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Application of Vertical Electrical Sounding (VES) for the Determination of Water-Bearing Zone in Karaworo, Lokoja Kogi State, Nigeria

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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ABSTRACT

The importance of water in our various communities and the difficulties faced so far to get good and clean water for both domestic consumption and industrial purposes can never be overemphasized. For these purposes to be accomplished, it is necessary to survey the area of study to know more about the geology of the area, which is characterized by the Lokoja Formation, Patti Formation, and Agbaja Ironstone and the possible reasons why there is a lack of water in the area. The geoelectric survey was conducted at Karaworo with the objective of determining the sedimentary formation's geoelectrical features and analyzing the potential of the groundwater in the study area. The most frequently used type of array for Vertical Electrical Sounding (VES) is the Schlumberger array, which needs a lot of space at both ends to yield deeper subsurface information. The Schlumberger configuration was used for data acquisition. About fifteen (15) VES points were acquired at different locations within the study area. For the different VES positions, the maximum AB/2 is within 100m to 180m. Partial curve matching was used to determine the layer parameters as part of the quantitative interpretation of the VES curves. The IP2WIN software was used in the final data analysis. The depth sounding interpretation revealed subsurface layers which comprises of topsoil/clay with a resistivity range between 1.42 ohm-m to 81.0ohm-m and a thickness of 0.253 m to 70.4 m, lateritic clay with a resistivity range between 01.06ohm-m to 1730 ohm-m and a thickness of 0.236 m to 19.2 m, siltstone with resistivity range between 0.423 ohm-m to 5069 ohm-m and a thickness of 4.09 m to 28 m and sandstone with resistivity range between 0.664 ohm-m to 137 ohm-m with the thickness at infinity. Sandstone constituted the aquiferous zone. In conclusion, different types of curves which include HA-type, H-type, KH-type, QH-type and HAK-type characterize the area and hence it is suggested that boreholes be placed in low resistivity zones and considerable depth and thickness as revealed in VES 4 and VES 8 but those with low resistivity without considerable depth, for example, VES 2, VES 5, VES 6, VES 7, etc. can be developed into a hand dug well.

Keywords: Resistivity; water; sandstone; data acquisition; aquiferous; borehole.

1. INTRODUCTION

Groundwater is heavily relied upon in the majority of nations not only as a primary source of drinking water but also as a source of water for both agricultural and industrial purposes. Due to the dependence on groundwater, it is imperative to provide both a sufficient supply and excellent quality of water.

The use of geophysics for groundwater resource mapping, water quality assessment, and other purposes has grown over the past few decades in great part because of the quick development of microprocessors and related numerical modelling techniques. Since the early days humans have been using groundwater for various purposes. Considering it has several advantages over surface water, groundwater is now the principal resource collected from the earth in terms of weight. Groundwater is often better protected from major contaminants than surface water because of the presence of protective surficial geological formations, their depth, the ability of most reservoirs to filter out pollutants, and the congested river banks.

In the early 1970s a shortage of water that affected much of the Sahel region of Africa, including Nigeria, was the original cause of the need for groundwater treaties. People travel long distances aimlessly with life stocks and water containers in search of water that is nowhere to be found. Under these prevailing conditions during those difficult days, groundwater provided only an alternative source of water supply.

Due to the increase in human population and infrastructural development around the nation, the demand for portable water for home, agricultural, and industrial purposes has rapidly increased, surpassing the capacity of the government's public water supply. Some residents have returned to making alternative arrangements for water through wells and boreholes as a result of the government's insufficient water supply, while others who could not afford it obtain water of poor quality from water vendors in carts and tankers as well as from surface water sources. However, due to their exposure to atmospheric pollutants (from both natural and anthropogenic sources) and pathogenic organisms that make these water sources contaminated than the groundwater, readily accessible bodies of water from the earth's surface, such as streams, rivers, oceans, and lakes are frequently not very safe for direct consumption. This has forced the need for chemical treatments before consumption or industrial use.

Groundwater resources play a vital role in meeting the water demands of Lokoja, Kogi State, Nigeria. The identification and characterization of water-bearing zones in the area are essential for sustainable groundwater management. Vertical Electrical Sounding (VES) is a widely used geophysical technique for investigating subsurface conditions and has been successfully applied in various hydrogeological studies [1,2]. VES involves measuring the resistivity of different geological layers to delineate subsurface structures, including potential aquifers and water-bearing zones [3].

Previous studies in Lokoja have employed VES to assess the groundwater potential and determine water-bearing zones. The VES surveys typically involved the use of resistivity meters, such as ABEM SAS 300C or Syscal R2, and a standard four-electrode configuration [4,5]. The data acquisition involved deploying the electrodes at predetermined locations along a vertical profile and measuring the apparent resistivity values at various electrode spacings [6,7]. The Schlumberger electrode configuration was commonly used due to its simplicity and suitability for both shallow and deep investigations [2].

