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Full Length Research

Aquifer delineation using Vertical Electrical Sounding (VES) and correlation of borehole logs in Opolo-Epie, Yenagoa Bayelsa State, Nigeria

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ABSTRACT: This study investigates the groundwater potential in Opolo-Epie, Yenagoa, Bayelsa State, Nigeria, deploying electrical sounding (VES) surveys and borehole log data analysis. Utilizing the Schlumberger electrode configuration and Terrameter SAS 1000 instrument, coupled with the Global Positioning System (GPS), three VES profiles were conducted and processed using IPI2win software and Starter 5. Key findings from the study reveal promising subsurface features and groundwater prospects. VES 1 identified distinct zones of fine to medium sand with resistivity value of 0.62-28.7 Ωm with a depth of (17.4–47.2 m) and coarse sand with resistivity value of 359 Ωm and a depth of (47.2–56.2 m). VES 2 indicated potential aquifers in the medium sand with resistivity value of 368.4 Ωm with a depth of (5.48–11.45 m) and coarse sand with resistivity value of 1089 Ωm and a depth (11.45-23.92 m), while VES 3 delineated a shallow aquifer in the fine sand layer with a resistivity of 117.4 Ωm and depth zone of (1.92–5.19 m) and a deeper, more promising aquifer in the coarse sand zone with resistivity value of 1680 Ωm and depth of (11.13–22.66 m). Borehole logging confirmed significant sand layers (3–30 meters) with potential for water storage and flow, along with a clay layer (27.1–30 meters) acting as a confining unit for underlying groundwater. The correlation between VES and borehole data revealed consistency in identifying clay layers but discrepancies in interpreting deeper aquifer zones, underscoring VES limitations in resolving thin layers. The study underscores the importance of integrating VES surveys with borehole data for a comprehensive evaluation of groundwater resources. Notably, the borehole logging-identified coarse sand layer (33.3–42.4 meters) appears to be an attractive prospect for a productive aquifer; therefore, additional research is necessary to resolve interpretational differences and determine whether clay layers exist and how thick they are in this zone.

Keywords: Aquifer delineation, borehole logs, correlation, geoelectric layers, Vertical Electrical Sounding (VES).

INTRODUCTION

Access to clean water stands as an elemental human right, firmly embedded within international legal frameworks and pivotal to realizing the Sustainable Development Goals (SDGs) set forth by the United Nations (UN) (United Nations, 2015). SDG 6, particularly, underscores the imperative of "ensuring available and prudent management of water and hospitable sanitary system for all," thereby constituting a cornerstone of global well-being and advancement (United Nations, 2015). In Nigeria, akin to numerous regions worldwide, groundwater serves as a lifeline for potable water, particularly in locales grappling with limited or tainted surface water reserves (Onugba and Yaya 2008; Amadi *et al.,* 2020). The urban expanse of Yenagoa, capitalizing Bayelsa State within Nigeria's Niger Delta terrain, confronts formidable hurdles concerning water accessibility and quality. Opolo, ensconced within

Is an adjourning Community in Yenagoa metropolis groundwater dynamics, propelled by its burgeoning populace and burgeoning water demands, further catalyzed by rapid urban sprawl (Jijingi *et al.,* 2019). The urgency of grappling with groundwater governance in Nigeria reverberates through recent inquiries. The World Bank's findings position Nigeria among the top five nations globally afflicted by water scarcity, with approximately 60 million individuals lacking access to improved water sources (World Bank, 2020). Moreover, the World Health Organization (WHO) estimates depict a stark reality where over 50% of water supply schemes in Nigeria remain non-operational, underscoring the gravity of the water crisis (WHO, 2019).

In response to these pressing challenges, scientific research has helped innovative methodologies to precisely delineate groundwater potential. Vertical Electrical Sounding (VES) emerges as a beacon of promise within the realm of geophysical techniques for mapping subterranean aquifers. The integration of VES surveys with hydrogeological investigations proffers invaluable insights into the distribution, depth, and quality of groundwater reservoirs (Alabi *et al*., 2016; Oladunjoye *et al.,* 2019). This reservoir of data, in turn, becomes instrumental for policymakers and stakeholders in formulating evidence-based water management strategies across Nigeria. Groundwater been a constituting significant reservoir of the global freshwater expanse, stands as a linchpin for potable water for myriad individuals globally, particularly in regions grappling with limited or unreliable surface water reservoirs (Gleeson *et al.,* 2020). In Nigeria, groundwater assumes a pivotal role in underpinning livelihoods, agricultural pursuits, and industrial activities, significantly contributing to the national water supply (Airen and Babaiwa, 2023; Rolia, and Sutjiningsih, 2018). Despite its paramount importance, sustainable groundwater resource management remains a herculean task, exacerbated by factors including over-exploitation, contamination, and inadequate comprehend-sion of aquifer systems (Kasidi and Victor, 2021). Hence, a dire need exists for systematic inquiries to unravel groundwater potential and devise sustainable manage-ment stratagems, particularly in realms such as Opolo-Epie, Yenagoa, Bayelsa State. Geophysical methodolo-gies proffer non-invasive and cost-effective avenues for delivering into subterranean structures and delineating aquifer attributes, thereby facilitating informed decision-making in water resource governance (Singh *et al.,* 2013). Among these methodologies, Vertical Electrical Sounding (VES) emerges as a preeminent technique for elucidating groundwater potential, predicated on the variation of subsurface resistivity contrast (Aizebeokhai *et al.,* 2010; Odey *et al.,* 2024; Ibrahim *et al.,* 2023). By gauging the apparent resistivity at diverse depths, VES surveys furnish invaluable insights into lithological variances, aquifer dimensions, and groundwater prospecting (Ibrahim *et al.,* 2023). Recent strides in VES instrumentation and data interpretation algorithms have augured well for bolstering the precision and efficacy of subsurface imaging, thereby cementing its status as an indispensable tool within hydrogeological explorations (Ezeh *et al*., 2022; Offodile, 1992).

