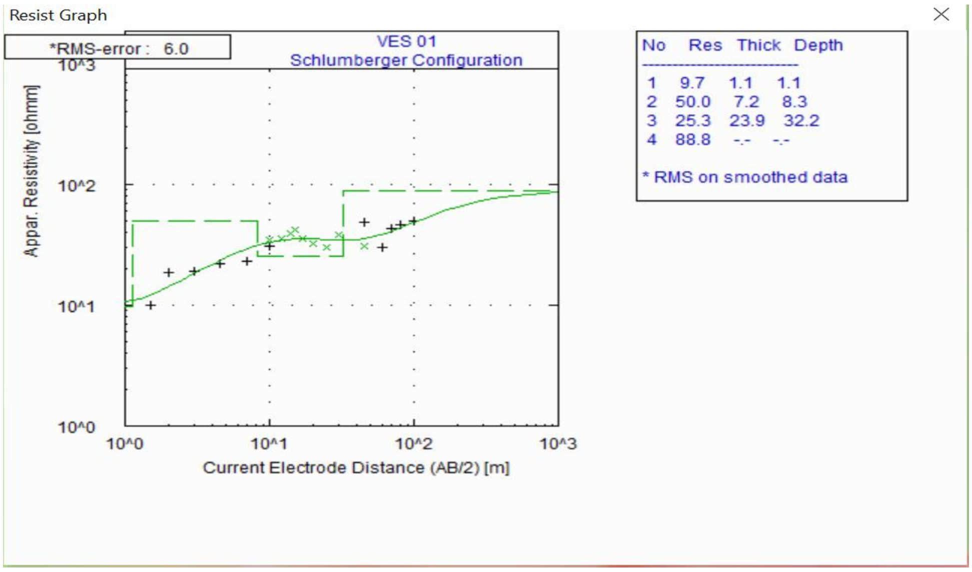

Figure 4.1: VES Curve for Location 1

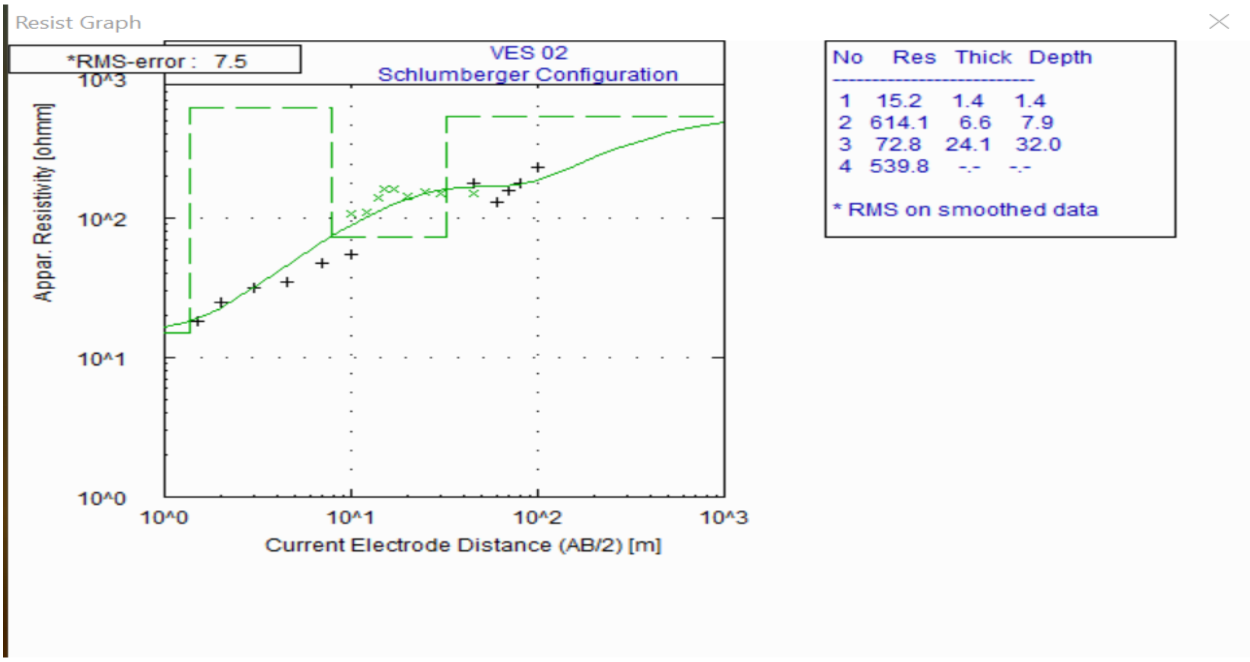

