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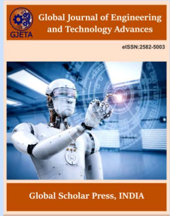

(Research Article)

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Application of VES and VLF-EM methods for groundwater exploration through overburden thickness estimation of aquiferous zones within Kabawa Area, Lokoja Kogi State, Nigeria

Abdulbariu Ibrahim [1,*], Bello Gloria Iyetunde [1], Abdulmajid Ibrahim [2], Adedolapo Olujuwon Adegbite [3], Musa Ojochenemi Kizito [1], Mu'awiya Baba Aminu [1,4], Ayinla Habeeb Ayoola [1], Hassan Jubril Izge [5], Gani Lukman Inuwa [6] and Abidemi Obatoyinbo Ajayi [7].

[1] *Department of Geology, Federal University Lokoja, Kogi State, Nigeria.*
[2] *Department of Civil Engineering, Faculty of Engineering, Ahmadu Bello University, Zaria, Nigeria.*
[3] *Schlumberger Oilfield Services.*
[4] *School of Material and Mineral Resources Engineering, Universiti Sains Malaysia, Engineering Campus, Nibong Tebal, Pinang, Malaysia.*
[5] *Department of Geology, Ahmadu Bello University, Zaria, Nigeria.*
[6] *Department of Physics, Federal University Lokoja, Kogi State, Nigeria.*
[7] *Department of Industrial Engineering, College of Engineering. New Mexico State University, Las Cruces. USA.*

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Abstract

The area of study was surveyed to know more about the geology of the area which was characterized by Lokoja Formation, Patti Formation, and Agbaja Ironstone. The geoelectric and electromagnetic survey was carried out at Kabawa with the view to delineate the overburden thickness and aquiferous zone in the area. Geological field mapping were carried out which was accompanied with acquisition of sixteen (16) Vertical Electrical Sounding (VES) data, and ten (10) Very Low Frequency Electromagnetic (VLF-EM) data. The major rocks encountered are sandstones, claystone, and siltstones. Further findings revealed that the VES result showed five (5) geo-electric layers in the area, these layers are the top soil having resistivity and thickness value ranges from 30.2-1194.9 Ωm and 0.3-4.0 m, highly ferruginous sandstone has resistivity and thickness value ranges from 3.6-39.5 Ωm and 1.2-8.3 m, dry sandstone has resistivity and thickness range of 4.4-1043.7 Ωm and 0.5-5.1 m, claystone has resistivity and thickness range of 2.1-1360 Ωm and 0.5-22.1 m, siltstone has resistivity and thickness ranges from 3.9-241.2 Ωm and 0.6-76.8 m, and the water-saturated sandstone has a resistivity ranging from 13.5-431.3 Ωm and an undefined thickness respectively. Generally, the VLF-EM result correlated with what was obtained from the VES data and further confirmed that the water-bearing strata (aquiferous zones) are in the overburden units. Therefore, the integration of geology, VES and VLF-EM techniques served as very important approaches for aquiferous zones delineation

Keywords: Aquifer; Resistivity and thickness; Exploration; Water-saturated.

1. Introduction

The surface geophysical investigation involving Very Low Frequency Electromagnetic (VLF-EM) and Vertical Electrical Sounding (VES) methods have proved very useful in the identification of weathered basement and fracture that is favorable for groundwater accumulation. The VLF-EM and VES have been used for many decades in hydrogeological, mining, and geotechnical study due to the relatively high electrical conductivities. This is the reason why the application of the VLF-EM method has been found useful in site investigation for groundwater development, especially, in the

* Corresponding author: Abdulbariu Ibrahim; Email: abdulbariu.ibrahim@fulokoja.edu.ng

Basement Complex area (Hazell et al., 1988; Olayinka, 1990; Olorunfemi et al., 2005; Adiat et al., 2009; Ariyo et al., 2009; Bayowa et al., 2014., Akinrinade and Olabode, 2015) with its relevance in overburden thickness estimation and basement fracture delineation (Abdulbariu et al., 2023b). The electromagnetic method is however more relevant in the delineation of near-surface fractures than in the estimation of overburden thickness as observed by Olorunfemi et al. (1995) and Abdulbariu et al., 2024.

The VES technique has been found effective in aquifer identification (Ako and Olorunfemi, 1989; Mbonu et al., 1991). The electrical resistivity survey (VES) is also widely employed in the delineation of basement regolith and location of fracture or fissured media and associated zones of deep weathering in crystalline terrains (Hazell et al., 1988; Beeson and Jones, 1988; Olayinka et al., 2004; Olorunfemi et al., 2005). Electrical resistivity is a geophysical method in which an electrical current is injected into the ground through steel electrodes to measure the electrical properties of the subsurface (Nwankwo et al., 2013; Evans et al., 2010; George et al., 2010). Also, an electrical resistivity survey using the vertical electrical sounding (VES) method is one of the simplest and most cost-effective geophysical surveys employed (Okiongbo et al., 2011; Ezeh and Ugwu, 2010).

The VLF-EM method was adopted as a reconnaissance tool to map possible linear features such as faults and fracture zones while the electrical resistivity (VES) method was used to investigate prominent VLF-EM anomalies and provide a geoelectric image of the subsurface sequence (Abdulbariu et al., 2023a, Nanfa et al., 2022). The vertical electrical sounding provides information on the vertical variation in electrical resistivity with depth (Aminu et al., 2022). It is commonly used to assess the reliability of the features delineated from the VLF-EM survey. The electromagnetic and resistivity methods are both responsive to water-bearing basement fracture columns due to the relatively high bulk electric conductivities; both methods were therefore found relevant and integrated into the geophysical investigation.

Alvin et al. (1997), in Utah County, USA, used VLF integrated with electrical resistivity for the delineation of shallow alluvial aquifer contaminated by hydrocarbon. Sharma and Baranwal (2005) delineated groundwater-bearing fracture zones in a hard rock area using integrated very low frequency electromagnetic and resistivity data. Taiwo et al (2016) used the combination of Very Low Frequency Electromagnetic (VLF-EM) and electrical resistivity survey for evaluation of groundwater potential of Modomo/Eleweran area, southwestern Nigeria. Ohwoghere-Asuma et al. (2018) and Aizebeokhai and Oyeyemi (2015); have at different places demonstrated the effectiveness of same methodology in aquifer vulnerability study and delineation of high resistivity layers in sedimentary terrains in the Niger Delta and southwestern Nigeria, respectively. Oluwayomi 2024a, 2024b emphasized on the geophysical and geotechnical methods in foundation studies to ensure construction projects achieve optimal outcomes by prioritizing safety and efficiency through solid infrastructure.

The aim of this research is to estimate the overburden thickness and its effect on the aquiferous zone in Kabawa Area, using surface geophysical methods.

The objectives of this study are as follows.

- Carry out geophysical surveys in order to obtain VLF-EM and VES data in the study areas.
- To produce a geological map of the study area
- To determine the geoelectrical layers of the subsurface geology.
- To determine the aquifer characteristics such as resistivity, thickness, and depth.
- To characterize the groundwater potential (aquiferous) zones of the area. See Figure 1 Topographical Map Showing the Location and Accessibility of the Study Area

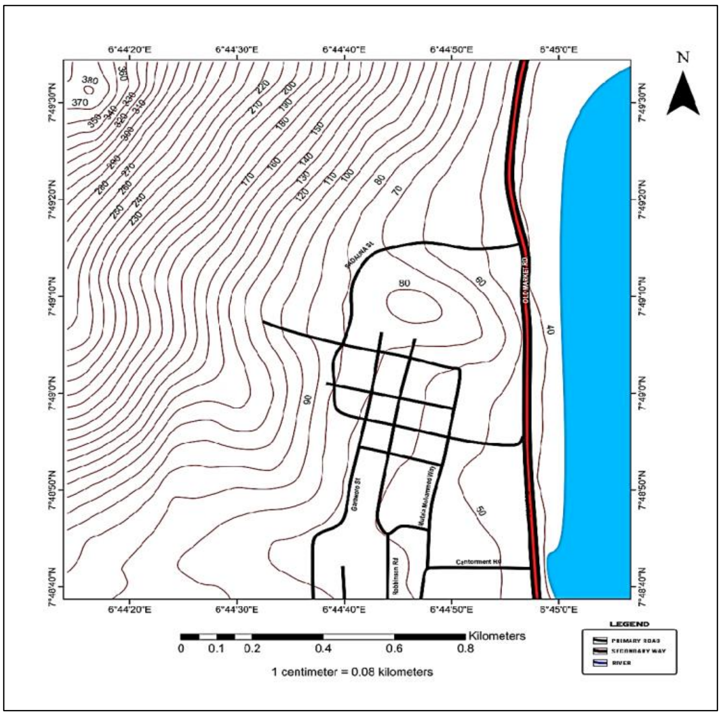

Figure 1 Topographical Map Showing the Location and Accessibility of the Study Area.

2. Materials and methodology

The study area is located within Longitudes E6^{0}44’20’’-E6^{0}45’00’’ and Latitude N^{0}48’40’’- N7^{0}49’30’’, located within Lokoja, Kogi state in the Northcentral part of the country.

Field mapping and geophysical surveys and some computer software were used to assess groundwater potential in basement rocks. Key factors include joint presence, fracturing, and their interconnectivity, influencing water transmission and storage. Integrated approaches like VLF Electromagnetic and VES are pivotal for delineating these structures (Ajayi and Hassan, 1990; Olayanju et al., 2009). Therefore, this research used an integrated geophysical approach involving the Very Low-Frequency Electromagnetic (VLF-EM) and Vertical Electrical Sounding (VES) methods to delineate the overburden thickness and aquiferous zones. The geology of the area was also studied through geological field mapping.

2.1. Materials

Field mapping and geophysical surveys utilised the following essential equipment such as: Base Map which guides exploration and locates rocks and VES points. Field Notebook: records observations. GPS captures coordinates. Terrameter: measures resistivity with electrodes. PQWT-TC300 detects fracture zones using VLF-EM. Electrodes: transmit current; Hammer drives them. Jumper Cable: connects equipment. Measuring tapes measure electrode positions.

2.2. Methodology

2.2.1. Geological Mapping

The geological field mapping commenced with a reconnaissance survey of the Kabawa. The field mapping was carried out, and data were collected in the form of rock samples, photographs, measurements, and notes. This was done to obtain basic knowledge about the prevailing field conditions through direct measurements and collecting and analyzing rock, minerals and measurements of geometric aspects. Geological mapping of the area was carried out with the following equipment: hammer, Global Positioning System (GPS), compass, chisel, hand magnifiers, and sample bags.