Opolo, nestled within Yenagoa, Bayelsa State, Nigeria, grapples with water scarcity conundrums, exacerbated by the spectre of rapid urbanization and industrialization. Despite its perch within the Niger Delta region, renowned for its hydrocarbon riches, access to clean and reliable water remains an arduous quest for the citizens of Opolo (Eteh *et al.,* 2021). Antecedent hydrogeological forays in the precinct have shed light on the presence of shallow aquifers but have underscored the imperative of meticulous inquiries to ascertain groundwater potential and sustainable yield (Okiongbo and Akpofure, 2012). Ovuru and Eteh (2021) have successfully wielded VES within Opolo, pinpointing potential aquifer locales pivotal for drilling productive wells. The ongoing investigation endeavours to build upon this foundation by orchestrating a comprehensive VES survey across Opolo-Epie, with the overarching aim of crafting a nuanced depiction of subsurface geoelectrical attributes and, by extension, the groundwater potential within the community. Within this narrative, the deployment of VES emerges as a promising modus operandi for delineating subterranean aquifer systems, comprehending their vicissitudes, and architec-ting efficacious groundwater management stratagems tailored to the unique exigencies of Opolo. In Opolo, Yenagoa, Bayelsa State, Nigeria, the availability and sustainability of groundwater resources are crucial for various aspects of daily life, including domestic, agricultural, and industrial purposes. However, despite its importance, there is a lack of comprehensive understanding regarding the groundwater potential in this region. This knowledge gap poses significant challenges for effective water resource management and sustainable development initiatives. One of the primary problems is the absence of detailed information regarding the spatial distribution, depth, and quality of groundwater aquifers in Opolo. Without this knowledge, local authorities, policymakers, and stakeholders face difficulties in making informed decisions regarding water resource allocation, land use planning, and infrastructure development. Furthermore, the reliance on surface water sources such as rivers and streams is becoming increasingly unsustainable due to pollution, climate change, and competing demands. Groundwater, therefore, represents a vital alternative, but its exploitation requires a thorough understanding of its potential and characteristics. The current methods used to assess groundwater potential in Opolo are limited and outdated. Traditional techniques such as manual drilling and random borehole installation lack precision and often fail to provide reliable data on aquifer properties and recharge rates. As a result, there is

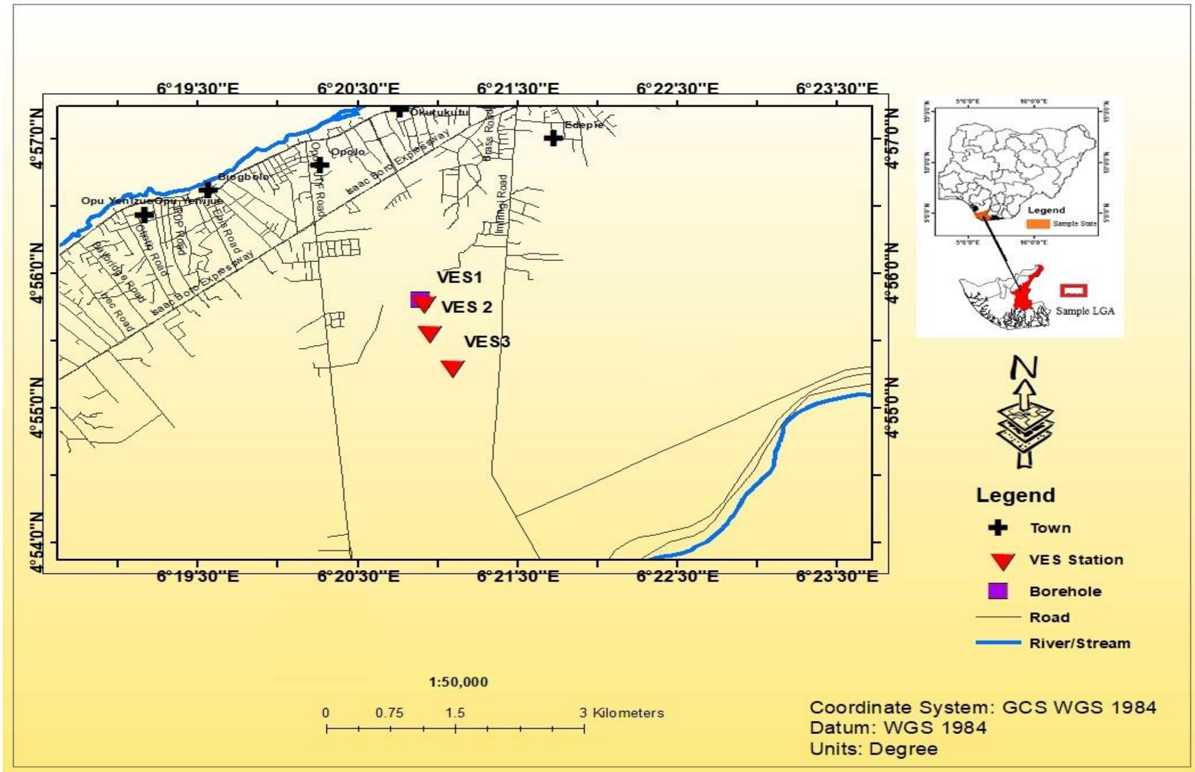

Figure. 1.. Map of the study areas.

a pressing need for more advanced and efficient methodologies to delineate groundwater possibilities in the area. Vertical Electrical Sounding (VES) is a promising geophysical method for mapping subsurface geological structures and assessing groundwater potential. However, its application in Opolo, Yenagoa, and Bayelsa State, Nigeria, remains largely unexplored. Thus, there is a need to investigate the effectiveness of VES in this region and its suitability for providing accurate and reliable information on groundwater resources. Addressing these challenges requires a systematic and interdisciplinary approach that integrates geological, hydrogeological, and geophysical data to delineate groundwater potential in Opolo effectively. Such efforts are essential for ensuring the sustainable management and utilization of water resources in the region, thereby supporting socio-economic development and environmental conservation initiatives.

MATERIALS AND METHODS

Study location

The area under investigation is located in the Opolo community along Imiringi Road, off Megastar (Figure 1) in Yenagoa Local Government, Bayelsa State. The area lies within Latitude 4°58'0"N - 4°56'25"N and Longitude 6°20'45"E - 6°21'30"E. There is organized road network that links to other parts of the state along Isaac Boro Expressway Yenago, Bayelsa State.

Geology of the study area

The geology described as part of the Niger Delta Sedimentary belt of Nigeria was described by many authors such as Bengtson (2018), Reijers (2011) and Gleeson *et al*. (2012). The deposition and initiations of the Niger Delta basin date back to the Late Createaceous (Maastrichtian) to Early Tertiary (Paleocene). Marine transgression was visibly terminated during the upper cretaceous to advance the Southern part of the Niger Delta thus heralding the Tertiary to Recent Niger Delta as it was referenced by Bengtson (2018). It is situated on the continental margin of the Gulf of Guinea in Equatorial West Africa between Latitude 3^{o} and 6^{o} and Longitude 5° and 8° E. About 75,000 km^2 aerial landmass (Short and Stauble, 1967). Calabar flank and the Abakiliki trough in Eastern Nigeria to the Atlantic Ocean are some of the extensions of the Niger Delta Basin. Short and Stauble (1967) further recognize three lithostratigraphic units in the modern Niger

Delta which are Akata, Agbada and Benin Formations in order of decreasing age.

Materials used

The research methodology comprised two main stages: initial fieldwork for collecting samples and subsequent laboratory analysis, followed by data interpretation. Various materials and tools were employed throughout these stages, each playing a critical role in the successful completion of the study. Abem SAS 1000 terrameter set was engaged in the fieldwork to acquire the data with the following accessories.

