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Hydrogeophysical Characterization of Aquifers in Parts of Central Cross River State, Nigeria: Insights from the Ikom-Mamfe Embayment

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Abstract

Groundwater is the primary source of potable water in Central Cross River State, Nigeria. This study investigates the hydrogeological and hydrogeophysical characterization of aquifers to optimize groundwater extraction in parts of the Ikom-Mamfe embayment. The research aims to evaluate the aquifer systems, address potential challenges and contamination risks limiting potable water exploration and exploitation, and propose sustainable groundwater management strategies for ensuring water availability and quality. To achieve these objectives, hydrogeological and hydrogeophysical methods were integrated to enhance groundwater exploration, mitigate contamination risks, and support sustainable water resource management. Key aquifer properties were assessed to determine groundwater availability, utilizing geophysical techniques such as Vertical Electrical Sounding (VES) and Electrical Resistivity Tomography (ERT) to delineate aquifer boundaries and identify zones with high groundwater potential. A multidisciplinary approach incorporating geophysical surveys, borehole data analysis, and GIS-based spatial mapping was employed. Field investigations at 35 VES locations identified two principal aquifer systems. The first, the Eze-Aku Sandstone aquifer, is located on the western and northwestern flanks, covering Ekori, Ugep, and most of Abi Local Government Area (LGA). The second, the Asu River Sandstone and Limestone aquifer, spans Abini, Adim, Idomi, Mkpani, Nko, Lebang, and Inyima in Yakurr LGA, as well as Ofat, Ofodua, and other parts of Obubra LGA. Substantial variations were observed in aquifer resistivity (9.5 to 446.5 Ωm), thickness (1.1 to 111.3 m), and depth (1.1 to 119.7 m). Transmissivity values peaked at 67.82 m²/day in high-potential zones, demonstrating a strong correlation between groundwater availability and geological formations. The study further revealed the presence of shallow aquifers (<30 m) and deeper aquifers (>60 m), with the latter exhibiting higher yields and better protective capacity. Emphasizing the importance of strategic groundwater management, this study recommends prioritizing deep aquifer drilling in high-transmissivity zones. The findings provide valuable insights for policymakers, hydrologists, and water resource managers, contributing to the broader goal of sustainable groundwater development in Central Cross River State.

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1.0 Introduction

Groundwater serves as the primary source of drinking water for billions of people worldwide, particularly in regions where surface water is unreliable due to seasonal fluctuations, pollution, and climate change (Alley *et al.*, 1999; Fetter, 2001). In sub-Saharan Africa, groundwater is increasingly relied upon due to rapid population growth and the declining availability of surface water (MacDonald *et al.*, 2012). However, the sustainable management of groundwater resources remains a major challenge due to over-extraction, contamination, and the lack of accurate aquifer characterization. Without a proper understanding of aquifer properties, water resource planning and management efforts remain inefficient (Edet & Esu, 1998).

Central Cross River State, Nigeria, experiences growing demand for groundwater due to urban expansion, agricultural activities, and industrialization. However, inadequate aquifer characterization has led to challenges in groundwater development and pollution risk assessment. Hydrogeophysical methods have emerged as essential tools for groundwater exploration, offering a non-invasive approach to delineating subsurface formations, evaluating aquifer properties, and assessing groundwater vulnerability (Telford *et al.*, 1990; Ehirim & Ebeniro, 2014).

In hydrogeophysical studies, Vertical Electrical Sounding (VES) and Electrical Resistivity Tomography (ERT) are commonly used for subsurface investigations to determine resistivity distribution, which enables the characterization of properties such as layer saturation, thickness, and boundaries. VES provides resistivity data that can be used to estimate aquifer depth, thickness, and transmissivity (Loke, 2004), while ERT, a subsurface profiling technique, records hundreds of subsurface data points to produce monochrome or multicolored two-dimensional cross-sections of the earth, measuring both horizontal and vertical variability of soil arrangement over several meters (Alam *et al.*, 2024). Although these techniques have been widely applied globally, their full potential remains underutilized in Nigeria’s Central Cross River State, where groundwater development is critical (Inim *et al.*, 2020; George & Thomas, 2023).

This paper explores the use of geo-electrical (VES and ERT) data in combination with borehole drill data to delineate aquifer systems in the Ikom-Mamfe embayment, as captured within NGSA Sheet 314 (also described as Ugep Sheet) in parts of Cross River State. Furthermore, it presents correlation features between formation resistivities and hydrogeological parameters to guide future geo-electrical data interpretation and serve as a quality control measure. The findings aim to improve the success rate of groundwater abstraction and enhance access to potable water in the study area.

1.1 Theoretical Background and Global Research

The use of hydrogeophysical methods in groundwater studies has been extensively documented. In India, Kumar *et al*. (2018) applied electrical resistivity and seismic methods to assess aquifers in semi-arid regions, demonstrating that integrating multiple geophysical techniques enhances aquifer delineation. In the United States, Nyquist and Corry (2002) incorporated geophysical imaging techniques with hydrological modeling, improving groundwater resource assessments. Similarly, South African researchers, such as Jolly *et al*. (2015), have used resistivity surveys to map aquifer variability across different geological settings, emphasizing the need for localized hydrogeophysical studies.

Among the most commonly used geophysical methods are Vertical Electrical Sounding (VES) and Electrical Resistivity Tomography (ERT), both of which have proven effective in characterizing subsurface formations and groundwater storage conditions (Loke, 2004; Fetter, 2001; Alam *et al*., 2024). Studies by Telford *et al*. (1990) and Ehirim & Ebeniro (2014) have shown that electrical resistivity methods can effectively map subsurface heterogeneity and identify groundwater-bearing zones. These techniques have been successfully applied in diverse geological settings, including sedimentary (George *et al*., 2016; Uwa *et al*., 2019), crystalline (Obiora *et al*., 2015), and coastal aquifer systems (Obiora *et al*., 2016).

In Nigeria, hydrogeophysical investigations have largely focused on coastal and deltaic regions, where groundwater development is crucial for water supply and irrigation. Edet & Esu (1998) conducted a hydrogeophysical study in the Niger Delta, demonstrating the influence of lithologic variations on groundwater occurrence and quality. Similarly, Olasehinde (2010) explored groundwater potential in Nigeria's basement complex terrains, highlighting the role of hydrogeophysical integration in water resource assessment. The growing application of these methods underscores their importance in groundwater studies, particularly in regions where site-specific investigations are essential for sustainable water management.

1.2 Aquifer Characterization and Hydraulic Properties

Hydraulic properties such as transmissivity, storativity, and specific yield play a vital role in understanding groundwater movement and sustainability. George *et al*. (2011a) conducted an integrated study on groundwater reserves in frequently exploited unconfined aquifers in the Niger Delta, employing a combination of geophysical and laboratory techniques to estimate aquifer transmissivity. Their findings revealed that hydraulic conductivity varies significantly with lithologic composition, emphasizing the importance of localized hydrogeophysical studies in groundwater management.

A related study by George *et al.* (2011b) in Akwa Ibom State examined aquifer hydraulic parameters using a combination of surficial geophysical techniques and laboratory measurements on core samples. Their work provided a robust assessment of pore fluid interactions, permeability, and aquifer storage capacity, which are critical factors in sustainable groundwater exploitation. The findings supported the use of geophysical models in estimating aquifer properties, a method that has been widely adopted in hydrogeological research.

Further investigations by George *et al*. (2016a) applied geohydraulic pore pressure gradient models to assess hydrogeological units in coastal sectors of Akwa Ibom State. Their study demonstrated the effectiveness of hydrogeo-physical integration in predicting groundwater availability and potential recharge zones. Similarly, George *et al.* (2016b) analyzed textural variations and electrical conductivity of Quaternary hydrolithofacies, providing insights into the relationship between lithologic texture and groundwater flow dynamics. These studies contribute significantly to the understanding of aquifer heterogeneity and groundwater productivity in sedimentary formations.

