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Geo-Electrostratigraphic Investigation of Gulak and Surrounding Areas, Northeastern Nigeria

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Abstract: *This study presents a quantitative geo-electrostratigraphic investigation of Gulak and its environs in northeastern Nigeria to evaluate subsurface lithology and groundwater potential within a basement complex terrain. Detailed geological field mapping guided the establishment of ten (10) Vertical Electrical Sounding (VES) stations distributed across the study area. Data were acquired using an ABEM SAS 1000 Terrameter with the Schlumberger array configuration, achieving a maximum current electrode spacing (AB/2) suitable for deep subsurface penetration. Sounding data were interpreted using INTERPEX inversion software to generate geoelectric layer models and electrostratigraphic sections. The results revealed three to four geoelectric layers across the VES locations, with resistivity values ranging from 2.02 to 73,900 Ωm and layer thicknesses varying between 0.019 m and 155.6 m, reflecting significant lithological heterogeneity. Identified curve types include HK (70%), QK, HQ, and AH, indicating alternating conductive and resistive subsurface sequences typical of weathered and fractured basement aquifers. Three geoelectric cross-sections (Profiles A–A', B–B', and C–C') delineated variations in overburden thickness and basement depth, which range from shallow weathered zones to deeper fractured bedrock horizons. Aquiferous layers were characterized by moderate resistivity values (typically 50–800 Ωm) and appreciable thickness, suggesting favorable groundwater storage conditions. Based on these parameters, seven VES points (1, 2, 3, 6, 7, 8, and 9) were classified as high groundwater potential zones, two points (5 and 10) as moderate, and one point (4) as low potential due to its high resistivity and thin weathered layer. The integration of resistivity data with geological mapping provides a reliable framework for groundwater targeting, borehole siting, and sustainable water resource development in the Gulak area.*

Keywords: *Vertical Electrical Sounding (VES), Resistivity, Curve Types, Electrostratigraphy, Groundwater Potential, Gulak, Northeastern Nigeria*

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1.0 Introduction

Gulak, situated in northeastern Nigeria, exhibits a variety of geological formations that are crucial for understanding subsurface processes, natural resource distribution, and environmental management. The stratigraphy of this region provides critical insights into its geological history and the processes that have shaped it over millions of years. Earlier studies in and around Gulak, including investigations in nearby Gulani, have focused mainly on surface mapping and petrographic analyses, identifying Precambrian Basement Complex rocks, Cretaceous sediments, and Tertiary/Quaternary volcanic formations (Adebayo *et al*., 2015). However, these studies provide limited insight into subsurface stratigraphy and aquifer potential. Also the advancement of geophysical techniques, particularly electrostratigraphic analysis, has provided new opportunities for a more detailed understanding of subsurface structures, particularly electrostratigraphic analysis, which remains underutilized in the Gulak region (Rezaee & Chehrazi, 2021a). Electrostratigraphy, which involves the interpretation of subsurface lithology using electrical log data, is a crucial tool for distinguishing stratigraphic units and understanding depositional environments (Serra, 2017).

Recent advancements in electro-sequence analysis have proven effective for delineating stratigraphic units and evaluating their geophysical properties. Rezaee & Chehrazi (2021b) underscored the value of electrostratigraphic techniques in assessing natural resource potential and enhancing subsurface geological characterization. However, such methodologies remain underutilized in the Gulak region of northeastern Nigeria. This study addresses that gap by applying detailed electrostratigraphic analysis to define subsurface stratigraphy and evaluate its implications for geological understanding and resource management in the area. Understanding the subsurface geology is essential for applications such as natural resource exploration, groundwater management, and environmental conservation (Serra, 2017).

Despite Gulak's complex geological framework, previous studies have largely relied on surface mapping and petrographic analyses, leaving subsurface stratigraphy poorly characterized. While electrostratigraphy has proven effective in other parts of northeastern Nigeria (Rahaman, 2020), its application in Gulak remains limited. This lack of high-resolution subsurface data hinders accurate aquifer identification, stratigraphic correlation, and resource management, highlighting the need for focused electrostratigraphic studies in the region.

The aim of this study is to perform an electrostratigraphic analysis of the Gulak region using Vertical Electrical Sounding (VES) data to evaluate subsurface resistivity variations, delineate stratigraphic units, and identify zones with high groundwater potential suitable for borehole siting

1.1 The study area

Gulak is in northeastern Nigeria, within Adamawa State, specifically in Madagali Local Government Area. It lies approximately between 10°46' to 10°50' N and 13°25' to 13°29' E (Fig. 1). The study area extends over 9.26 km from north to south and 9.18 km from east to west, covering a total area of 85.02 km². Accessibility is facilitated by major roads that link Gulak to Mubi and surrounding towns, ensuring ease of transportation.

The primary objective of this study is to perform an electrostratigraphic analysis of the Gulak region in Northeastern Nigeria using Vertical Electrical Sounding (VES) data. The investigation aims to evaluate subsurface resistivity variations to identify zones with high groundwater potential and delineate electrostratigraphic profiles that inform borehole siting. This geophysical approach provides a more accurate characterization of subsurface lithology, which is essential for sustainable groundwater development and resource planning.

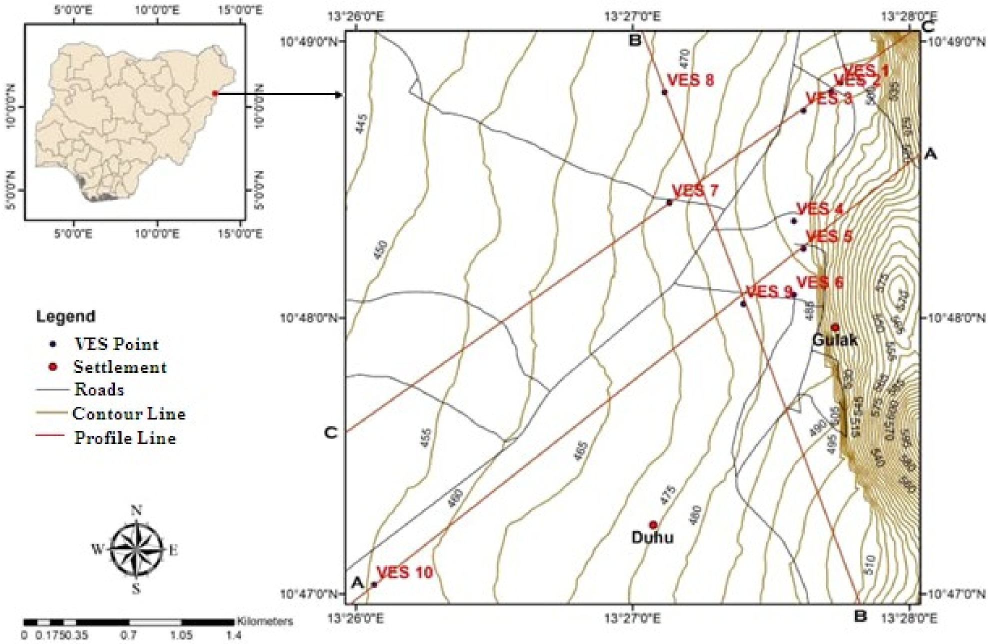


Fig. 1: Topographic Map of the Area (Made after DEM, 2024)

Gulak is characterized by a landscape of plains, low hills, and river valleys that influence drainage patterns and sediment deposition. The presence of river valleys indicates periodic fluvial activities that may have contributed to the sedimentary sequences in the region. Studies in similar areas (Okoye & Igbokwe, 2018) highlight the role of fluvial processes in shaping sedimentation and geomorphology in Adamawa State, suggesting that Gulak landscape has evolved due to river dynamics, especially during periods of high rainfall.