Figure 4.2: VES Curve for Location 2

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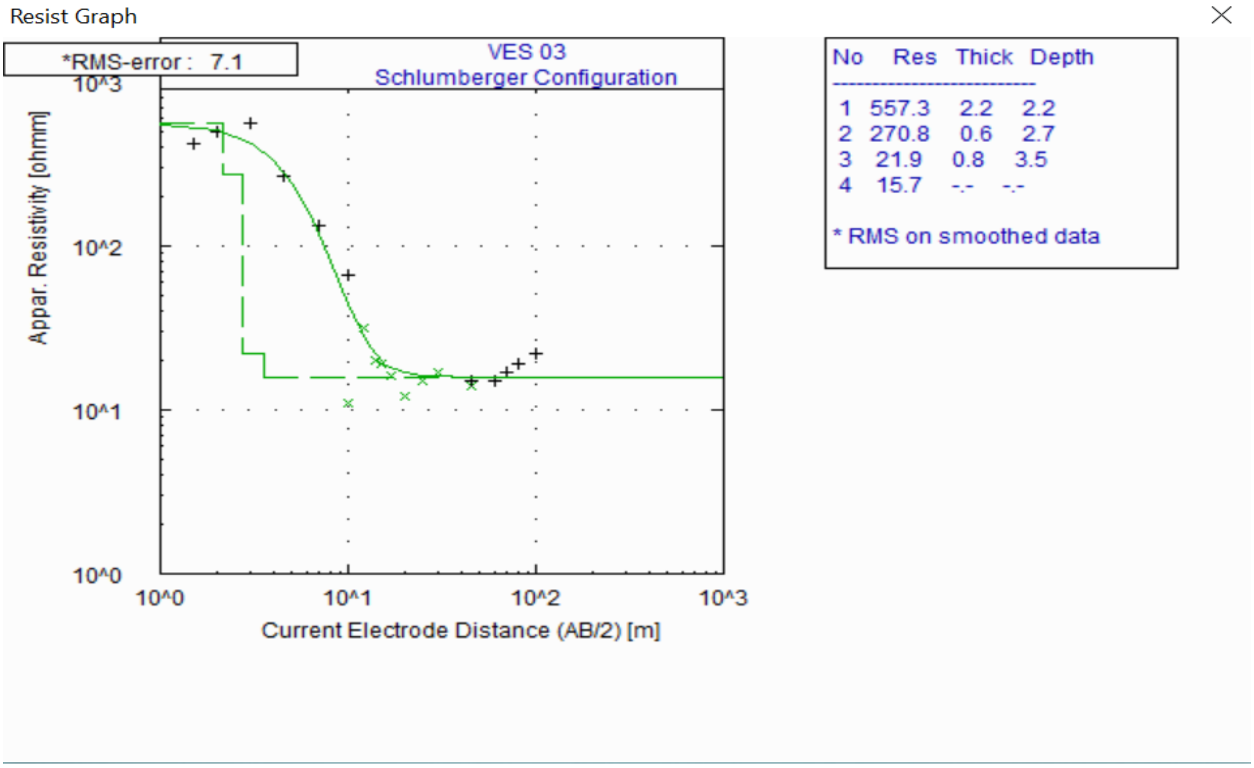