2.2.2. Geophysical Mapping

Both VLF-EM and VES were carried out on the study site to geophysically evaluate the underlying subsurface geological content. Ten EM profiles were carried out along specific profile lines and along specific direction. This were followed with sixteen VES on the EM profile lines to investigate the conductive zones earlier isolated from the profiles.

3. Result

Results from geological field mapping, Vertical Electrical Sounding (VES), and VLF-EM data are presented. From the study, the resistivity, thickness and depth as well as the groundwater potential zone within the area were ascertained.

3.1. Presentation of VES and VLF-EM Result

The result of processed VES field data and VLF-EM data are presented in the following figures. Table 1 Tabular Analysis of the Geoelectric Layer Showing the Thickness and Aquiferous Zones shows the summary of the interpreted geo-electric layer (thickness and depth of the aquiferous zone) from VES curves.

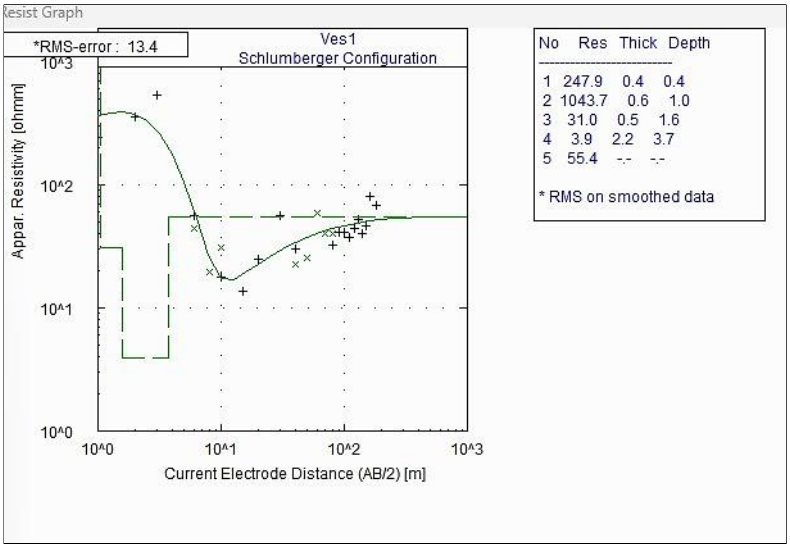

Figure 2 VES 1 Curve Showing Resistivity Curves, Layer Resistivity and Thickness

Figure 3 VLF Cantonment Profile Showing Conductivity/resistivity variation along the entire profile line.

The Figure denoted as VES 1 (Figure 2 VES 1 Curve Showing Resistivity Curves, Layer Resistivity and Thickness) illustrates a distinctive curve pattern designated as KQH curve type. The graphical representation visually captures notable differences in apparent resistivity, indicating differences among five discrete geological layers. These layers encompass a resistivity spectrum spanning from 3.9 Ωm to 1043 Ωm, accompanied by layer thicknesses ranging from 0.4 to 2.2 meters. These identified strata are interpreted as topsoil, dry sandstone, claystone, siltstone and water saturated sandstone. It is suggested that a hand dug well will strive in this area.

The VLF-EM data (**Error! Reference source not found.** isolated particular zones distinguished by low resistivity (Red box and blow the box). Comparing the outcomes of the VES 1 and the VLF 1, it becomes feasible to establish correlations between the strata characterised by low resistivity as identified in the VES graph and the regions manifesting high conductivity (low resistivity) as presented in the VLF data. Both the VES and VLF show shallower depth water occurrence.

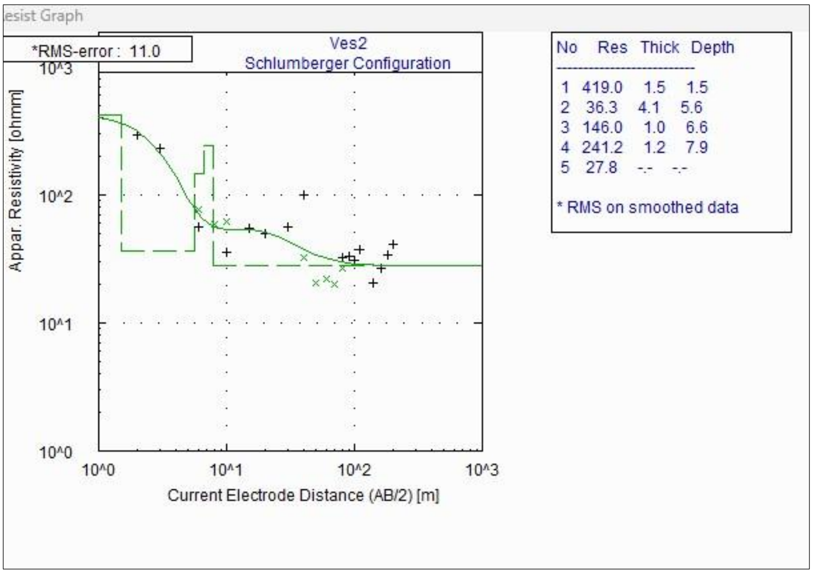

Figure 4 VES 2 Curve Showing Resistivity Curves, Layer Resistivity and Thickness.

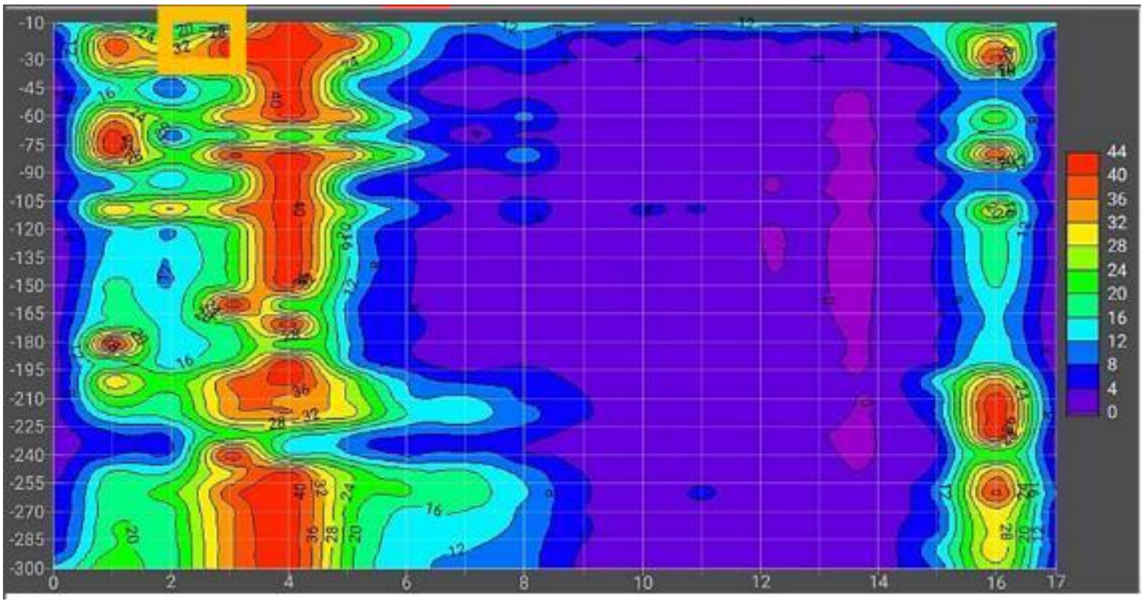

Figure 5 VLF Angwa Kura 1 Profile Showing Conductivity/resistivity variation along the entire profile line.

Figure 4 VES 2 Curve Showing Resistivity Curves, Layer Resistivity and Thickness shows a curve pattern classified as type HAK. There is variation in apparent resistivity, among the five distinct geological layers. There resistivities range between 27.8 Ωm to 419 Ωm, with corresponding layer thicknesses ranging from 1.0 to 4.1 meters. These identified strata are primarily composed of topsoil, dry sandstone, claystone, siltstone and water saturated sandstone. Of particular significance is the fifth layer, which displays a reduction in resistivity at this specific depth, suggesting the possible presence of an aquifer, and a hand dug well is also suggested in this area.

The result of the VLF-EM (**Error! Reference source not found.** shows particular zones distinguished by high resistivity (low conductivity). The VES 2 is on this VLF 2 profile indicated by the orange colour box (data point labeled as 3), and the two results correlates indicating only moderate water occurrence at very shallow depth which can only be developed into hand dug well.