1. Global Positioning System (GPS): Utilized for accurate positioning and mapping.
2. Fieldnotes: Used to document observations and findings during fieldwork.
3. Abem Terrameter SAS 1000: A sophisticated device for measuring electrical resistivity in subsurface layers.
4. Four Electrodes: Metallic components employed for injecting current into the ground and measuring potential differences.
5. Measuring Tape: Used for precise measurement of distances during fieldwork.
6. Four Hammers: Essential for securely placing electrodes into the ground.
7. Battery: Crucial power source for operating electronic equipment during field activities.

Data collection and analysis

The data collection process involved utilizing the Schlumberger array, a specific electrode arrangement designed for Vertical Electrical Soundings (VES). This arrangement consisted of four electrodes arranged linearly around a central point: the outer electrodes (A and B) served as current electrodes, while the inner electrodes (M and N) (Figures 2 and 3) acted as potential electrodes placed closely together. Vertical Electrical Soundings were conducted using this array at various locations within the study area, deploying four electrodes aligned in a row with the outer ones serving as current electrodes and the inner ones as potential electrodes. The distance between these electrodes, specifically half of the current electrode spacing (AB/2), was maintained at 100 meters. In the Opolo Community, three VES profiles were conducted. During the Schlumberger array tests, the current electrode spacing was systematically increased while the potential electrode spacing remained relatively constant to ensure reliable measurement acquisition. The primary instrument used was the Abem Terrameter SAS 1000, capable of digitally displaying resistance values, with meticulous recording of these values in a dedicated fieldwork journal. Additionally, the Global Positioning System (GPS) was utilized to ensure accurate collection of coordinates.

The data processing was initiated with the initial step, of launching software tools such as PI2win+IP, Starter 5, and Microsoft Excel 2016. These tools facilitated the creation of spreadsheets containing sample parameters, which served as a foundation for subsequent analysis. The analysis method employed for Vertical Electric Sounding (VES) involved plotting the apparent resistivity values (ρa) obtained during fieldwork against the electrode spacing ((AB)/2) on a logarithmic scale. This plotting process was conducted utilizing specialized computer software, specifically IPI2win+IP. The resulting graphs, known as VES sounding curves, provided valuable insights into the subsurface properties. Interpreting these field curves entailed the use of partial curve matching techniques. Theoretical master curves were computed and utilized alongside auxiliary curves of various types (A, Q, K, and H). This method enabled the extraction of layer parameters, which were crucial for interpreting the sounding data. Subsequently, a one-dimensional (1-D) inversion technique was applied, utilizing the IPI2win software. This inversion technique utilized the derived layer parameters to reconstruct subsurface properties and obtain deeper insights into the geological structure.

RESULTS AND DISCUSSION

The results present the interpreted geo-electric layers from VES 1 to 3 at Opolo, along with their respective resistivity values (ρ), layer thickness, depth, curve type, and inferred lithology.

Vertical Electrical Sounding 1 (VES1)

Tables 1, 2 and 3 from a Vertical Electrical Sounding (VES) survey offer valuable insights into the subsurface geology and potential groundwater resources at Opolo, Yenagoa, Bayelsa State, Nigeria. By analysing the electrical resistivity (ρ) and thickness values of each layer, the lithology (rock type) and its potential for holding groundwater can be inferred. Table 1 is comprised of five layers, each characterized by resistivity, thickness, depth, curve type, and inferred lithology. **Layer 1** was interpreted as Clay - This uppermost layer has a resistivity of 76.7 Ωm (Ohm-meter) and a thickness of 3.71 meters (Table 1 and Figures 4). Clay is a fine-grained material with low permeability, meaning it does not allow water to easily pass through. This layer is likely to act as a confining layer, restricting the downward movement of surface water. **Layer 2** indicates Fine Sand - This second layer has a resistivity of 162 Ωm and a thickness of 17.4 meters. Fine sand can store groundwater, but the yield (amount of

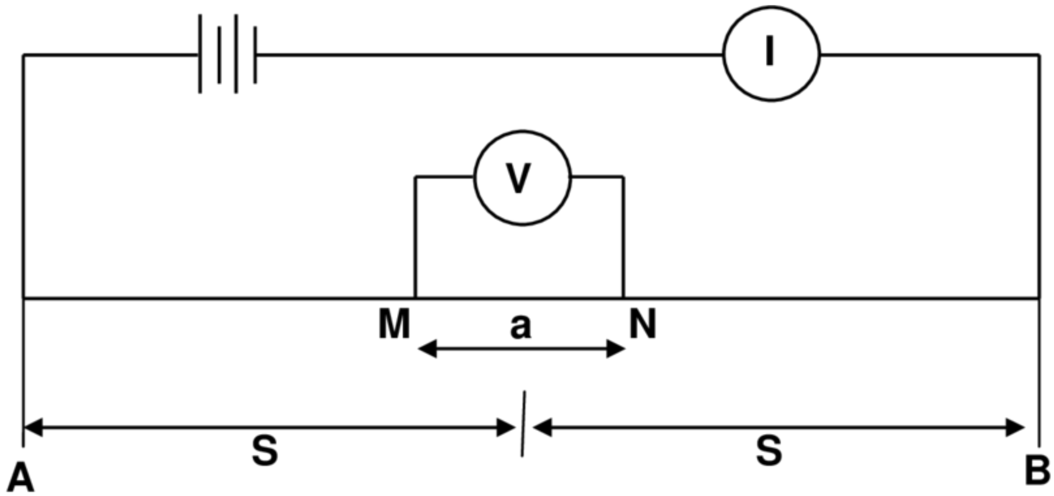

Figure 2. Configuration of the Schlumberger Array. **Key:** AB = Current Electrodes, MN = Potential Electrodes, L = Length (m), I = Electric current (Ampere), V = Potential Difference (Volt).