Figure 4.3: VES Curve for Location 3

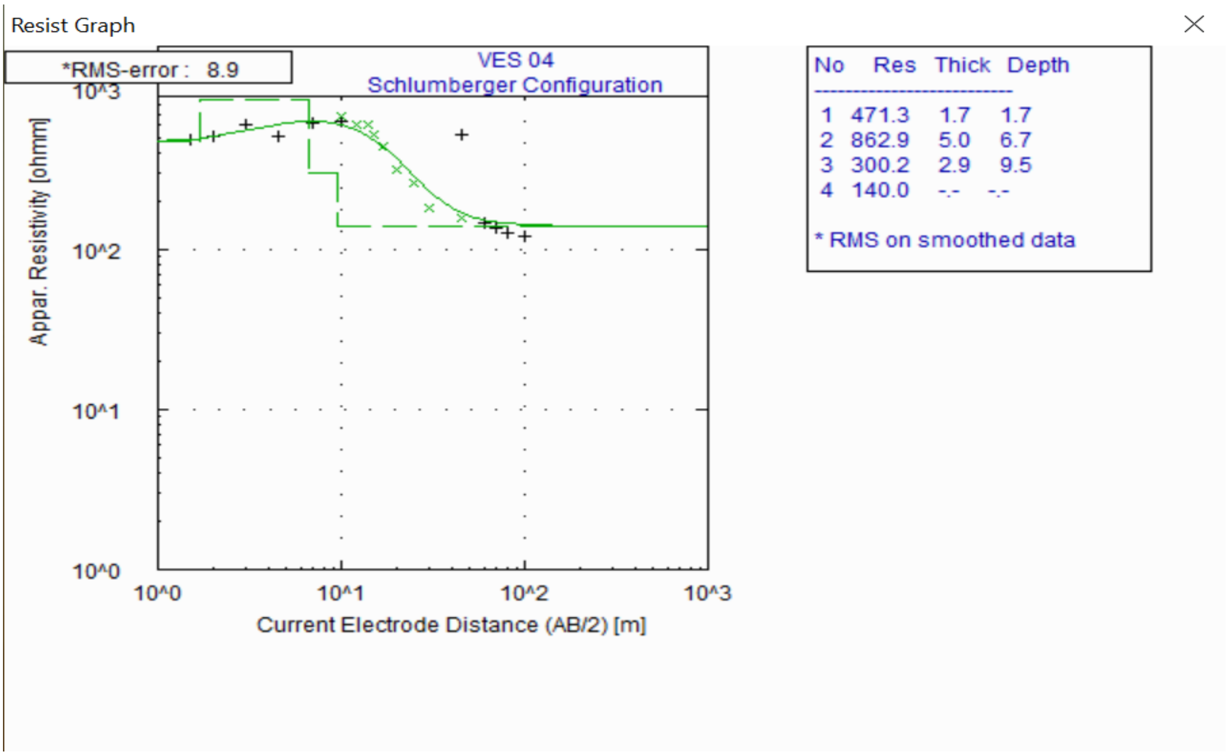

Figure 4.4: VES Curve for Location 4