In Central Cross River State, increased groundwater demand due to population growth, agricultural expansion, and inadequate surface water resources has intensified the need for comprehensive hydrogeophysical assessments. However, limited studies have explored the hydrogeophysical characteristics of aquifers in this region. Previous research has largely relied on geochemical analysis (Edet, 2004) or geological mapping (Olasehinde, 2010), which do not provide sufficient insights into aquifer transmissivity, depth variations, and resistivity properties. The absence of integrated hydro-geophysical investigations has led to uncertainties in groundwater potential assessments, making it difficult to implement effective water resource policies.

This study aims to assess the hydrogeophysical characteristics of aquifers in Central Cross River State using Vertical Electrical Sounding (VES) and Ground Penetrating Radar (GPR). The primary objectives are to characterize the aquifers in the study area, analyze aquifer productivity through transmissivity and resistivity variations, and evaluate groundwater vulnerability based on protective capacity and aquifer depth. To achieve these objectives, a total of 35 VES stations were surveyed using the Schlumberger electrode configuration with the ABEM SAS 1000 Terameter. GPR surveys were conducted using 250 MHz and 500 MHz antennas to detect shallow fractures and determine aquifer geometry. The data were processed and analyzed using WINRESIS software, classifying the resistivity curve types into H, A, KH, and QH formations.

This study represents one of the first hydrogeophysical assessments of aquifers in Central Cross River State, offering critical insights into groundwater availability, transmissivity variations, and vulnerability to contamination. The findings will provide empirical data necessary for improving water resource management policies in the region, ensuring the sustainable development and utilization of groundwater. By integrating VES and Electrical Resistivity Tomography (ERT) techniques, this study contributes to a more comprehensive understanding of the region’s hydrogeology and supports informed decision-making for groundwater development and conservation.

1.4 Study Location

The region lies between latitudes 5°30'N and 6°15'N and longitudes 7°45'E and 9°00'E and is part of the Central Cross River State, South-South Nigeria. It experiences a sub-equatorial climate, with annual rainfall exceeding 300 cm and temperatures ranging from 21.9°C to 31.7°C. The study area is situated within the Ikom-Mamfe Embayment, a geological setting that significantly influences groundwater occurrence and quality. The geology comprises formations of the Eze-Aku Group, Nkporo Shales, and basaltic intrusions, which host aquifers with substantial water potential. However, hydrogeochemical interactions within these formations often affect water quality, making it unsuitable for human consumption. Figure 1 shows the geology map of the study area.

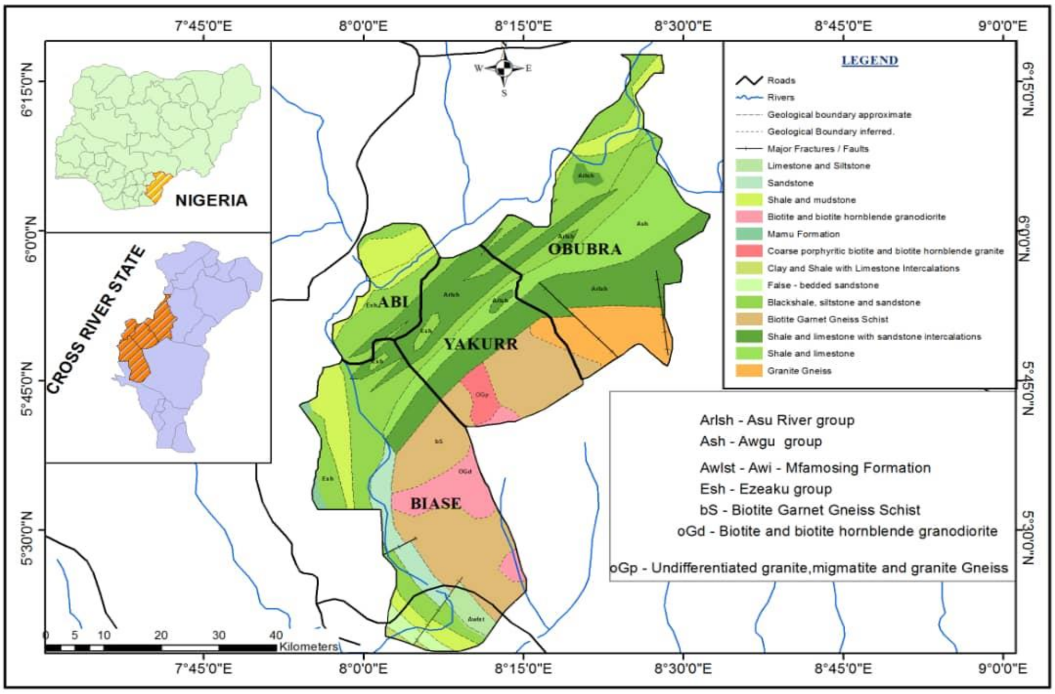

Fig. 1: Geology Map of the Study Area

2.0 Methodology

This study employs a systematic and multidisciplinary approach to investigate groundwater resources in Central Cross River State, Nigeria. The methodology integrates desk-based research, field surveys, laboratory analysis, geophysical techniques, and spatial data analysis to ensure a comprehensive and reproducible assessment of aquifer properties. The primary goal is to characterize aquifers, evaluate groundwater productivity, and assess vulnerability, ensuring the sustainability of groundwater resources in the study area.

The research began with an extensive desk study to establish a strong theoretical foundation. Relevant literature, including peer-reviewed academic publications, technical reports, and government documents, was reviewed to gain insights into groundwater resources, hydrogeological properties, and geophysical methods applicable to the study area. Foundational studies by Edet and Esu (1998), Alley *et al*. (1999), Fetter (2001), and MacDonald *et al.* (2012) provided critical information on regional and global groundwater challenges, aquifer characterization techniques, and sustainable water management practices. Previous studies on groundwater potential, aquifer productivity, and hydrogeophysical assessments in sedimentary basins and tropical environments were evaluated to ensure that this research builds upon existing knowledge while addressing identified gaps.

To provide a spatial framework for hydrogeophysical investigations, a base map of the study area was developed using Geographic Information System (GIS) tools such as ArcGIS and QGIS. The base map integrated topographical maps, satellite imagery, and geological maps to delineate key geographical and hydrogeological features, including drainage networks, land use patterns, borehole locations, and geological formations. This mapping process facilitated systematic planning for field investigations and enabled spatial analysis of groundwater potential zones.

To understand terrain variations and surface hydrology, Digital Elevation Models (DEMs) were extracted from Shuttle Radar Topography Mission (SRTM) data and LiDAR datasets. Using GIS-based 3D visualization tools, slope, elevation changes, and surface runoff dynamics were analyzed to assess their influence on groundwater recharge and flow patterns. Understanding terrain morphology was crucial for identifying potential recharge areas and determining interactions between surface water and aquifers. Similar approaches have been successfully applied in hydrogeological studies in South Africa by Jolly *et al*. (2015) and in Nigeria by Bassey and Ehirim (2018).

Field investigations included the collection of extant lithologic log data from the Cross River State Rural Water Supply and Sanitation Agency and the Cross River Basin Development Authority from control boreholes at strategic locations. The lithologic log data was subjected to analysis, interpretation, and correlation with layer resistivity data. This analysis was critical for delineating aquifer units and assessing the geological controls on groundwater movement. Borehole lithology data were compared with regional geological maps to refine the understanding of subsurface stratigraphy and hydrogeological conditions.