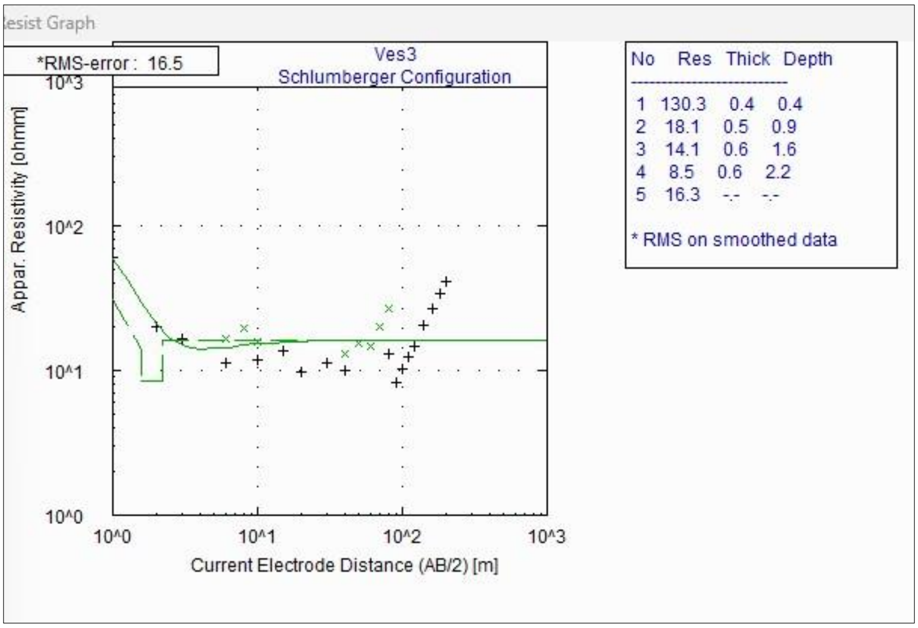

Figure 6 VES 3 Curve Showing Resistivity Curves, Layer Resistivity and Thickness

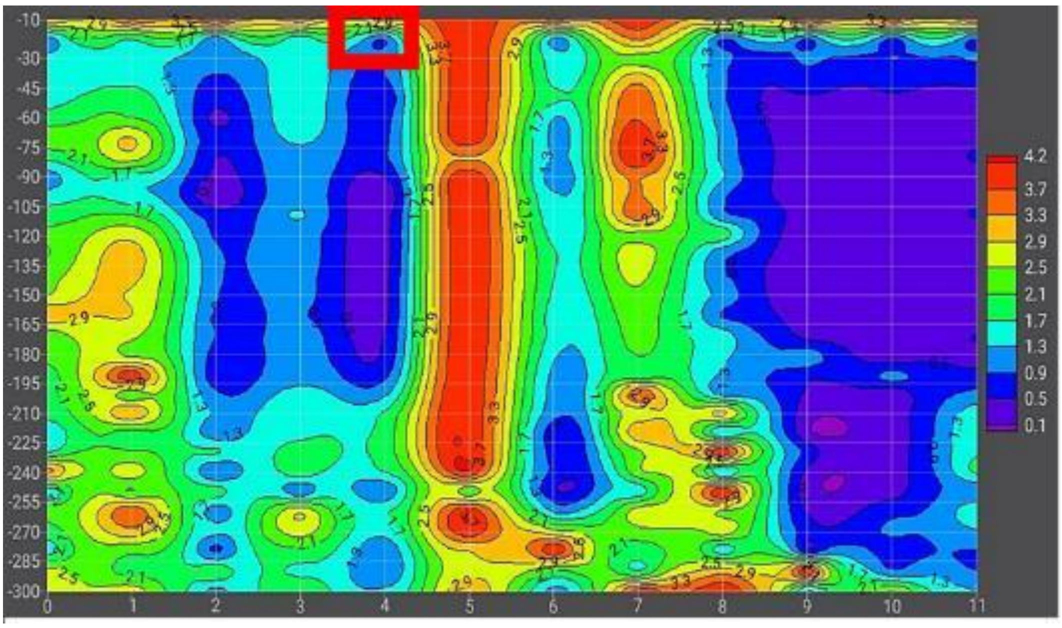

Figure 7 VLF Angwa Kura 2 Profile Showing Conductivity/resistivity variation along the entire profile line.

The graph labeled as VES 3 (Figure 6 *VES* 3 Curve Showing Resistivity Curves, Layer Resistivity and Thicknessdisplays a curve categorized as type QQH. Five distinct geological layers were identified with varying resistivities, thicknesses and depths. These layers encompass a range of resistivity values from 8.5 Ωm to 130.3 Ωm, along with corresponding layer thicknesses ranging from 0.4 to 0.6 meters. These identified layers are interpreted as topsoil, dry sandstone, claystone, siltstone and water saturated sandstone. The most noticeable change occurs when the distance between electrodes reaches 15 meters and a resulting decrease in resistivity was observed. All the layers exhibit very low resistivity except the topsoil which can be interpreted as lateritic unit. Borehole and hand dug well cannot be developed in this VES location because of presence of non-appreciable depth.

The results obtained from the VLF-EM data (Figure 7) highlights specific zone with low resistivity (higher conductivity). The VES 3 is on this VLF 3 profile at data point marked as 4 (red colour box). The low resistivity is also at depth up to 30 meters with moderate water content which can be developed into the medium yield shallow borehole, though the VES suggested no hand dug well and borehole to be drilled at this location.

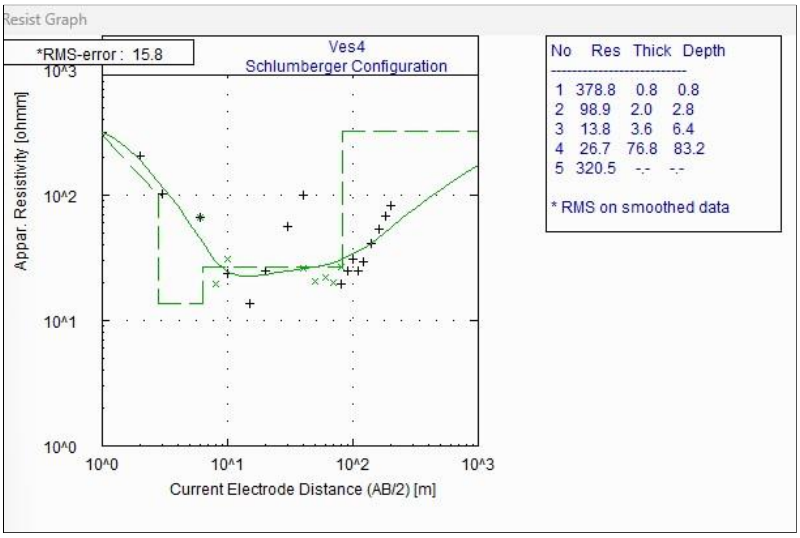

Figure 8 VES 4 Curve Showing Resistivity Curves, Layer Resistivity and Thickness.

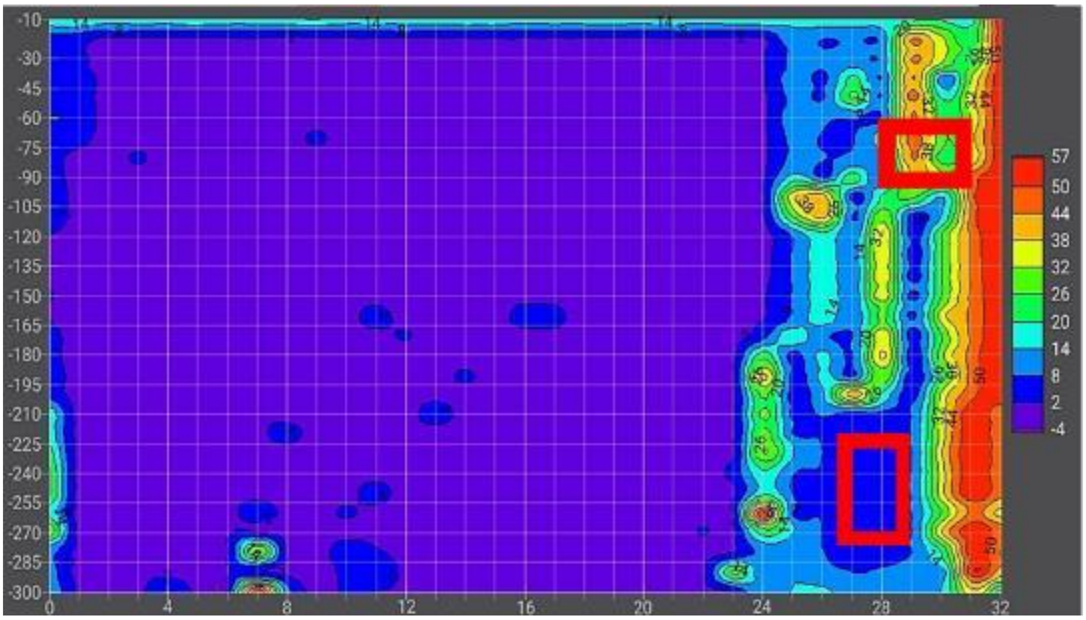

Figure 9 VLF Angwa Kura 3 Profile Showing Conductivity/resistivity variation along the entire profile line.

VES 4 (Figure 8 VES 4 Curve Showing Resistivity Curves, Layer Resistivity and Thickness. shows a QHA curve pattern. There is five layers. These units range in resistivity from 13.8 Ωm to 378.8 Ωm, accompanied by layer thicknesses ranging from 0.8 to 76.8 meters. These identified layers consist of topsoil, dry sandstone, claystone, siltstone and water saturated sandstone. A borehole is suggested to be drilled at this location because of the low resistivity and appreciable depth.

The results obtained from the VLF-EM (**Error! Reference source not found.** emphasizes specific zones characterized by high resistivity (low conductivity) at depth of 60-90 meters and low resistivity (high conductivity) at depth below 225 meters. VES 4 is on this VLF 4 profile. This lower depth (red color square box) may not contain groundwater but the deeper one (indicated by a rectangular red box) contain groundwater and this will be tapping water from the upper part of the Lokoja Formation or Sandstone.

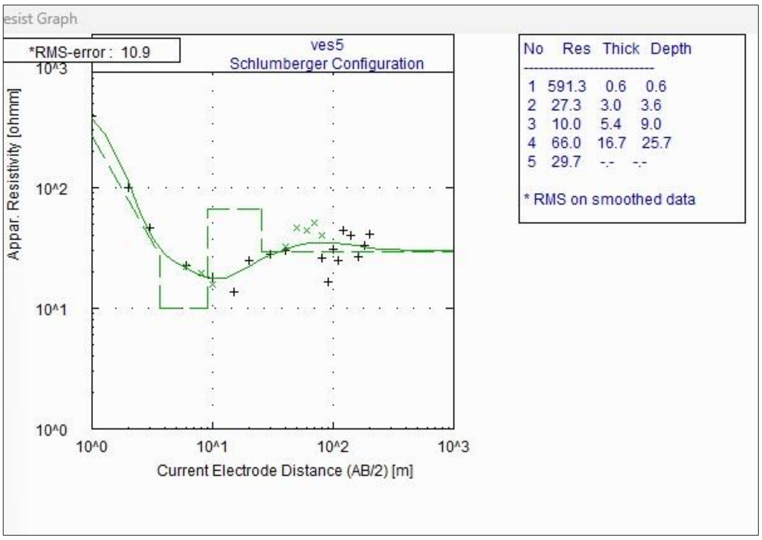

Figure 10 VES 5 Curve Showing Resistivity Curves, Layer Resistivity and Thickness.

Figure 10 shows QHK curve type. Variations in apparent resistivity were observed from the graph, and five specific geological lithological units were identified with a resistivity range of between 10.0 Ωm to 591.3 Ωm, with layer thicknesses ranging from 0.4 to 16.7 meters. They are interpreted as lateritic topsoil, highly ferrunginous sandstone, claystone, siltstone and water saturated sandstones. The fifth layer which also shows a low resistivity value can be interpreted as the potential aquifer. This aquifer is believed to be made up of sandstone with resistivity values of 29.7 Ωm with an undefined thickness. Borehole is suggested to be drilled to an undefined depth until another lithology is encountered which will determine the discontinuation of the further drilling. Therefore, a Geologist and or Geophysicist must be on ground during drilling operation.

