



Hydrogeophysical and Hydrogeological Characterization of Groundwater in Parts of the Benin Formation, Akwa Ibom State, Nigeria: Implications for Sustainable Water Resource Management

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Abstract

This study investigates the hydrogeophysical and hydrogeological characteristics of groundwater within Nigeria's Benin Formation, aiming to support sustainable water resource management. Through 80 Vertical Electrical Soundings (VES) using a Schlumberger array, the study identified three key subsurface layers: topsoil with high resistivity (1,200–5,000 Ωm), an unsaturated zone (1,500–2,000 Ωm), and main aquifer units (1,000–3,500 Ωm), predominantly composed of medium to coarse-grained sands and gravels. The dominant resistivity curve types are KH, HK and KQ (63%), which indicates a high-energy sedimentary terrain with mainly sandy formations or unconsolidated sediments with a mixture of clayey formations. These curve types indicate an alternating layer of conductive (clay) and resistive (sand) materials, reflecting a heterogeneous subsurface. This sand-clay intercalation provided for the unconfined and semi-confined auriferous units. The sandy aquifer units, located at depths between 20 and 75 meters, exhibit high groundwater potential, particularly in the central and northern parts of the Formation. Groundwater flow analysis indicated a predominant north-to-south direction, influenced by regional topography and subsurface lithology, with key recharge zones identified in the northern and central regions. The findings underscore the need for the protection of these recharge zones and careful management of extraction rates to maintain groundwater sustainability. This combined method, which uses both geophysical surveys and hydrogeological analysis, presents a complete framework for the management of groundwater in the Benin Formation.

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1.0 Introduction

Groundwater is a critical resource globally, particularly in regions where surface water availability is insufficient or unreliable (Ekanem *et al.*, 2020). In Nigeria, it provides approximately 65% of the total water supply (FMWR-NBS, 2019), playing an essential role in domestic, agricultural, and industrial activities (George & Thomas, 2023). However, the growing dependence on groundwater resources has led to increased pressure on available aquifers, often without adequate hydrogeological assessments to guide sustainable exploitation. The Benin Formation, which underlies much of Southeastern Nigeria, is a major groundwater-bearing unit with significant potential, but its hydrogeological characteristics remain underexplored (Ekanem *et al.*, 2022b).

Despite substantial investments in borehole development, a high failure rate persists due to poor hydrogeological planning and inadequate groundwater characterization (Amah *et al.*, 2012; George *et al.*, 2021a). Many boreholes are drilled without considering subsurface heterogeneity, resulting in low-yield wells and wasted financial resources. Additionally, seasonal fluctuations, poor recharge estimates, and the risk of contamination from anthropogenic activities further challenge the sustainable management of groundwater in the region.

To address these challenges, hydrogeophysical methods such as Vertical Electrical Sounding (VES) and Magnetotelluric (MT) surveys provide a non-invasive means of delineating aquifer structures and characterizing groundwater flow systems. These techniques offer insights into subsurface lithology, resistivity variations, and groundwater potential,

enabling more informed decision-making regarding water resource management. Additionally, integrating geospatial techniques such as GIS-based hydrological mapping enhances the understanding of groundwater recharge and discharge zones, providing a more comprehensive framework for sustainable water resource planning. This study seeks to evaluate the groundwater potential within the Benin Formation through an integrated approach that combines hydrogeophysical and hydrogeological methodologies. A key objective of this research is to delineate aquifer zones by utilizing Vertical Electrical Sounding (VES) and Magnetotelluric (MT) surveys, providing a detailed characterization of subsurface water-bearing formations. Additionally, the study aims to assess groundwater flow patterns and recharge mechanisms, offering insights into how water moves through the subsurface and the factors influencing its replenishment. Ultimately, the findings will be used to develop recommendations for the sustainable exploitation and management of groundwater resources, ensuring their long-term availability and optimal utilization within the region.

1.2 Geologic Setting

The geology of the study area, as indicated in Figure 1, is underlain by late Cretaceous to Quaternary sediments. The lowermost sediment is lateritic sandstone with minor shale of the Maastrichtian Nsukka Formation. Throughout the Paleocene to Early Eocene, a thick shale intercalated with sandstone and limestone was deposited (Imo Shale Formation) (Reyment, 1965), while in the middle of the Eocene semi-consolidated sandstone, siltstone and minor shale were deposited (Bende Ameki Formation). Since the Miocene-Oligocene grit and sand with intercalations of clay and lignite beds were

deposited, constituting the Ogwashi-Asaba Formation, they have influenced the regional stratigraphy. Overlying this Formation is a thick sequence of gravel, sand, silt, and clay constituting the Benin Formation, also known as the Coastal Plain Sands and alluvial ridges (Evans *et al.*, 2010).

1.3 Hydrogeologic Setting:

The area has three major hydrostratigraphic units, including the Alluvial Deposit, Coastal Plain Sand and Lower Sand Aquifers. The Coastal Plain Sand aquifer is the most extensive and is separated from the Lower Sand aquifer by the Imo Shale aquiclude. The aquifer is composed of sand, gravel, and sandstone with clay intercalations (Edet, 1993). The thickness of the aquifer varies between 35m in the north and 200 m in the south. The aquifer is considered to be semi-confined or unconfined, especially in the southern parts of the area (Ibuot *et al.*, 2024).

The main groundwater flow direction is from north to south into the Atlantic Ocean. There are also variations in the northeast-southwest and northwest-east directions into the Imo River and the Cross River (Esu *et al.*, 1999)

1.4 Study Location

The study area lies in Southeastern Nigeria, covering approximately 4,080.5 km², between latitudes 5°19'N and 4°36'N and longitudes 7°27'E and 8°19'E as in Fig. 1 below. The region experiences a humid tropical climate characterized by annual rainfall exceeding 300 cm and an average temperature range of 25°C to 28°C.

The Benin Formation dominates the geology of the area, comprising gravel, sand, silt, and clay intercalations. This Formation represents the primary aquifer system, with depths ranging from 35m in the north to over 200m in the south.

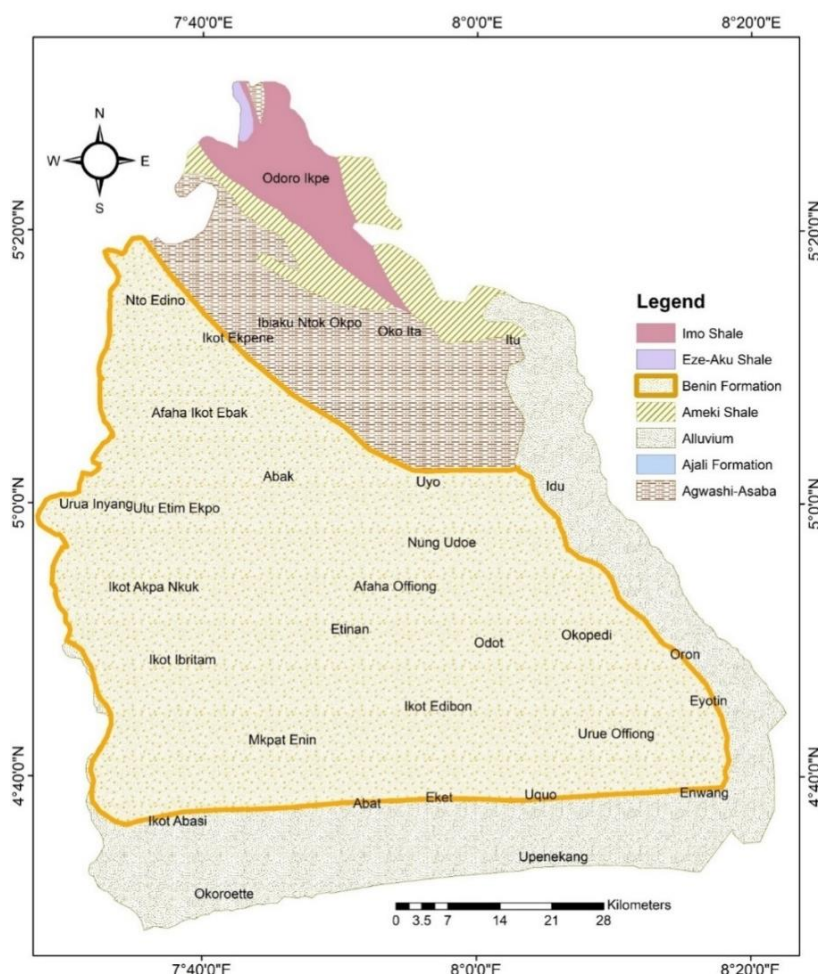


Fig. 1: Geologic Map of Akwa Ibom State highlighting the study area

2.0 Literature Review

2.1 Hydrogeophysical Techniques for Groundwater Assessment

Hydrogeophysical techniques have gained widespread use in groundwater exploration due to their ability to characterize subsurface geology non-invasively. The electrical resistivity method, particularly VES using the Schlumberger configuration, is widely used to estimate aquifer depth, lithology, and

groundwater potential (Abija & Nwankwoala, 2018). The method is based on the principle that different geological formations exhibit varying electrical resistivities, allowing for the differentiation of saturated and unsaturated zones (George *et al.*, 2020). Fig. 2 below shows the distribution of VES points with grid spacing of 5 minutes (Northing and Easting) and the borehole locations where well cuttings were obtained.