The climate of Gulak is tropical, with distinct wet and dry seasons. The wet season spans from April to October, bringing annual rainfall between 900 mm and 1,200 mm, which affects surface water distribution and vegetation cover. The dry season lasts from November to March and is marked by lower humidity, increased temperatures, and reduced water availability. Average temperatures range from 21°C during the cooler months to 40°C in the hottest periods (Akinyemi & Eze, 2017).

The region is predominantly covered by savannah vegetation, consisting of scattered shrubs and trees, with occasional denser growth along river courses. Physiographically, the area exhibits gentle undulating plains with elevations generally ranging between 200 m and 500 m above sea level, interspersed with low hills. These environmental and physiographic factors collectively shape the region's sedimentary characteristics and influence groundwater recharge and mineral resource distribution (Adamu *et al.,* 2019; Bello & Adebayo, 2020).

This study provides a detailed electrostratigraphic framework of the Gulak area, enhancing the accuracy of subsurface stratigraphic correlations and lithological interpretations. The findings support groundwater exploration, facilitate sustainable borehole development, and contribute to regional geological knowledge, serving as a reference for future research in northeastern Nigeria.

Electrostratigraphy is a geophysical stratigraphic method that utilizes electrical log data such as Vertical Electrical Sounding

(VES) and spontaneous potential to interpret subsurface lithology. These logs provide valuable insights into the petrophysical and geotechnical properties of rock units, allowing for the differentiation of stratigraphic layers without direct sampling. When integrated with complementary geological and geophysical datasets, electrostratigraphic techniques significantly enhance subsurface modeling accuracy, making them indispensable for both petroleum and groundwater exploration (Rezaee & Chehrazi, 2021a).

Electrostratigraphy plays a pivotal role in stratigraphic correlation by enabling geologists to trace both lateral and vertical lithological variations across geological formations. Its effectiveness in delineating key stratigraphic boundaries and correlating units over wide areas has been well documented in recent studies. For instance, Faye *et al*. (2021) demonstrated how electrostratigraphic techniques can reconstruct depositional environments and enhance subsurface interpretation. In the sedimentary basins of Nigeria and broader West Africa, electrostratigraphy has proven instrumental in identifying transgressive and regressive sequences, offering valuable insights into paleoenvironments and sequence stratigraphy (Adeleye & Salami, 2021; d'Almeida *et al*., 2016). These applications underscore its relevance in both academic research and practical exploration efforts.

Electrostratigraphy offers a powerful framework for subsurface characterization by leveraging resistivity data to differentiate lithological units. Its utility spans groundwater exploration, environmental assessment, and engineering geology, where it aids in identifying aquifer zones, mapping subsurface heterogeneity, and guiding infrastructure development. The method's effectiveness continues to grow with innovations in geophysical instrumentation and computational modeling, enabling more precise interpretation of complex geological settings

The study area lies within the Hawal Massif, a structurally complex basement terrain composed of Precambrian to Pan-African metamorphic and igneous rocks, which influence groundwater occurrence and subsurface stratigraphy. The research area is part of the Hawal Massif, which is a major crystalline basement complex in northeastern Nigeria, forming a crucial structural and lithological unit within the Nigerian Basement Complex. It is primarily composed of Precambrian to Pan-African-aged rocks, including granites, migmatites, gneisses, and schist, which have undergone multiple deformation and metamorphic events (Tijani*.,* 2023). The massif represents a tectonically stable block within the West African Craton, separated from the Upper Benue Trough by major fault systems and structural lineaments (Adekeye *et al.,* 2017). These geological features influence the area's hydrogeology, mineralization, and overall tectonic evolution.

Lithologically, the Hawal Massif consists of migmatitic gneisses and schist, which dominate the basement complex and represent high-grade metamorphic rocks that have been subjected to multiple deformation phases (Dada, 2016). These rocks are interspersed with widespread Pan-African granitic intrusions, which were emplaced during the 600 Ma Pan-African orogeny, indicating significant magmatic and tectonic activity during the Neoproterozoic (Uduma *et al,* 2021). Additionally, metasedimentary and metavolcanic units occur as remnants within the massif, providing insights into the early crustal evolution of the region. These lithologies indicate a long history of crustal reworking, tectonothermal events, and continental collision, characteristic of the Pan-African belt (Udi *et al*., 2021).

The tectonic and structural evolution of the Hawal Massif has been shaped by multiple deformation events. The Pan-African orogeny played a crucial role in its structural configuration, leading to extensive faulting, folding, and shearing, which influenced regional structural trends (Ekwueme &

Kroner, 2018). Major NE-SW trending fault systems define the massif's boundary with the Upper Benue Trough, representing significant zones of crustal weakness that facilitated tectonic movements (Obiora *et al.,* 2020). Evidence of ductile and brittle deformation is present, contributing to the development of foliation, mylonitic zones, and fracture systems, which impact both groundwater flow and mineralization. The massif's structural complexity suggests a history of crustal uplift, extension, and reworking, with implications for both regional geology and resource exploration (Davis & Turk, 2011).

The Hawal Massif is significant for understanding the geodynamic evolution of the West African Craton and the Pan-African Orogenic Belt. It serves as a tectonic boundary between the Nigerian Basement Complex and the Upper Benue Trough, highlighting the influence of faulting and regional metamorphism on basin formation (Odeyemi, 2016). Granitic intrusions within the massif have been linked to mineralization processes, particularly the formation of gold and rare earth element (REE) deposits, which are of economic importance (Olarewaju & Rahaman, 2021).

In addition to its structural and economic significance, the Hawal Massif has undergone considerable weathering and erosion, leading to the development of regolith-covered terrains. This has important implications for groundwater recharge and soil formation, particularly in northeastern Nigeria, where groundwater availability is a crucial factor for local communities. The geomorphological evolution of the massif, as influenced by tectonic uplift and denudation processes, continues to shape the hydrogeological characteristics of the region. The Hawal Massif remains a structurally complex crystalline basement unit with a rich geological history, characterized by high-grade metamorphic rocks, Pan-African intrusions, and extensive faulting (Adekeye *et al.,* 2017; Odeyemi, 2016)). Its tectonic evolution, magmatic history, and structural configuration provide critical insights into the broader geodynamics of the Nigerian Basement Complex (Fig. 2) illustrates the spatial distribution of crucial lithological unit of the area.

Several studies have applied electrostratigraphy in Nigeria, such as Nur *et al.,* (2011), who conducted electrostratigraphic and hydrogeochemical research in Michika Adamawa state Northeastern Nigeria. They used vertical electrical sounding (VES) and electrical resistivity tomography (ERT) to define subsurface strata and assess aquifer potential, demonstrating the utility of electrostratigraphy in resource management.

Similarly, Ezekiel *et al*., (2018) utilized geo-electrical study in Gella Mubi, Adamawa state, Nigeria, employing VES and 2D electrical resistivity tomography to delineate subsurface layers and evaluate groundwater resources. These studies underscore the significance of electrostratigraphy in hydrogeological studies across different sedimentary basins. However, a significant gap exists in electrostratigraphic research focused specifically on the Gulak area. Most research in the region has concentrated on geological mapping and petrographic analysis. For instance, Adetunde *et al*., (2018) provided valuable insights into the petrography and geology of rocks around Gulani, a neighboring town to Gulak.

Despite these efforts, the application of electrostratigraphy in Gulak remains underexplored, highlighting the need for further research to better understand the region's subsurface geology. This study addresses the lack of high-resolution electrostratigraphic data in Gulak, aiming to provide practical insights for groundwater development and subsurface geological understanding.

Electrostratigraphy, using VES resistivity data, allows differentiation of lithological units without direct sampling, providing a practical tool for both groundwater assessment and geological characterization in complex basement terrains.