Several case studies have been conducted in Lokoja using VES to identify water-bearing zones. For instance, Ajayi et al. [1] conducted a VES survey in selected locations within Lokoja and observed distinct lithological variations, correlating with variations in the resistivity values. The interpreted VES results revealed multiple subsurface layers, including clayey and sandy formations, with indications of potential aquifers. Similarly, Ehirim and Onwuka [2] conducted VES surveys in Lokoja and identified several subsurface lithologies, including weathered layer, clay, sand, and fractured basement complex, which influenced the occurrence of water-bearing zones. The interpretation of VES data in the reviewed studies involved various techniques. Curve matching, which involves comparing measured and modelled resistivity curves, was commonly employed to determine the resistivity-depth distribution of subsurface layers [3]. In addition, partial curve matching techniques were used to estimate the resistivity of specific layers and identify potential aquifers [4]. Furthermore, computer-aided inversion algorithms, such as Schlumberger and Occam's inversion methods, were utilized to generate resistivity-depth models [5].

The study by Adeoye and Ajayi [8] utilized VES surveys in selected locations within Lokoja, identifying different lithologic units and potential aquifer zones. Olorunfemi et al. [9] conducted a comprehensive study, employing VES surveys to delineate multi-layered aquifer systems and estimate the depth and thickness of aquifers. Owoade et al. [10] conducted a VES survey in parts of Lokoja, emphasizing the integration of VES results with other hydrogeological data for a comprehensive understanding of the groundwater system.

The reliability of VES in determining water-bearing zones in Lokoja was assessed by comparing the interpreted results with available borehole data and conducting field validations. Ajayi et al., [1] found good agreement between the VES interpretations and borehole lithological logs, indicating the reliability of VES in identifying water-bearing zones. Pumping tests and water quality analysis were also conducted to validate the VES results and confirm the presence of productive aquifers in the study area [2]. Despite its utility, the application of VES in Lokoja faced certain challenges. These challenges included the presence of complex subsurface lithologies, the difficulty in accurately interpreting data in areas with significant geological heterogeneity, and the need for more extensive calibration with borehole data [3]. Future research should focus on integrating VES data with other hydrogeological investigations, such as borehole drilling, pumping tests.

Adeoye and Ajayi [8] conducted a VES survey in selected locations within Lokoja, aiming to evaluate the groundwater potential. They used the Schlumberger electrode configuration and interpreted the VES data using computer software. The study revealed the presence of different lithologic units, identified potential aquifer zones, and provided insights into the groundwater occurrence patterns in the area.

The application of Vertical Electrical Sounding (VES) has played a crucial role in evaluating groundwater occurrence in Lokoja, Nigeria. Through the reviewed studies, it is evident that VES surveys have provided valuable insights into the hydrogeological characteristics and potential groundwater resources of the study area. The studies conducted by Adeoye and Ajayi [8], Olorunfemi et al. [9], and Owoade et al. [10] have contributed significantly to the understanding of groundwater occurrence in Lokoja through the application of VES.

Study by Olorunfemi et al., [9]: In a comprehensive study conducted in Lokoja and its environs, Olorunfemi et al., [9] utilized VES surveys to assess the geoelectric characteristics and evaluate groundwater potential. They employed the Schlumberger electrode configuration and interpreted the resistivity data using computer software. The study delineated multi-layered aquifer systems, determined aquifer resistivity variations, and provided valuable information about the depth and thickness of aquifers.

The issue of identifying water-bearing zones at the Federal University Lokoja Adankolo FUL campus and environs was researched and addressed by Aminu et al. [11]. Electrical resistivity has been used to measure the resistivity variation of the subsurface formations with depth in groundwater investigations. Vertical electrical sounding VES was used to the Adonkolo area and its surroundings and is compatible with the Schlumberger configuration.

Study by Owoade et al. [10]: Owoade et al. [10] conducted a VES survey in parts of Lokoja and its environs to explore groundwater potential and subsurface characteristics. The study employed the Schlumberger electrode configuration and applied computer software for data interpretation. The results facilitated the identification of lithologic units, delineation of aquifer layers, and estimation of aquifer resistivity distribution. The study emphasized the importance of integrating VES results with other hydrogeological data for a comprehensive understanding of the groundwater system.

These aforementioned studies have made significant contributions to the understanding of groundwater occurrence and the hydrogeological framework of Lokoja, Nigeria. They highlight the effectiveness of VES surveys in characterizing aquifer systems, identifying potential groundwater zones, and assessing the overall groundwater potential in the Lokoja area,

A major aspect of the fieldwork involved an Electrical Resistivity Survey using the Vertical Electrical Sounding VES technique. The Schlumberger array of electrical resistivity surveys is to be adopted. The four electrodes were positioned symmetrically along straight lines: the current electrodes on the outside and the potential electrodes on the inside (Changde et al., 2022).