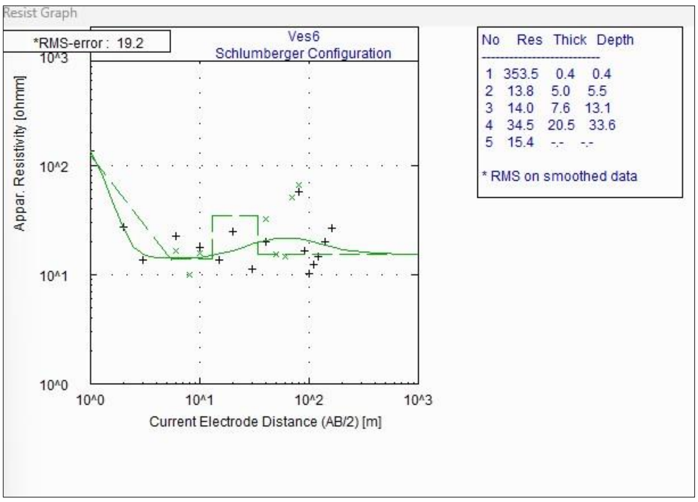

Figure 11 VES 6 Curve Showing Resistivity Curves, Layer Resistivity and Thickness

VES 6 of Figure 11 VES 6 Curve Showing Resistivity Curves, Layer Resistivity and Thickness11 shows a curve pattern identified as type HAK with five layers. These units have resistivity range of between 13.8 Ωm to 353.5 Ωm, accompanied by layer thicknesses ranging from 0.4 to 20.5 meters. These identified layers are topsoil, dry sandstone, claystone, siltstone and water saturated sandstone. This aquifer has low resistivity values of 34.5 and 15.4 Ωm, with a thickness of 20.5 meters and above, meaning layers four and five can serve as the aquifer. Borehole may be suggested here.

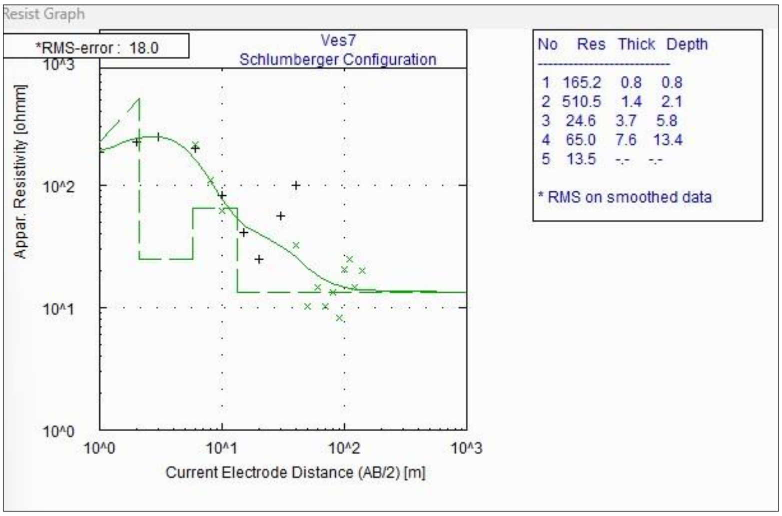

Figure 12 VES 7 Curve Showing Resistivity Curves, Layer Resistivity and Thickness

Figure 12, VES 7 showcases a KHK curve type with five distinct geological units. These units have resistivity spectrum varying from 13.5 Ωm to 510.5 Ωm, and layer thicknesses ranging from 0.8 to 7.6 meters. They are topsoil, dry sandstone, claystone, siltstone and water saturated sandstone. The fifth layer is the aquiferous zone characterized by resistivity values measuring 13.5 Ωm and an undefined thickness. A hand dug well is suggested in this location because of low depth.

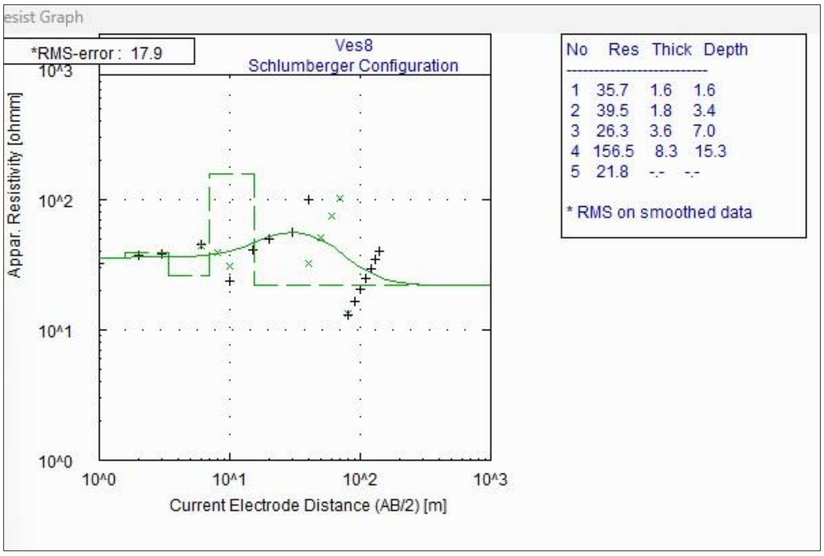

Figure 13 VES 8 Curve Showing Resistivity Curves, Layer Resistivity and Thickness.

Figure 13, VES 8 exhibits a curve pattern identified as type KHK with five layers. The layers show a resistivity value ranging from 21.8 Ωm to 156.5 Ωm, accompanied by layer thicknesses ranging from 1.6 to 8.3 meters. These identified layers comprise of topsoil, wet sandstone, claystone, dry siltstones and water saturated sandstones. Because of low depth, hand dug well is suggested to be the best in this VES point.

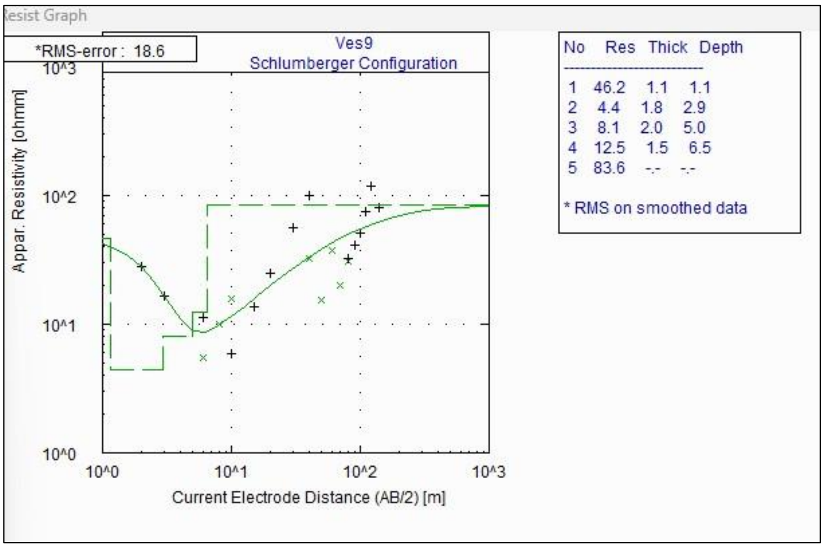

Figure 14 VES 9 Curve Showing Resistivity Curves, Layer Resistivity and Thickness.

VES 9 (Figure 14) is HAA curve type characterised five layers with resistivity range between 4.4 Ωm to 83.6 Ωm, and layer thicknesses ranging from 1.1 to 2.0 meters. Identified layers are topsoil, weathered clay, claystone, siltstone and water saturated sandstone. The aquifer has a resistivity value of 83.6 Ωm, with infinite thickness and a depth of 6.5m. A hand dug well is the best option at this VES location.

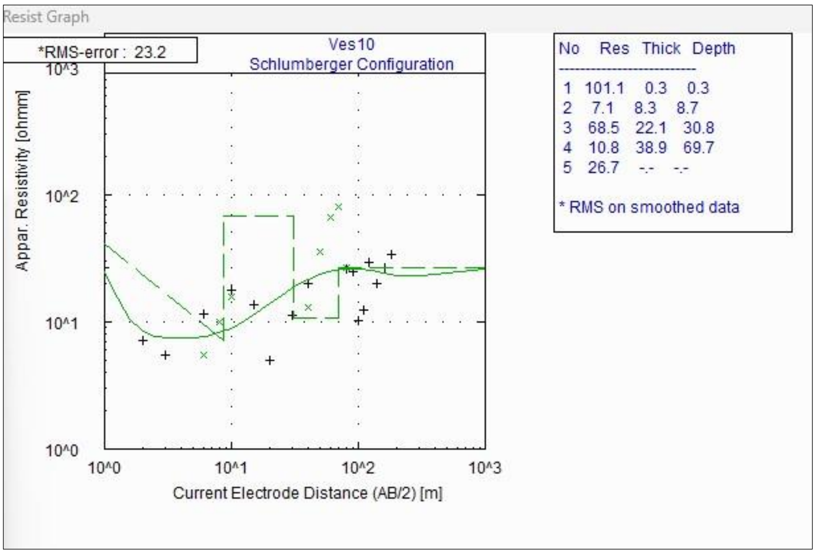

Figure 15 VES 10 Curve Showing Resistivity Curves, Layer Resistivity and Thickness.

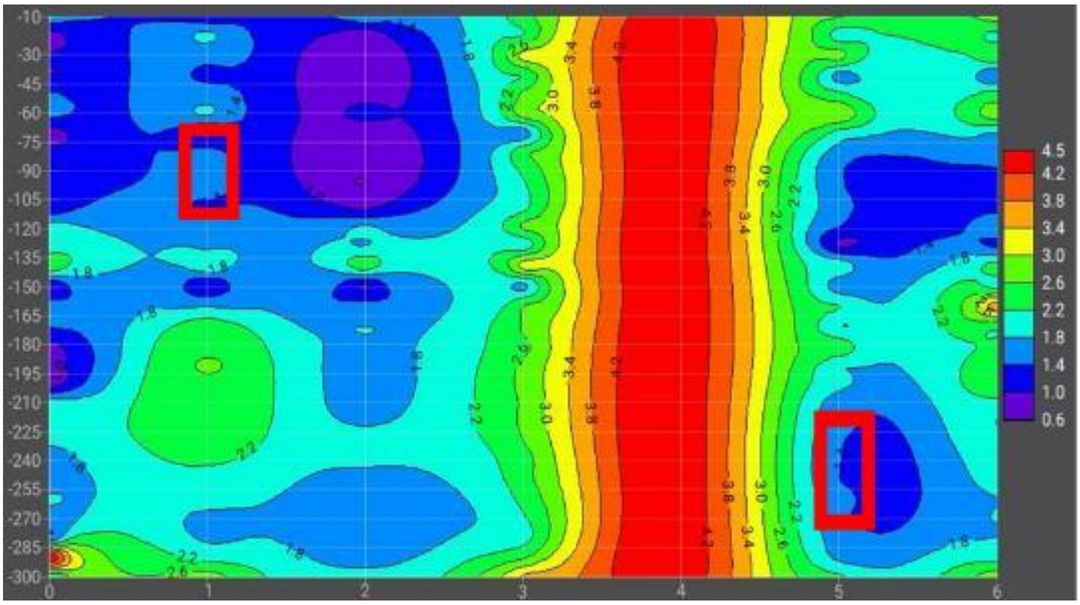

Figure 16 VLF Gbanchukwu Profile Showing Conductivity/resistivity variation along the entire profile line**.**

Figure 15 VES 10 Curve Showing Resistivity Curves, Layer Resistivity and Thickness. (VES 10) showcases a unique curve pattern recognized as type HKH, showing differences in resistivities among five distinct geologic units with resistivity values ranging from 7.1 Ωm to 101.1 Ωm. The thicknesses of these layers vary between 0.3 and 38.9 meters. The fifth layer is the aquiferous unit believed to be composed of sandstone characterized by resistivity values measuring 26.7 Ωm, with appreciable depth of 69.7 meters. It is suggested that a borehole should be drilled at this VES point.