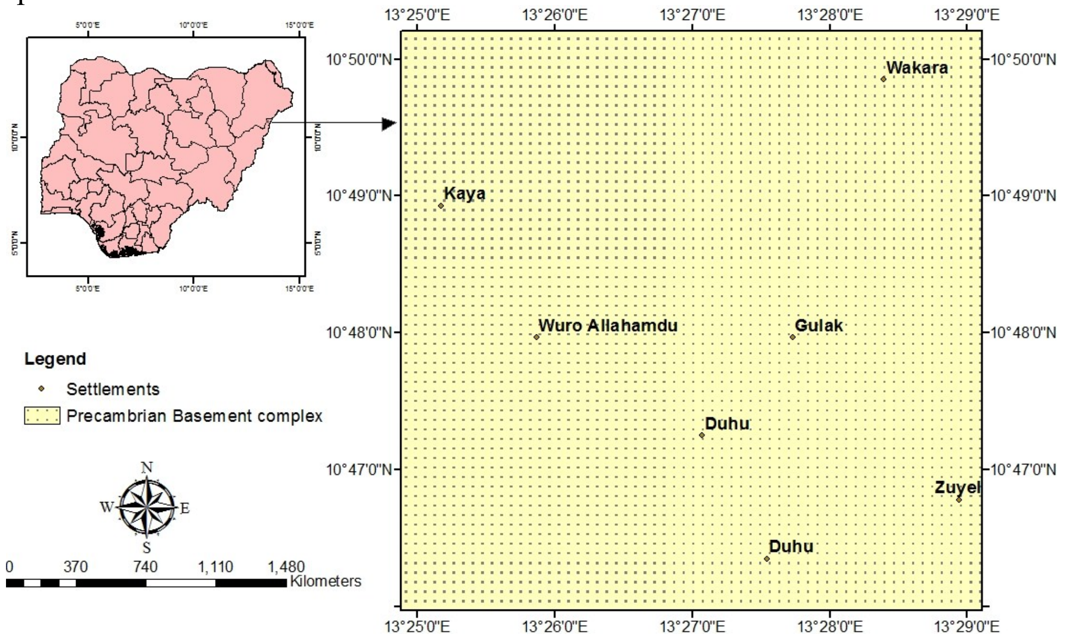


Fig. 2: Geologic Map of the Area (After NSGS, 2024)

2.0 Materials and Methods

The instrument used in this study included a Terrameter (ABEM SAS 1000) for geophysical surveys, a DC power supply (car battery) for current injection, a measuring tape, GPS, and a compass for location tracking and mapping, a geological hammer for rock sampling, four metal electrodes, a field notebook, and a topographic map for navigation.

Vertical Electrical Sounding (VES) surveys were conducted using a Terrameter in the Schlumberger configuration to measure subsurface resistivity. Data were collected at multiple strategically selected locations across the study area to delineate lithological boundaries, structural features, and potential aquifer zones. Simultaneously, geological field mapping documented surface rock types, outcrops, and structural features such as faults and folds. GPS and compass measurements ensured accurate location tracking, and field observations of lithology and structures were recorded to complement geophysical data Geological field mapping was also conducted to document surface rock types, outcrops, and structural features such as faults and folds. GPS and compass

2.1 Data collection

mapping ensured accurate location tracking, while representative observations of lithology and structures were recorded. The field data served as ground-truth references, complementing the geophysical interpretations for a comprehensive understanding of the subsurface geology of Gulak.

The primary data acquisition involved geophysical surveys using the Vertical Electrical Sounding (VES) method with a Terrameter, employing the Schlumberger configuration to measure subsurface resistivity. Geological field mapping was carried out simultaneously to document rock outcrops, lithological variations, and structural features using standard mapping tools such as a GPS and a compass clinometer.

Following data collection, validation and analysis were conducted to ensure accuracy and consistency. Geophysical resistivity data were processed using specialized computer software to generate subsurface model layers, while lithological observations from field mapping were integrated to strengthen interpretation and provide a reliable understanding of the geology of the study area.

2.2 Schlumberger Array

The Schlumberger array uses four electrodes: two outer current electrodes (A and B) inject current into the ground, while two inner potential electrodes (M and N) measure the resulting voltage difference. The spacing between current electrodes is gradually increased while keeping the potential electrodes fixed, allowing for deeper penetration and measurement of subsurface resistivity variations. "The depth of investigation (d) is approximately one-third to one-half of the total current electrode spacing, allowing deeper exploration compared to other arrays (Reynolds, 2011). The distance between the current electrodes gradually increased while keeping the potential electrodes fixed until the measured voltage became too small. This method provided high-resolution subsurface resistivity data, making it useful for groundwater exploration, electrostratigraphic correlation, and mineral prospecting (Lowrie, 2018; Telford *et al.,* 2019).

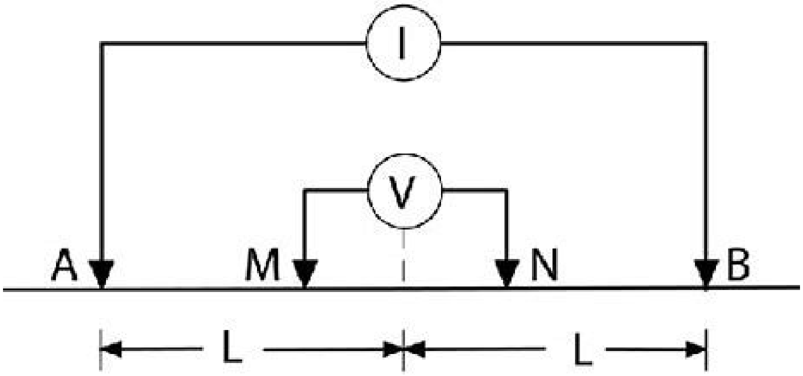


Fig. 2: Schlumberger Array Configuration (Villalobos *et al.,* 2019)

The apparent resistivity (Ωm) for the Schlumberger array is calculated using the equation:

$$\rho a = \pi \left(\frac{L^2 - a^2}{2a}\right)\frac{\Delta V}{I} \qquad (1)$$

where: ρa= apparent resistivity (Ωm), L= half the distance between current electrodes (A and B), a= half the distance between potential electrodes (M and N), ΔV= measured potential difference (V) and I= injected current (A)

This method follows Ohm's Law, which states that resistivity is a function of voltage and current:

$$R = \frac{\Delta V}{I} \qquad (2)$$

where resistance R is related to resistivity ρ through the geometric factor of the electrode configuration. The depth of penetration (d) in a Schlumberger array is approximately one-third to half of the total current electrode spacing, allowing deeper investigations compared to other configurations like the Werner array (Reynolds, 2011).

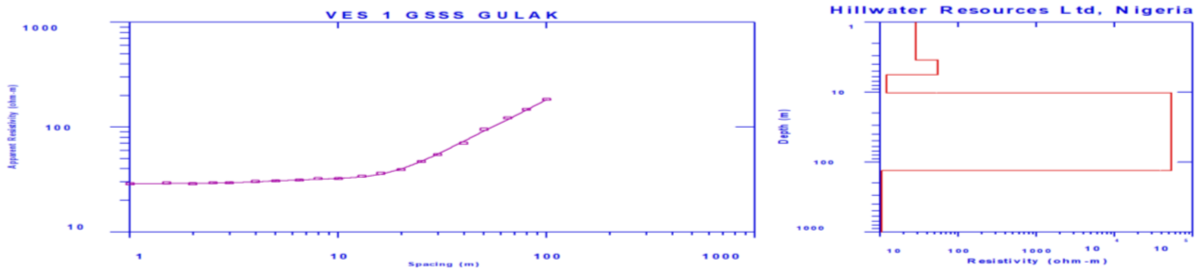
Studies have demonstrated that the Schlumberger array is effective for delineating lithological boundaries and identifying aquifer zones. For example, Oladapo *et al.* (2020) applied this method in a groundwater study in Nigeria, successfully mapping subsurface variations and confirming aquifer presence. Similarly, Jekayinfa *et al.* (2023) showed its reliability in mineral exploration, highlighting its ability to distinguish between different rock formations based on resistivity contrasts.