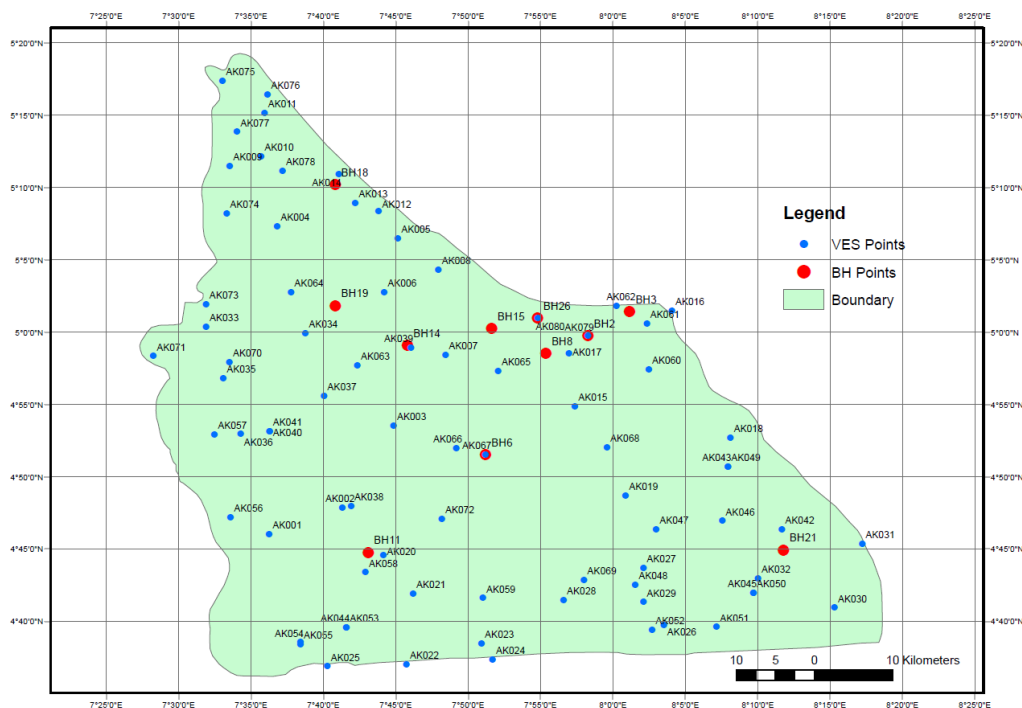


Fig. 2: Spatial view of VES and Borehole Locations

Recent studies in hydrogeophysical groundwater assessments have shown that resistivity methods are effective in identifying groundwater-bearing formations and distinguishing between confined, semi-confined, and unconfined aquifers (Akanbi, 2018). These methods provide critical parameters such as hydraulic conductivity and transmissivity, which are essential for estimating groundwater availability.

Magnetotelluric (MT) surveys, which utilize natural electromagnetic fields, offer a deeper penetration capability, making them suitable for delineating deep-seated aquifers and hydrogeological structures (El-Sayed *et al.*, 2023). The integration of MT with VES data

enhances subsurface characterization, improving groundwater resource assessments.

2.2 Groundwater Flow and Aquifer Characterization

Groundwater flow and aquifer dynamics influence the sustainability of water extraction. In sedimentary basins such as the Benin Formation, aquifers can be classified as semi-confined or unconfined, with significant spatial variations in porosity, permeability, and recharge rates (Edet, 1993). Hydraulic conductivity estimates derived from resistivity surveys and borehole data provide insight into aquifer productivity and groundwater movement (Ekanem *et al.*, 2022a).

Several studies have demonstrated that groundwater flow patterns in Southeastern Nigeria are controlled by topographic gradients and lithologic variations. Recharge zones are often located in areas of high permeability, while discharge occurs in lowland regions and river basins (Hassan *et al.*, 2019; George *et al.*, 2025). Proper delineation of these zones is necessary for sustainable groundwater management.

2.3 Groundwater Management Challenges in Nigeria

Despite efforts to improve groundwater infrastructure, challenges such as poor borehole performance, declining water levels, and contamination risks persist. Studies have reported that one in four public water points in Nigeria fail within the first year of completion, with over 21% of boreholes exhibiting seasonal fluctuations (NORM, 2019). The lack of

integrated water resource management (IWRM) strategies has exacerbated these challenges, emphasizing the need for a comprehensive hydrogeophysical approach (Fidelis *et al.*, 2020).

3.0 Methodology

This study employed a multidisciplinary approach integrating hydrogeophysical, hydrogeological, and geospatial methodologies to assess the groundwater potential within the Benin Formation. The research methodology was designed to systematically collect, process, and analyze data to delineate aquifer zones, evaluate groundwater flow dynamics, and recommend sustainable groundwater management strategies. Below is a chart showing the workflow of the methodology applied in this work (Fig. 3).

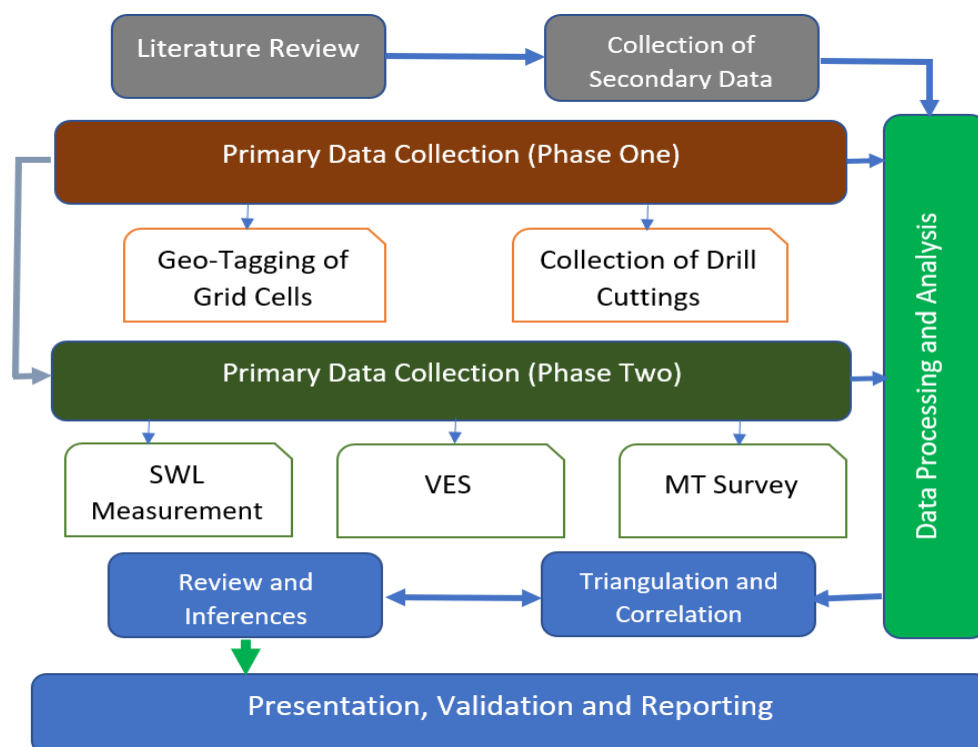


Fig. 3: Workflow of the methodology used in the study

3.1 Desk Study and Reviews

The study commenced with an extensive desk study and literature review, which involved analyzing existing geological, hydrogeological, and geophysical research related to the Benin Formation. Available borehole records, previous

resistivity and seismic surveys, groundwater level data, and topographic maps were reviewed to establish baseline information and identify knowledge gaps (Freeze & Cherry, 1979; Fetter, 2001). Additionally, an inventory of existing hydrogeological and geophysical data was

compiled to aid in selecting appropriate methodologies and determining areas requiring further investigation.

To understand the topographical variations influencing groundwater recharge and flow, Digital Elevation Models (DEMs) were extracted for 3D analysis. The DEMs provided insights into surface drainage patterns, elevation-induced groundwater distribution, and geomorphological influences on aquifer recharge (Jenson & Domingue, 1988). This step was instrumental in selecting suitable data collection locations and guiding hydrogeophysical surveys.

A grid system was established to determine data collection points and intervals, ensuring uniform spatial coverage and improving the resolution of hydrogeophysical and hydrogeological analyses (Milsom & Eriksen, 2011). Each field data point was geo-tagged using GPS technology to enhance accuracy, facilitate spatial correlation, and improve visualization.

3.2 Hydrogeophysical Surveys

Hydrogeophysical investigations were a core component of this study, providing subsurface resistivity variations essential for delineating aquifers. A total of 80 Vertical Electrical Soundings (VES) were conducted using the Schlumberger configuration, with electrode spacings ranging from 1 m to 500 m. The Schlumberger array, widely used in hydrogeological surveys, offers enhanced vertical resolution and deeper penetration, making it suitable for aquifer characterization (Zohdy *et al.*, 1974; Loke, 2000). The VES data facilitated the identification of subsurface water-bearing formations based on low-resistivity zones indicative of groundwater presence.

To investigate deeper aquifer structures beyond the penetration depth of VES, six Magnetotelluric (MT) soundings were performed. The MT method utilizes natural electromagnetic fields to probe deep geological

structures, making it a powerful tool for detecting deep-seated aquifers and their connectivity with shallower formations (Simpson & Bahr, 2005).

The data obtained from the VES and MT surveys were processed and interpreted using WINRESIST and INTERPEX software programmes. These software tools facilitated inversion modeling of resistivity data, allowing for accurate identification of stratigraphic layers, aquifer thickness, and water-bearing zones (Loke, 2000). The processed geophysical data were cross-validated with borehole lithologic logs to enhance interpretation accuracy (George & Thomas, 2024).

3.3 Hydrogeological Data Collection

Hydrogeological data were collected in Fig. 4 to assess groundwater flow characteristics and aquifer properties. Static Water Level (SWL) measurements were conducted in 23 boreholes to determine groundwater table fluctuations, hydraulic gradients, and potential recharge zones (Todd & Mays, 2005). These measurements provided critical insights into regional groundwater flow directions and aquifer dynamics.

To validate resistivity-based interpretations, lithologic logging was performed on 11 boreholes. The analysis of drill cuttings from these boreholes provided essential information on grain size distribution, lithologic composition, and aquifer material properties (Schlumberger, 1989). This ensured a direct correlation between geophysical resistivity variations and actual subsurface geological formations. Furthermore, hydraulic conductivity estimates were derived from geophysical interpretations using empirical relationships between resistivity and permeability (Fetter, 2001). These estimates were crucial for assessing aquifer transmissivity and potential groundwater yield.