The outcomes of VLF-EM 5 (**Error! Reference source not found.** isolated some low resistivity (high conductivity) zones as shown by the rectangular boxes. VES 10 is on this profile (data point labeled as 1 in the VLF dataset) with the depth from 70 to 101 meters. This indicates substantial groundwater presence. Also, at point line 5 (vertical oriented rectangular red box) is there is an indication for possible existence of another layer at approximately around 240 meters with good water occurrence.

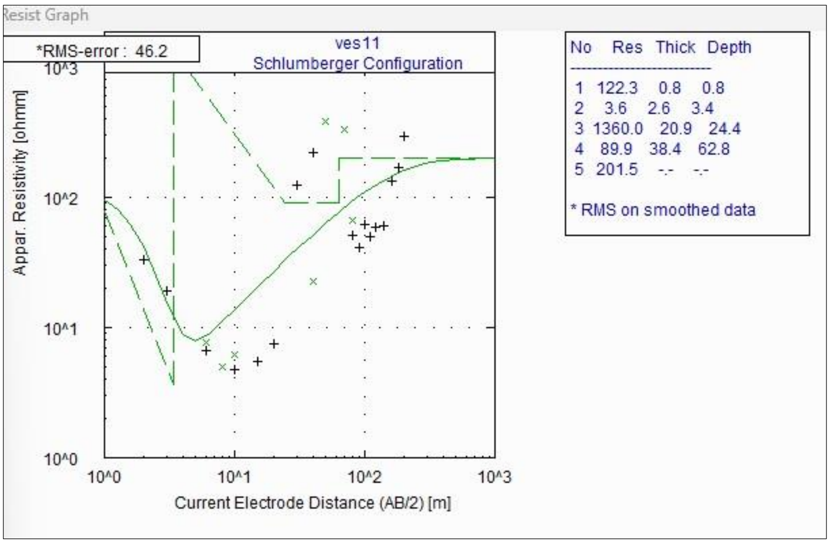

Figure 17 VES 11 Curve Showing Resistivity Curves, Layer Resistivity and Thickness.

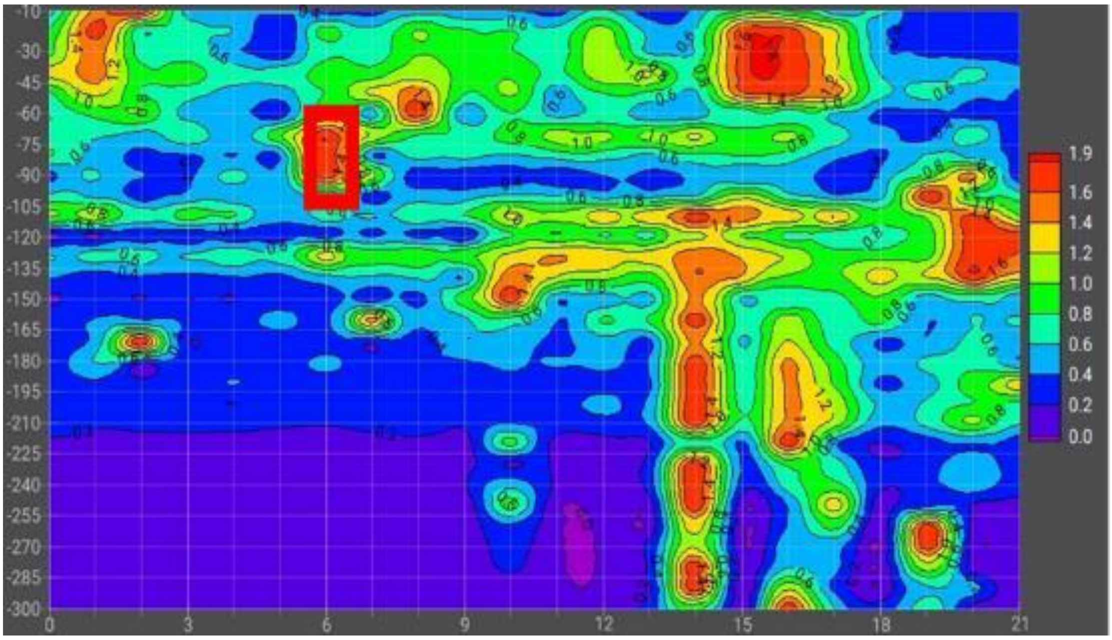

Figure 18 VLF IRS Madi 1 Profile Showing Conductivity/resistivity variation along the entire profile line.

VES 11 of Figure 17 illustrates a curve pattern denoted as type HKH. This graphical representation captures different in apparent resistivity, with distinctions among five geoelectric layers. The layers show a wide range of resistivity values, spanning from 3.6 Ωm to 1360 Ωm. Similarly, the thicknesses of these layers vary between 0.8 to 38.4 meters. The fourth and fifth layers can be exploited for groundwater. A drill hole or borehole is suggested in this VES location to a depth far beyond the 63.8 meters depending on the geology of samples coming out of the hole and therefore, a Geologist and/Geophysicist must be on site during the drilling.

VLF 6 (**Error! Reference source not found.** isolates many possible zone for groundwater abstraction as shown by pockets of low resistivity zones. VES 11 is positioned on this profile and it also shows this low resistivity units indicating groundwater presence. The VES 11 is at location labeled 6 on the VLF profile. The VES 11 indeed shows a correlating information about the depth range of 63 to 87 meters as also indicated by the VLF as shown in the Figure 18.

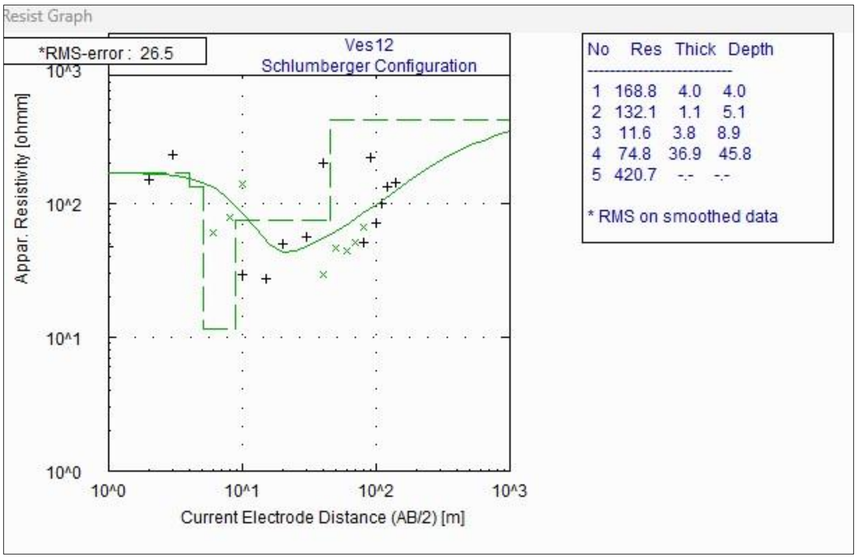

Figure 19 VES 12 Curve Showing Resistivity Curves, Layer Resistivity and Thickness.

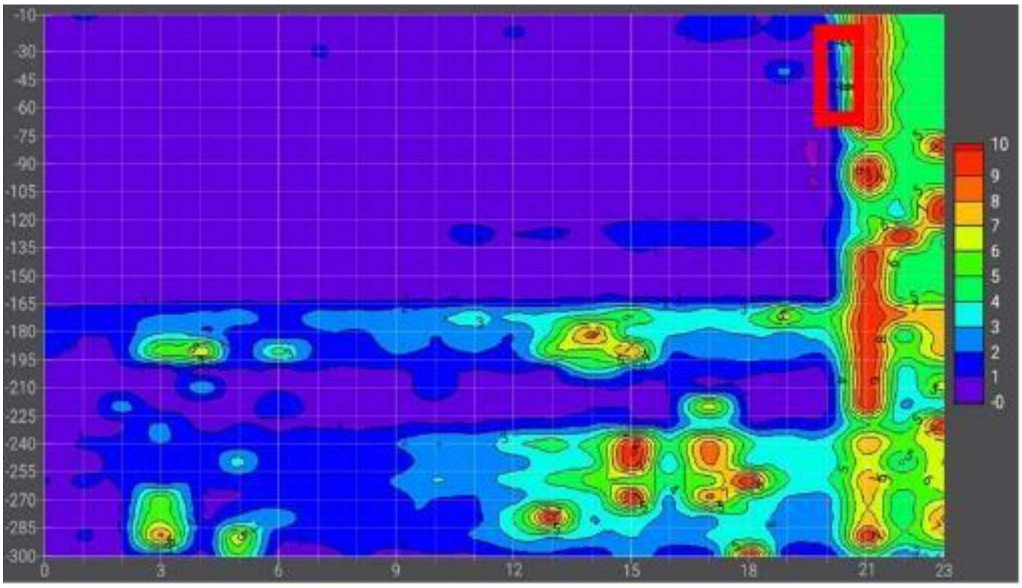

Figure 20 VLF Madi 2 Profile Showing Conductivity/resistivity variation along the entire profile line**.**

VES 12 (Figure 19 VES 12 Curve Showing Resistivity Curves, Layer Resistivity and Thickness. displays a curve type of QHA with significant variations in apparent resistivity, revealing distinctions in the underlying geology with five distinct geoelectric layers. These layers are characterised with resistivity values ranging between 11.6 Ωm to 420.7 Ωm. Likewise, the thicknesses of these layers vary from 1.1 to 36.9 meters. It is suggested to drill a borehole in this VES location to tap groundwater from the fourth layer.

VLF 7 (**Error! Reference source not found.** showed the area is generally characterised with low resistivity except at extreme right side of the profile with high resistive unit. The VES 12 exploited the boundaries between the low and high resistive units especially at point marked and labeled as 21. VES 12 also showed the low resistivity with appreciable depth and hence the results corroborate well. The two results corroborate well and a borehole can be sited at this point.