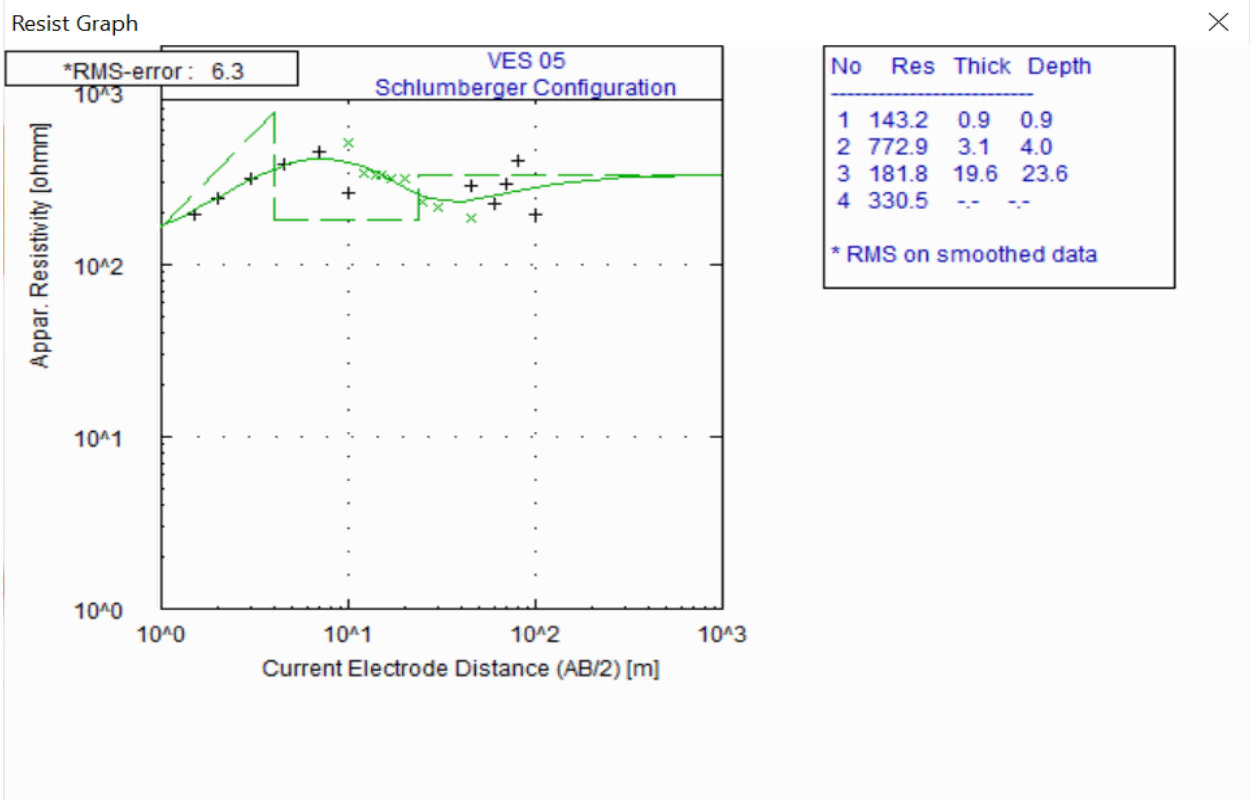

Figure 4.5: VES Curve for Location 5

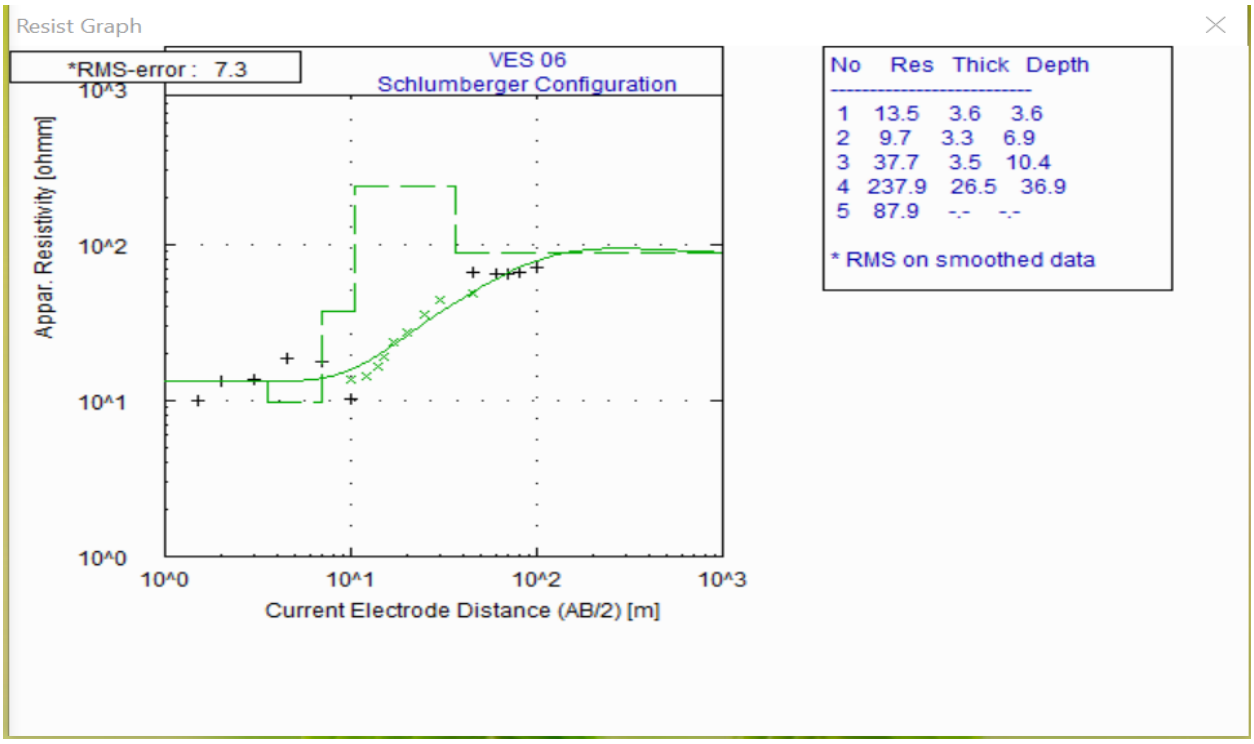