Fig. 4: Hydrogeophysical and Hydrogeological data collection during fieldwork

3.5 Data Processing, Analysis, and Interpretation

The acquired VES apparent resistance data from the field techniques were first transformed into apparent resistivity ρ_a by the use of equation 1.

$$\rho_a = R_a \times GF \quad (1)$$

where GF is the geometric factor, which for the Schlumberger electrode layout is given by equation 2.

$$GF_s = \pi \cdot \left[\frac{(AB/2)^2 - (MN/2)^2}{MN} \right] \quad (2)$$

The one-dimensional (1D) VES data were interpreted qualitatively and quantitatively. First, the computed values of ρ_a were plotted against $AB/2$ on a log-log graph for each of the sounding points to yield the sounding curves. The curves were manually smoothed by averaging the two ρ_a values at the cross-over distances and eliminating extreme deviations while preserving the overall curve trend at locations where necessary. This in essence was to reduce mismatched errors in the computer-aided interpretation stage (Inyang *et al.*, 2023; Thomas *et al.*, 2020). Partial curve matching procedure was implemented on the smoothed

curves to generate the preliminary thickness and resistivity values of the subsurface layers penetrated by the transmitted current (Obiora *et al.*, 2016). These preliminary layer parameters were used as starting models in the computer modelling stage of the data interpretation, which in this study was implemented by the use of the WINRESIST software computer program (Thomas *et al.*, 2020). The WINRESIST software program uses the input starting models to compute a theoretical model and matches it with the field data to produce the final 1D model curves (Figs. 5 and 6), which showcase the subsurface resistivity variation pattern in the area of study as given in curve distribution in Fig. 7. The goodness of the matching is expressed in terms of the root mean square error (RMSE) (Ibuot *et al.*, 2019), which was generally less than 6 % in this study. The borehole lithological information was very handy in the refinement and interpretation of the detected layers. The true layer resistivity, thickness and depth were inferred from the final 1D model curves (Tables 1- 3). In Fig. 8, the magnetotelluric (MT) meter also generated the interpreted microresistivity profile of the subsurface. The diagram in Fig. 9 correlates the

nearby VES-MT resistivity of the study area while Fig. 10 shows correlation of VES Data with Well Cutting for ground-truthing. From the, depth to water table were estimated as shown in Fig.11.

Following data collection, multiple visualization and interpretation techniques were employed to analyze, integrate, and validate findings. The processed geophysical and hydrogeological data were used to plot pseudo-sections in 2D (Figs.12 and 13), and iso-resistivity 3D maps (Fig. 14). The resistivity sections with inferred lithology from Resistivity Values in the Study (Fig. 15), provided a two and three-dimensional visualization of subsurface stratigraphy, aiding in the spatial correlation of aquifer units (Dobrin & Savit, 1988). The sections graphically represented resistivity variations with depth, enhancing aquifer zone identification, while iso-resistivity maps were generated to show lateral resistivity variations, aiding in hydrogeological zoning and potential groundwater resource identification.

To ensure data reliability, data triangulation and correlation were performed. This process involved cross-checking hydrogeophysical findings with lithologic logs, piezometric data, and historical hydrogeological records, improving result accuracy and minimizing uncertainties (Loke, 2000).

By integrating these diverse datasets, this study provided a holistic assessment of the Benin Formation's groundwater potential, ensuring a scientifically robust approach to groundwater evaluation, exploration, and management.

4.0 Results and Discussions

4.1 Hydrogeophysical Interpretations

Tables 1-3 show the data acquired from the hydro-geophysical surveys carried out during the research. The analysis and interpretation delineate all prominent geo-electrical boundaries, revealing the thickness of the sediment beds within the most prolific point in

the survey area. The computerized analysis data is captured below. The VES points along each of the profiles were plotted to generate resistivity pseudo-cross sections, and the results of these sections were used to infer the subsurface lithology using data from the drill cuttings, as shown in Figure 14. A summary of the curve types is shown in Fig. 7.

The dominant curve type identified in the study area is the KH ($\rho_1 < \rho_2 > \rho_3 < \rho_4$) type curve, which accounts for 25% of the total occurrences. This curve is indicative of high-energy sedimentary terrain primarily composed of sandy formations or unconsolidated sediments. The prevalence of KH-type curves suggests substantial sand content, which is characteristic of high-yield aquifers. Next are HK ($\rho_1 > \rho_2 < \rho_3 > \rho_4$) and KQ ($\rho_1 < \rho_2 > \rho_3 > \rho_4$) type curves accounting for 19% each. These curve types suggest a mixture of sandy and clayey formations and indicate alternating layers of conductive (clay) and resistive (sand) materials, reflecting a heterogeneous subsurface. This sand-clay intercalation provided for the semi-confined to confined auriferous units found at deeper depths within the Benin Formation. These curves distribution typically exhibit high hydraulic conductivity, high transmissivity, and rapid groundwater flow, which are all hallmarks of high-energy aquifer systems and, therefore, ideal for groundwater extraction, supporting the potential for sustainable water resource development in the region. The distribution of these curve types provides valuable insights into the sedimentary environment and aquifer characteristics of the study area. These findings contribute to a better understanding of the subsurface hydrostratigraphy, which is essential for effective groundwater management and resource exploitation.

Table 1: Data for VES points 1 for 30 locations within the Akwa Ibom section of the Benin Formation

VES NO.	LOCATION	LATITUD E	LONGITUD E	NO. OF LAYERS	ρ_1 (Ω m)	ρ_2 (Ω m)	ρ_3 (Ω m)	ρ_4 (Ω m)	ρ_5 (Ω m)	h1 (m)	h2 (m)	h3 (m)	h4 (m)	d1 (m)	d2 (m)	d3 (m)	d4 (m)	Depth to Aquifer (m)	Curve Type
AK001	Ikot Ebak, Oruk Anam1	4.76708	7.60419	5	1514.7	4428.2	1586.1	1024.2	2053.1	1.2	2.2	21.9	46.6	1.2	3.4	25.3	71.9	51	KQH
AK002	Ibesit Numj Ikot Oruk Anam	4.79839	7.68839	5	713.6	482.8	246.8	1267	2470.7	6.2	20.9	41.5	72.4	6.2	27.1	68.6	141	48	QHA
AK003	Ntak Ibesit Oruk Anam	4.89228	7.74739	5	99.6	2570.9	263.8	1527.3	939.9	0.4	1.4	9.2	167.1	0.4	1.6	11	178.1	53	KHK
AK004	Essien Udim 1	5.12208	7.61328	4	1160.1	254.9	1443.9	598		2.6	8.2	63.9		2.6	10.7	74.7		64	HK
AK005	Essien Udim 2	5.10819	7.75228	4	363.4	1343	1746.5	857.3		1.5	18	111		1.5	19.5	130.5		68	AK
AK006	ABAK 1	5.04628	7.73650	4	157.7	40.9	1305.5	425		1.3	10.4	75.7		1.3	11.7	87.4		45	HK
AK007	ABAK 2	4.97419	7.80700	4	1477.5	143.3	501.9	1872.2		2.8	52.6	54.1		2.8	55.4	109.4		44	HA
AK008	Abak 3	5.07250	7.79878	4	372.7	116.9	598.4	57		2.5	6.5	51.4		2.5	9	60.5		46	HK
AK009	Ubon Ukwa, Obot Akara	5.19178	7.55875	5	728.3	1294.6	739.7	1288.3	577.9	1.2	2.3	13.7	70.8	1.2	3.5	17.2	88	73	KHK
AK010	Nto Eton, Obot Akara	5.20264	7.59483	5	635.7	159.2	915.7	397.7	283.5	2.5	6.8	76.6	88	2.5	9.3	88	173.9	76	HKQ
AK011	Nto Edino Housing Estate, Obot Akara	5.25317	7.59892	4	317.3	756.3	1400.5	538.9		2.6	15.9	84.5		2.6	18.5	103		63	AK
AK012	Abak Oko, Ikot Ekpene	5.13978	7.73017	4	388.7	121.7	2063.2	227.9		3.3	6.9	52.4		3.3	10.1	62.5		56	HK
AK013	Abiakpo Edem Idim, Ikot Ekpene	5.14908	7.70328	4	683.9	282.5	1860.7	757.8		1.3	7.4	70.7		1.3	8.7	79.4		35	HK
AK014	Ifuho, Ikot Ekpene	5.18269	7.68439	4	177.3	691.1	1210	981		1.6	8.4	89.9		1.6	10	100		38	AK
AK015	Ibesikpo 1	4.91500	7.95600	4	439	1964.7	940.2	607		2.2	32.8	77.3		2.2	35	112.3		29	KQ
AK016	Ibesikpo 2	5.02500	8.06800	4	214.8	53	22.2	277.2		1.7	4.5	69.7		1.7	6.2	75.9		31	QH
AK017	Ibesikpo 3	4.97553	7.94942	5	1167.7	237	2896.2	1231.1	851.1	1.9	3.9	20.8	63.5	1.9	5.8	26.6	90.1	26	HKQ
AK018	Ikot Edebe, Nsit Atai	4.87889	8.13528	5	1459.6	890.9	1971.2	953.4	1663.8	1.4	3.2	11.6	113.7	1.4	4.6	16.2	129.9	19	HKH
AK019	Ibakang, Nsit Atai	4.81142	8.01453	4	1707.7	714.9	1835.7	610.8		2.5	8.1	85.6		2.5	10.6	96.2		16	HK
AK020	Esa Ekpo, Mkpata Enin	4.74308	7.73553	4	1274.3	3014.7	1750.1	502.4		8.1	126.3	53.7		8.1	134.4	188.1		21	KQ
AK021	Technical college Mkpata Enin	4.69894	7.76978	4	623.5	173.3	415.3	829.2		2.9	9.6	136.1		2.9	12.6	148.6		22	HA
AK022	AKSU Road	4.61706	7.76217	4	236.6	1383.9	251.4	886.4		1	8	85.8		1	9	94.8		17	KH
AK023	Afaha Atai	4.64181	7.84850	4	226.9	1470.3	395.5	1099.6		1.3	43.1	72.7		1.3	44.4	117.1		31	KH
AK024	Abat	4.62264	7.86142	4	147.7	2968.2	1515	2513.4		3	21.7	88.3		3	24.8	113		33	KH
AK025	Ikot Akan	4.61494	7.67108	4	1445	2125.7	855.8	1126.4		3.5	8.9	151.1		3.5	12.4	163.5		29	KH
AK026	Ukwo, Eket	4.66217	8.05856	4	64.2	2351.2	127.4	869.2		6	36.7	156.4		6	42.7	199.1		22	KH
AK027	Ikot Nkebek	4.72800	8.03506	4	577.6	2998.8	529.4	327.6		2.7	22.4	127.7		2.7	25.1	152.8		31	KQ
AK028	Ikot Ekpene Udo	4.69189	7.94303	5	650.6	957.7	1895.4	612.6	1076.4	1.7	7.7	20.4	83.2	1.7	9.4	29.8	113	29	AKH
AK029	Ebughu	4.68917	8.03506	4	160.9	1297	2910	1791.8		10.2	30.6	138.8		10.2	40.7	179.5		29	AK