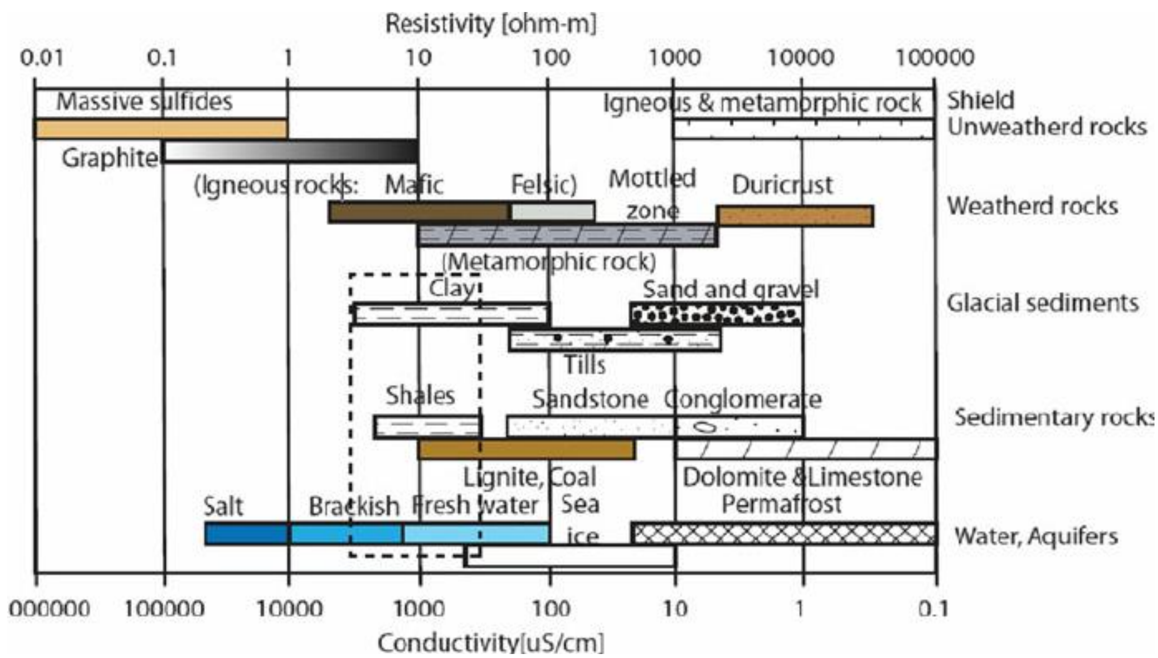

Figure 3. The estimated range of resistivity values of common rock types (Keller and Frisschknecht 1966).

extractable water) may be limited due to the smaller pore spaces between grains. **Layer 3:** Medium Sand - This layer shows a resistivity of 287 Ωm and a thickness of 29.8 meters. Medium sand generally possesses good permeability and water storage capacity. This layer has the potential to be a good aquifer due to the increased space between larger sand grains, allowing for easier water flow and potentially higher yield (Table 1 and Figure 4). **Layer 4:** Course Sand - The fourth layer has a resistivity of 359 Ωm and a thickness of 8.97 meters. Similar to medium sand, coarse sand can be a good aquifer due to its high permeability and storage capacity. **Layer 5:** Fine Sand (possibly saturated): This bottom layer has a resistivity of 131 Ωm and extends beyond the depth explored (indicated by the ∞ symbol for thickness). The resistivity value here is interesting. Generally, fine sand has a higher resistivity than coarse sand. The lower resistivity in this layer might be due to water saturation. However, with only the information provided, it is difficult to definitively say this layer is saturated. Further investigation (e.g., borehole

Table 1. Interpreted geo-electric layers (VES 1) at Opolo.

Layer	ρ (Ωm)	Layer thickness (m)	Depth (m)	Curve type	Inferred Lithology
1	76.7	3.71	0		Clay
2	162	17.4	21.1		Fine sand
3	287	29.8	50.9	A	Medium sand
4	359	8.97	59.9		Coarse sand
5	131	∞	>59.9		Fine sand

Table 2. Interpreted geo-electric layers (VES 2) at Opolo.

Layer	ρ (Ωm)	Layer thickness (m)	Depth (m)	Curve type	Inferred Lithology
1	99.67	0.6	0		Clay
2	72.87	0.65	1.25		Fine sand
3	56.83	4.22	5.48		Clay
4	368.4	5.97	11.45	HK	Medium sand
5	1189	12.48	23.92		Coarse sand
6	19.26	26.08	50		Clay
7	5.29	∞	>50		Clay

Table 3. Interpreted geo-electric layers (VES 3) at Opolo.

Layer	ρ (Ωm)	Layer thickness (m)	Depth (m)	Curve type	Inferred lithology
1	887	0.45	0		Clay
2	26.75	0.35	0.8		Clay
3	117.4	1.12	1.92		Fine sand
4	34.46	3.26	5.19	HK	Clay
5	1680	5.94	11.13		Coarse sand
6	707.5	11.52	22.66		Coarse sand
7	6.81	∞	>22.66		Clay

data) would be necessary to confirm groundwater presence.

Groundwater potential

Based on the VES results, the two most promising zones for groundwater potential in Opolo are I VES 1:

1. Medium Sand (Layer 3): This layer has a relatively high resistivity, indicating clean and well-permeable sand, ideal for storing and transmitting groundwater. Its significant thickness (29.8 meters) further enhances its potential as a productive aquifer (Table 1 and Figure 4).
2. Coarse Sand (Layer 4): Similar to the medium sand layer, the coarse sand layer also has good characteristics for an aquifer due to its high resistivity and permeability which is also agreeable with the publications of Egai and Oki (2020).

Vertical Electrical Sounding 2 (VES2)

This VES results presented in Table .2, which presents the interpreted geo-electric layers obtained from VES 2. The table provides valuable information for delineating groundwater potential in the area. Seven distinct geo-electric layers were delineated, each characterized by its resistivity (ρ), thickness, depth, curve type, and inferred lithology: **Layer 1** (0-0.6 m): This layer is the topmost with a high resistivity of (99.67 Ωm) and a very small thickness of (0.6 m) in table 2, Figure 5 The curve type (HK) suggests a topsoil layer, likely composed of clay due to its high resistivity. Clayey soils are generally poor conductors of electricity in Figures 5 and 7. **Layer 2** (0.6-1.25 m): This layer shows a lower resistivity (72.87 Ωm) and a slightly higher thickness (0.65 m) compared to the top layer. The inferred lithology is fine sand. The decrease in resistivity indicates a less resistant material compared to clay. **Layer 3** indicated a depth range of 1.25-5.48 m and significantly lower resistivity of (56.83 Ωm) and a considerably larger