Figure 4.6: VES Curve for Location 6

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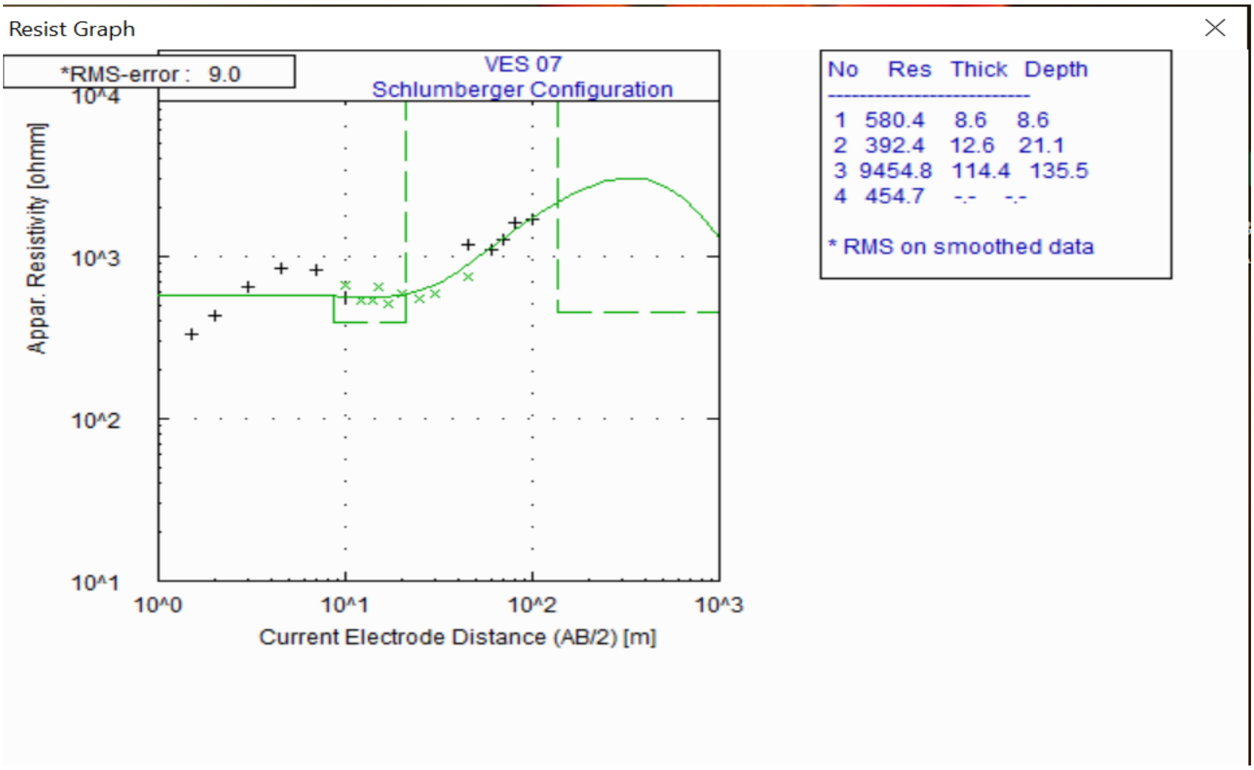