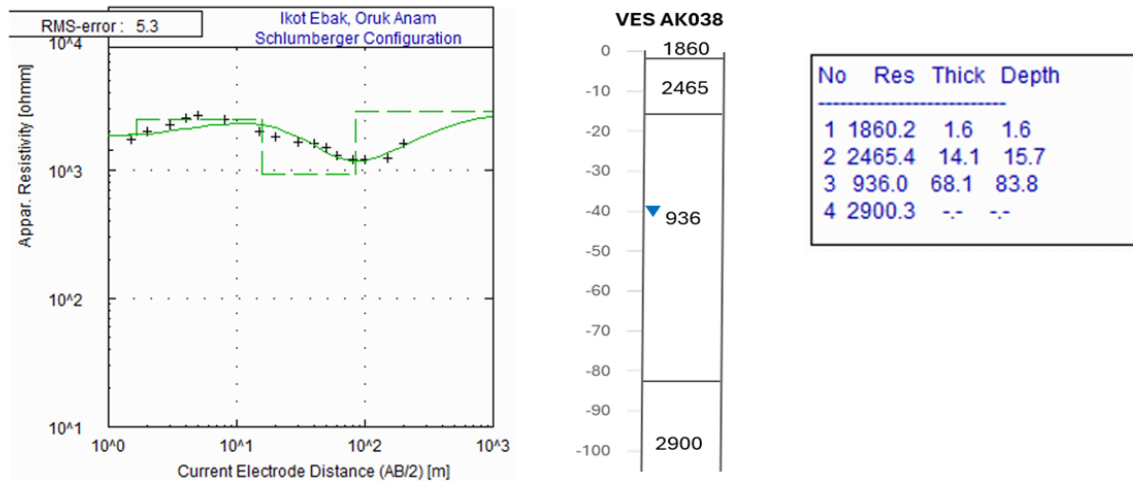
Table 2: Data for VES points for 31 to 60 locations within the Akwa Ibom section of Benin Formation

VES NO.	LOCATION	LATTITUD E	LONGITUD E	NO. OF LAYERS	ρ_1 (Ωm)	ρ_2 (Ωm)	ρ_3 (Ωm)	ρ_4 (Ωm)	ρ_5 (Ωm)	h1 (m)	h2 (m)	h3 (m)	h4 (m)	d1 (m)	d2 (m)	d3 (m)	d4 (m)	Depth to Aquifer (m)	Curve Type
AK031	Ewang, Mbo	4.75600	8.28700	4	545.6	194.1	1722.1	1077.3		2.5	12.1	208.2		2.5	14.6	222.8		19	HK
AK032	Obio Iyata	4.71600	8.16700	5	264.4	66	2174.1	1080.4	786.6	2.2	3.5	45.7	125.7	2.2	5.7	51.5	177.1	20	HKQ
AK033	Ika	5.00639	7.53150	4	524.6	212.6	1828.7	226.6		6.4	11.2	83.3		6.4	17.6	100.8		87	HK
AK034	Etim Ekpo 1	4.99900	7.64569	4	259.7	505.7	896.4	1292.6		12.4	59.9	136.2		12.4	72.2	208.5		49	AA
AK035	Etim Ekpo 2	4.94728	7.55128	4	227.2	806.9	1212.1	340.4		2.3	21	151.9		2.3	23.4	175.3		50	AK
AK036	Ukanafun 1	4.88333	7.57119	4	191.8	1181.2	906.8	1584		11.9	28.6	134.6		11.9	40.5	175.2		50	KH
AK037	Ukanafun 2	4.92669	7.66728	4	214.7	1256.1	307.5	135.1		1.3	31.3	104.8		1.3	32.6	137.4		54	KQ
AK038	Ikot Ebak, Oruk Anam	4.79945	7.69845	4	1860	2465.4	936	2900.3		1.6	14.1	68.1		1.6	15.7	83.8		41	KH
AK039	Oruk Anam 2	4.98237	7.76740	4	701.2	349	2890	1940		10.6	88.8	207.1		10.6	99.4	306.5		34	HK
AK040	Oruk Anam 3	4.88600	7.60450	5	105.6	2402.8	268.6	1521	952.8	0.4	1.5	9.4	168.4	0.4	1.9	11.3	179.7	44	KHK
AK041	Ikot Udo Mbang, Ukanafun	4.88600	7.60453	4	609.5	1322.4	130.9	4245.9		2.5	52.1	57.6		2.5	54.6	112.3		47	KH
AK042	VES 14	4.77269	8.19442	4	1375.7	2953.7	257	900.6		18.8	33	58.3		18.8	51.8	110		24	KH
AK043	VES15	4.84489	8.13219	4	1632.1	2996	524	1579.4		1.5	34.8	81.7		1.5	36.3	118		48	KH
AK044	Nduk, Ikot Abasi	4.65961	7.69292	4	779.2	2999	709.5	412.3		0.4	8.8	86.1		0.4	9.2	95.4		23	KQ
AK045	Oruefong Oruko	4.69936	8.16161	4	2098.3	1247.4	815.3	291.8		1.5	61.5	115.8		1.5	63	178.8		44	QQ
AK046	Utine Ndung, Okobo	4.78253	8.12589	4	498.2	2846.3	540.2	1385.9		0.9	32.5	53.3		0.9	33.4	86.7		54	KH
AK047	Nsit Atai	4.77300	8.04958	4	1402.6	744.4	155.4	2676.5		1.4	15.7	49.9		1.3	17	66.9		34	QH
AK048	Ikot Okpudo, Nsit Ubium	4.70894	8.02550	4	1422.2	1897.1	315	770.6		9.1	19.4	66.6		9.1	28.6	95.1		47	KH
AK049	Okobedi, Okobo	4.84489	8.13219	4	647	2837.7	858.7	1500		1.1	26	137.4		1.1	27.1	164.5		48	KH
AK050	Udung Uwe, Urue Offong Oruko	4.69936	8.16161	4	1181.3	2895	632.5	1205.6		5.5	15.3	163.6		5.5	20.8	184.4		39	KH
AK051	Akwata, Esit Eket	4.66042	8.11925	4	255.4	909.5	307.8	1441.9		4.4	18.3	68.8		4.4	22.7	91.5		19	KH
AK052	Ikpa Town, Esit Eket	4.65700	8.04500	4	225.8	2337.9	1050.1	484		1.4	103.9	26		1.4	105.3	131.3		20	KQ
AK053	Eket (Girls Secondary School)	4.65960	7.69290	5	63.7	1584	165.2	983	163.8	0.6	3.5	10	61	0.6	4.1	14.1	75.1	25	KHK
AK054	Nduke, Ikot Abasi	4.64270	7.64000	5	1011	2953.6	603	1087.5	398.9	1	7.6	56.5	24.4	1	8.6	65.1	89.5	29	KHK
AK055	Atan Ikpe, Edemaya Clan, Ikot Aba	4.64000	7.64000	5	672.9	2538.9	901.7	294.7	1184.9	1.1	4.5	27.1	90.5	1.1	5.6	32.7	123.2	28	KQH
AK056	Inen Ekeffe, Oruk Anam	4.78672	7.55947	4	1100.8	2680.5	1597.5	378.4		1.2	8.1	50.3		1.2	9.3	59.6		49	KQ
AK057	Ikot Udo Obobo, Ukanafon	4.88250	7.54108	4	1371.2	2677.8	483.6	1012		1	43.6	34.2		1	44.6	78.9		54	KH
AK058	Ikot Ntot, Mkpato Enin	4.72328	7.71489	4	1300.5	2893.1	843.1	443.1		2.5	5.7	72.3		2.5	8.2	80.5		28	KQ
AK059	Nung Oku Ekanem, Onna	4.69378	7.85011	4	924.4	1776	538.6	1144		1.1	15.4	108.8		1.1	16.5	125.2		22	KH
AK060	Ikot Akan Uran	4.95750	8.04111	4	1234.6	1668.1	988	1500		1.7	20.2	172.6		1.7	21.8	194.6		22	KH

Table 3: Data for VES points 61 to 80 locations within the Akwa Ibom section of Benin Formation