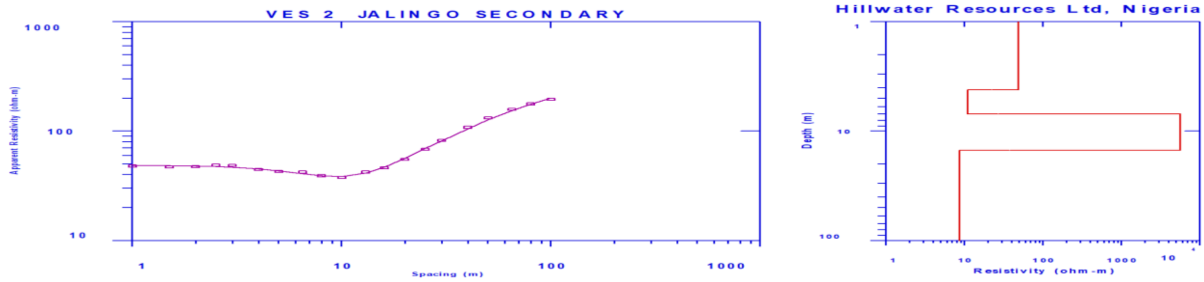
2.3 Data Analysis

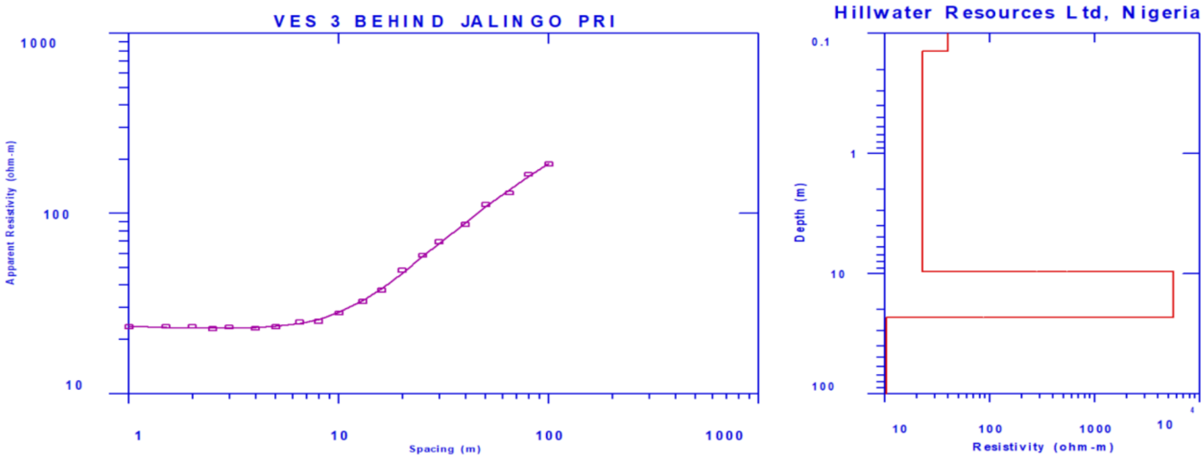
VES data were processed using INTERPEX MODE software, which applies inverse modeling techniques to generate 1D and 2D resistivity profiles. These profiles were interpreted to delineate lithological boundaries, identify potential aquifer zones, and correlate electrostratigraphic units with field observations (Lowrie, 2018). Integrating geophysical and geological data ensured reliable characterization of the subsurface geology of the Gulak area.

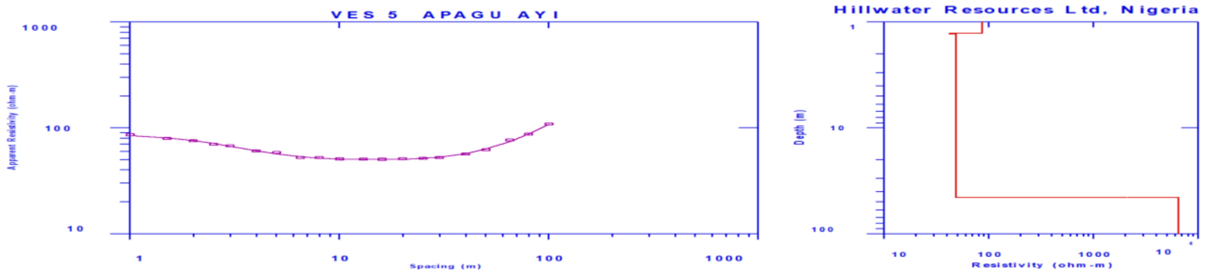
3.0 Results and Discussion

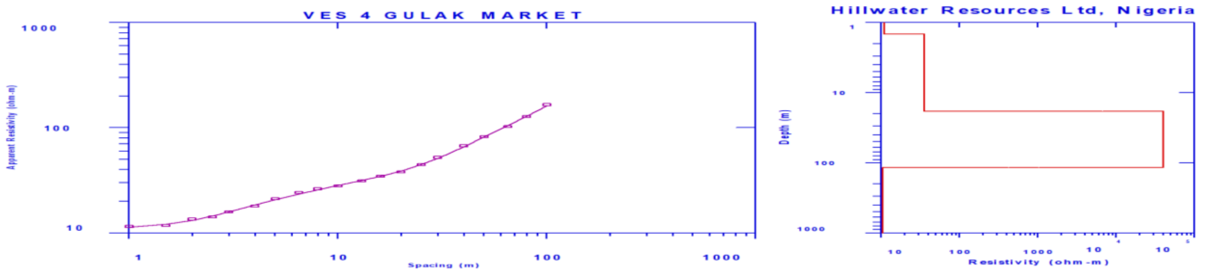
The results revealed that VES 1 has four layers with resistivity ranging from 12.20 to 53946.5 ohms-m with aquifer thickness of 2.17 to 4.66 m, with HK curve type, VES 2 has three layers with resistivity ranging from 10.84 to 5563.1 ohm-m, with aquifer thickness of 2.78, to 8.07 m, with HK curve type, VES 3 has three layers with resistivity ranging from 10.40 to 5579.4 ohms-m, with aquifer thickness of 0.139, to 13.42 m, with HK curve type, VES 4 has three layers with resistivity ranging from 10.86 to 40161.1 ohm-m, with aquifer thickness of 1.48, to 98.94 m with QK curve type, VES 5 has three layers with resistivity ranging from 42.35 to 6436.7 ohm-m, with aquifer thickness of, 0.0194 to 1.27 m, with HQ curve type, VES 6 has three layers with resistivity ranging from 29.77 to 73900.0 ohm-m, with aquifer thickness of 3.30, to 128.9 m, with HK curve type, VES 7 has three layers with resistivity ranging from 36.98 to 54670.2 ohm-m, with aquifer thickness of 0.554, to 115.7 m, with HK curve type, VES 8 has three layers with resistivity ranging from 9.66 to 3031.6 ohm-m, with aquifer thickness of 1.15, to 7.22 m, with HK curve type, VES 9 has four layers with resistivity ranging from 2.20 to 235.8 ohm-m, with aquifer thickness of 0.0910, to 2.24 m, with HK curve type, and VES 10 has four layers with resistivity ranging from 2.02 to 42627.3 ohm-m, with aquifers thickness of 0.384, to 155.6m, with AH curve type.