To delineate subsurface resistivity variations, electrical resistivity surveys were conducted using Vertical Electrical Sounding (VES) and High-Resolution Profiling (HRP) techniques. The Schlumberger electrode configuration was used at 35 VES stations with the ABEM SAS 1000 Terameter for data acquisition. The VES method was chosen for its effectiveness in estimating aquifer depth, transmissivity, and protective capacity, as outlined by Loke (2004) and Fetter (2001). Data were processed and analyzed using WINRESIS software, with curve types classified into H, K, A, Q, KH, AQ, and QH formations. The interpretation of resistivity profiles was guided by previous studies in Nigeria, including those conducted by Edet and Esu (1998) and Olasehinde (2010), and compared with standard resistivity values to infer aquifer boundaries, lithologic variations, and groundwater potential zones.

This methodology adheres to international hydrogeophysical survey standards, ensuring reproducibility in similar geological settings. The use of standardized geophysical protocols, GIS-based spatial analysis, and quantitative aquifer assessments allows for adaptation in future groundwater studies across sedimentary basins (Ekanem *et al*., 2024). The study builds on methodologies successfully applied in India, the United States, and sub-Saharan Africa, offering valuable insights for regional groundwater resource management (Ghouili *et al*., 2020; Ganla *et al.*, 2024). By integrating geophysical techniques, hydrological measurements, and numerical modeling, the study provides data-driven insights essential for sustainable groundwater management (Ekanem *et al*., 2024). The approach offers a robust framework for characterizing aquifers, evaluating groundwater productivity, and assessing vulnerability, supporting informed decision-making in groundwater development.

3.1 Hydrogeological and Hydrogeophysical Insights for VES

The electrical resistivity method involves injecting an electric current into the ground and measuring the resulting potential difference to determine the resistance of subsurface materials. Resistivity variations are influenced by factors such as lithology, porosity, water saturation, and the presence of voids or cavities within rocks. Figures 2–6 illustrate the VES models for VES stations 1 to 5, showcasing variations in resistivity and lithological structures. These models highlight the stratification of subsurface layers, aiding in the identification of potential aquifer zones. They provide a comprehensive understanding of the geoelectric subsurface framework, emphasizing the method’s utility in addressing groundwater challenges. Additionally, the electrical resistivity method plays a crucial role in identifying shallow, layered sequences or vertical discontinuities (Figs. 2–6), enhancing its applicability in various environmental and engineering studies. This makes it an indispensable tool for geophysical surveys aimed at understanding subsurface conditions.