VES NO.	LOCATION	LATTIUD E	LONGITUD E	NO. OF LAYERS	ρ_1 (Ωm)	ρ_2 (Ωm)	ρ_3 (Ωm)	ρ_4 (Ωm)	ρ_5 (Ωm)	h1 (m)	h2 (m)	h3 (m)	h4 (m)	d1 (m)	d2 (m)	d3 (m)	d4 (m)	Depth to Aquifer (m)	Curve Type
AK061	Anakpa, Uran	5.00989	8.03900	4	318.1	577.9	1202.3	834.6		0.7	39.5	31.9		0.7	40.2	72.1		42	AK
AK062	Idu Uran Estate	5.03058	8.00386	4	292.3	2581.6	1039.5	627.3		1.8	52.6	77.8		1.8	54.4	132.2		25	KQ
AK063	Nnkak Abak, Ukanafon	4.96197	7.70558	4	1397.3	541.4	2169.4	811.7		4.1	7.1	84.8		4.1	11.2	96		47	HK
AK064	Nto Udo, Midim, Essien Uduim	5.04650	7.62917	4	969.2	1895.3	1079	781.1		3.5	68.6	19.9		3.5	72.1	92		52	KQ
AK065	Ekasara, Ekpene Ukpa, Etinan	4.95508	7.86786	4	1020.2	2874.5	1959.8	1319.3		3.1	18.7	114		3.1	21.8	135.8		20	KQ
AK066	Ndon Eyo1, Etinan	4.86647	7.81944	4	329.5	118.2	1416.3	779.2		1.2	3.9	164.5		1.2	5.1	169.7		28	HK
AK067	Ikot Abasi 1, Ekinan	4.85872	7.85328	4	936	1912.9	1297.9	760.6		1.1	14.8	65.9		1.1	16	81.9		27	KQ
AK068	Ibesikpo Asutan	4.86731	7.99308	4	1254.6	2966.3	329.4	1001.9		1.1	31.6	61.1		1.1	32.6	93.7		24	KH
AK069	Mbio Etene, Nsit Ubium	4.71475	7.96653	4	1326.4	2631.4	1076	740		3.1	16.1	113		3.1	19.2	132.2		33	KQ
AK070	Omum Unyam, Etim Ekpo	4.96533	7.55831	4	490.7	2091.2	1390.3	890.2		1.4	81.6	79.5		1.4	82.9	162.4		75	KQ
AK071	Ikot Uko, Ika	4.97250	7.47069	4	437.3	1800.9	2904	630.8		1.8	12.8	91.3		1.8	14.7	105.9		88	AK
AK072	Ikot Akpan, Obio Okot, Etinan	4.78481	7.80283	4	1293.6	163.4	2453.3	1207.5		9	10.5	131.3		9	19.5	150.9		33	HK
AK073	Ikot Udo, Ika	5.03189	7.53147	4	479.8	1506.7	2549.6	717		1	13.1	64.1		1	14.1	78.2		94	AK
AK074	Ikot Umossien Odorikot, Essien U	5.13653	7.55506	3	1904.1	2684.5	877.3			7	61.2			7	68.2			72	K
AK075	Usaka Annang, Obot Akara	5.29031	7.55028	4	1016	1989.8	753.1	964.6		1.5	45.2	48.9		1.5	46.6	95.6		69	KH
AK076	Obot Akara	5.27439	7.60217	4	469.5	1045.3	2606.4	1496.4		1.2	20.9	120		1.2	22.1	142.1		73	AK
AK077	Ikot Ideh, Obot Akara	5.23117	7.56692	4	265.9	2893.8	1653.8	1014.4		1.8	12.3	102.8		1.8	14.1	116.9		73	KQ
AK078	Notridam Sec Sch. Esseim Udium	5.18603	7.61956	4	1946.5	1303.9	2577.1	1420.6		6.5	4.5	93.5		6.5	11	104.5		70	HK
AK079	Mbiabon Ikot Ntem, Uyo	4.99575	7.97131	4	272.6	42.7	2695.7	119.9		2.8	2	95.5		2.8	4.8	100.3		54	HK
AK080	Obon Street Off IBB, Uyo	5.01675	7.91342	4	882.6	417.3	994.5	1932.1		2	68.4	45.5		2	70.4	115.8		48	HA

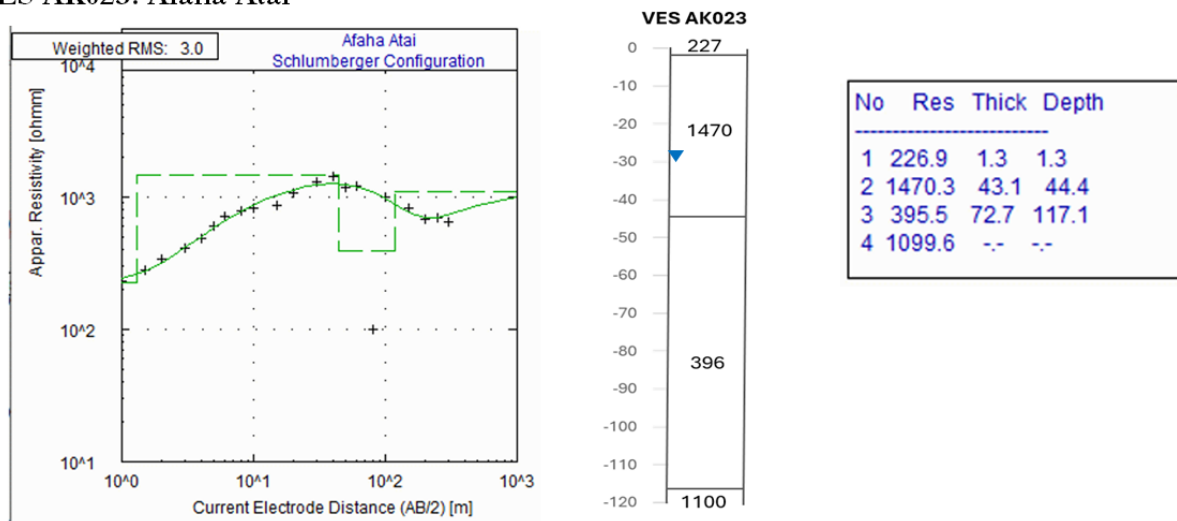
VES AK038: Ikot Ebak, Oruk Anam



S/N	(Ωm)	Thickness (m)	Depth (m)	Geologic description
1.	1860	1.6	1.6	Poorly sorted wet lateritic topsoil
2.	2465.4	14.1	15.7	Medium to coarse grained sand with minor clay intercalations (not saturated)
3.	936.0	68.1	83.8	Small to medium grained sand with minor clay intercalations (saturated at 41m)
4.	2900.3			Conglomerate (saturated)

Fig. 5: Representative VES Curve and their tabular interpretation for Ikot-Ebak, Oruk Anam LGA

VES AK023: Afaha Atai



S/N	(Ωm)	Thickness (m)	Depth (m)	Geologic description
1.	226.9	1.3	1.3	Poorly sorted topsoil
2.	1470.3	43.1	44.4	Medium grained sand (saturated at 29m)
3.	395.5	72.7	117.1	Fine grained sand(saturated)
4.	1099.6			Small to medium grained sand (saturated)

Fig. 6: Representative VES Curve and their tabular interpretation for Afaha Atai

4.2 Magnetotelluric Interpretations

The Magnetotelluric (MT) profile reveals a stratigraphic sequence characterized by alternating sand and mud (clay/shale)

formations. This variation in lithology is reflected in the apparent resistivity values, which range from 0.13 Ωm to 0.67 Ωm across the geo-electric profile. The resistivity

distribution, as depicted in the legend to the right of the profile, provides insights into the subsurface composition and potential hydrogeological significance of the identified layers.

The lowest resistivity values, ranging from 0.13 Ωm to 0.25 Ωm (represented by deep blue to

purple), are indicative of clay/shale formations. These fine-grained materials are known for their low permeability and high water retention capacity, suggesting that these layers act as aquitards, restricting vertical fluid movement. Their presence plays a crucial role in controlling groundwater flow and may serve as confining layers for underlying aquifers.