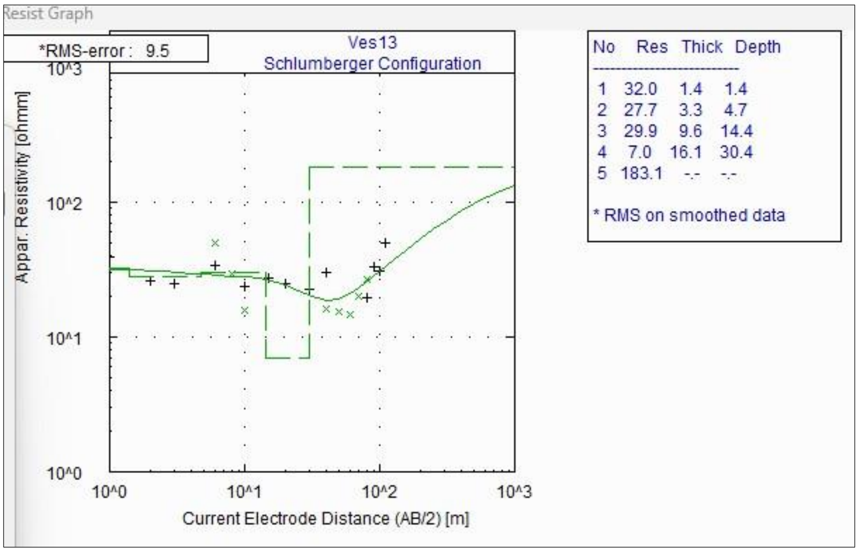

Figure 21 VES 13 Curve Showing Resistivity Curves, Layer Resistivity and Thickness**.**

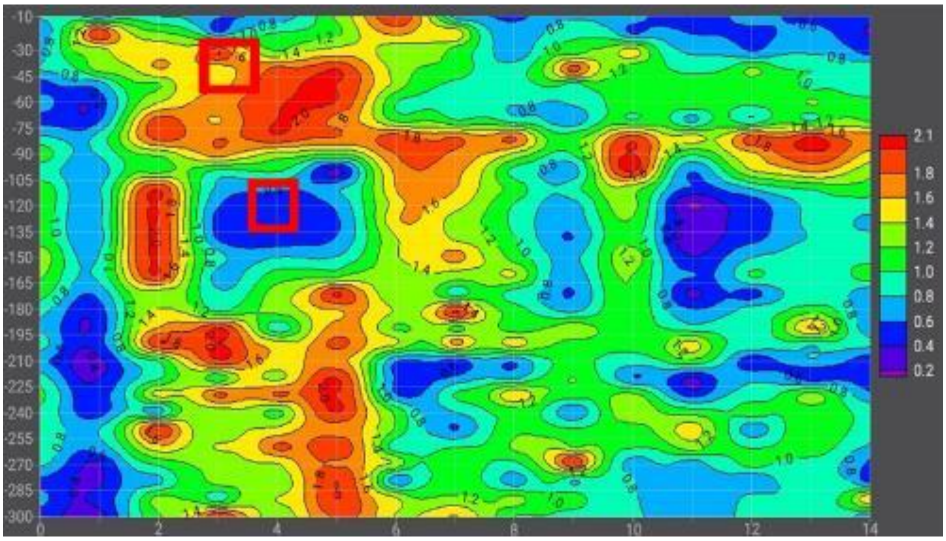

Figure 22 VLF Angwa TIV Profile Showing Conductivity/resistivity variation along the entire profile line.

VES 13 of Figure 21 exhibits a distinct curve pattern denoted as type HKH. This plot shows variations in apparent resistivities. The resistivity varies between 7.0 Ωm to 183.1 Ωm. Similarly, the thicknesses of these layers vary between 1.4 and 16.1 meters. The last (fifth) layer is the aquiferous unit and a borehole is suggested in this location.

The outcomes derived from the VLF-EM 8 data are shown in (**Error! Reference source not found.**, highlighting specific areas characterized by low resistivity. The VES 13 (Figure 21 *VES* 13 Curve Showing Resistivity Curves, Layer Resistivity and Thickness.is positioned on this profile and their results tally. The data point labeled as 3 on the profile correspond to the VES point (red square box) and it shows groundwater occurrence at the depth range of 120 meters.

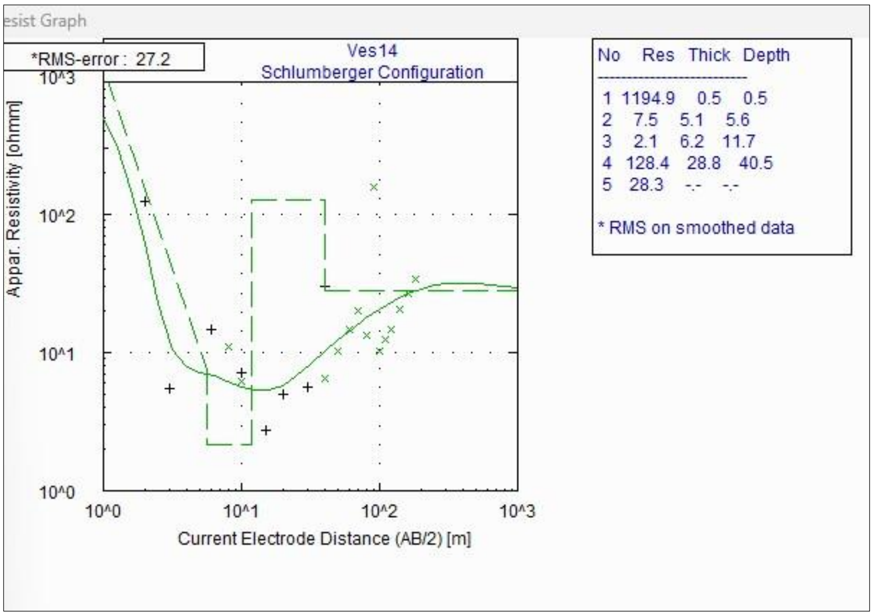

Figure 23 VES 14 Curve Showing Resistivity Curves, Layer Resistivity and Thickness**.**

VES 14 (Figure 23 VES 14 Curve Showing Resistivity Curves, Layer Resistivity and Thickness. displays a QHK curve type with five layers. The resistivities of the geoelectric layers is between 2.1 Ωm to 1194.9 Ωm with thicknesses between 0.5 to 28.8 meters. Units four and five are the aquifers capable of providing the needed groundwater for the borehole and a drill hole is suggested.

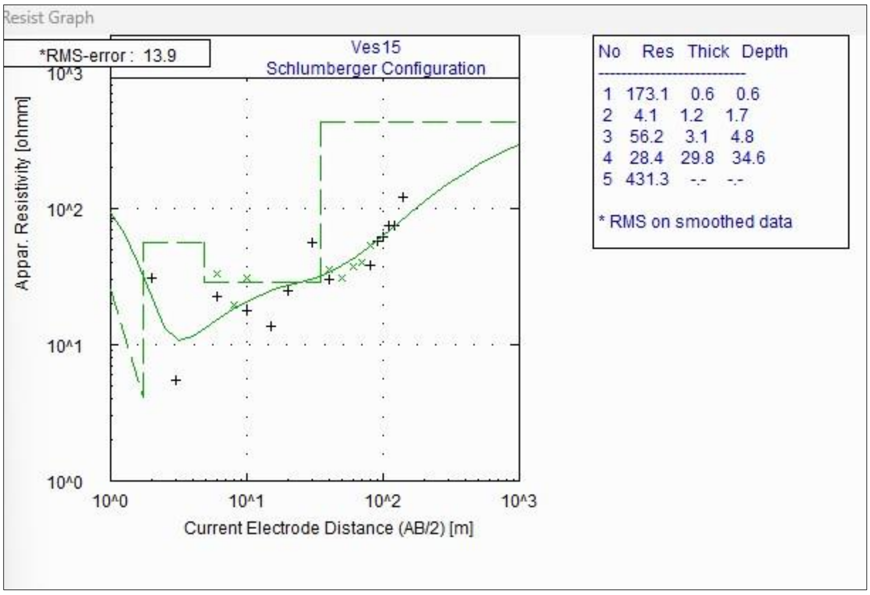

Figure 24 VES 15 Curve Showing Resistivity Curves, Layer Resistivity and Thickness.

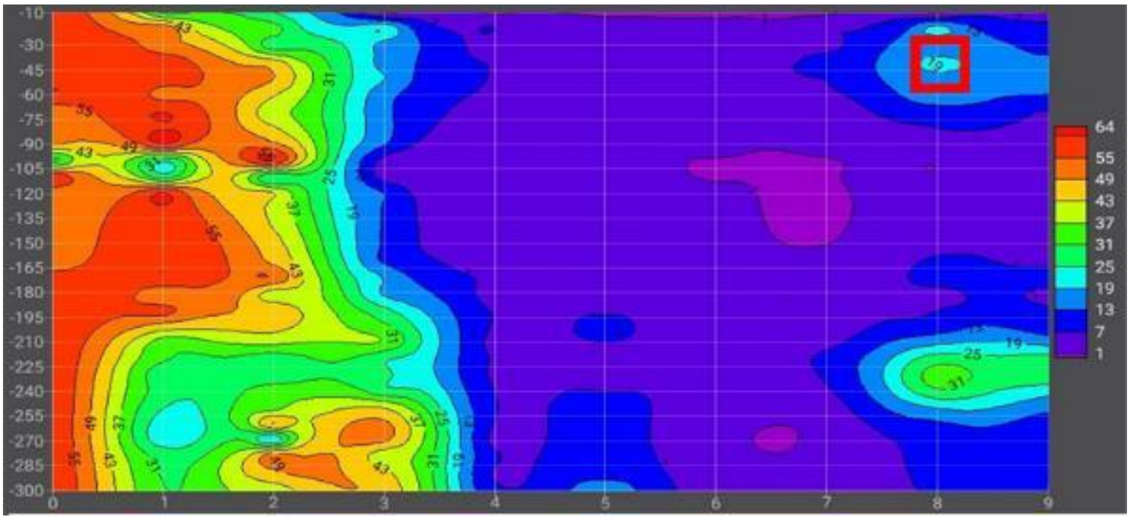

Figure 25 VLF Kabawa 1 Profile Showing Conductivity/resistivity variation along the entire profile line.

VES 15 (Figure 24 VES 15 Curve Showing Resistivity Curves, Layer Resistivity and Thickness. is a HKH curve type with variation in apparent resistivity. Five layers with a range of resistivity values between 4.1 Ωm to 431.3 Ωm with thicknesses varying between 0.6 and 29.8 meters. The fourth layer is the aquiferous unit and believed to be composed of saturated sandstone characterized by resistivity values of 28.4 Ωm and a thickness of 29.8 meters. A borehole is suggested to be drilled in this VES location to exploit this 28.8 meter thick unit.

The evaluation of the VLF-EM 9 data (**Error! Reference source not found.** showed high resistivity at the western edge of the profile and extends towards the centre. This region show no groundwater presence. VES 15 which is on this VLF 15 was positioned at the data point marked as 8 (red square box) with moderate resistivity indicating groundwater abstraction possibility at the depth range of 40 meters or so.