To evaluate the parameters of a study area, the area has to be predominantly good to moderate groundwater potential. The numerous occurrences of failed/aborted boreholes in an area could be linked to a variety of factors, including poor data quality, lack of technical know-how, incorrect point selection, and poor drilled hole development, all of which are common in Basement Complex terrains [12].

These studies collectively demonstrate the effectiveness of VES in characterizing aquifer systems, identifying potential groundwater zones, and assessing overall groundwater potential in Lokoja, Nigeria. The resistivity data obtained from VES surveys have provided crucial information about the subsurface geoelectric properties, enabling a better understanding of the hydrogeological framework.

The literature review reveals that factors such as lithology and geology, hydrogeological conditions, electrode configurations and survey design, data quality, interpretation techniques, and seasonal variations influence the interpretation of VES data in Lokoja, Nigeria. Addressing these factors is essential for obtaining accurate and reliable interpretations.

Overall, the application of VES for evaluating groundwater occurrence in Lokoja has proven to be a valuable tool, providing insights into the hydrogeological framework and contributing to sustainable groundwater management in the region. Further research efforts should focus on addressing the identified challenges, integrating VES data with other hydrogeological data sources, and conducting more comprehensive studies to enhance the understanding of groundwater resources in Lokoja, Nigeria. The research aims and objective is to apply the Electrical Resistivity Method (ERM) to delineate the area with the highest potential for water-bearing, where it is possible to dig productive boreholes for both home and commercial/industrial uses.

1.1 Aim and Objectives

The aim of the work is to characterize the aquiferous zones and to determine their parameters within the study area.

The objectives of this research are as follows:

- To determine the depth of the aquifer

- ❖ To identify an appropriate aquifer for groundwater development
- ❖ To create a geological map of the research area.

2. METHODS AND MATERIALS

The study location is situated in and around Lokoja, Kogi State in the north-central region of Nigeria [13,14]. Its coordinates are within a range of Latitudes **N07°48'01.1" N** to **07° 48'29.1" N** and Longitudes **E06°41'03.1**" to **06°44'08.1" E** (see Fig. 1. The topography of Lokoja is generally high and has numerous outcrops. However, the Mount Patti Ridges covers the research area.

The mapped location is classified as sedimentary terrain in the geological map of Nigeria, located in the southwestern part of the country, characterized by three different lithologies which include Lokoja Formation, Agbaja ironstone and Patti Formation see Fig. 2.

- The Lokoja Formation

The Lokoja Formation is the oldest formation in the lower Bida Basin overlapping the basement complex, it is composed of sandstone, they are located near Lokoja and Felele, the formation is mainly noted for its pebbly quality in nature. and Koton-karfe, they are coarse-grained combined with a coarsening upwards sequence, they are darkish brown in colour and are composed of cobbles, pebbles etc. that are sub-angular to sub-rounded in form [17,18].

- The Patti Formation

These formations are distinguished by fine-medium pinkish-white, greyish-grey, and siltstone as well as oolitic Ironstone. They appear in a fining upward succession and cross-stratification and slumps were noted as sedimentary features., which must have occurred as a result of changes in the current directions at the time when the sand was deposited [13].

- The Agbaja Ironstone

Agbaja Ironstone is the topmost layer overlying both the Lokoja and the Patti Formations. It is composed of oolitic ironstone; it is coarse-grained, poorly sorted, and reddish to brown in colour [19].

The approach used to collect the data is described in this chapter. The Vertical Electrical Sounding (VES) has proven to be particularly effective with groundwater exploration and prospecting, thus it was applied in this research. The research strategy and resources employed to carry out this research and data were thoroughly analyzed and interpreted and recommendations were made. Below is the workflow for the research.

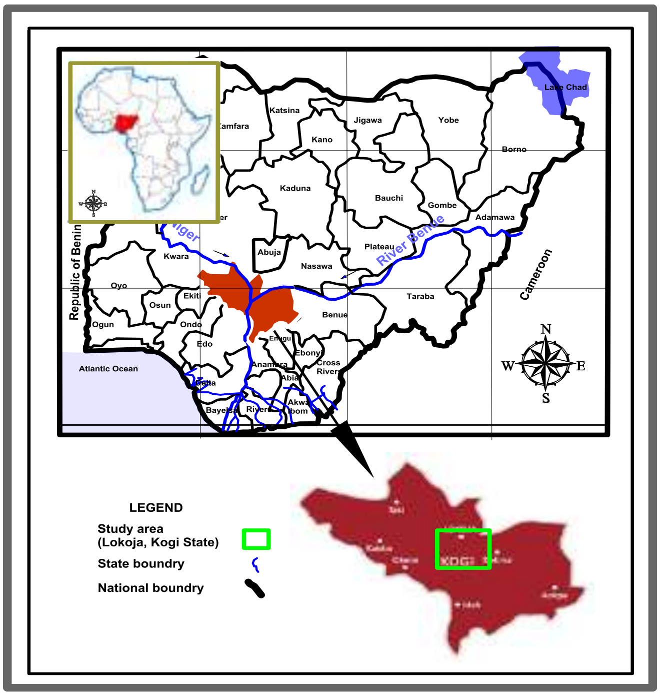

Fig. 1. Map of the study area (Modified after Baba Aminu et al., [15])