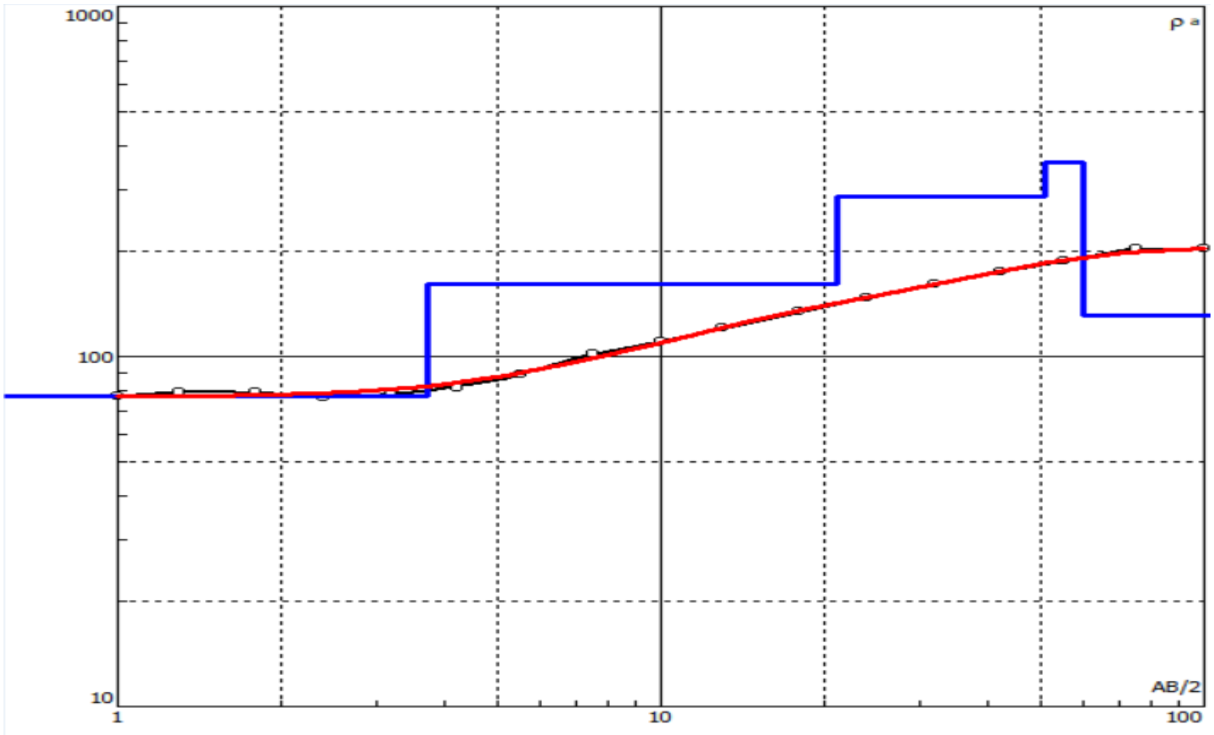

Figure 4. Computer Modelling for VES 1 at Opolo.

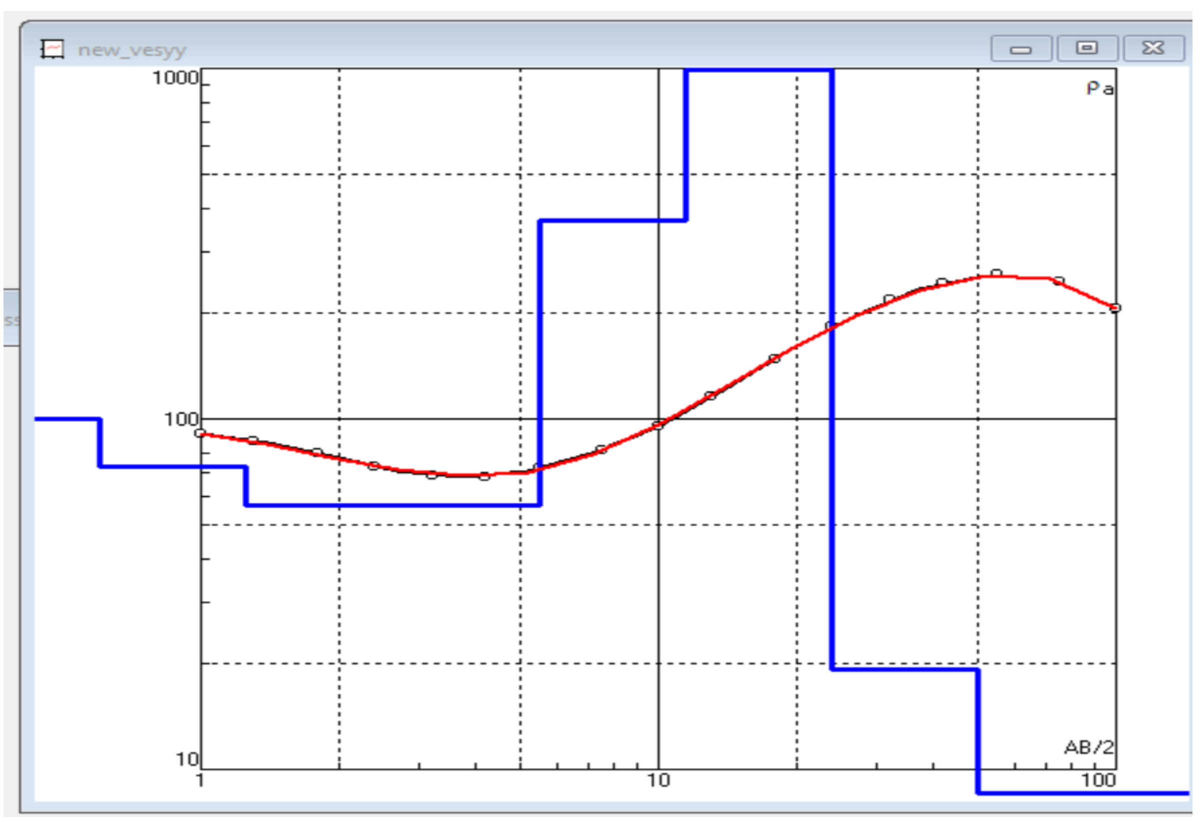

Figure 5. Computer Modelling for VES 2 at Opolo.

thickness of (4.22 m) which when compared to the previous layers was Clay as the inferred lithology. The lower resistivity also suggests higher moisture content or the presence of conductive minerals within the clay. **Layer 4** exhibited a sharp increase in resistivity (368.4 Ωm) with a depth range of 5.48-11.45 m and a moderate thickness of (5.97 m). The inferred lithology is medium sand. The higher resistivity indicates a good conductor of electricity, suggesting a potential water-bearing zone with saturated sand which can yield water into wells during pumping but may not be substantial. **Layer 5:** This layer has the highest resistivity value (1189 Ωm) in VES 2 (Table 2 and Figure 5), and a depth range of 11.45-23.92 m with a significant thickness of (12.48 m) inferred as Coarse sand which is agreeable with the resistivity chart as well as previous studies from Egai and Douglas 2015, Oki and Eteh, 2019; Eteh *et al*., 2019, Nwankwoala *et al*., 2015; Oborie and Nwankwoala, 2012. The exceptionally high resistivity further strengthens the possibility of a good aquiferous zone with clean and well-saturated coarse sand. **Layer 6** highlighted a drastic decrease in resistivity (19.26 Ωm), a depth range of (23.92-50 m) and substantial thickness of (26.08 m). The inferred lithology is Clay as the dominant material which was also validated with the resistivity range and also from previous studies such as Egai and Oki (2020). The low resistivity suggests a return to a less conductive zone, possibly acting as an aquitard (a layer that restricts groundwater flow). **Layer 7** indicated depth less than 50 m (>50 m): The layer delineates the lowest resistivity value of 5.29 Ωm and extends infinitely downwards (represented by the infinity symbol). Clay is inferred as the lithology (Table 2 and Figure 5). The very low resistivity suggests highly conductive material, possibly saturated clay with dissolved salts or minerals.

Groundwater potential

The analytical nomenclature of VES 2 data proved two potential zones for groundwater development which can be identified as:

1. Medium Sand Aquifer (Layer 4): Located between 5.48 and 11.45 meters in depth, this layer exhibits the characteristics of a good aquifer. The medium sand allows for water storage and flow, making it a viable source for groundwater extraction.
2. Coarse Sand Aquifer (Layer 5): This deeper layer (11.45 to 23.92 meters) presents the most promising potential for groundwater development (Figure 5). The coarse sand offers excellent permeability and storage capacity, making it a highly attractive target for boreholes.