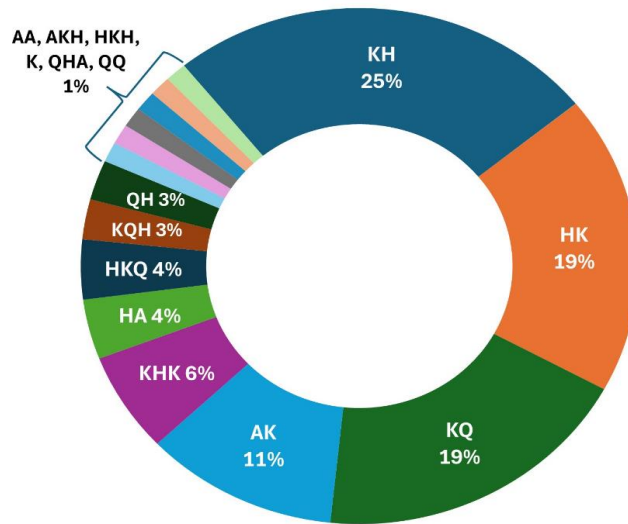


Fig. 7: VES curves distribution

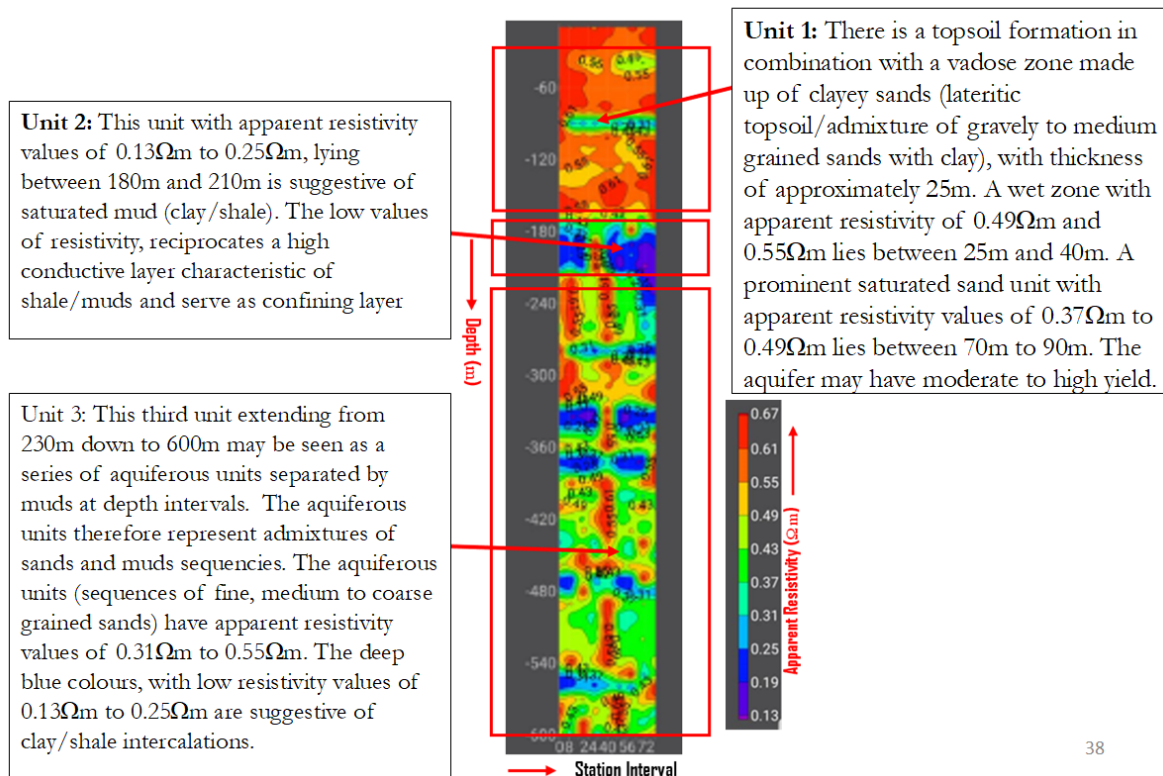


Fig. 8: MT Profile Interpretation Ikot Abasi 1, Etinan

In contrast, resistivity values between $0.26 \Omega\text{m}$ and $0.55 \Omega\text{m}$ (light blue to yellow) correspond to saturated sand formations. These sands, being more permeable, are likely to function as potential aquifer units, facilitating groundwater storage and transmission. Their saturation suggests the presence of significant groundwater reserves, making them important targets for groundwater exploration and extraction. The highest resistivity values, ranging from $0.56 \Omega\text{m}$ to $0.67 \Omega\text{m}$ (orange to red), are associated with compacted sands and clayey sands. The presence of compacted sands indicates reduced porosity and permeability, which may influence groundwater movement within these units.

Clayey sands, on the other hand, suggest a partial mixture of fine-grained sediments, potentially leading to localized variations in hydraulic conductivity.

Overall, the observed resistivity variations provide critical insights into the subsurface heterogeneity, aquifer potential, and hydrogeological framework of the study area. The delineation of clay/shale layers, saturated sands, and compacted sands offers valuable information for groundwater resource assessment and sustainable management strategies.

VES AK067: Ikot Abasi 1, Etinan

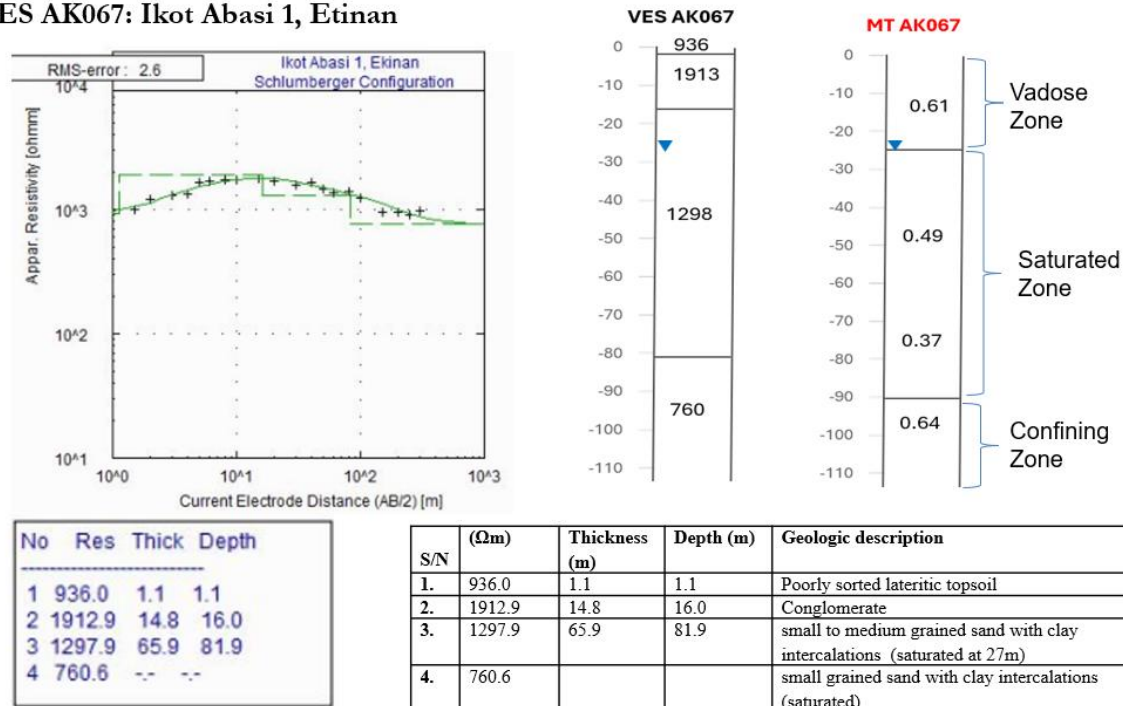


Fig. 9: VES-MT correlation and their tabular interpretation

The analysis of the Magnetotelluric (MT) profile and the geo-electrical layered model derived from Vertical Electrical Sounding (VES) data reveals a strong correlation between both methods, highlighting their reliability in subsurface characterization. The MT profile delineates the lateritic topsoil extending to a depth of approximately 25 meters, whereas the combined first and second geo-electrical layers from the VES model yield an average depth of

16 meters, forming the vadose zone. This variation in depth estimates is likely due to differences in resolution and sensitivity of the two geophysical techniques in detecting subtle changes in subsurface material properties (George et al. 2021a). Further comparison of the models suggests a close agreement in estimating the depth to the water table. The MT profile places the water table at approximately 25 meters, while the VES-derived geo-electrical

model estimates it at 27 meters, resulting in a minimal discrepancy of 2 meters. This slight variation can be attributed to differences in measurement techniques, data processing, or localized heterogeneities in the subsurface conditions (George *et al.*, 2021b).

The MT model further indicates that the saturated zone extends from 25 meters to 90 meters, with a particularly prolific aquiferous layer occurring between 70 meters and 90 meters. In comparison, the VES model identifies the saturated zone as extending from 27 meters to 80 meters, resulting in a 10-meter difference in estimated depths. Despite this variation, both models consistently highlight the presence of a significant groundwater-bearing formation at

greater depths, reinforcing the reliability of these geophysical methods in aquifer delineation.

Overall, the close agreement between the MT and VES models supports their effectiveness in characterizing the hydrogeological framework of the study area. While minor variations exist in the estimated depths of key subsurface features, these discrepancies are within acceptable limits and do not compromise the overall interpretation of the groundwater system (George *et al.*, 2021a; Obioanwu *et al.*, 2011). The integration of both methods provides a more comprehensive understanding of subsurface conditions, which is crucial for groundwater exploration and sustainable resource management.

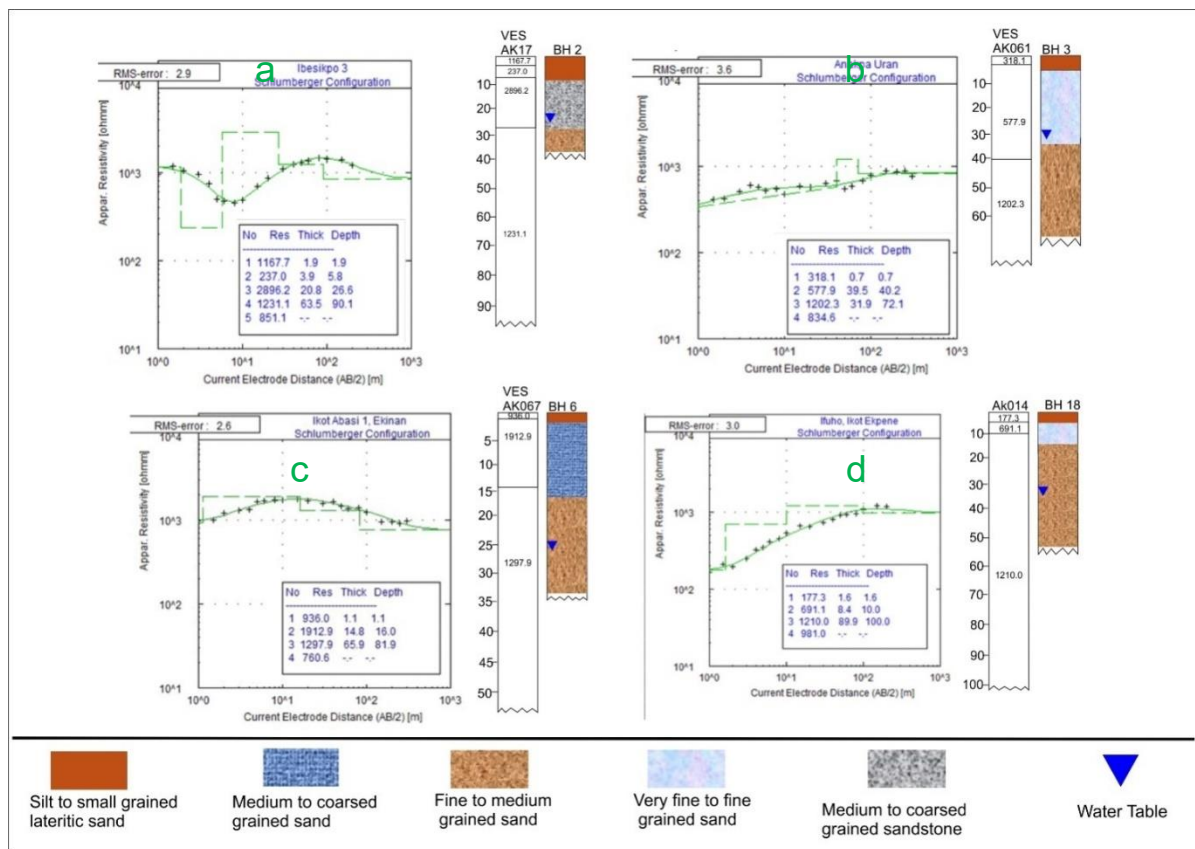


Fig. 10: Correlation of VES Data with Well Cutting for ground-truthing

The comparison of Vertical Electrical Sounding (VES) data with well-cutting logs, as illustrated in Figures 10a, 10b, 10c, and 10d, demonstrates a strong correlation between the two datasets across the study area. The close resemblance between the VES profiles and the lithologic logs