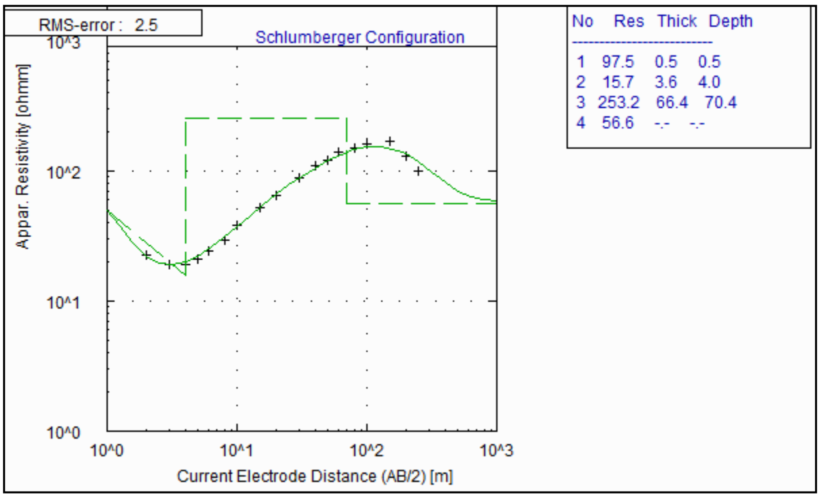

Fig 2: Model curve for VES 1: Aduma roundabout

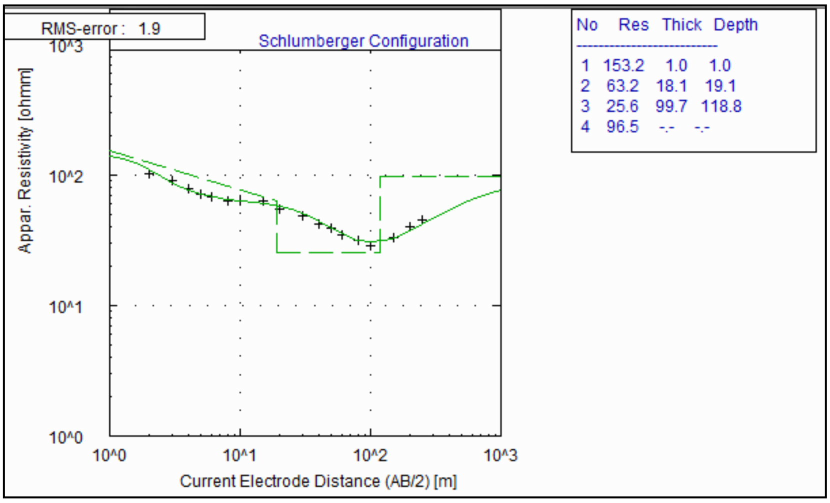

Fig. 3: Model curve for VES 2: Kowu-Yoduma by Never's Residence

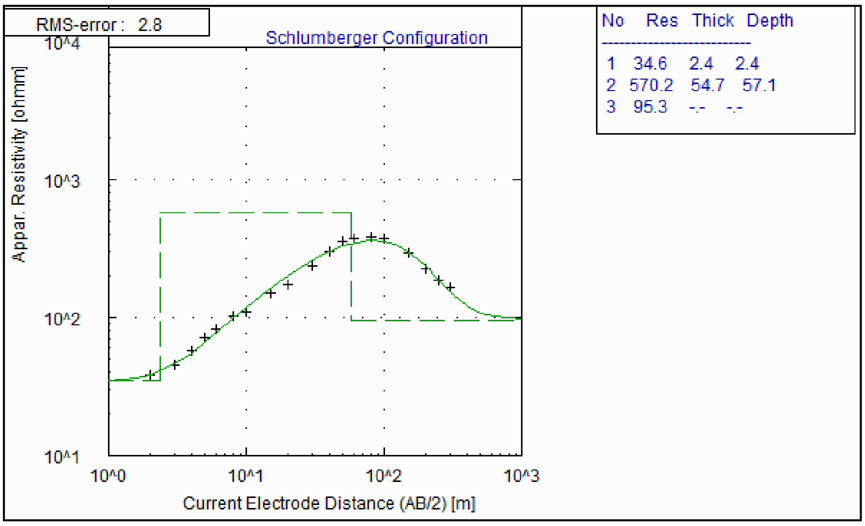

Fig. 4: Model curve for VES 3: Obol Lopon palace Akonta-Afaben, Mkpani

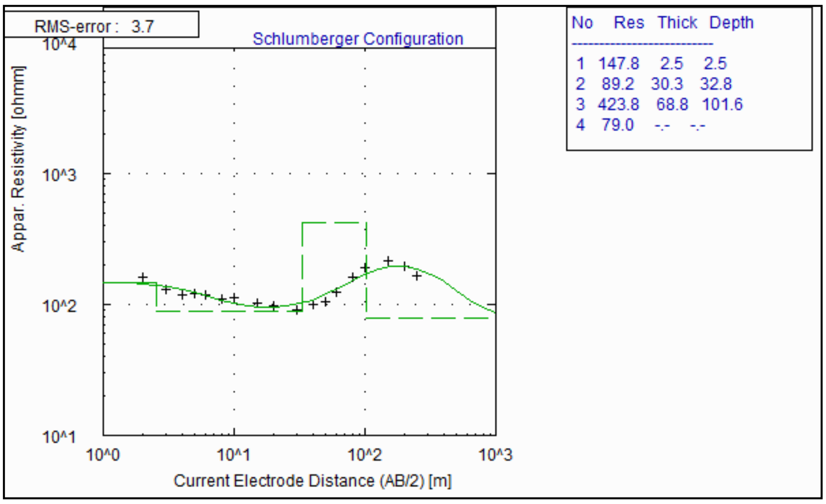

Fig. 5: Model curve for VES 4: Roman Catholic Church, Mkpani

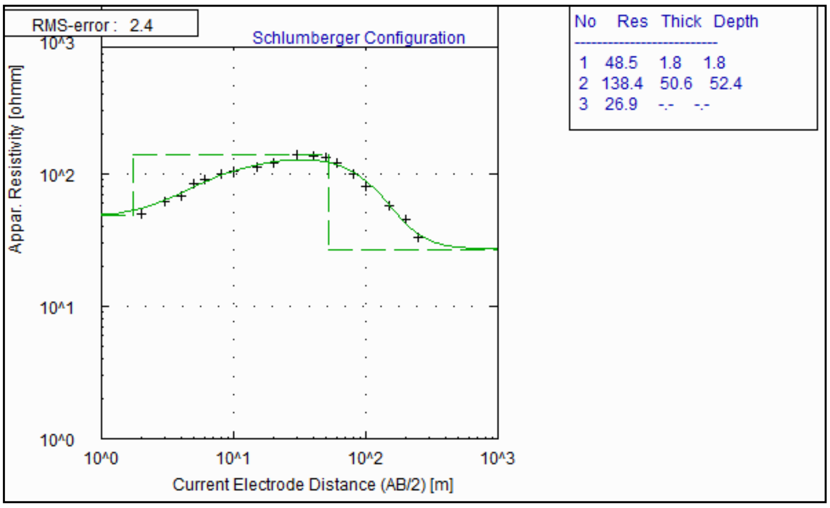

Fig. 6: Model curve for VES 5: PCN Seminary gate on Ikom - Calabar highway

3.1 Correlation of Lithologic Sections with Geoelectric Data

The relationship between Vertical Electrical Sounding (VES) data and borehole lithologic logs was examined to assess the accuracy of resistivity-based lithologic interpretations within the study area. Apparent resistivity values obtained from VES surveys were classified into different lithologic units based on established resistivity ranges and then compared with borehole lithologic logs obtained from drill cuttings to validate the interpretations (Ibuot et al., 2024).

The results for VES 3, 5, 12, 28, and 35 (Obol Lopon Palace Afaben-Mkpani, PCN Seminary Gate Yakurr, Inyima Palace, Kokomkpol-Ajere Mkpani, and Ugep Market Ketabebe) all exhibited K-curve types, where the resistivity of the first layer was lower than that of the second layer, and the second layer had a higher resistivity than the third. At Inyima, the first layer, with a resistivity of 62 Ωm at a depth of 10.4 m, was interpreted as sandstone interbedded with shale, corresponding to the litholog BB7. The second layer, with a resistivity of 200.7 Ωm at a depth of 80 m, was identified as an unconfined aquifer primarily composed of sandstone with shale intercalations, indicative of a freshwater-bearing unit. The third layer, with a resistivity of 60.7 Ωm, was interpreted as a confined sandstone aquifer, separated from the unconfined aquifer by a thin shale layer.

The VES and Electrical Resistivity Tomography (ERT) results closely correlated with the borehole lithology, providing a clear delineation of the subsurface layers and aiding in the identification of lithological boundaries, including those of the unconfined and confined aquifers. The correlation between VES data and borehole logs (Fig. 7) confirmed that major lithological boundaries were effectively delineated by the resistivity survey, with sandy surface layers and lateritic deposits matching closely with borehole observations. The estimated accuracy of VES-based interpretations was approximately 75 percent, reinforcing the reliability of this method as a preliminary tool for subsurface geological characterization.

However, certain limitations were noted, particularly in areas with thin interbedded layers where the bulk resistivity response of the VES method led to generalization effects. Additionally, overlapping resistivity ranges between silty sand and fine sand introduced some degree of uncertainty in classifying lithologic units, suggesting the need for supplementary techniques such as seismic refraction surveys or hydrochemical analysis to enhance interpretational accuracy.

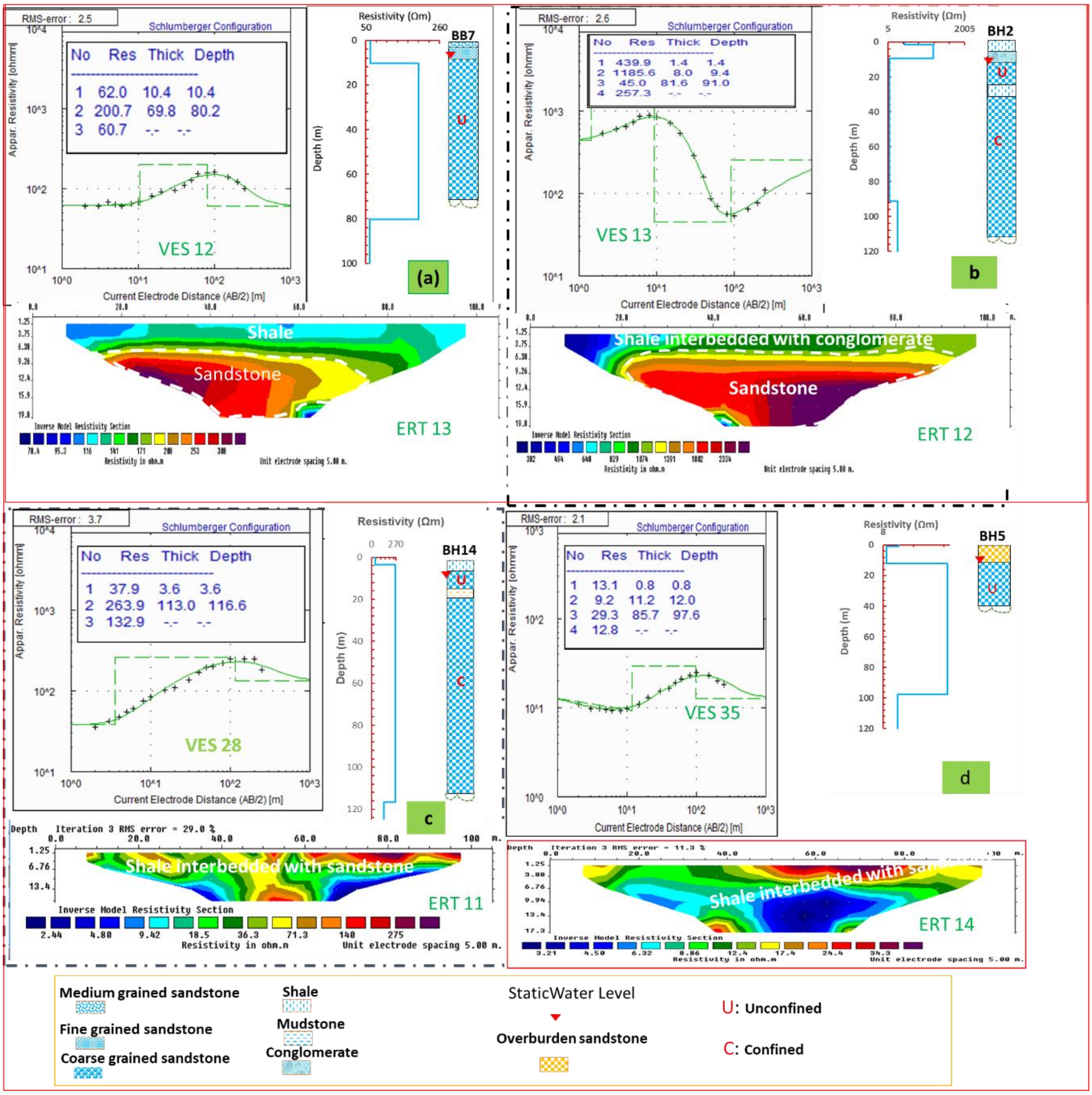

Fig. 7: Representatives of geo-resistivity results showing correlations with nearby boreholes