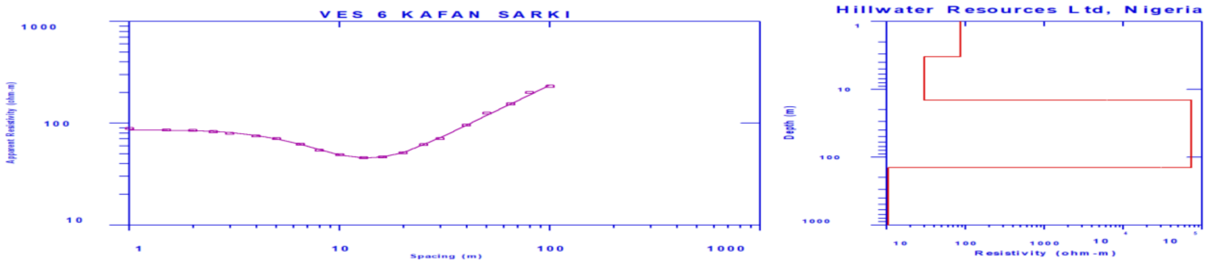


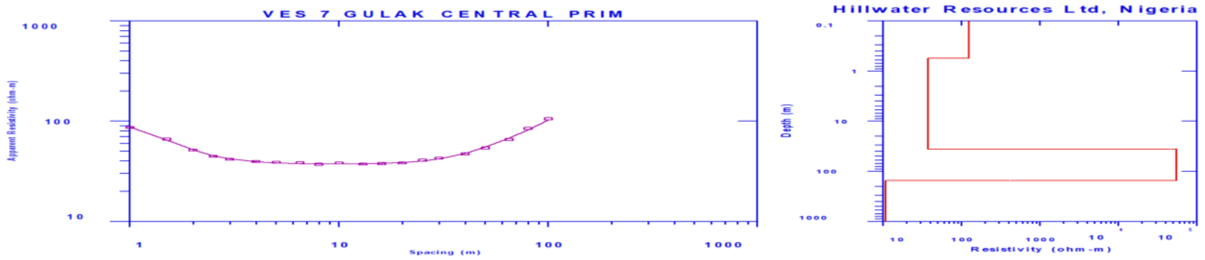


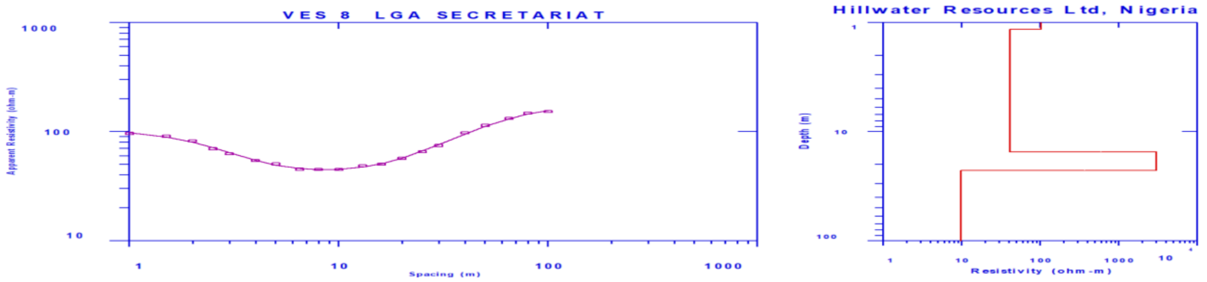


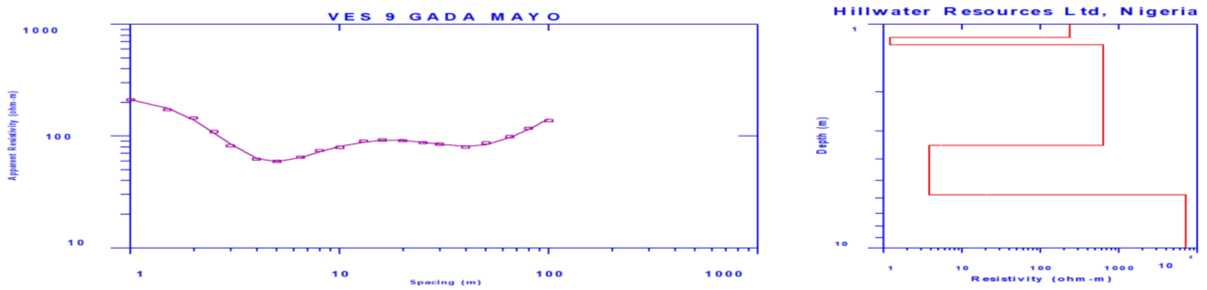

VES 5 APAGU AYI
Hillwater Resources Ltd, Nigeria
Apparent Resistivity (ohm-m)
Spacing (m)
Depth (m)
Resistivity (ohm-m)


VES 4 GULAK MARKET
Hillwater Resources Ltd, Nigeria
Apparent Resistivity (ohm-m)
Spacing (m)
Depth (m)
Resistivity (ohm-m)


VES 6 KAFAN SARKI
Hillwater Resources Ltd, Nigeria
Apparent Resistivity (ohm-m)
Spacing (m)
Depth (m)
Resistivity (ohm-m)


VES 7 GULAK CENTRAL PRIM
Hillwater Resources Ltd, Nigeria
Apparent Resistivity (ohm-m)
Spacing (m)
Depth (m)
Resistivity (ohm-m)


VES 8 LGA SECRETARIAT
Hillwater Resources Ltd, Nigeria
Apparent Resistivity (ohm-m)
Spacing (m)
Depth (m)
Resistivity (ohm-m)


VES 9 GADA MAYO
Hillwater Resources Ltd, Nigeria
Apparent Resistivity (ohm-m)
Spacing (m)
Depth (m)
Resistivity (ohm-m)

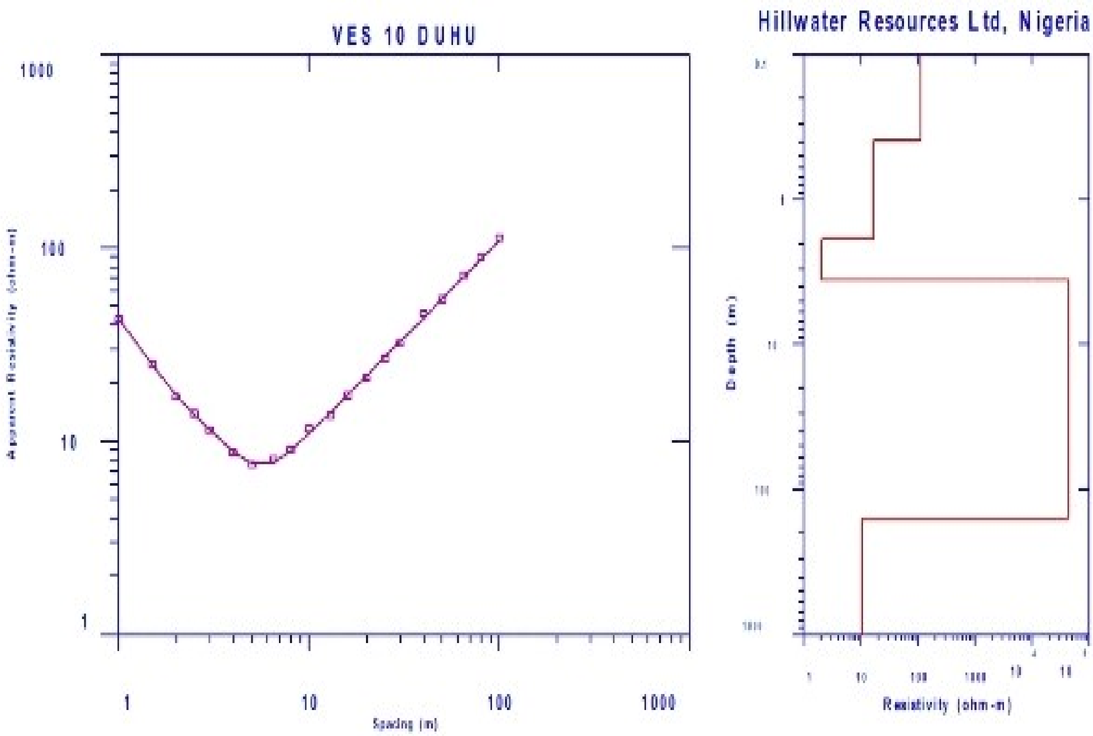


Fig. 4: Modelled resistivity curve types for VES 1–10

A summary of layer resistivity, thickness, longitudinal conductance, and transverse resistance for all VES points is presented in Table 1. These parameters were used to evaluate aquifer protective capacity and groundwater potential.