from nearby boreholes reinforces the reliability of the VES method in subsurface characterization. This consistency highlights the effectiveness of VES in identifying key geological features such as unconfined and confined aquifers, as well as impermeable

layers, as previously noted by Ogunge *et al.* (2010).

Despite the inherent limitations of the VES method, such as the potential suppression of thin or low-resistivity layers, the overall interpretation remains robust (Ikpe *et al.*, 2022). The integration of VES data with borehole lithologic logs enhances the accuracy of subsurface investigations, mitigating some of the challenges associated with individual geophysical techniques. This combined approach is particularly valuable in hydrogeological studies, where accurate delineation of aquifer systems is critical for groundwater exploration and sustainable management. The findings confirm that VES, when supported by borehole log data, provides a reliable and cost-effective means of assessing subsurface hydrostratigraphy, making it a practical tool for groundwater resource evaluation and exploitation (Ekanem *et al.*, 2024).

4.3 Depth to Aquifers

The depth to the top of aquifers, as illustrated in Fig. 11, exhibits significant variability across the study area, ranging from as shallow as 16 meters at location AK-019 to as deep as 91 meters at AK-073. This considerable variation underscores the heterogeneous nature of the Benin Formation, reflecting differences in sediment deposition, lithologic composition, and structural influences on groundwater occurrence. The variability in aquifer depth has important implications for groundwater accessibility and extraction feasibility (George *et al.*, 2021a).

In areas where aquifers occur at shallower depths, such as AK-018 at 19 meters and AK-019 at 16 meters, groundwater is more readily accessible, making these locations potentially more economical for water extraction. The reduced drilling depth in these areas minimizes costs associated with borehole development,

pump installation, and long-term maintenance. Conversely, locations with deeper aquifers, such as AK-073, require more extensive drilling efforts and higher energy input for groundwater abstraction, which may impact the overall feasibility of water resource development in those regions.

The observed differences in aquifer depths further emphasize the need for site-specific hydrogeological assessments when planning groundwater exploration and development. Mechanistic understanding the spatial distribution of aquifers within the Benin Formation is crucial for optimizing well placement, ensuring sustainable yield, and managing groundwater resources effectively (Umoh *et al.*, 2022). The findings reinforce the importance of integrating geophysical surveys with borehole data to refine aquifer characterization and improve decision-making in groundwater management strategies.

4.4 Aquifer Potential

The evaluation of aquifer potential across the study area reveals distinct variations in groundwater yield based on resistivity characteristics and lithologic composition. High-yielding aquifers are identified at locations such as AK-001, AK-005, and AK-025, where high resistivity values correspond to sandy lithology. The presence of these permeable sand formations suggests excellent groundwater storage and transmission properties, making these sites highly suitable for groundwater extraction (Umoh *et al.*, 2022). Given their significant aquifer potential, these locations could serve as reliable sources for sustainable water supply, supporting both domestic and commercial water needs. In contrast, moderate-yielding aquifers are observed at locations such as AK-002 and AK-004, where resistivity values indicate the presence of sand or clayey sand layers.

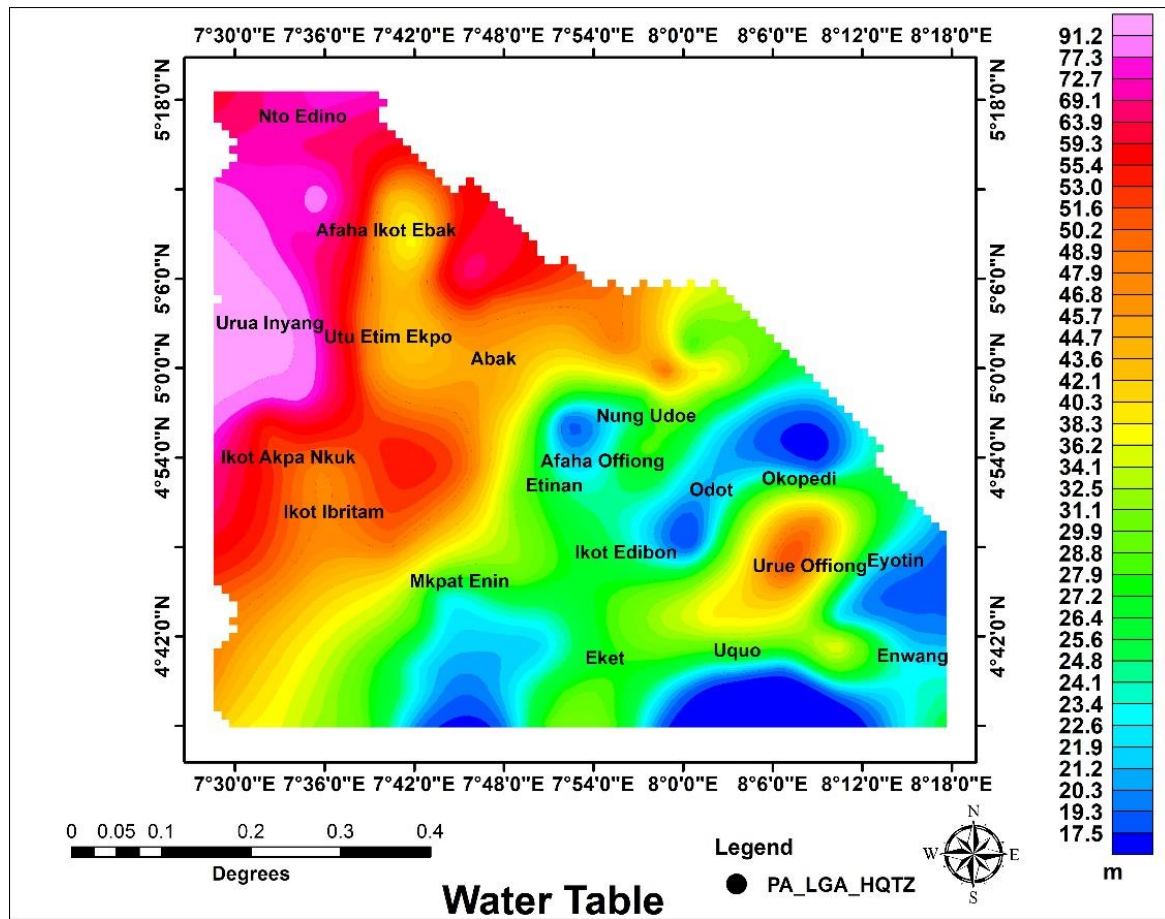


Fig. 11: Depth to water table within the study area

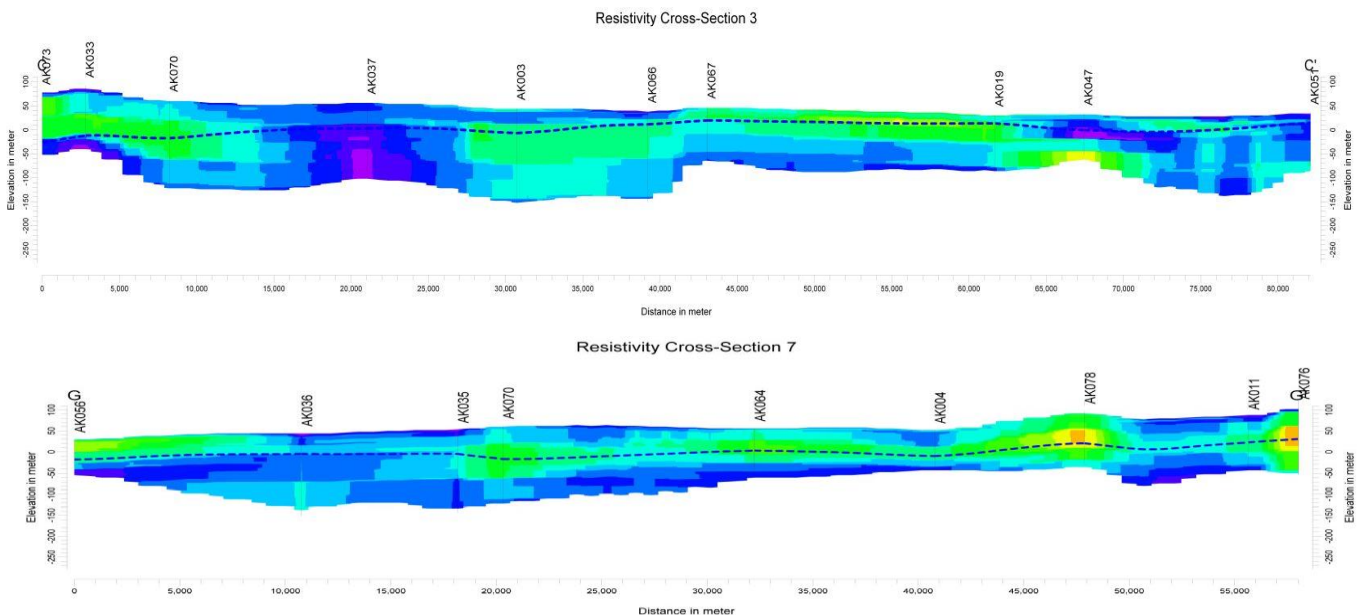


Fig. 12: Pseudo cross section for Resistivity to Lithologic Section

While these formations are capable of storing and transmitting groundwater, their yield is expected to be moderate compared to the high-

yielding zones. These aquifers may be more suitable for localized water supply needs, such as small-scale irrigation or community water

projects, where demand is relatively lower. At the other end of the spectrum, low-yielding aquifers are identified at locations such as AK-006 and AK-007, where low resistivity values indicate clay-rich layers. The high clay content in these formations significantly reduces permeability, restricting groundwater movement and limiting the potential for water extraction

(George, 2020). As a result, these areas are less suitable for groundwater development due to their poor aquifer quality and low yield potential. The variation in aquifer productivity across the study area highlights the importance of site-specific hydrogeological assessments when planning groundwater exploration and utilization.