Figure 4.7: VES Curve for Location 7

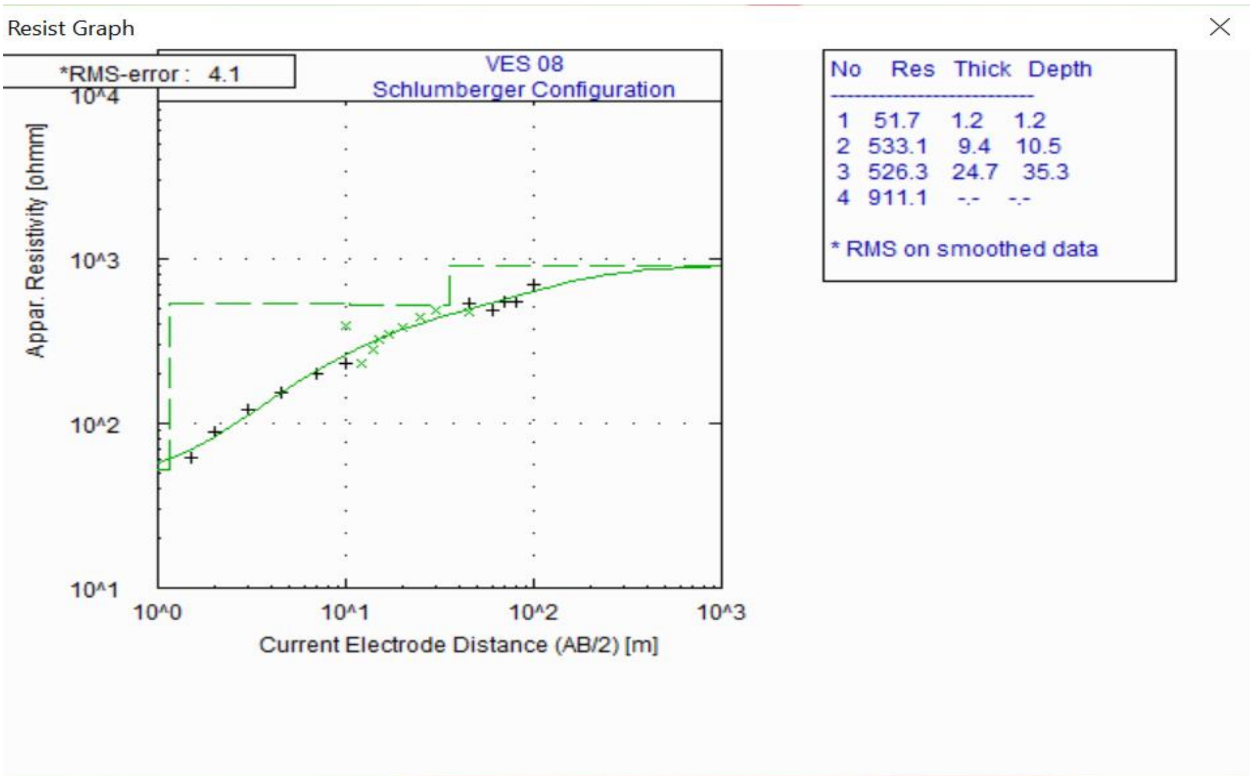

Figure 4.8: VES Curve for Location 8

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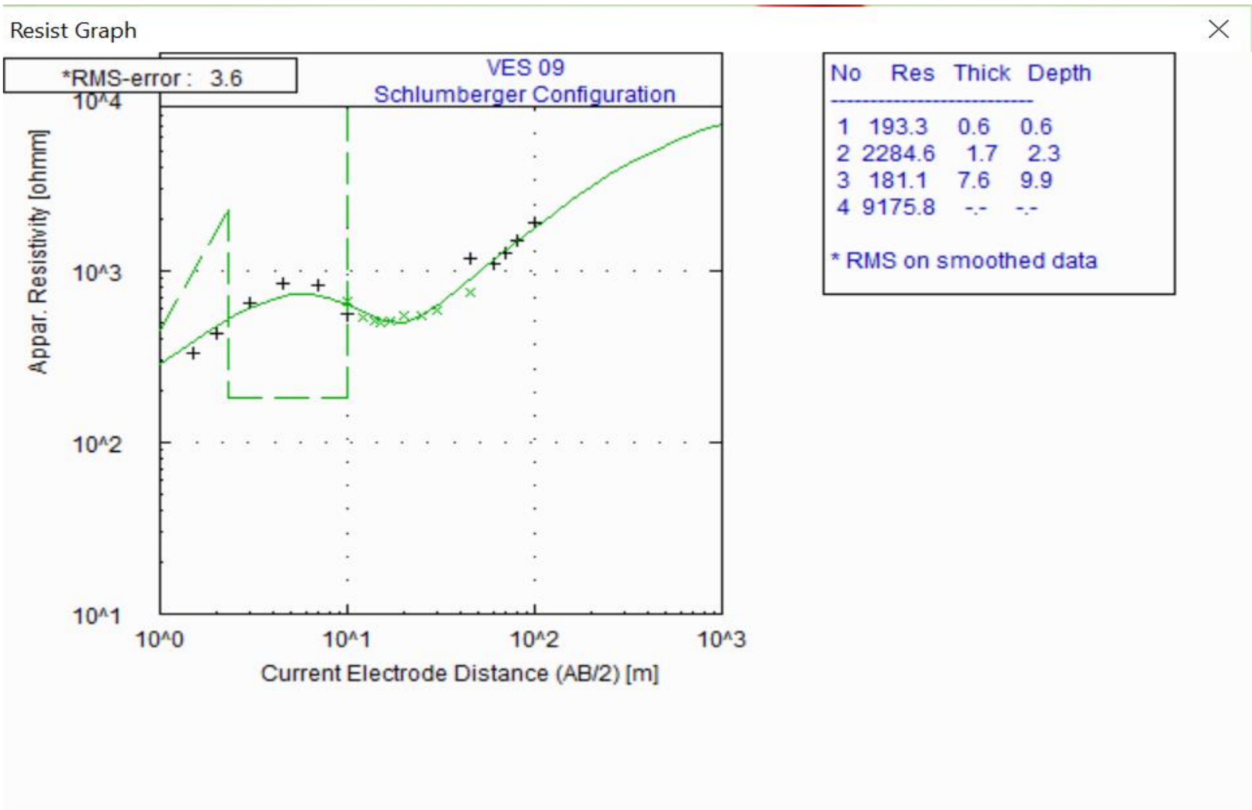