Vertical Electrical Sounding 3 (VES3)

The interpretation of VES 3 is summarised in Table 3, it interpreted geo-electric layers obtained from Vertical Electrical Sounding (VES) at Opolo, Yenagoa, Bayelsa State, Nigeria. The data from this VES survey helps assess the groundwater potential in the area. Table 3 provides the interpreted geo-electric layers with their resistivity (ρ), thickness, depth, curve type, and inferred lithology. It started with **Layer 1** with a distinct lithology as clay with a depth range of 0-0.8 m, a high resistivity value of 887 Ωm and a very thin thickness of 0.45 m (Figure 6). This layer likely represents a dry, compacted clay cap, which can be beneficial as it restricts surface water infiltration and potential contamination of underlying aquifers. **Layer 2 {Clay (0.8-1.92 m)}:** The second layer is also clay but with a lower resistivity (26.75 Ωm) and slightly greater thickness (0.35 m). This suggests a less compacted clay layer, possibly containing some moisture. **Layer 3** suggests Fine Sand with a depth range of 1.92-5.19 m, this agrees with the bore logs and the publications of Oki and Eteh (2019). The third layer has a moderate resistivity value of 117.4 Ωm and a thickness of 1.12 m as shown in Figure 6. Fine sand can have variable water-holding capacity depending on its porosity and grain size. However, its presence suggests a potential zone for groundwater accumulation, although the yield might be limited. **Layer 4 {Clay (5.19-11.13 m)}:** The fourth layer is also clay, but it is a thicker clay with thin lenses of sand (3.26 m) with a lower resistivity (34.46 Ωm) comparable to the first clay layer. This indicates a more saturated clay zone, potentially acting as an aquitard (a layer that restricts groundwater flow) Ovuru and Eteh (2021) suggest aquitard formations yield a low substantive amount of water to wells during pumping. **Layer 5 and 6 {Coarse Sand (11.13-22.66 m)}:** The presence of two coarse sand layers with high resistivity values (1680 and 707.5 Ωm) and significant thicknesses (5.94 and 11.52 m) which is a very promising sign for groundwater potential. Coarse sand has good porosity and permeability, allowing for significant water storage and ease of wellbore extraction, this was also elucidated with the bore logs. **Layer 7 {Clay (> 22.66 m)}:** The bottommost layer identified by VES 3 is a thick clay layer with very low resistivity (6.81 Ωm). This suggests a saturated clay formation that likely acts as the base of the aquifer system explored in this VES survey which is also in line with the publications of Oki and Egai (2020), Eteh and Oki (2021) and Ozcep *et al*. (2009).

Groundwater potential

Analytical deductions from VES 3 results at Imiringi Road provided two main insights as observations regarding groundwater potential:

1. Shallow aquifer with limited potential: The presence of a thin layer of fine sand (layer 3) at a shallow depth (around 1 m) suggests a possible shallow aquifer. However, the fine grain size might limit the amount of

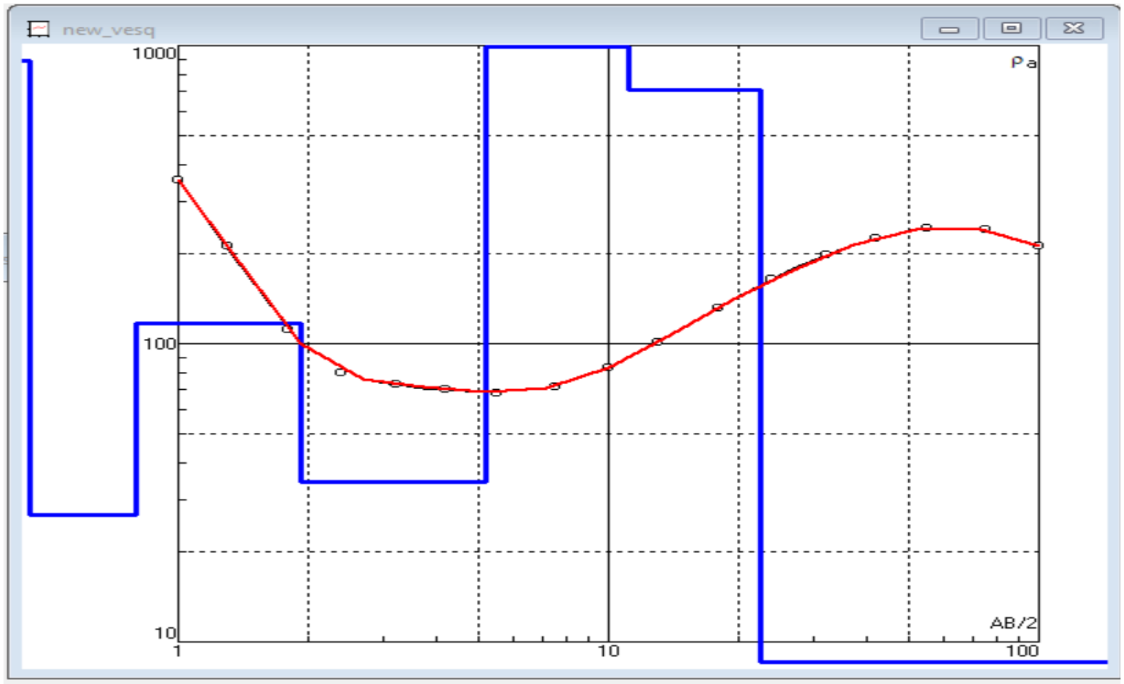

Figure 6. Computer Modelling for VES 3 at Opolo.