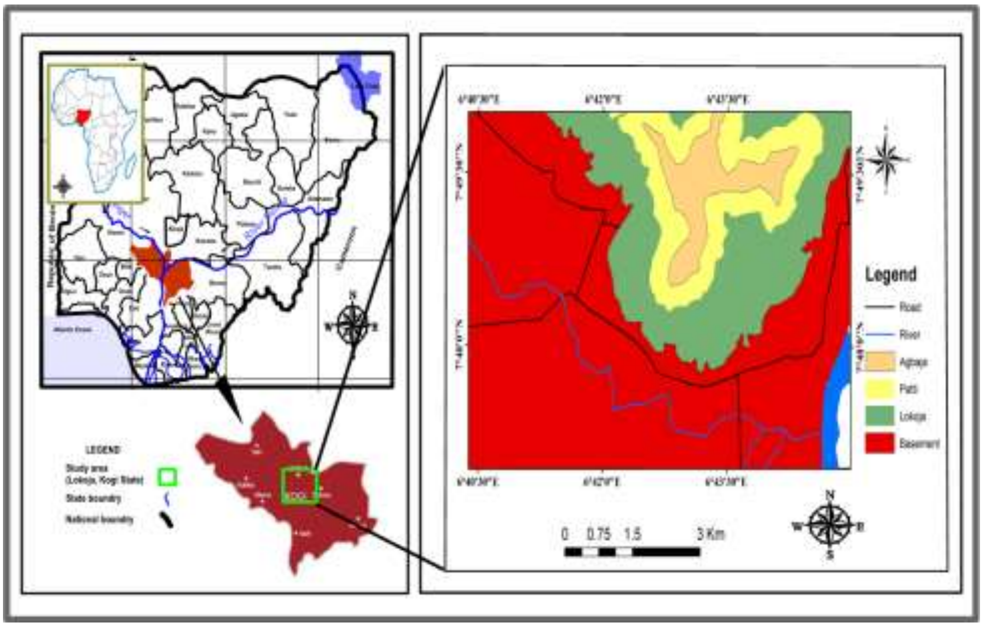

Fig. 2. Geological maps of the study area showing different geology (Modified after Abdulbariu et al; Aminu et al., [16,11])