The electrostratigraphic interpretation indicates high groundwater potential at VES 1, 2, 3, 6, 7, 8, and 9. These locations are dominated by HK-type curves, which typically represent a conductive weathered layer underlain by a more resistive fractured basement, a favorable condition for groundwater accumulation. Moderate resistivity values combined with significant aquifer thicknesses (for example, 128.9 m at VES 6) suggest well-developed weathered/fractured zones capable of storing and transmitting groundwater. Moderate groundwater potential was identified at VES 5 and VES 10, characterized by HQ and AH curve types. These curve types indicate less favorable layering, often reflecting thinner weathered zones or discontinuous fractures. At VES 5, the extremely thin conductive layer (0.019 m) limits groundwater storage capacity despite moderate resistivity values. Low groundwater potential is observed at VES 4, which exhibits a QK curve type. This suggests a resistive near-surface layer overlying a conductive unit, a configuration often associated with compacted or clay-rich materials that restrict groundwater movement. The very high resistivity values (up to 40,161 Ωm) further indicate the presence of dry, compacted, or crystalline basement rocks with limited water storage capacity.

The dominance of HK curve types across the study area suggests a layered aquifer system typical of basement complex terrains, where clayey or sandy overburden overlies a saturated weathered/fractured basement. Strong resistivity contrasts between layers are reliable indicators of groundwater-bearing formations. The electrostratigraphic profiles (Figs. 5a–c) further illustrate the lateral continuity of these aquifer zones and help define optimal locations for borehole siting.

The findings from Gulak are consistent with other resistivity-based groundwater investigations across northeastern Nigeria. Dong *et al*. (2024) reported increasing aquifer thickness and confined aquifer conditions in parts of Yola South using Schlumberger VES, similar to the thick saturated zones observed at VES 6 and 7 in Gulak. Likewise, Sunday & Usman (2023) identified high groundwater potential in Mubi South where low resistivity and HK-type curves dominated, a pattern also evident at VES 2 and 3 in this study. Ayigun *et al*. (2025) further demonstrated that fractured and weathered basement zones with moderate resistivity values correspond to productive aquifers in Hong, Adamawa State, aligning with observations at VES 9 and 10 in Gulak. Dong *et al*. (2024) conducted a resistivity survey using the Schlumberger array across 17 VES points in Yola South, Adamawa State.

Their findings revealed increasing aquifer thickness from south to north. Confined aquifers dominant in the west, unconfined in the east. Use of transverse resistance and longitudinal conductance to estimate aquifer properties.

Gulak's VES points 6 and 7, which show thick saturated zones and HK curve types, align with the confined aquifer zones identified in western Yola.

Sunday & Usman (2023) used ABEM SAS 1000 Terrameter and Schlumberger array across five VES points in Mubi South, Adamawa State. Their study found VES 24 had high groundwater potential due to low resistivity and high conductivity. Other VES points showed poor potential due to high resistivity. Gulak's VES 2 and 3, which exhibit low resistivity and HK curve types, mirror the favourable conditions found in Mubi's VES 24. Ayigun *et al*. (2025) assessed groundwater potential using ten VES points in Hong, Adamawa State. They identified VES 5 to 10 as high-potential zones due to fractured/weathered basement and low resistivity. VES 1 to 4 had high resistivity and poor groundwater prospects. Gulak's VES 9 and 10 show similar resistivity contrasts and lithological layering, supporting their classification as moderate to high potential zones.

Across northeastern Nigeria, resistivity surveys consistently identify HK curve types and moderate resistivity values as indicators of viable aquifers. The Gulak study reinforces this regional pattern, validating the use of Schlumberger array and Interpex software for subsurface characterization. The correlation also highlights the importance of integrating resistivity data with geological mapping to improve groundwater exploration accuracy.

Subsurface Geology and Groundwater Potential in Gulak, Northeastern Nigeria to investigate the subsurface geology of Gulak and assess its groundwater potential using geoelectrical methods. Field Mapping identified local geology and topography to guide VES point selection.

Vertical Electrical Sounding (VES) of Ten VES points surveyed using ABEM SAS 1000 Terrameter with Schlumberger array. The data processed using Interpex software to derive resistivity and layer thickness. The findings revealed characteristics of VES points 3 to 4 subsurface layers with varying resistivity (2.02 to 73,900 ohm-m) and thickness (0.0194 to 155.6 m). Curve types of dominantly HK-type curves, indicating alternating conductive and resistive layers favourable for groundwater. Groundwater Potential were classified as high in VES 1,2,3,6,7,8, and 9; moderate in VES 5 and 10; and Low in VES 4. Electrostratigraphic Profiling of three profiles (A-A′, B-B′, and C-C′) were developed to visualize lithological variations and aquifer geometry across the study area.

Generally, the integration of VES interpretation and electrostratigraphic profiling demonstrates that groundwater occurrence in Gulak is strongly controlled by the thickness and continuity of weathered and fractured basement layers. Areas exhibiting HK-type curves, moderate resistivity values, and significant layer thickness are recommended as priority zones for groundwater development.

Table 1a: VES Location and Layer Parameters

VES No	Location	Coordinates (Lat, Long)	Curve Type	No. of Layers	Groundwater Potential	h_1 (m)	h_2 (m)	h_3 (m)	h_4 (m)	ρ_1 (Ωm)	ρ_2 (Ωm)	ρ_3 (Ωm)	ρ_4 (Ωm)
VES 1	GSSS Gulak	10°41′N, 13°24′E	HK	4	High	3.46	2.17	4.66	122.9	28.86	54.32	12.20	53946.5
VES 2	Jalingo Sec. Sch.	10°42′N, 13°25′E	HK	3	High	4.18	2.78	8.07	—	48.42	10.84	5563.1	—
VES 3	Behind Jalingo Prim. Sch.	10°43′N, 13°23′E	HK	3	High	0.139	9.55	13.42	—	40.02	22.76	5579.4	—
VES 4	Gulak Market	10°44′N, 13°25′E	QK	4	Low	1.46	17.07	98.94	—	10.86	35.75	40161.1	—
VES 5	Apagu Ayi	10°42′N, 13°26′E	HQ	3	Moderate	1.27	0.019	44.09	—	86.66	42.35	49.01	6436.7
VES 6	Kofan Sarki	10°43′N, 13°27′E	HK	4	High	3.30	11.19	128.9	—	86.57	29.78	73900.0	—
VES 7	Gulak Central Prim. Sch.	10°41′N, 13°28′E	HK	3	High	0.554	35.70	115.7	—	112.4	36.98	54670.2	—
VES 8	LGA Secretariat	10°45′N, 13°26′E	HK	4	High	1.15	14.25	7.22	—	102.9	40.64	3031.6	9.66
VES 9	Gada Mayo	10°44′N, 13°27′E	HK	3	High	1.14	0.091	2.24	—	235.8	1.20	637.0	3.83
VES 10	Duhu, Gulak	10°42′N, 13°24′E	AH	4	Low	0.38	1.48	1.69	155.6	110.8	16.61	2.07	42627.3