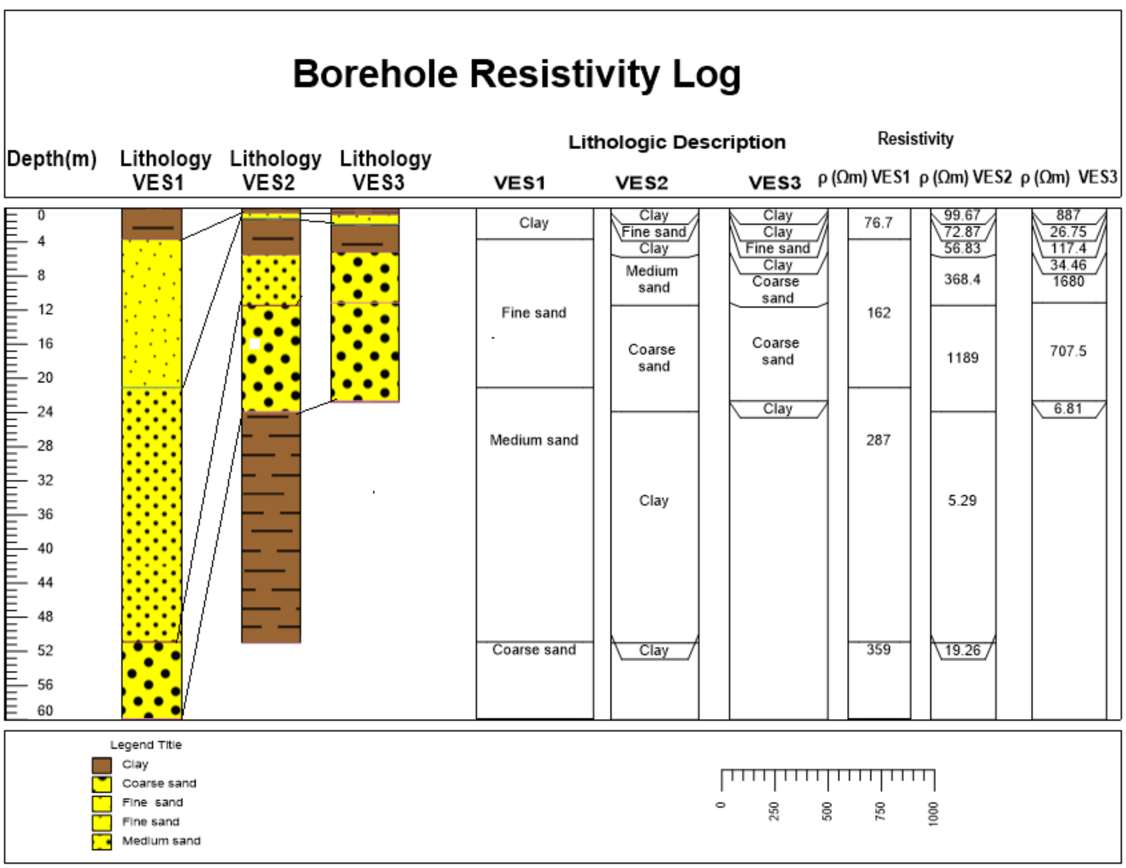

Figure 7. Borehole Resistivity log for Opolo VES 1, 2 and 3.

water it can store and transmit.

2. Promising deeper aquifer: The most significant finding is the presence of a thick zone of coarse sand (layers 5 and 6) between 5.19 m and 22.66 m depth (Figure 6). This zone has high resistivity, indicating good potential for storing and transmitting large quantities of groundwater.

Analysis of borehole log

Figure 7 presents a borehole log from Opolo, Yenagoa, Bayelsa State, Nigeria. It details the encountered lithology (rock types) and descriptions from the surface down to a depth of 42.4 meters.

Stratigraphy (Soil and Rock Layers)

Topsoil (0-3 meters): This uppermost layer consists of loose soil likely rich in organic matter. Topsoil generally has low permeability, meaning water infiltration is slow.

Sand layers (3-30 meters): The borehole log indicates a significant thickness (27 meters) of sand deposits. Sand is a good aquifer material due to its high porosity and permeability, allowing water to flow through it easily. This section is further categorized into coarse, medium, and fine sand. Coarse sand generally has higher permeability compared to finer sands (Nwokocha *et al*., 2018).

Clay layer 27.1-30 meters: This section consists of indurated plastic clay. Clay is generally considered an aquitard due to its low permeability, hindering groundwater flow. The presence of a clay layer at this depth is positive as it can act as a cap, confining and protecting any underlying aquifer from surface contaminants.

Aquifer zone

Coarse sand 30-42.4 meters: This zone comprises coarse sand layers identified as potential aquifer zones. The presence of coarse sand at this depth is a good sign for groundwater potential, as coarse sand typically has high hydraulic conductivity, facilitating water storage and well yield which is agreeable to the findings of Ovuru and Eteh (2021).

Groundwater potential

Two observations were drawn correlating with the borehole logs with respect to aquifer potentiality:

1. Shallow aquifer: The upper sand zone (3-27.1 meters) represents the most likely source of groundwater in this borehole. The coarse and medium sands indicate good porosity and permeability, allowing for water storage and flow.
2. Deeper aquifer: The coarse sand layer at the bottom (30-42.4 meters) might hold groundwater. However, its potential yield and quality require further investigation due to the presence of the overlying clay layer. The current study was in agreement with the studies of Ozcep *et al*. (2009), Okiongbo and Akpofure (2012), and Okiongbo and Oborie (2015).

Static water level

The static water level (SWL) refers to the depth at which groundwater sits in the borehole during the dry season (2.2 meters in this case). This information is crucial for understanding the well's depth requirement to access groundwater throughout the year. Here, a well drilled to at least 2.2 meters would encounter groundwater even during the dry season.

Borehole correlation with Vertical Electrical Sounding (VES)

This analysis examines the correlation between borehole log data and Vertical Electrical Sounding (VES) interpretations from Opolo, Yenagoa, Nigeria, to assess groundwater potential. This helps validate the VES results and identify potential groundwater zones (Tables 1, 2 and 3 and Figures 7 and 8).

Topsoil (0-3m): Both borehole logs and VES interpretations consistently identify clay as the topmost layer.

Shallow sand layers (3-21.2m): The borehole log details present various sand types (coarse, medium, and fine) within this depth range. While VES interpretations don't perfectly match these variations, they generally identify a fine sand layer throughout this zone. This discrepancy could be due to the limitations of VES in resolving thin layers or the averaging effect of the technique.

Clay layer (27.1-30m): Both data sources concur on the presence of a clay layer at this depth. This is crucial as clay layers often act as aquicludes (impermeable barriers), restricting groundwater flow.

Potential aquifer zone (33.3-42.4m): The borehole log in Figure 8 identifies coarse sand as the dominant lithology in this zone, suggesting a potential aquifer with good water-holding capacity. Interestingly, VES interpretations across Tables 1, 2, and 3 show some variation. Table 1 identifies coarse sand within this depth, aligning with the borehole log (Figure 9). However, Tables 2 and 3 depict