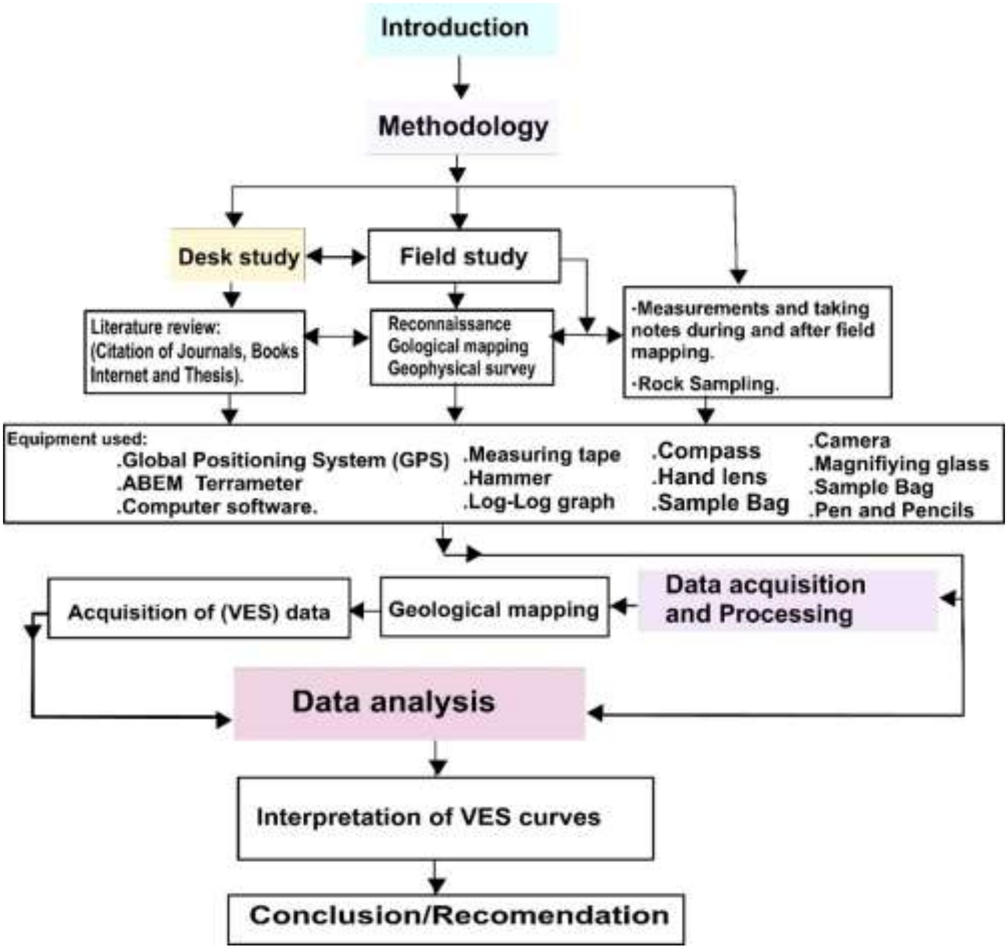

Fig. 3. Workflow chart used for this research, (Modified after Abdulbariu et al., [16])

3. METHODOLOGY

The methodology and the materials used for this research are conducted to study is to delineate the area with the highest potentiality for water-bearing is discussed in this section and illustrated in Fig. 3. The survey was carried out in two stages: desk study and field geophysical surveys.

1. Desk Study: During the desk study, researchers conducted a thorough review of previously published work related to the area under study. This involved examining existing literature, reports, and relevant studies that provided information on the water resources potential of the study area and its environs. The desk study also included sourcing maps that were relevant to the research objectives. These maps likely contained details about geological features, hydrological information, land use, and other pertinent data.
2. Field Geophysical Surveys: Following the desk study, field geophysical surveys were conducted in the study area. Geophysical methods involve measuring and analyzing the physical properties of the subsurface to infer the presence or characteristics of underground water resources.

3.1 Geophysical Survey

3.1.1 Wenner array

This is the most basic array; that has (4) four electrodes A, M, N, & B lined up and equally distanced apart. The two inner electrodes, M & N, are potential electrodes, the two external electrodes, A&B, however, are current electrodes. Its geometric factor (Kg) is 2π a, where a is specified for each example. Shifting the (4) four electrodes across the outer layer retaining a constant electrode separation authorizes the detection of horizontal variations in resistivity. Wenner arrays are sometimes used in VES for vertical ground research, such as constructing horizontal strata, and are often used in profiling for lateral groundwater exploration. The Wenner array approach has a number of disadvantages including the fact that each point of profile necessitates the movement of all the electrodes, it is a process that requires time.

3.1.2 Schlumberger array

In order to determine the depth of the various layers using Vertical Electrical Soundings VES, an ABEM terrameter was employed for the electrical resistivity survey. The suggestion was based on a comprehensive examination together with the analysis of the field data.

Normally, the graph shows the current $AB/_2\,(m)$ horizontally. However, the values of apparent resistivity that were obtained directly from the Terameter are shown vertically. Where:

A Current one
B Current two
M Potential one
N Potential two

The configuration method is called the SCHLUMBERGER ARRAY, also known as (VES) Vertical Electrical Sounding.

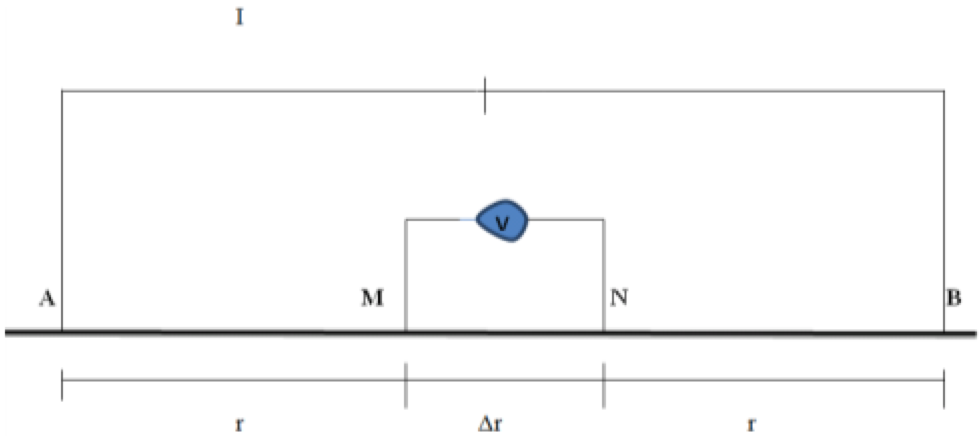

Fig. 4. Configuration of Schlumberger Array

C2= r; M= 1st potential electrode; N= 2nd potential electrode; A= 1st current electrode B= 2nd current electrode; a distance between the potential and current electrode; r= current electrode at equidistance thus, the expression of apparent resistivity is as follows:

$$\rho a = KR \qquad \text{Equation 1}$$

The earth resistance (*R*) is stated as:

$$R = \frac{\Delta V}{I} \qquad \text{Equation 2}$$

The geometric factor ***K***, is expressed as

$$K = \pi \left[\frac{\left(\frac{AB}{2}\right)^2 - \left(\frac{MN}{2}\right)^2}{MN} \right] \qquad \text{Equation 3}$$