Table 1b: Derived Geoelectrical Parameters

VES No	σ_1 (S)	σ_2 (S)	σ_3 (S)	σ_4 (S)	T_1 (Ωm^2)	T_2 (Ωm^2)	T_3 (Ωm^2)	T_4 (Ωm^2)	Transverse Resistance (Ωm^2)	Longitudinal Conductance (S)
VES 1	0.120	0.0400	0.381	0.00228	99.99	118.0	56.91	6.635E+06	—	—
VES 2	0.086	0.0257	0.00145	—	202.7	30.21	44939.9	—	—	—
VES 3	0.0035	0.419	0.00241	—	5.60	217.5	74895.2	—	—	—
VES 4	0.134	0.477	0.00246	—	15.88	610.4	3.974E+06	—	—	—
VES 5	0.0147	4.596E−04	0.899	—	110.7	0.824	2161.3	—	—	—
VES 6	0.0381	0.376	0.00175	—	286.1	333.5	9.531E+06	—	—	—
VES 7	0.0045	0.0965	0.00212	—	67.85	1320.4	6.328E+06	—	—	—
VES 8	0.011	0.350	0.00238	—	118.5	578.8	21914.6	—	—	—
VES 9	0.00485	0.0075	0.00353	0.602	270.0	0.109	1431.5	8.86	—	—
VES 10	0.00347	0.0894	0.813	0.00365	42.68	24.69	3.51	6.634E+06	—	—

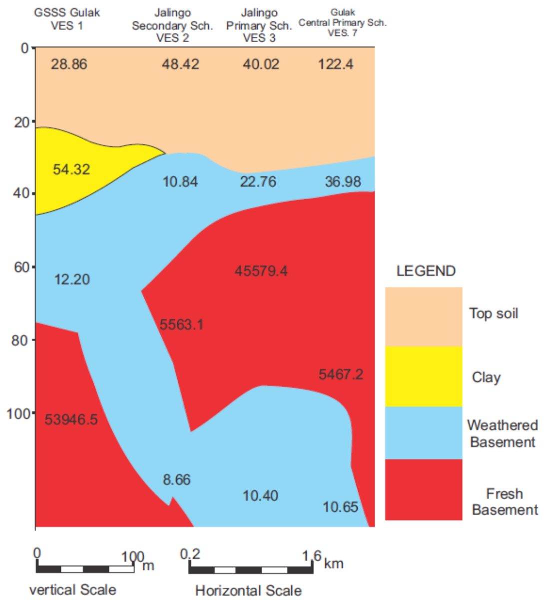


Fig. 5a: Electrostratigraphic Section of profile A-A′

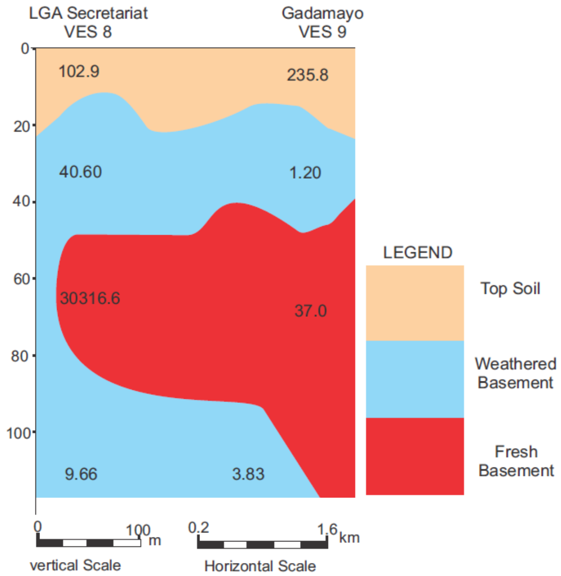


Fig. 5b: Electrostratigraphic Section of profile B-B′

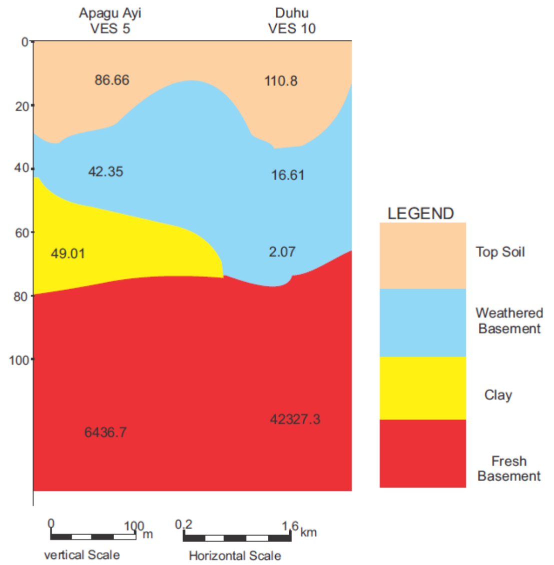


Fig. 5c: Electrostratigraphic Section of

4.0 Conclusion

This study successfully delineated groundwater-bearing zones in Gulak and its environs using Vertical Electrical Sounding (VES). The subsurface stratigraphy is highly variable, with three to four geoelectric layers identified across the ten VES locations. Resistivity values range from 2.02 to 73,900 Ωm, reflecting diverse lithological units such as clay, sandy formations, lateritic overburden, and fractured basement rocks.

The dominance of HK curve types at VES 1, 2, 3, 6, 7, 8, and 9 indicates alternating conductive and resistive layers, a characteristic signature of weathered and fractured basement aquifers favorable for groundwater accumulation. These locations exhibit moderate resistivity values and significant aquifer thickness, suggesting high groundwater potential. VES 5 and 10 show moderate potential due to thinner aquifer layers and less favorable geoelectric configurations, while VES 4 represents a low-potential zone characterized by very high resistivity and thick, dry subsurface layers.

The electrostratigraphic profiles (A–A′, B–B′, and C–C′) further enhanced subsurface interpretation by clearly delineating lithological boundaries and aquifer geometry, thereby improving the reliability of groundwater targeting. The results are consistent with similar resistivity-based studies conducted in northeastern Nigeria, confirming the effectiveness of the VES method with the Schlumberger array for groundwater exploration in basement complex terrains.

Based on the results and findings from the study, we proposed several recommendations. Consequently, borehole drilling and groundwater development should be prioritized at VES points 1, 2, 3, 6, 7, 8, and 9, as these locations exhibit favorable resistivity characteristics and substantial aquifer thickness, indicating a high potential for sustainable groundwater yield. Prior to full-scale development, pumping tests should be carried out to determine aquifer transmissivity, storage capacity, and sustainable yield, while hydrochemical analysis should be conducted to assess water quality and confirm its suitability for domestic, agricultural, or industrial use. VES points 5 and 10 may be considered for groundwater development only after further validation through additional geophysical investigations and test drilling, as their aquifer characteristics are moderate and less consistent. In contrast, VES point 4 should be avoided or given low priority for groundwater exploitation due to its high resistivity values and thick dry layers, which indicate poor groundwater potential.

5.0 References

Adamu, A. A., Umar, A. S., & Yusuf, M. A. (2019). Physiographic features and geomorphic evolution of the basement complex terrain in Northeast Nigeria. *Journal of Geography and Regional Planning,* 12m 5, pp. 85–97. https://doi.org/ 10.5897 /JGRP2019.0785

Adebayo, S. A., Yusuf, M. T., & Adamu, M. I. (2015). Geology and petrography of the rocks around Gulani area, northeastern *Nigeria. Journal of Geology and Mining Research*, 7, 5, pp. 45-56.