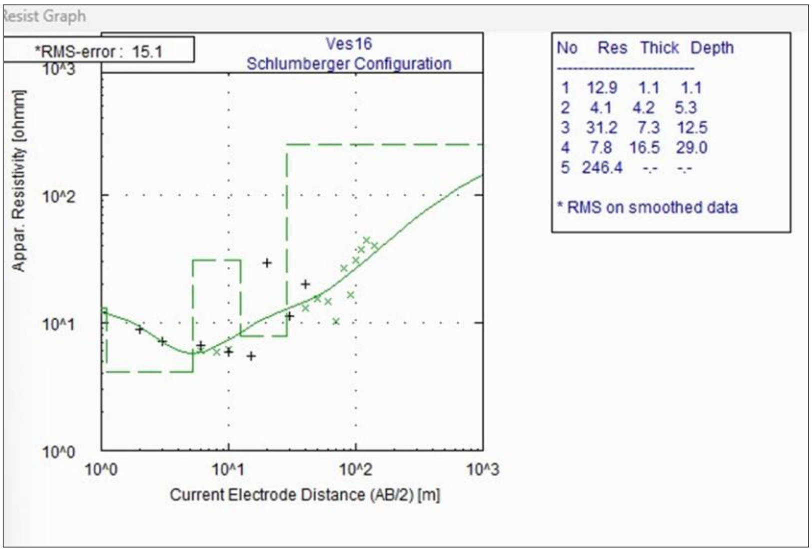

Figure 26 VES 16 Curve Showing Resistivity Curves, Layer Resistivity and Thickness

Figure 3 VLF Kabawa 2 Profile Showing Conductivity/resistivity variation along the entire profile line.

VES 16 of Figure 26 VES 16 Curve Showing Resistivity Curves, Layer Resistivity and Thickness6 is a HKH curve type with five layers with a resistivity range between 4.1 Ωm to 246.4 Ωm and accompanied with layer thicknesses ranging from 1.1 to 16.5 meters. These identified layers consist of topsoil, weathered clay, claystone, siltstones and water saturated sandstones. A borehole can also be sited in this location.

VLF 10 (**Error! Reference source not found.** generally shows high resistivity, except at the western part with low resistivity. The VES 16 at data point labeled as 3 (red square box) showed moderate resistivity and indicating moderate groundwater occurrence as also revealed by the VES 16. The depth range is 42 meters.

Table 1 Tabular Analysis of the Geoelectric Layer Showing the Thickness and Aquiferous Zones

VES	LAYERS	RESISTIVITY (ohm-m)	THICKNESS (m)	DEPTH (m)	ZONES	CURVE TYPE
1	1	247.9	0.4	0.4	Topsoil	KQH-type
	2	1043.7	0.6	1.0	Dry sandstone	
	3	31.0	0.5	1.6	Claystone	

	4 5	3.9 55.4	2.2	3.7	Siltstone Water saturated sandstone	
2	1 2 3 4 5	419.0 36.3 146.0 241.2 27.8	1.5 4.1 1.0 1.2	1.5 5.6 6.6 7.9	Topsoil Dry sandstone Claystone Siltstone Water saturated sandstone	HAK-type
3	1 2 3 4 5	130.3 18.1 14.1 8.5 16.3	0.4 0.5 0.6 0.6	0.4 0.9 1.6 2.2	Topsoil Dry sandstone Claystone Siltstone Water saturated sandstone	QQH-type
4	1 2 3 4 5	378.8 98.9 13.8 26.7 320.5	0.8 2.0 3.6 76.8	0.8 2.8 6.4 83.2	Topsoil Dry sandstone Claystone Siltstone Water saturated sandstone	QHA-type
5	1 2 3 4 5	591.3 27.3 10.0 66.0 29.7	0.6 3.0 5.4 16.7	0.6 3.6 9.0 25.7	Top soil Highly ferruginous sandstone Claystone Siltstone Water saturated sandstone	QHK-type
6	1 2 3 4 5	353.5 13.8 14.0 34.5 15.4	0.4 5.0 7.6 20.5	0.4 5.5 13.1 33.6	Topsoil Dry sandstone Claystone Siltstone Water saturated sandstone	HAK-type
7	1 2 3 4 5	165.2 510.5 24.6 65.0 13.5	0.8 1.4 3.7 7.6	0.8 2.1 5.8 13.4	Topsoil Dry sandstone Claystone Siltstone Water saturated sandstone	KHK-type
8	1 2 3 4 5	35.7 39.5 26.3 156.5 21.8	1.6 1.8 3.6 8.3	1.6 3.4 7.0 15.3	Top soil Highly ferruginous sandstone Claystone Siltstone Water saturated sandstone	KHK-type
9	1 2 3 4 5	46.2 4.4 8.1 12.5 83.6	1.1 1.8 2.0 1.5	1.1 2.9 5.0 6.5	Topsoil Weathered clay Claystone Siltstone Water saturated sandstone	HAA-type
10	1 2	101.1 7.1	0.3 8.3	0.3 8.7	Top soil Highly ferruginous sandstone	HKH-type

	3	68.5	22.1	30.8	Claystone	
	4	10.8	38.9	69.7	Siltstone	
	5	26.7			Water saturated sandstone	
11	1	122.3	0.8	0.8	Top soil	HKH-type
	2	3.6	2.6	3.4	Highly ferruginous sandstone	
	3	1360.0	20.9	24.4	Claystone	
	4	89.9	38.4	62.8	Siltstone	
	5	201.5			Water saturated sandstone	
12	1	168.8	4.0	4.0	Topsoil	QHA-type
	2	132.1	1.1	5.1	Dry sandstone	
	3	11.6	3.8	8.9	Claystone	
	4	74.8	36.9	45.8	Siltstone	
	5	420.7			Water saturated sandstone	
13	1	32.0	1.4	1.4	Topsoil	HKH-type
	2	27.7	3.3	4.7	Highly ferruginous sandstone	
	3	29.9	9.6	14.4	Claystone	
	4	7.0	16.1	30.4	Siltstone	
	5	183.1			Water saturated sandstone	
14	1	1194.9	0.5	0.5	Topsoil	QHK-type
	2	7.5	5.1	5.6	Dry sandstone	
	3	2.1	6.2	11.7	Claystone	
	4	128.4	28.8	40.5	Siltstone	
	5	28.3			Water saturated sandstone	
15	1	173.1	0.6	0.6	Topsoil	HKH-type
	2	4.1	1.2	1.7	Highly ferruginous sandstone	
	3	56.2	3.1	4.8	Claystone	
	4	28.4	29.8	34.6	Siltstone	
	5	431.3			Water saturated sandstone	
16	1	12.9	1.1	1.1	Top soil	HKH-type
	2	4.1	4.2	5.3	Weathered clay	
	3	31.2	7.3	12.5	Claystone	
	4	7.8	16.5	29.0	Siltstone	
	5	246.4			Water saturated sandstone	

4. Discussion

The study area is classified into three different formations which include Lokoja Formation, Patti Formation and Agbaja Ironstone. Sandstone, claystone, siltstone are the lithologies found at the location with angular to sub-rounded cobbles and pebbles which corresponds to the previous studies (Obaje 2009). The low resistivity in the area as observed from the resistivity reading was found to be associated with the water saturated sandstone or siltstone and may serve as the aquiferous zone. It was observed that most of the modeled curves show five layers curves. The result from the interpreted VES data, as shown in Table 1 above, revealed that the study area is characterised by geoelectric layers namely: topsoil, highly ferruginous sandstone, dry sandstone, weathered clay, claystone, siltstone and water-saturated sandstone. The resistivity and thickness of topsoil range from 30.2-1194.9 Ωm and 0.3-4.0 meters, highly ferruginous sandstone has resistivity and thickness ranging from 3.6-39.5 Ωm and 1.2-8.3 meters, dry sandstone has resistivity ranges from 4.4-1043.7 Ωm with 0.5-5.1 meter thickness, claystone has resistivity and thickness ranges from 2.1-1360 Ωm and 0.5-22.1 meters, siltstone has resistivity ranging from 3.9-241.2 Ωm with 0.6-76.8 meters thickness and the water saturated sandstone has resistivity ranging from 13.5-431.3 Ωm and an undefined thickness. The observed VES curve types are KQH (for VES 1), HAK (for VES 2 and 6), QQH (for VES 3), QHA (for VES 4 and 12), QHK (for VES 5 and 14), KHK (for VES 7 and 8), HAA (for VES 9), HKH (for VES 10, 11, 13, 15 and 16).

The VLF-EM result isolated pockets of conductive zones associated with groundwater and the results correlated with what was obtained from the VES data and further confirmed that the water-bearing strata are the aquiferous zones. VLF-EM is best suited in basement terrain to map basement vertical fracture, but it can also be used to provide a bit fair information about the conductive zones in this study, though not as expected in the basement rocks.

5. Conclusion

The geology of the study area was evaluated through geological field mapping and integrated geophysical methods of Very Low-Frequency Electromagnetic (VLF-EM) and Vertical Electrical Sounding (VES) methods. The major rocks encountered are sandstone, claystone and siltstones of the sedimentary rocks. The VES result showed that there are five (5) geo-electric layers in the study area. The results from the VES 1, 2, 3, 5, 7, 8 and 9 shows that these areas have thin overburden thickness with depth to the aquifer less than 20m, while VES 4, 6, 10, 12, 13, 14, 15 and 16 show thick overburden thickness with depth to the aquiferous units greater than 25m, therefore making it possible to suggest areas to site hand dug well and the area to place borehole. The encountered layers are the topsoil, highly ferruginous sandstone, dry sandstone, weathered clay, claystone, siltstone and water saturated sandstone. The VLF-EM result correlated with what was obtained from the VES data and further confirmed the overburden thickness and aquiferous zones. Therefore, this study concluded that integrated geological and geophysical techniques can be used as a portent approach to isolate aquiferous zones for groundwater mining.

Recommendation

More details geological field mapping should be carried out to further understand the geology of the area and their aquiferous potentials. Other hydro-geophysical methods such as seismic refraction and remote sensing should also be used for better understanding of the subsurface geology of the study area.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest regarding this research work.

References

[1] Abdulbariu, I., Baba-Aminu, M., and Achonwa, K. O. (2023a). Frequency-Domain Electromagnetic and VLF Data with an Application of Modeling Basement Structures: A Case Study within Ibadan Area, Southwestern Nigeria, International Journal of Research and Innovation in Applied Science (IJRIAS), volume 8, issue 6, pp. 156-175. DOI: https://doi.org/10.5184/IJRIAS.2023.8616

[2] Abdulbariu, I., Hassan, J. I., Mu'awiya, B. A., Habeeb, A. A. (2023b). Applications of Vertical Electrical Sounding (VES) and Two-Dimensional (2-D) Imaging Methods for Groundwater Exploration and Basement Configuration at GOFAMINT Church Camp, Ibadan, Southwestern. Nigeria, Science Forum (Journal of Pure and Applied Sciences), 23(2023), 336 – 356.