The lengths between the previously aforementioned current electrode and potential electrode are AB and MN, respectively.

3.2 Field Geophysics (Procedures)

With the aid of an ABEM terrameter (plate 1), a geophysical investigation was carried out using the electrical resistivity method. conveying electrical currents of familiar voltage (5mA–10mA) between two-point electrodes (AB) and determining the potential decreases between the electrodes through two interior electrodes (MN) are the steps in the procedure.

3.3 Modes of Configuration

Schlumberger configuration was mainly used in the field of geoelectrical sounding. The base point of the configuration is kept fixed while the gap between the electrodes is gradually increased. Depending on the vertical conductivity distribution, these cause the current lines to penetrate even deeper. The electrodes A and B were used to send current into the ground for each reading, and the electrode MN was used to measure the size of the potential difference that developed. The geometrical configuration and electrical properties of the ground both affect resistance (V/I).

The potential differences between MN quickly diminish and disappear below the measurement range of the device as the current electrode spacing AB increases. This is the result of the fact that the field at the configuration typically varies contrary to the square of the configuration AB. It is recommended that the distance between the potential electrodes MN be raised so that the new values are greater than the previous value. Using Vertical Electrical Soundings (VES) methods, fifteen (15) geophysical surveys (Vertical Electrical Survey) were conducted in various areas within the study location and were analyzed.

3.4 Instrumentation

- Geo sensor Resistivity Meter: - this is the most important used in carrying out an electrical resistivity survey of an area of interest. The electronic device that displays and reads the resistance of a spot beneath a subsurface sector.

Plate 1. Electrical resistivity equipment and other accessories

- Electrodes: These are bright metallics instruments which are like huge nails and conduct electricity enabling the system to create a closed circuit. These electrodes must be firmly inserted into the subsurface for the highest conductivity.
- Hammers: - They are employed to both pound electrodes into the ground and remove them from it.
- Current reels: - They send current supplied to the Abem Terrameter ends where they are connected to pinned electrodes thereby conveying electricity into the subsurface. To obtain the resistivity readings of any point, this current, potentials, and resistivity meter must be used in pairs with one another.
- Measuring tapes: A round narrow thin strip of cover fabric that is used for linear measurements. Each measuring tape is 100m long.
- Global positioning system (G.P.S): The Global Positioning System (GPS) is used to precisely locate a three-dimensional position (Latitude, Longitude, and Elevation). The system works with satellites. It shows the distance of places and the positions on the map, and gives accurate time and bearing directions of the place.
- Log-log graph: It is applied to plot the readings acquired from the area of study, the curve generated by the graph it can be able to answer the questions of whether the study area potentially provides water or not and the lithological information of the area as well. The instability of the raw data at any given time could be used to provide a rough assessment of the scenario at hand.
- Compass: A compass was used to measure the dip and strike of an outcrop.
- Hand Lens: A hand lens was used for magnification.
- Field Notebook: The field notebook was used for taking records of all information on the field.
- Sample Bag: The sample bag was used for the collection of samples for further analysis in the lab.
- Pen and Pencil: Pen and pencil were used for recording and sketching outcrop structures and litholog.
- Camera: The camera was used for taking photographs of the outcrop.