Figure 4.9: VES Curve for Location 9

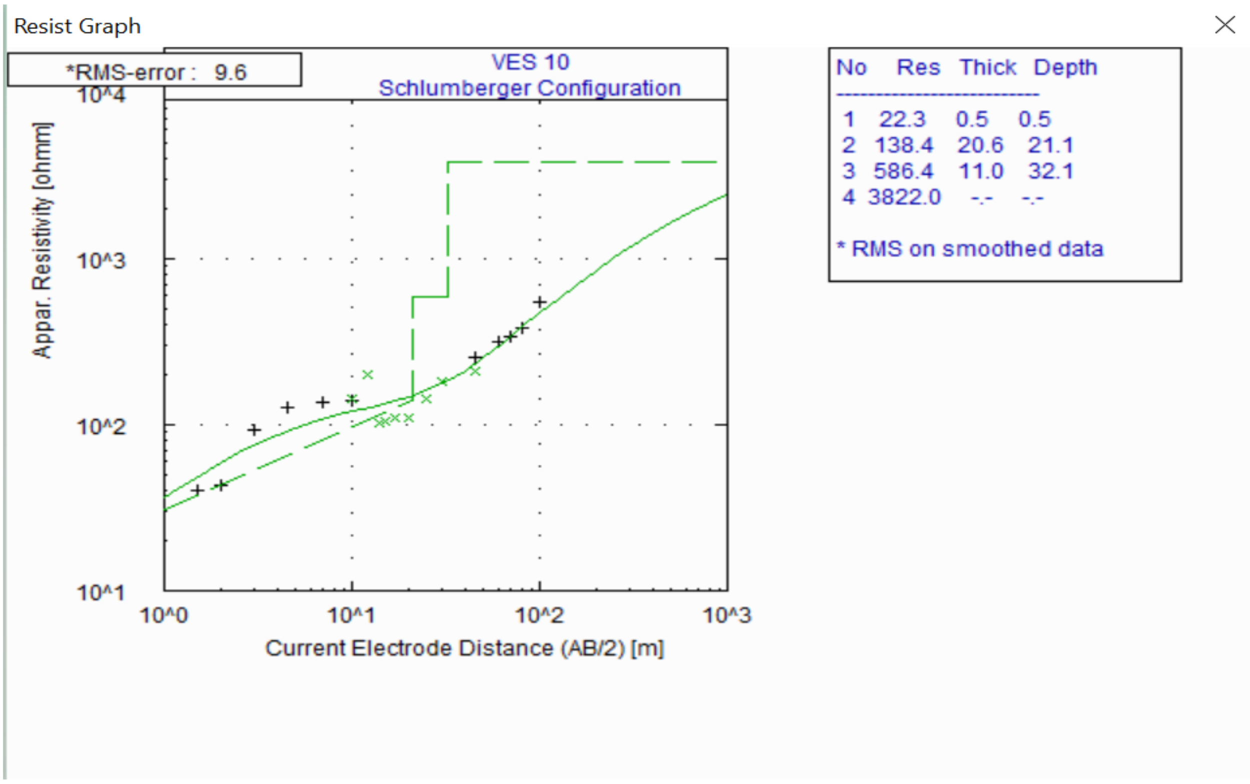

Figure 4.10: VES Curve for Location 10.

TRESEARCH

REFERENCES

[1] Abubakar, M. B., Dike, E. F. C., & Obaje, N. G. (2011). Sedimentological and geochemical characteristics of the Gombe Formation, Gongola Basin, Upper Benue Trough, Nigeria. Journal of African Earth Sciences, 61(1), 1–15.

[2] Alabi, A. A., Bello, R., Ogungbe, A. S., & Oyerinde, H. O. (2016). Hydro-geophysical investigation of groundwater potential of Ilorin East Local Government Area, Kwara State, Nigeria. Journal of African Earth Sciences, 116, 95–106.

[3] Arabi, S. A., Mohammed, A. G., & Tukur, A. I. (2009). Geoelectrical investigation of groundwater potential around Gombe and environs, northeastern Nigeria. Journal of Environmental Hydrology, 17(3), 1–12.

[4] Arabi, S. A., Mohammed, A. G., & Tukur, A. I. (2022). Assessment of groundwater resources in semi-arid regions of northeastern Nigeria using geophysical methods. Journal of African Earth Sciences, 186, 104430.