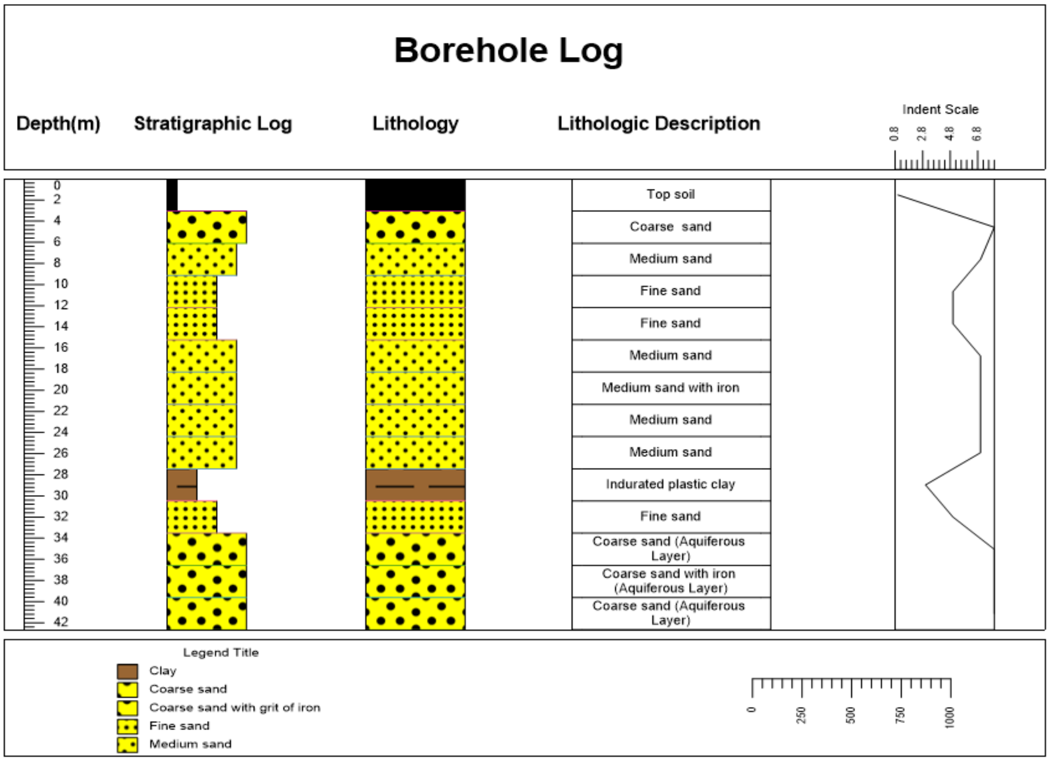

Figure 8. Borehole log for Opolo.

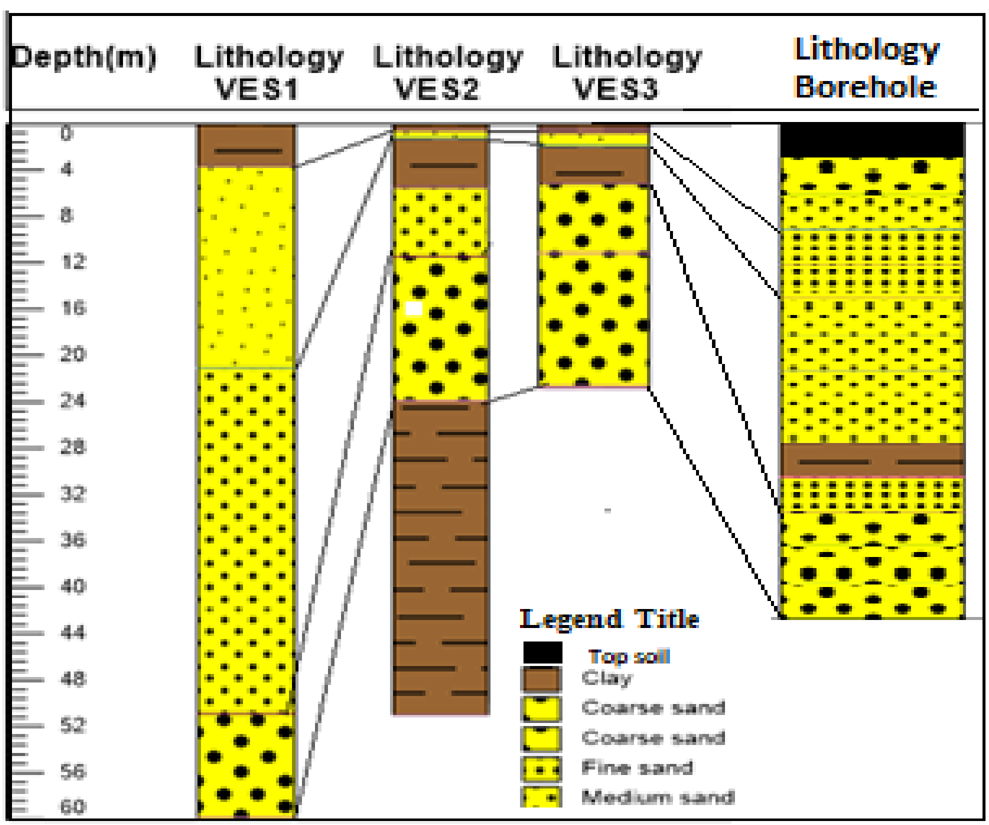

Figure 9. Correlation of borehole and resistivity log for Opolo.

clay at varying depths within this zone. These discrepancies highlight the potential limitations of VES in resolving thin layers or accurately distinguishing between certain materials with similar electrical properties. This agrees with the findings of Eteh *et al*. (2021).

Groundwater potential

Correlation of the borehole log depicted that the coarse sand layer between 33.3 and 42.4 m is a strong indication of a productive aquifer. However, the inconsistencies in VES interpretations regarding the presence and thickness of clay within this zone require further analysis. Here are some possibilities:

1. **Clay lenses:** The clay layers identified by VES in Tables 2 and 3 might be localized lenses within the aquifer zone, not continuous across the entire area.
2. Resolution limitations: As mentioned earlier, VES might not be able to perfectly resolve thin clay layers within the coarse sand aquifer.
3. Data integration: Combining VES data with other geophysical techniques like seismic refraction could provide a clearer picture of the subsurface layering.

Conclusion

In conclusion, the comprehensive analysis of Vertical Electrical Sounding (VES) data, borehole logs, and their correlation provides valuable insights into the groundwater potential and subsurface geology of Opolo, Yenagoa, Bayelsa State, Nigeria. Through the interpretation of resistivity values and lithological characteristics, several layers with promising aquifer properties have been identified. In the VES 1 survey, layers of medium sand and coarse sand stand out as potential aquifers due to their high resistivity values and favourable thicknesses. These layers offer significant potential for groundwater storage and extraction, presenting opportunities for sustainable water resource management in the region. Similarly, the VES 2 survey reveals layers of medium sand and coarse sand as favourable aquifer zones, particularly highlighting the deeper coarse sand layer for its excellent potential in groundwater development. In the VES 3 survey, the presence of coarse sand layers at considerable depths further reinforces the groundwater potential of the area. Despite the presence of clay layers, the identified coarse sand zones offer favourable opportunities for groundwater extraction. The borehole log analysis complements the VES data, confirming the presence of sand layers with good aquifer characteristics. The correlation between the borehole log and VES interpretations enhances our understanding of the subsurface geology and groundwater distribution in Opolo. However, discrepancies between VES interpretations and borehole logs highlight the limitations of each method. While VES provides valuable insights into subsurface structures, its ability to resolve thin layers and accurately distinguish between materials is limited. Borehole logs offer detailed information but are limited to specific locations. To fully assess the groundwater potential and optimize water resource management in Opolo, further investigations, such as pump tests and groundwater quality assessments, are recommended. Additionally, integrating data from multiple sources, including VES, borehole logs, and hydrogeological studies, can provide a more comprehensive understanding of the aquifer system and support informed decision-making for sustainable water supply and management strategies.

CONFLICT OF INTEREST

The authors declare the they have no conflict of interest.

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