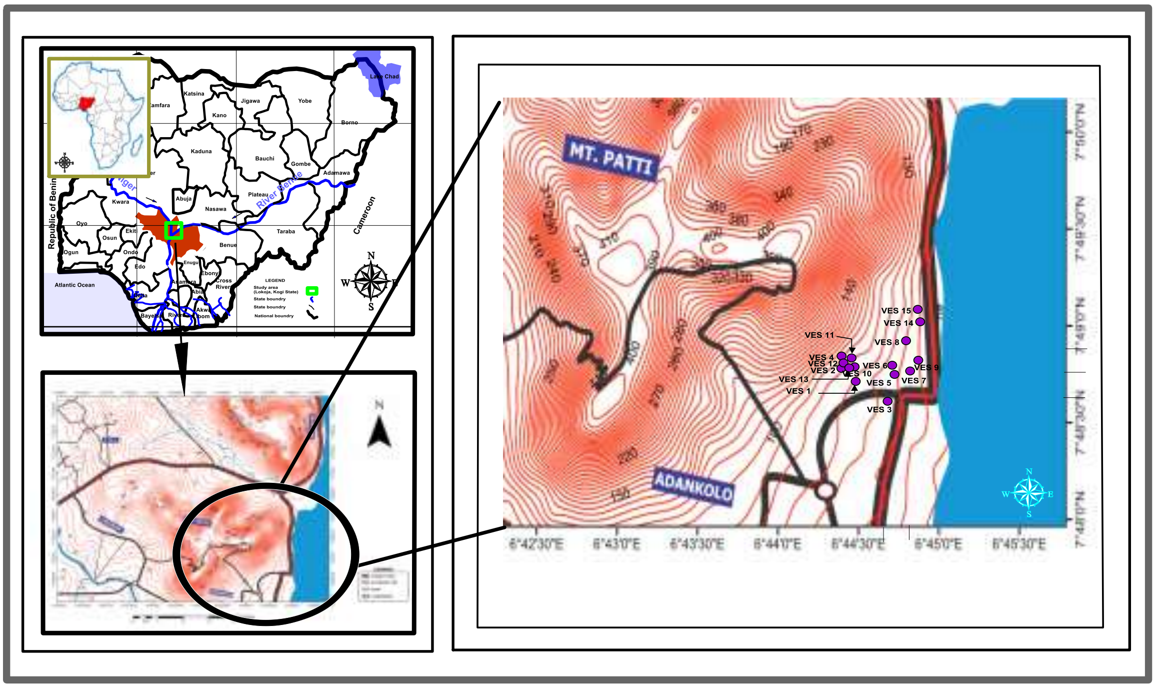

Fig. 5. Map of the study area showing the VES positions (Modified after Baba Aminu et al., [15]; Akagbue et al., [20])

4. RESULTS

4.1 Presentation and Interpretation of Field Data

Three stages were taken in the data processing and interpretation procedure. The first stage entails plotting the vertical electrical sounding curves for each of the study locations using the calculated apparent resistivity and electrode spacing. The second stage entails smoothing and analyzing the VES profiles with respect to their different layers of existent resistivity.

The third stage involves interpreting using IP2WIN computer application software. This direct interpretation method produces quantitatively the resistivity, depth, and thickness of the subsurface parameters.

Plotting a graph of apparent resistivity against current electrode spacing $AB/_2\,(m)$ on a log-log graph sheet is the first step in interpreting a resistivity-sounding survey. The interpretation of a resistivity-sounding survey can be determined by categorizing the observed result of an apparent resistivity curve into types. This classification is based on the shapes of the curves, but at the same time, it is also dependent on the geological characteristics of the subsurface. About fifteen (15) VES were taken at intervals across the study area; the shape of the VES curve is dependent on the number of layers in the subsurface and the thickness of each layer.

VES 1 (LOCATION: Karaworo, LONGITUDE: **6° 44' 30"**, LATITUDE: **7° 48' 43"**, ELEVATION: **80.5m**)

Table 1. Field Data for VES 1 showing apparent resistivity

Electrode position	Electrode spacing		Apparent Resistivity (Ohm-m)
	AB/2 (m)	MN/2 (m)	
1	1	0.5	43.68
2	2	0.5	18.87
3	3	0.5	12.01
4	4	0.5	2.50
5	6	0.5	9.02
6	6	1.0	174.28
7	10	1.0	30.65
8	20	1.0	2000.125
9	30	1.0	$14.9*10^3$
10	30	2.5	$19.7*10^3$
11	40	2.5	19.90
12	50	2.5	15.50
13	60	2.5	75.18
14	70	2.5	24.40
15	70	5.0	61.83
16	100	5.0	56.12
17	120	5.0	71.10

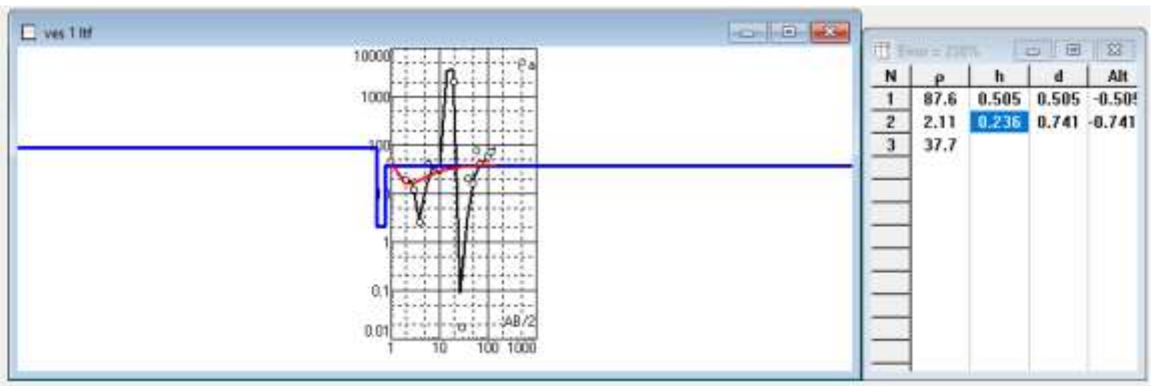

Fig. 6. VES Station 1 showing the graph of apparent resistivity against electrode spacing

It was observed that VES 1 has three (3) layers as shown in the curve, the possible lithologies and other important information are shown in Table 17.