3.2 Delineation of Aquifer Systems in the study area

An assessment of the geology of the study area, as depicted from the geological map on NGSA 314 (Ugep Sheet), aligns with extant literature and field observations, revealing two sedimentary regimes with two principal aquifer systems. The first aquifer system is situated within the Eze-Aku Formation in the western and northwestern parts of the study area, comprising primarily the Eze-Aku Sandstones overlying Eze-Aku Shales across Ugep and Ekori towns in Yakurr LGA, as well as the entire Abi LGA. This region is drained by the Cross River and occasionally features intermediate to basic intrusions dotting the plains. Geoelectrical investigations from this study have identified the Eze-Aku Sandstones as a major groundwater repository, with resistivities ranging from 35.6 to 446.5 Ωm, aquifer layer thicknesses between 26.5 and 111.3 m, and depths ranging from 27.6 to 119.7 m (Table 1).

Table 1: Aquifer resistivity, thickness and depth for the Eze-Aku Aquifer in the study area

VES No.	Location	No. of layers	Aquifer Layer				curve type
			Layer No.	Resistivity (Ωm)	Thickness	Depth	
14	Assiga Old Town new Palace, Yakurr LGA	4	3	63.3	38.4	51.2	HK
15	Igbo Imabana, Abi LGA	4	3	35.6	63.1	65.6	H
16	Ekori Beach, Yakurr LGA	4	3	376.6	44.0	51.8	KH
17	KesekpangEpenti, Ekori,	4	3	97.0	111.3	119.7	KH
20	Itigidi beach, Abi LGA	4	3	90.4	57.4	63.6	HK
23	Agba Itigidi, Abi LGA	3	2	446.5	58.2	88.2	H
24	Agbara Primary school, Ekureku, Abi LGA	4	3	185.5	54.6	63.6	KQ
25	Agbara community by Abaomege, Abi LGA	4	3	189.7	40.2	57.5	HK
30	Ntamkpo, Ugep, Yakurr LGA	3	2	355.4	26.5	27.6	K
35	Ugep market, Ugep, Yakurr LGA (BH 5, Ketabebe**)**	3	2	398.5	81.5	92.5	K
	Minimum			**35.6**	**26.5**	**27.6**	
	Maximum			**446.5**	**111.3**	**119.7**	
	Average			**223.9**	**57.5**	**68.1**	

The second aquifer system is found within the Asu River Group of sediments, comprising the Asu River Limestones, Asu River Sandstones, Asu River Shales, and Asu River Siltstones, which are also intruded by dolerites. These intrusions have baked and fractured the shales in various locations, such as Iyamoyong and its environs, as well as the Mkpani and Nko general areas, where highly weathered contact zones have created secondary porosities and permeability. These characteristics have proven to make these formations effective alternate unconfined aquifers (Akpan et al., 2013, 2018).

The results of this geophysical investigation indicate that a combination of the Asu River Sandstones-sourced from the adjacent Oban Massif-intercalating in most cases with Limestones, serves as the major aquifer system for the eastern and northeastern parts of the study area. This aquifer system spans Abini and Adim towns of Biase LGA; Idomi, Aduma, Afaben, and Ajere communities of Mkpani town; Agoi Eko, Nko, and Inyima towns of Yakurr LGA; and Ofodua, Oyadama, Ofat, Apiapum, and Iyamoyong in the general area of Obubra LGA.

Findings from this study reveal resistivity values ranging from 18.7 to 570.2 Ωm, aquifer layer thicknesses between 20.5 and 113.0 m, and aquifers encountered at depths varying from 34.2 to 118.8 m.

Table 2: Aquifer resistivity, thickness and depth for the Asu River Aquifer in the study area

VES No.	Location	No. of layers	Aquifer Layer				curve type
			Layer No.	Resistivity (Ωm)	Thickness	Depth	
1	Aduma roundabout, Aduma, Mkpani	4	3	253.2	66.4	70.4	HK
2	Kowu Yoduma by Never's Residence, Aduma, Mkpani	4	3	25.6	99.7	118.8	QH
3	Obol Lopon palace Akonta Afaben Mkpani	3	2	570.2	54.7	57.1	K
4	Roman Catholic church Mkpani	4	3	423.8	68.8	101.8	HK
5	Seminary gate on Ikom - Calabar highway, Mkpani	3	2	138.4	50.6	52.4	K
6	Lesomi by Basin Authority, Ajere, Mkpani, Yakurr	3	2	61.7	74.8	77.9	Q
7	Mkpani Mission, Yakurr	3	2	66.0	101.8	105.5	H
8	Ebilebit Primary School, Ebilebit, Mkpani, Yakurr	3	2	18.7	76.1	78.6	H
12	Inyima Palace, Inyima, Yakurr LGA (BH 7)	3	2	200.7	69.8	80.2	K
13	St Eugenes primary school Inyima, by Water Small Town Water Scheme, Yakurr LGA (BH 19)	4	3	198.6	102.3	110.7	KH
18	Adim secondary school, Biase LGA	4	3	62.3	46.9	72.2	H
19	Abini Community in front of Palace, Biase LGA	4	3	133.0	76.0	91.8	HK
22	IdomiYakurr LGA	4	3	56.2	72.1	85.4	KH
26	Ebri's Compound, Mkpani, Yakurr	4	3	97.0	41.0	61.2	HK
27	Ofodua (Itteh) Pond, Obubra LGA	4	3	386.1	50.8	64.1	HK
28	Kokomkpol-Ajere, Mkpani, Yakurr LGA (BH 14, Yoli) and BH 37 Lekpankom,	3	2	263.9	113.0	116.6	K
29	IyamayongObubra LGA	3	2	222.4	20.5	34.2	Q
31	Lebang Mkpani, Yakurr	3	2	138.2	62.1	67.6	Q
32	Agoi Ekpo, Yakurr LGA (BH 44, Agoi Ekpo)	3	2	292.7	69.5	79.1	K
33	Nko, Yakurr LGA (BH 2, Nko-Mbongho)	4	3	250.0	39.4	53.1	HK
34	Mkpani hotel by living faith church, Yakurr LGA	3	2	69.7	83.4	86.5	H
	Minimum			**18.7**	**20.5**	**34.2**	
	Maximum			**570.2**	**113.0**	**118.8**	
	Average			**187.1**	**68.6**	**79.3**	

3.3 General Aquifer Resistivity

Analysis of the VES resistivity data of the study area showed considerable variation in lithological properties, providing insights into the subsurface characteristics. The lowest resistivity value recorded in the study was 9.50 Ωm at Assiga Old Town Palace (VES 14, with a layer thickness of 9.1 m at a depth of 12.8 m), indicating the presence of clay-rich sediments or silty formations with low permeability and limited groundwater yield. Conversely, the highest resistivity of 2,364 Ωm was recorded at Agba, uphill Itigidi (VES 23, top layer with a thickness of 10.0 m), coinciding with dry, friable, fine- to medium-grained sandstones.