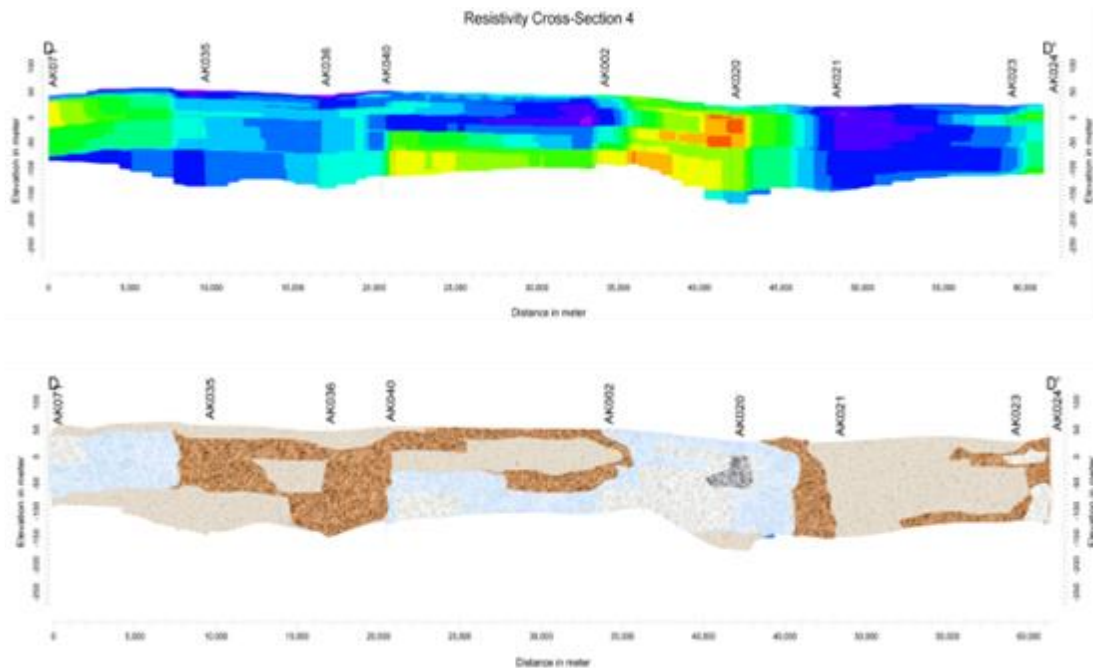


Fig 13: Pseudo cross for Resistivity to Lithologic Section

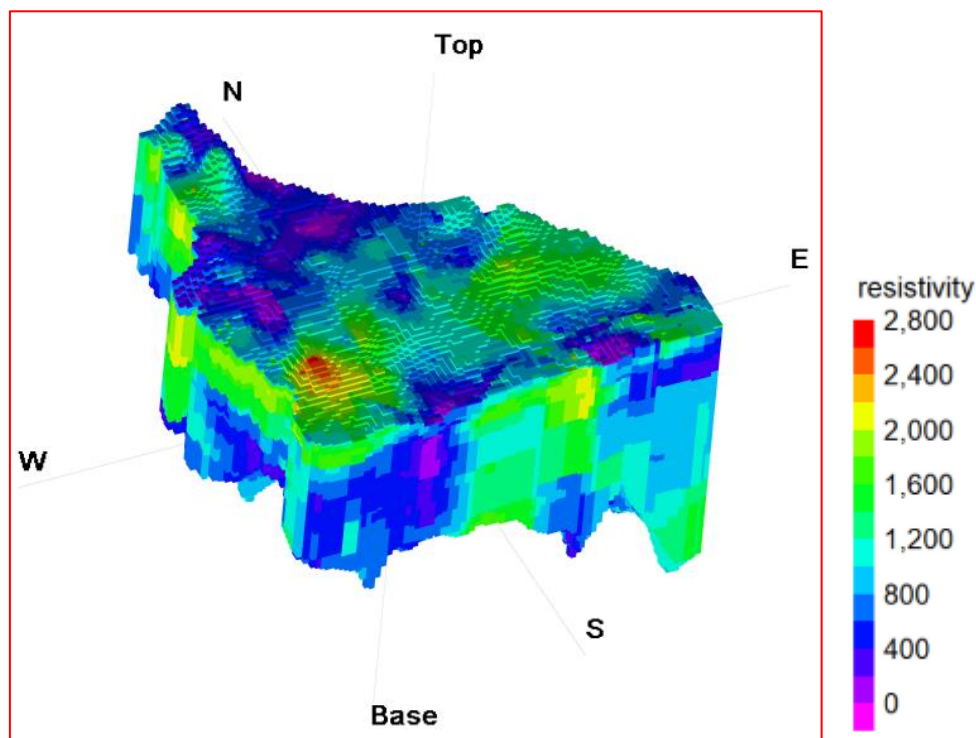


Fig. 14: 3D resistivity Section of the Study Area

Apparent resistivity Colour Ramp (Ωm)	Apparent resistivity rang (Ωm)	Inferred lithology	Litho. Symbol
	2600 – 3000	Conglomerate to consolidated sandstone or siltstone	
	2200 – 2599	Coarse grained sand to pebbly sand	
	1800 – 2199	Coarse grained sand	
	1400 – 1799	Medium grained sand	
	1000 – 1399	Small to medium grained sand	
	600 – 999	Small grained sand	
	200 – 599	Silty to small grained sand	
	1 – 199	Clay, mottled mud, shale, salt intrusion,	

Fig. 15: Inferred Lithology from Resistivity Values in the Study

The 3D resistivity section provides a comprehensive view of the subsurface resistivity distribution, integrating data from all the longitudinal cross-sections. This model enhances the understanding of lithologic variability, groundwater potential, structural influences, and vulnerabilities within the study area. The study area exhibits a heterogeneous resistivity distribution, indicating variations in lithology, aquifer characteristics, and groundwater flow patterns. The top layer (surface sediments) is characterized by apparent resistivity values ranging from 999 to 2199 Ωm , corresponding to coarse- to medium-grained sands, which dominate the unsaturated zone. Deep-seated low-resistivity zones cover resistivity values of 1 to 199 Ωm with localized high-resistivity anomalies (2600 to 3000 Ωm), particularly in the central and western regions, suggesting consolidated sandstone and conglomerates. The Benin Formation exhibits a well-developed aquifer system with localized variations in groundwater potential, structural controls, and vulnerability to contamination.

5.0 Summary and Conclusion

The study reveals significant lithological and hydrogeological variations across the northwest to southeast regions, characterized

by a diverse subsurface environment influenced by different geological processes and depositional settings. The detailed analysis of VES and MT profiles has identified key geological units and aquiferous layers, indicating zones with higher permeability and better groundwater storage capabilities. The NW region predominantly features poorly sorted lateritic topsoil transitioning into conglomerates and medium to small-grained sands. The central region shows an increased presence of sorted materials with higher energy depositional environments. While the southeast exhibits a mix of well-sorted sands and occasional conglomerates influenced by fluvial and marine processes.

These variations are critical for understanding the hydrogeological potential and for planning sustainable groundwater management strategies. The integration of VES and MT data has provided a comprehensive understanding of the subsurface geology, confirming the presence of prolific aquiferous layers and highlighting the reliability of these geophysical methods.

The study's findings are essential for groundwater management, geotechnical assessments, and environmental studies in the region, offering valuable insights for

developing effective water resource management strategies and ensuring the long-term sustainability of groundwater supplies.

Overall, this research enhances the scientific understanding of the Benin Formation's hydrogeological framework, introduces advanced methodology for subsurface investigation and zonation, and provides valuable insights for sustainable groundwater management. These contributions not only advance academic knowledge but also have practical implications for water resource management in Akwa Ibom State and other regions with similar geological settings.

This research provides several significant contributions to the body of knowledge in groundwater science and resource management, particularly within the context of sedimentary basin environments in Nigeria and similar geological settings.

Advanced Hydrogeological Zonation Methodology: This study has demonstrated the effective use of resistivity and depth data from Vertical Electrical Sounding (VES) for detailed hydrogeological zonation. This methodology can be adapted and applied to other sedimentary basins, contributing to more precise groundwater resource assessments.

The research has revealed significant spatial variability in the hydrogeological properties of the Benin Formation, highlighting the diverse nature of aquifer systems within the study area. By identifying zones with varying resistivity and depth profiles, the study provides a nuanced understanding of the subsurface, which is crucial for targeted groundwater exploration and exploitation. This zonation approach adds a new dimension to the understanding of sedimentary aquifers in the region, which has traditionally relied on more generalized assessments.

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