Adekeye, J. I. D., Akande, S. O., & Orazulike, D. M. (2017). Structural deformation and fracture systems in the Precambrian basement rocks of north-central Nigeria: Implications for tectonic evolution. *Journal of African Earth Sciences, 134*, 1–14. https://doi.org/10.1016/j.jafrearsci.2017.05.003

Adetunde, L. A., Ojo, M. S., & Bello, O. A. (2018). Geology and petrography of rocks around the Gulani area, northeastern *Nigeria. Geological Journal,* 53, 4, pp. 1280-1295. https://doi.org/10.1111/gj.12576

Akinyemi, F. O., & Eze, T. C. (2017). Climate and vegetation dynamics in the savannah regions of Nigeria: Implications for sustainable land use. *Journal of Environmental Science and Policy*, 38, 1, pp. 55–63. https://doi.org/10.1016/j.jespol.2017.06.003

Ayigun, S., Saidu, I., & Francis, K. F. (2025). Assessment of groundwater potential zones using electrical resistivity method in Hong, Hong Local Government Area of Adamawa State, North Eastern Nigeria. *International Journal of Applied and Advanced Engineering Research*, 9, 5, https://doi.org/10.70382/mejaaer .v9i5.0311

Bello, Y., & Adebayo, A. A. (2020). Analysis of rainfall and temperature changes in Gombe State, Northeastern Nigeria: Evidence of environmental influence. *FUDMA Journal of Sciences,* 4, 1, pp. 632–646. https://doi.org/10.33003/fjs-2020-0401-123

Dada, S. S. (2016). Geology and tectonic evolution of the Hawal Massif, northeastern Nigeria. *Journal of African Earth Sciences,* 124, pp. 123–135.

Davis, S. N., & Turk, L. J. (2011). *Structural geology applied to fractured aquifer characterization: Brittle versus ductile deformation*. In S. P. Neuman (Ed.), Crystalline aquifers and groundwater flow (pp. 45–67). Springer. https://doi.org/10.1007/978-3-642-20462-53

Dong, D. E., Ankidawa, B. A., Obiefuna, G. I., Seli, A. B., & Kwami, I. A. (2024). Delineation of groundwater potential using resis tivity method of Yola South, North-Eastern Nigeria. Nigerian *Journal of Environmental Sciences and Technology Research*. 1-,2, pp. 185-200.

Ekwueme, B. N., & Kröner, A. (2018). Geochronology and tectonic evolution of the Pan-African basement rocks in northeastern Nigeria: Insights from the Hawal Massif. *Journal of African Earth Sciences,* 145, 123–139. https://doi.org/10.1016/j.jafrearsci.2018.05.012

Ezekiel, K., Pwavodi, J., & Others. (2018). *Geo-Electrical Study over Gella and Environs, Northeastern Nigeria*. *Adamawa State University Journal of Scientific Research*, 6, 1, pp. 70–79. ISSN: 2251-0702.

Faye, S., Mendy, F., & Diallo, M. (2021). Electrostratigraphy and hydrogeochemical analysis of the coastal aquifers of Senegal: A case study in the Cap-Vert Peninsula. *Water Resources Research*, 57, 6, https://doi.org/10.1029/2020WR029051

Jekayinfa, S., Oladunjoye, M. A., & Doro, K. (2023). Imaging the distribution of bitumen contaminants in shallow coastal plain sands in southwestern Nigeria using electrical resistivity. *Environmental Earth Sciences*, 82, 2, https://doi.org/10.1007/s12665-022-10718-w

Lowrie, W. (2018). *Fundamentals of Geophysics* (3rd.ed) Cambridge University Press.

Nur A, Kujir AS (2011) Hydrogeoelectrical study in the North-eastern Nigeria part of Adamawa state. *Journal of Environmental hydrology,* 14, 19, pp. 1-7.

Odeyemi, S. O. (2016). Structural geology and tectonic evolution of the Nigerian basement complex: Insights from shear zones and fracture systems. *International Letters of Natural Sciences,* 58, pp. 16–28. https://doi.org/10.56431/p-m654ru

Okoye, C. O., & Igbokwe, P. M. (2018). Geomorphology and sediment transport in the Adamawa Plateau: Insights into river valley formation. *Journal of African Earth Sciences,* 148, 225–234. https://doi.org/10.1016/j.jafrearsci.2018.06.003

Oladapo, M. I., Akintorinwa, O. J., & Adepelumi, A. A. (2020). "Geophysical Investigation of Road Failures in the Basement Complex Areas of Southwestern Nigeria." Research *Journal of Applied Sciences, Engineering and Technology*, 2(, 6, pp. 631-637.

Olarewaju, V. O., & Rahaman, M. A. (2021). Petrology and geochemistry of the Nigerian Precambrian basement complex: Implications for tectonic evolution. *Journal of African Earth Sciences,* 181, 104223. https://doi.org/10.1016/j.jafrearsci.2021.104223

Rahaman, M. A. (2020). Stratigraphic review and tectonic implications of the Nigerian basement complex. *Journal of African Earth Sciences,* 172, 103983. https://doi.org/10.1016/j.jafrearsci.2020.103 9833

Reynolds, J. M. (2011). *An Introduction to Applied and Environmental Geophysics* (2nd Ed.). Wiley-Blackwell.

Rezaee, M. R., & Chehrazi, A. (2021a). Electro-sequence analysis and natural resources potential of a sedimentary basin. *Journal of Petroleum Exploration and Production Technology*, 11, 2, pp. 723-737.

Rezaee, R., & Chehrazi, A. (2021b). Electrostratigraphy and its role in subsurface characterization for resource exploration. *Journal of Petroleum Science and Engineering*, 196, 107682. https://doi.org/10.1016/j.petrol.2020.1076822

Serra, O. (2017). Electrofacies in reservoir characterization. Springer.

Sunday, A., & Usman, A. (2023). Investigation of groundwater potential zones using electrical resistivity method in Mubi South Local Government Area of Adamawa State, Northeastern Nigeria. European-American *Journal of Scientific Research*. https://doi.org/10.37745/ijp sr.167

Telford, W. M., Geldart, L. P., & Sheriff, R. E. (2019). *Applied Geophysics* (2nd Ed.). Cambridge University Press.

Tijani, M. N. (2023). Geology of Nigeria: Precambrian basement complex, sedimentary rocks, Cretaceous–Quaternary alluvial deposits. In *Landscapes and landforms of Nigeria* (p. 291). Springer.

Udi, E. M., Imasuen, O. I., Avwenagha, E. O., & Odokuma-Alonge, O. (2021). Examination of the Pan-African orogeny: Implications on the architecture of basement rocks in Igarra, Southwestern Nigeria. *International Journal of Earth Sciences Knowledge and Applications,* 3, 1, pp. 9–21. https:// doi.org/10.47277/IJESKA/3103

Uduma, I. C., Orunna, C., & Chinwendu, A. I. (2021). A review of the petrography and geochemical characteristics of the Pan-African granites in the Nigerian Precambrian basement complex. *Communication in Physical Sciences, 7, 4, pp.* 289–311. https://doi.org/10.4314/cjps.v 7i4.6

Villalobos, Alejandro & Espejel-García, Vanessa & Espejel-Garcia, Daphne & Rivas-Lobera, Lucio. (2019). Shallow Subsurface Stratigraphy Inferred from the Use of Vertical Electrical Soundings (VES) Survey in Central Chihuahua, Mexico. *Open Journal of Geology*. 09, pp.15-28. Doi:10.4236/ojg.2019.91002.

Declaration

Conflict of interest

No conflict of interest declared by the authors.

Availability of Data

Data shall be made available upon request.

Ethical Consideration

Not applicable

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Availability of Data

Both authors contributed to all aspects of the work

Author Contributions

Kamureyina Ezekiel conceived and supervised the study, led data interpretation, and drafted the manuscript. Titus Thama Kwanye, Brian Benjamin and Victor Vitalis conducted field mapping, VES data acquisition, and preliminary analysis. Idris Salihu Jauro correlated geological and geophysical results and prepared figures. Victor Gambo Na'Allah handled modeling, groundwater evaluation, and manuscript editing, ensuring scientific accuracy and publication readiness.