Other notable aquifer resistivities include 446.5 Ωm for layer 2 at VES 23 (Agba Itigidi) with a thickness of 58.2 m, 398.5 Ωm at VES 35 (Ugep Market, Ketabebe, 81.5 m thick), and 376.6 Ωm at VES 16 (Ekori Beach in Yakurr LGA, 44 m thick). These values suggest the presence of coarse-grained sands and gravels, which typically correspond to high-yield aquifer zones within the Eze-Aku aquifer system.

On the other hand, aquifer resistivities recorded a minimum of 18.7 Ωm at Ebilebit Primary School along Agoi Road and a maximum of 570.2 Ωm at Obol Lopon Palace, Akonta, a zone of weathered dolerites that had intruded the Asu River Sandstones with limestone and shale intercalations. These variations suggest considerable heterogeneity in the subsurface lithology, which influences groundwater availability and quality (Umoh et al., 2022; George *et al*., 2024).

Table 3: Aquifer Resistivity, Thickness, and Depth across VES Locations in the Study Area.

VES NO	Aquifer Resistivity (Ωm)	Aquifer Thickness (m)	Aquifer Depth (m)
VES 1	253.2	66.4	70.4
VES 2	25.6	99.7	118.8
VES 3	570.2	54.7	57.1
VES 4	423.8	68.8	101.8
VES 5	138.4	50.6	52.4
VES 6	61.7	74.8	77.9
VES 7	66.0	101.8	105.5
VES 8	18.7	76.1	78.6
VES 9	111.2	74.3	86.0
VES 10	209.4	48.2	14.4
VES 11	82.7	32.6	23.9
VES 12	200.7	69.8	80.2
VES 13	198.6	102.3	110.7
VES 14	63.3	38.4	51.2
VES 15	491.4	63.1	65.6
VES 16	376.6	44.0	51.8
VES 17	97.0	111.3	119.7
VES 18	62.3	46.9	72.2
VES 19	133.0	76.0	91.8
VES 20	90.4	57.4	63.6
VES 21	154.4	50.9	64.7
VES 22	56.2	72.1	85.4
VES 23	446.5	58.2	88.2
VES 24	185.5	54.6	63.6

VES 25	189.7	40.2	57.5
VES 26	97.0	41.0	61.2
VES 27	386.1	50.8	64.1
VES 28	263.9	113.0	116.6
VES 29	222.4	20.5	34.2
VES 30	355.4	26.5	27.6
VES 31	138.2	62.1	67.6
VES 32	292.7	69.5	79.1
VES 33	250.0	39.4	53.1
VES 34	69.7	83.4	86.5
VES 35	398.5	81.5	92.5

Figure 8 illustrates the spatial distribution of aquifer apparent resistivity, revealing distinct patterns. The statistical analysis of aquifer resistivity data provides further insights. The mean apparent resistivity is calculated at 192.1 Ωm, with a standard deviation of 94.23 Ωm, reflecting a high degree of variability in subsurface properties. The median resistivity is 62.00 Ωm, indicating that half of the VES points recorded resistivity values below this threshold, while the range spans 437.00 Ωm (from 9.50 to 446.50 Ωm). The coefficient of variation, calculated at approximately 90.7%, underscores the heterogeneity of the aquifer materials.

High resistivity values, such as those recorded at VES 16 and VES 23, may indicate the presence of less permeable formations, possibly due to the dominance of sandstones or crystalline rocks. These variations in resistivity values (Figure 8) across different locations highlight the complex geological setting of the study area, where fine-grained sediments, clay layers, and highly permeable sandy formations coexist, influencing groundwater availability and movement.

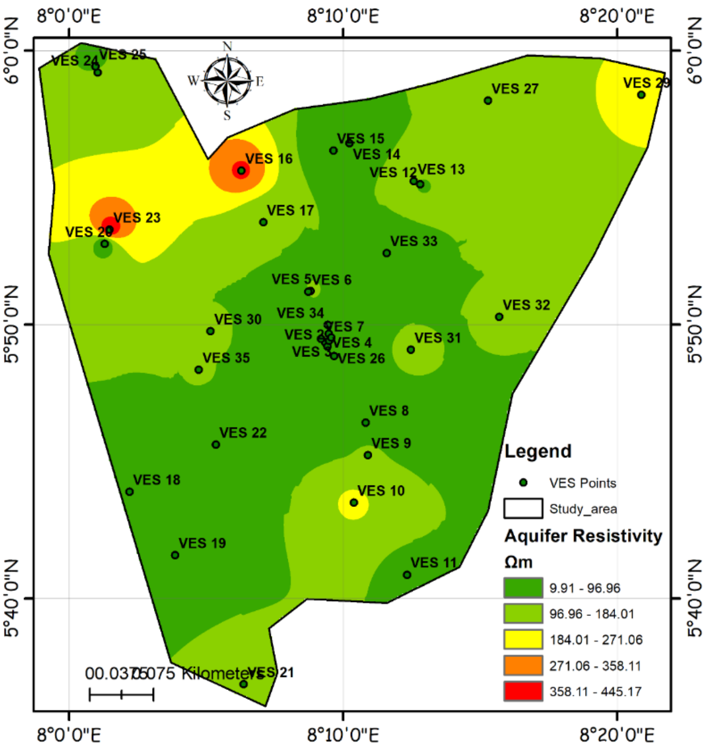

Fig. 8: Spatial map of aquifer resistivity from VES in the study area

The study also revealed significant variability in aquifer resistivity, thickness, and depth, underscoring differences in groundwater storage potential across the study area (Obianwu *et al*., 2011). Aquifer resistivity values ranged from as low as 18.7ΩmatEbilebit Primary Schoolin Yakurr LGA to as high as 446.5Ωm under the Ezeaku Sandstone aquifer system at Agba Itigidi in Abi LGA, and as high as 570.2 Ωm at the Obol Lopon Palace at Afaben Mkpani.

Low resistivity values below 50 Ωm, recorded at locations such as KowuYoduma, Ebilebit Primary School, Assiga Old Town Palace, Igbo Imabana, Adim School, etc. indicate the predominance of clay-rich formations with limited groundwater flow, which in some locations act as confining bed especially in 4-layer settings.

Moderate resistivity values between 50Ωm and 150 Ωm, observed at Mkpani Mission, Roman Catholic Church Mkpani, Lesomi by Basin Authority, Kesekpang Epenti, Abini Palace in Biase, Itigidi Beach in Abi, Idomi, Ekpowoh, Lebang, and Living Faith Church Mkpani, suggest sandy formations that could support moderate-yield aquifers.

High resistivity values above 200 Ωm, observed at various locations such as Agba Itigidi, Ekori Beach, NtamkpoUgep, Ketabebe-Ugep market within the Ezeaku aquifer system; Aduma roundabout, Obol Lopon palace at Afaben, Roman Catholic Church, OffoduaItteh pond, Kokomkpol-Ajere, and Nko within the Asu-River aquifer system correspond to highly permeable coarse-grained sands and gravels, which are expected to have the best groundwater potential.

3.4 General Aquifer Thicknesses

The analysis of aquifer layer thickness in the study area reveals substantial spatial variation, as shown in Fig. 9 and Tables 1–3. The aquifer thickness values range from 20.5 m at Iyamoyong in Obubra LGA (VES 28) to a maximum of 113.0 m at Kokomkpol-Ajere, Mkpani (VES 28) for the Asu River aquifers, closely followed by 111.3 m at Kesekpang Epenti, Ekori (VES 17) for the continental Eze-Aku Sandstones. The mean aquifer thickness is 57.5 m for the Eze-Aku Sandstone aquifers, 68.6 m for the Asu River aquifers, and an overall 63.5 m thickness for the study area.