[5] Basharat, U., Zhang, W., Abbasi, A. et al. Geoinformatics and hydrogeophysical-based delineation of groundwater potential zone through surface and subsurface indicators. Appl Water Sci 15, 222 (2025). https://doi.org/10.1007/s13201-025-02580-5

[6] Ebong Dickson Ebong, Chimezie Ndunagum Emeka, Oualid Melouah, Rose Illa Ullah, Anthony and Edet Ita (2023): Delineation of groundwater potential zones using electrical resistivity technique in Obudu basement terrain of Cross River State, Southeastern Nigeria. Water Practice and Technology (2023) 18 (11): 2884–2900. https://doi.org/10.2166/wpt.2023.174

[7] Chou, et al. (2021): Improving evapotranspiration computation with electricalresistivity tomography in a maize fieldVadose Zone Journal. DOI: 10.1002/vzj2.20290

[8] Fajana, A. O. (2020): Groundwater aquifer potential using electrical resistivity method and porosity calculation: a case study. NRIAG Journal of Astronomy and Geophysics, 9(1), 168–175. https://doi.org/10.1080/20909977.2020.1728955

[9] Farid, H. U., & Bakhsh, A. (2015). Use of vertical electrical sounding (VES) techniques to explore the groundwater potential. Asian Journal of Science and Technology, 6(01), 915-923. DOI: 10.18280/eesrj.040102

[10] Ezikiel, K., Anthony, M. S., Garba, M. A., & Musa, H. (2026). *Assessment of groundwater and mineralization potentials of Jada and environs, Northeastern Nigeria, using high-resolution aeromagnetic data*. *Journal of Engineering Advancements, 7*(1), 38–45. https://doi.org/10.38032/jea.2026.01.004

[11] Johnson T.C, and Wellman B. (2023). Time-lapse electrical resistivity imaging and PFLOTRAN simulations of vadose-zone contaminant migration at the BC Cribs and Trenches, Hanford. Journal of Environmental Quality Journal of Environmental Quality.

[12] Mbiimbe, E. Y., Samaila, N. K., & Akanni, D. K. (2010). Groundwater exploration in a basement complex terrain using electrical resistivity sounding (VES): A case study of Rimin Gado town and environs, Kano State, North Central Nigeria. Continental Journal of Earth Sciences, 5(1), 56–63.

[13] Mohammed, A. G., Saidu, A. D., & Mustafa, A. G. (2021). Hydro-geoelectrical investigation of Gwoza town and environs, Northeastern Nigeria. IOSR Journal of Applied Geology and Geophysics, 9(3), 48–55.

[14] Mohammed Ali Garba, Celestina Sani Zubairu, Mustapha Ali Garba, Ali Mohammed Ali. (2026): Groundwater Quality in Kano Region, Nigeria: A multivariate hydrochemical characterization and spatial variation of groundwater quality, to reveal insights into the natural geology and anthropogenic influence. (2026). *International Journal of Inventive Engineering and Sciences, 13 (1). doi/10.35940/IJIES.C4733.13010126

[15] Mohamed Haythem Msaddek, Yahya Moumni, Lahcen Zouhri, Ismail Chenini and Adel Zghibi. (2023): Groundwater Quality Evaluation of Fractured Aquifers Using Machine Learning Models and Hydrogeochemical Approaches to Sustainable Water-Irrigation Security in Arid Climate. Water 2023, 15, 3332. https://doi.org/10.3390/w15193332.

[16] Garba, M. A., Ezikiel, K., Garba, M. A., & Ali, A. M. (2026). *Ecotoxicological and hydrogeochemical assessment of groundwater in Kano: Determining the areas of pollutants and the health hazards*. *International Journal of Inventive Engineering and Sciences, 13*(3). https://doi.org/10.35940/IJIES.E1240.13030326.

[17] Nur, A., & Ayuni, N. K. (2003). Hydro-geophysical study of groundwater potential in Michika and environs, northeastern Nigeria. Journal of Applied Sciences and Environmental Management, 15(1), 91–98.

[18] Olorunfemi , M.O. and Oni, A.G (2019): INTEGRATED GEOPHYSICAL . (2019): METHODS AND TECHNIQUES FOR SITING PRODUCTIVE BOREHOLES IN BASEMENT COMPLEX TERRAIN OF SOUTHWESTERN NIGERIA . . Ife Journal of Science vol. 21, no. 1 (2019). https://dx.doi.org/10.4314/ijs.v21i1.2

[19] Raj, S. (2017). *Geophysical resistivity survey VES for selection of appropriate artificial recharge structures for augmentation of groundwater resources in Gwalior, M.P, India*. *Environmental and Earth Sciences Research Journal, 4*(1), 7–11.