[3] Abdulbariu I., Hassan J. I., Mu'awiya, B. A., Jamal O., Habeeb, A. A., David A., and Ibrahim O. I. (2024). Geophysical Characterization of Basement Rock for Groundwater and Mineralization Potential Using Very Low Frequency – Electromagnetic (VLF-EM) Techniques at Site "G" Around Ibadan Metropolis, Southwestern Basement Complex, Nigeria, Geological Behaviour, 8(1): 13-22.

[4] Adiat K.A.N, Olayanju G.M, Omosuyi G.O. and Ako B.D, (2009). Electromagnetic profiling and electrical resistivity soundings in groundwater investigation of a typical basement complex – A case study of Oda Town Southwestern Nigeria. Ozean J. Social Sci., 2(4): 33-359.

[5] Aizebeokhai A.P, Oyeyemi K.D, (2015). Application of geoelectrical resistivity imaging and VLF-EM for subsurface characterization in a sedimentary terrain Southwestern Nigeria. Arab J Geosci. 8(6):4083–4099.

[6] Ajayi, C. O., & Hassan, M. (1990). The delineation of the aquifer overlying the basement complex in western part of the Kubanni Basin of Zaria (Nigeria). Journal of Mining and Geology, 26(1), 117-125.

[7] Akande S.O., Ojo, Erdtmann B.D, Hetenyi M. (2005). Paleoenvironments, organic petrology and rock eval studies on source rock facies of lower Maastrichatian, Patti Formation southern Bida Basin, Nigeria J.Afric. Earth Sci.41:394-406.

[8] Akinrinade, O.J and Olabode, O.P, (2015). Integrated Geophysical Approach to Aquifer Delineation in Crystalline Basement Environment. Int. J. Scient. & Engr. Res., 6(10): 107-127.

[9] Ako B.D, Olorunfemi M.O. (1989). Geoelectric survey of groundwater in the newer basalts of Vom, Plateau State. J. Mining & Geol., 25(1 & 2): 247-250.

[10] Alvin K.B, Kelly L.P, Melissa A.S, (1997). Mapping groundwater contamination using dc resistivity and VLF geophysical methods—A case study. Geophysics 62(1):80–86

[11] Aminu, M. B., Nanfa, C. A., Hassan, J. I., Yahuza, I., Christopher, S. D., & Aigbadon, G. O. (2022). Application of Electrical Resistivity for Evaluation of Groundwater Occurrence within Adankolo Campus and Environs, Lokoja North Central, Nigeria. European Journal of Environment and Earth Sciences, 3(1), 14–22. https://doi.org/10.24018/ejgeo.2022.3.1.235

[12] Ariyo S.O, Adeyemi G.O & Oyebamiji A.O. (2009). Electromagnetic VLF survey for groundwater development in a contact terrain; A case study of Ishara-Remo, Southwestern Nigeria. J. Appl. Sci. Res., 5(9): 239-1246.

[13] Bayowa O.G, Olorunfemi M.O, Akinluyi F.O & Ademilua O.L. (2014). Integration of hydrogeophysical and remote sensing data in the assessment of groundwater potential of the basement complex terrain of Ekiti State, Southwestern Nigeria. Ife J. Sci., 16(3): 353-363

[14] Beeson, S. and Jones, C. (1988). "The Combined EMT/VES Geophysical Method for Siting Boreholes". Groundwater. 26(1): 54-63.

[15] Braide, S.P., (1992). Syntectonic fluvial sedimentation in the central Bida Basin. J. Mining Geol.28:55–64.

[16] Burke, K.C. and Dewey, J.F., (1972); Orogeny in Africa. In: Dessauvagie TFJ, Whiteman AJ (Eds). African Geology, University of Ibadan Press, Ibadan pp. 583-608.

[17] Coorey, P. G., (1974). Some aspects of the Precambrian of Nigeria: A review. J. Min. Geol.8, 17-43.

[18] Dada, S. S., (2006). Proterozoic evolution of Nigeria. In O. Oshin (Ed.), The basement complex of Nigeria and its mineral resources (A tribute to Prof. M.A.O. Rahaman). Akin Jinad and Co. Ibadan, p. 29-44.

[19] Ezeh C.C, Ugwu G.Z. (2010). Geoelectrical Sounding for Estimating Groundwater Potential in Nsukka L.G.A, Enugu State, Nigeria. Int J Phys Sci 5(5):415–420.

[20] Evans U.F, George N.J, Akpan A.E, Obot I.B, Ikot A.N. (2010). A study of superficial sediments and aquifers in parts of Uyo local government area, Akwa Ibom State, Southern Nigeria, using electrical sounding method. Eur J Chem 7(3):1018–1022.

[21] Federal Ministry of Aviation, (2007).

[22] George N.J, Akpan A.E, Obot I.B (2010). Resistivity study of shallow aquifer in parts of southern Ukanafun Local government area, Akwa Ibom State. Eur J Chem 7(3):693.

[23] Hazel, J., Cratchley, C.R., and Preston, A.M. (1988). "The Location of Aquifer in Crystalline Rocks and Alluvium in Northern Nigeria using Combined Electromagnetic and Resistivity Techniques". Quarterly Jour. Enh. Geol. 21:159-175

[24] Iweana, (2012), A Geo-electrical Investigation of Ground Water: 34.

[25] Mbonu P.D.C, Ebeniro J.O, Ofoegbu C.O & Ekine A.S. (1991). Geoelectric sounding for the determination of aquifer characteristics in parts of the Umuahia area of Nigeria. Geophysics, 56(2): 284-291

[26] Ladipo K.O, Akande SO, Mucke A. (1994). Genesis of ironstones from the Mid-Niger sedimentary basin: evidence from sedimentological, ore microscopic and geochemical studies. J. Mining and Geol. 30: 161-168

[27] Nanfa, C. A., Aminu, M. B., Christopher, S. D., Akudo, E. O., Musa, K. O., Aigbadon, G. O., & Millicent, O. I. (2022). Electric Resistivity for Evaluating Groundwater Potential Along the Drainage Zones In the Part of Jos North, Plateau State, Nigeria. European Journal of Environment and Earth Sciences, 3(6), 59–68. https://doi.org/10.24018/ejgeo.2022.3.6.347

[28] Nwankwo,I.I., Olasehinde,P.I. and Osundele, O.E.. (2013). Application of Electrical Resistivity Survey for Groundwater Investigation in a basement rock region; Akobo - Ibadan., Nigeria. Ethiopian Journal of Environmental Studies and Management. Vol 6, no 2, 124-134.

[29] Obaje, N.G (2009). Geology and Mineral Resources of Nigeria, Springer Books. USA pp. 15-35.

[30] Obiora, S.C., (2005). Field Descriptions of Hard Rocks with examples from the Nigerian Basement Complex (1st Edition). Snap Press (Nig.) Ltd. Enugu, 14.

[31] Ohwoghere-Asuma O., Aweto K.E, Chinyem F.I, Nwankwoala O.H. (2018). Assessing the protective capacity of aquifers using very low- frequency electromagnetic survey. Geosciences 8 (150):1-11.

[32] Okiongbo, K.S., Akofure, E. and Odubo, E. (2011). Determination of Aquifer Protective Capacity and Corrosivity of Near Surface Materials in Yenagoa City, Nigeria. Research Journal of Applied Sciences, Engineering and Technology, 3, 785-791.

[33] Olayinka A.I (1990). Electromagnetic profiling and resistivity soundings in groundwater investigation near Egbeda Kabba and Kwara State. Journal of Mining & Geology, 26: 243-250.

[34] Olayanju A., Omosuyi G.O, Ako B.D. (2009). Electromagnetic Profiling and Electrical Resistivity Soundings in Groundwater Investigation of a Typical Basement Complex-A case study of Odatown Southwestern Nigeria. Ozean J. Appl. Sci. 2:4.

[35] Olayinka A.I, Amidu S.A & Oladunjoye M.A. (2004). Use of electromagnetic profiling and sounding for groundwater exploration in the crystalline basement area of Igbeti, Southwestern Nigeria. Global J. Geological Sci., 2(2):243-253.

[36] Olorunfemi M.O, Dan – Hassan M.A & Ojo J.S. (1995). On the scope and limitations of the electromagnetic methods in groundwater prospecting in a Precambrian basement terrain a Nigerian case study. J. Afr. Earth Sci., 20(2): 151 – 160.

[37] Olorunfemi M.O, Fatoba J.O & Ademilua, L.O. (2005). Integrated VLF- electromagnetic and electrical resistivity survey for groundwater in a crystalline basement complex terrain of Southwest Nigeria. Global J. Geol. Sci., 3(1): 71-80.

[38] Oluwayomi, O. T. (2024a). Bridging the Digital Chasm: Addressing The Growing Digital Divide among Marginalized Communities in the United State and Africa. Global Scientific Journal, 12(6), 839–843.

[39] Oluwayomi, O. T. (2024b). The Regulatory Framework: Fostering Circular Economy Practices in E-Waste Management. Global Scientific Journal, 12(6), 579–587.

[40] Oyawoye, M.O. (1965). "Nigerian Basement Geology". In: Aspect of Nigerian Geology. Reyment R.A (e.d). University of Ibadan press: Ibadan, Nigeria.

[41] Ozulu J. U., Grace P. E., Ernest O. A. (2021). Geological and Geospatial Mapping of Vulnerability Areas for Proper Flood Mitigation: Ganaja, Lokoja Metropolis, North-Central Nigeria. International Journal of Environment and Geoinformatics (IJEGEO), 8(3):267-275.

[42] Sharma SP, Baranwal V.C. (2005). Delineation of groundwater-bearing fracture zones in a hard rock area integrating very low frequency electromagnetic and resistivity data. J Appl Geophys 57:155-166

[43] Taiwo S. M., Awoyemi M. O. and Onyedim G. C. (2016). Combined use of Very Low Frequency Electromagnetic (VLF-EM) and electrical resistivity survey for evaluation of groundwater potential of Modomo/Eleweran area, southwestern Nigeria. African Journal of Environmental Science and Technology, 10 (7), 192- 206.

[44] Rahaman M.A. (1976). Review of the basement geology of southwestern Nigeria. In: Kogbe CA (ed) Geology of Nigeria, 2nd edn. Elizabethan Publication, Lagos, pp 41–58

[45] Rahaman M.A. (1988). Recent advances in the study of the basement complex of Nigeria. In: Geological Survey of Nigeria (ed) Precambrian Geol Nigeria, pp 11–43