Aquifers with thicknesses exceeding the mean thickness values and corresponding with moderate to high resistivities are the most promising groundwater reservoirs in the region. Such locations include Ugep Market Ketabebe (VES 35), Agba Itigidi (VES 25), Aduma Roundabout (VES 1), Roman Catholic Church Mkpani (VES 4), Inyima Palace (VES 12), St. Eugene’s Inyima (VES 13), Kokomkpol-Ajere (VES 28), and Agoi Ekpo (VES 32). These areas are expected to support sustainable borehole development due to their high storage capacity (Akpan *et al*., 2013).

In contrast, thin aquifer zones below the mean thickness value and corresponding to low resistivities have limited water storage potential and may not be viable for large-scale, long-term groundwater exploitation. These locations include Assiga Old Town Palace (VES 14), Adim School (VES 18), Iyamoyong Obubra (VES 29), and Ekpohwoh by Ebri’s compound (VES 26).

The aquifer thickness distribution shows a positively skewed pattern, with a higher frequency of moderate thickness values (20–60 m) and fewer occurrences of extremely high or low values. Approximately 68.57% of the VES points (24 out of 35) have thickness values above the mean, indicating that the majority of the study area exhibits moderate to high aquifer thickness (Asfahani *et al*., 2023). This supports the conclusion that the region has significant groundwater potential, albeit with marked variability.

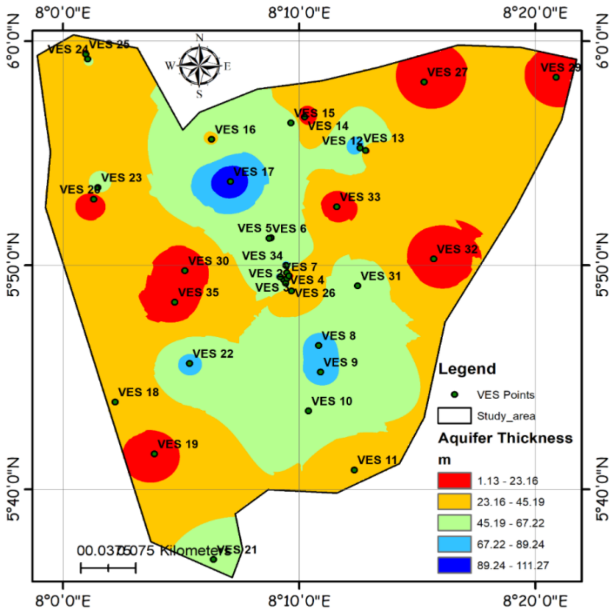

Fig. 9: Spatial map of aquifer thickness from VES in the study area

3.5 General Depth to Aquifer Units

The aquifer apparent depth across the study area exhibits notable spatial variability, as shown in Figure 10 and Table 1. The central part of the study area, particularly around Ebilebit Primary School, Mkpani (VES 8: 78.60 m), Mbarokom Agoi Ibami (VES 9: 86.00 m), Kesekpang Epenti, Ekori (VES 17: 119.70 m), Idomi Yakurr (VES 22: 85.40 m), and Agba Itigidi (VES 23: 88.20 m), records the highest aquifer depths. Conversely, locations in the eastern part of the study area, including Ugep (VES 30: 1.10 m) and Mkpani Hotel by Living Faith Church (VES 34: 3.10 m), show the lowest depths. This variation underscores the geological complexity and hydrogeological heterogeneity within the study area (Akpan *et al*., 2013).

The mean aquifer depth across all the VES points is 72.40 m, with a standard deviation of 37.71 m, indicating significant variability in subsurface characteristics. The range spans from a minimum depth of 1.10 m at Ugep (VES 30) to a maximum of 119.70 m at Kesekpang Epenti, Ekori. The data show that over 25% of the VES locations have aquifer depths exceeding 60 m, emphasizing the potential for deep groundwater exploration in specific zones, particularly in central areas.

The high depths observed at locations such as Kesekpang Epenti and Idomi Yakurr are likely influenced by subsurface lithology and structural controls that allow for the accumulation and storage of groundwater at greater depths. These areas are characterized by thicker sedimentary deposits, contributing to their high aquifer depths. On the other hand, the low depths in the eastern zones can be attributed to the shallow bedrock and limited sediment cover, which constrain groundwater storage potential.

Statistical analysis of the aquifer depths reveals a skewness of 0.68, indicating a slight positive skew in the data distribution. This suggests that while most VES locations exhibit moderate aquifer depths, a few locations show significantly high values. The kurtosis value of -0.21 implies a relatively flat distribution, reflecting the diverse range of depths recorded across the study area.

The spatial distribution of aquifer depths is critical for groundwater resource management and planning. The central part of the study area, with its deeper aquifers, presents favorable conditions for long-term groundwater extraction, as these depths are less susceptible to surface contamination (Udosen *et al*., 2014a, b).

The presence of shallow aquifers at locations such as Ntamkpo (VES 30), Nko (VES 33), Ofodua (Itteh VES 27), and Iyamoyong (VES 29) suggests vulnerability to contamination and seasonal fluctuations in recharge. In contrast, deeper aquifers, found in locations such as Kowu Yoduma (VES 2), Roman Catholic Church (VES 4), Mkpani Mission (VES 7), St. Eugene Inyima (VES 13), and Kokomkpol Ajere (VES 28), offer better protection against pollution and more sustainable groundwater yields (George et al., 2025). The eastern part, with its shallow aquifers, requires careful monitoring and protection to prevent contamination and over-extraction (George *et al*., 2025).

The depth variations also have implications for drilling costs and feasibility (George *et al*., 2021). Deeper aquifers, such as those at Kesekpang Epenti and Agba Itigidi, may require advanced drilling techniques and increased financial investment but offer sustainable water yields. Shallow aquifers, as seen in Ugep, present lower drilling costs but are more vulnerable to seasonal fluctuations and pollution. The findings from Figure 10 provide valuable insights into the hydrogeological framework of the study area.

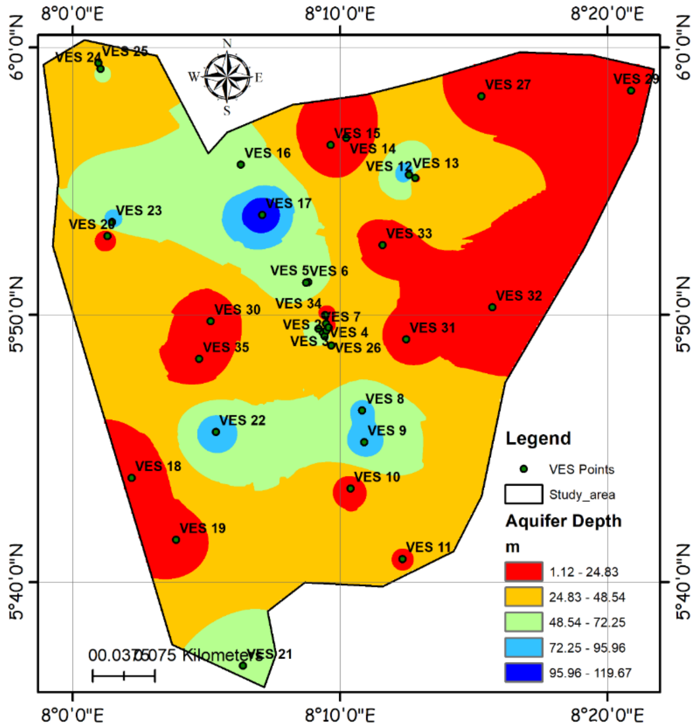

Fig. 10: Spatial map of aquifer depth from VES in the study area

The identification of zones with significant aquifer depths highlights areas of groundwater potential, while the recognition of shallow zones informs the need for protective measures (George *et al*., 2021). The spatial patterns observed align with the regional geological features, where sedimentary formations dominate the central regions, contributing to greater aquifer depths, whereas crystalline bedrock underpins the shallow aquifers in the eastern areas (Akpan *et al*., 2013).

3.7 Curve Types of the Study area

The curve types observed in the VES locations exhibit significant variability, as illustrated in

Fig. 11, which presents the frequency distribution of curve types. Among the 35 VES points analyzed, the predominant curve types are HK, K, and H, collectively accounting for 48.6% of the total observations. The HK curve type, represented at 9 locations, is the most frequent, reflecting the geological characteristics of the study area, where heterogeneous layers with varying resistivities are likely present. In most cases, the HK-type curve correlates with a thin, dry overburden overlying thin lenses of shale that serve as confining layers to thick sandstone and limestone aquifers.

The K-type curve, observed at 7 locations (VES 3, 5, 12, 24, 28, 30, and 32), is also common, indicating a relatively more uniform subsurface structure, possibly with less variation in resistivity between layers and correlating with unconfined sandstone and limestone aquifers.

The H-type curve, found at 6 locations, indicates higher resistivity in the deeper layers, typically associated with consolidated bedrock or denser materials. The Q-type curve, observed at 3 locations, suggests a different geological profile, potentially indicating the presence of more conductive layers, such as clay or water-saturated zones near the surface (George *et al*., 2025).

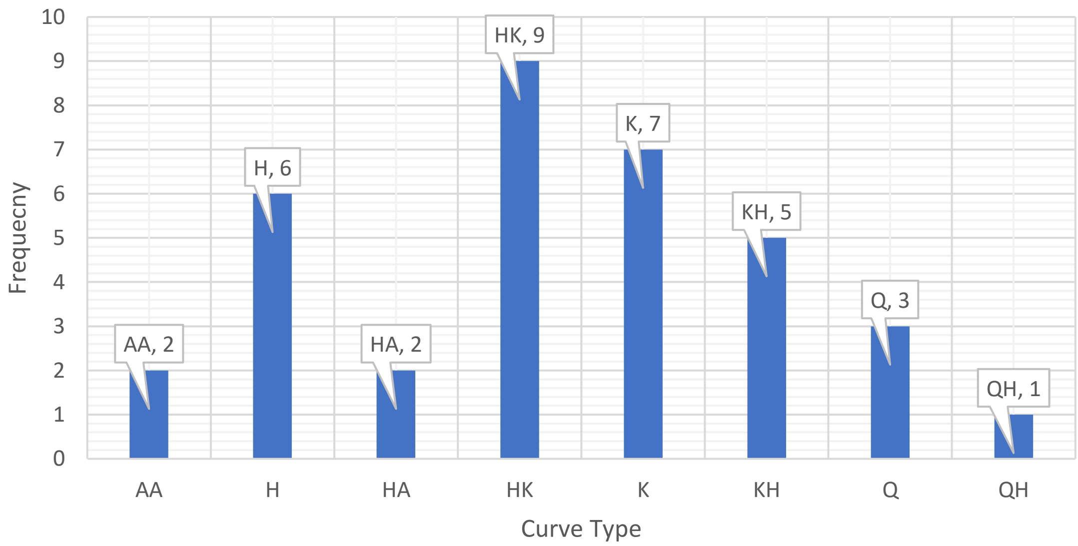

Fig.11: Curve type distribution in the study area

The curve type distribution shows that 62.85% of the VES locations are dominated by just three curve types (HK, K, and H), indicating a relatively predictable subsurface structure in the study area. The distribution also suggests that 14.28% of the locations exhibit more complex or less typical geological features, as reflected in the lower frequency of the QH, HA, and AA curve types.

This frequency distribution of curve types is crucial for understanding the general hydrogeological conditions in the study area (George et al., 2025). The predominance of the HK curve type suggests that most of the study region is characterized by varying resistivity layers, likely corresponding to different geological formations. Conversely, the lower frequency of the AA curve type, which represents more stable and homogeneous subsurface conditions, indicates that the area has relatively few zones with such uniform resistivity profiles. These insights are essential for planning groundwater exploration and assessing the potential for water resources in different parts of the study area.

The results highlight the need for a strategic approach to groundwater development and management in Central Cross River State. Given the high vulnerability of shallow aquifers to contamination, particularly in Iyamoyong and Anong, careful borehole siting and protective measures are necessary to ensure water quality and sustainability. Deep aquifers, which were found to be more productive and less susceptible to pollution, should be prioritized in groundwater abstraction efforts. Borehole drilling should be guided by resistivity data to optimize well placement and avoid low-yielding areas with excessive clay content. Integrating hydrogeophysical surveys with long-term monitoring of piezometric levels and seasonal recharge variations will be essential for sustainable groundwater resource management.

4.0 Conclusions

The assessment of aquifers for optimized groundwater extraction in parts of Central Cross River State, using hydrogeophysical and hydrogeological investigations spanning parts of Biase, Abi, Yakurr, and Obubra LGAs, has successfully delineated two principal aquifer systems in the study area. These are the Eze-Aku Sandstone Aquifer, occupying the western and northwestern parts of the study area, with resistivities ranging from 35.6–446.5 Ωm, aquifer layer thicknesses ranging from 26.5–111.3 m, and encountered at depths of 27.6–119.7 m. The other aquifer is the Asu-River Sandstone Aquifer system, with resistivities ranging from 18.7–570.2 Ωm, aquifer layer thicknesses ranging from 20.5–113 m, and encountered at depths of 34.2–118.8 m.

The hydrogeophysical characterization of aquifers in Yakurr, Abi, and parts of Obubra and Biase LGAs has provided a comprehensive understanding of the aquifer systems in the study area. High-yield groundwater zones have been delineated, predominantly located around the Kesekpang spring of Epenti in Ekori, Ketabebe around Ugep Market, and Ekori Beach in Yakurr LGA, as well as Itigidi Beach, Agba Itigidi, and Agbara Primary School in Abi LGA. These zones, within the Eze-Aku Sandstone Aquifer system, exhibit high resistivity and significant thickness, with depths ranging from 52 to 120 m, suggesting favorable conditions for groundwater development.

Additionally, locations such as Inyima, Aduma Roundabout, Kowu-Yoduma, Obol Lopon Palace at Akonta-Afaben, Roman Catholic Church Mkpani, Mpani Mission, Kokomkpol-Ajere-Mkpani, and Lebang in Yakurr LGA, within the Asu-River Sandstone Aquifer system, exhibit high resistivity and significant thickness, with depths ranging from 57 to 119 m, suggesting favorable conditions for groundwater development with low vulnerability to contamination.

In contrast, thin aquifer zones, with thicknesses below the mean value and corresponding low resistivities (low permeability formations), have limited water storage potential and may not be viable for large-scale, long-term groundwater exploitation. These locations include Assiga Old Town Palace (VES 14), Adim School (VES 18), and Iyamoyon Obubra (VES 29). Areas characterized by low-permeability formations are not suitable for high-yielding boreholes. Areas with good water yield around Iyamoyon are most likely shales that have been baked and fractured by the intrusions around the area (Akpan *et al*., 2013).

Overall, the study confirms that deep aquifers with high resistivity values should be prioritized for sustainable groundwater development, while shallow aquifers require additional protection from contamination and seasonal depletion. The findings provide a scientific basis for informed water resource management, ensuring that groundwater development in Central Cross River State aligns with long-term sustainability goals. Integrating geophysical surveys, borehole analysis, and hydrochemical assessments will be critical for achieving a comprehensive understanding of groundwater potential and optimizing water resource utilization in the region.

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