From the observed resistivity and depth of the layers of VES 1, it does not have the potential of bearing enough water because of non-appreciable depth (even a hand-dug well will not yield in this location).

VES 2 (LOCATION: Karaworo LONGITUDE: **6° 44' 28"** LATITUDE: **7° 48' 42.8"**, ELEVATION: **85.40m**)

Table 2. Field data for VES 2 showing apparent resistivity

Electrode position	Electrode spacing		Apparent Resistivity (Ohm-m)
	AB/2(m)	MN/2(m)	
1	1	0.5	26.43
2	2	0.5	8.36
3	3	0.5	6.09
4	4	0.5	6.16
5	6	0.5	7.47
6	6	1.0	7.21
7	10	1.0	6.84
8	20	1.0	13.15
9	30	1.0	11.78
10	40	1.0	12.34
11	50	1.0	5.10
12	50	2.5	28.04
13	60	2.5	30.60
14	70	2.5	25.37
15	70	2.5	21.30
16	100	2.5	16.12
17	100	5.0	24.49
18	120	5.0	22.08

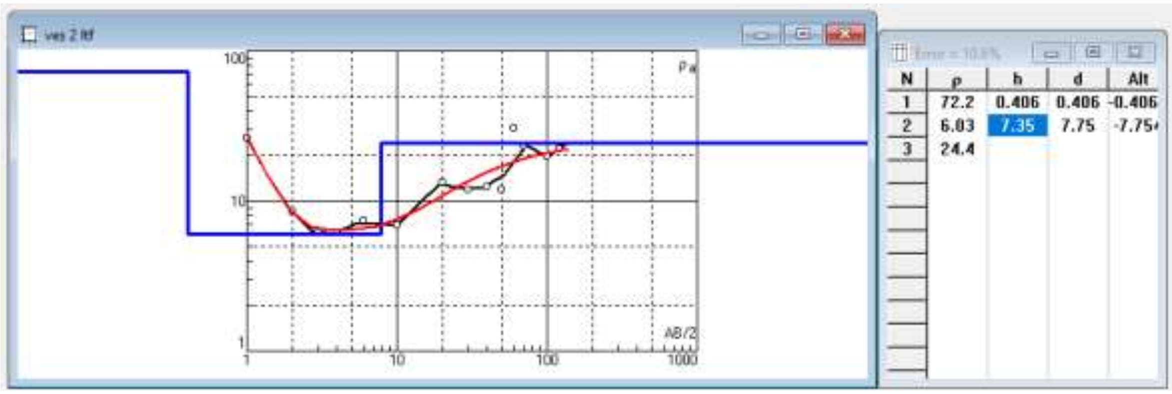

Fig. 7. VES Station 2 showing the graph of apparent resistivity against electrode spacing

As observed from the table and the curve above, it shows that this VES has three (3) layers, the first layer has a resistivity of 72.2 ohm-m, a depth of 0.406 m and a thickness of 0.406 m, the second layer has a resistivity of 6.03 ohm-m, depth of 7.75 m and a wideness of 7.35 m, the 3rd layer having a resistivity of 24.4ohm-m the thickness and depth are at infinity. From the above data collected and interpreted a hand-dug well will probably be advised at this particular location if the community is in dire need of water as it will be able to penetrate the groundwater, other significant details are shown in Table 17.

VES 3 (LOCATION: Karaworo LONGITUDE: **6° 44' 43"** LATITUDE: **7° 48' 32"**, ELEVATION: **90.50 m**)

Table 3. Field data for VES 3 showing apparent resistivity

Electrode position	Electrode spacing		Apparent Resistivity
	AB/2(m)	MN/2(m)	(Ohm-m)
1	1	0.5	34.62
2	2	0.5	70.57
3	3	0.5	23.21
4	4	0.5	3.47
5	6	0.5	4.71
6	6	1.0	5.78
7	10	1.0	6.62
8	20	1.0	1371
9	30	1.0	10.59
10	40	2.5	24.8
11	50	2.5	18.60
12	60	2.5	11.06
13	70	2.5	12.33
14	70	2.5	30.68
15	100	2.5	27.24
16	120	2.5	24.05

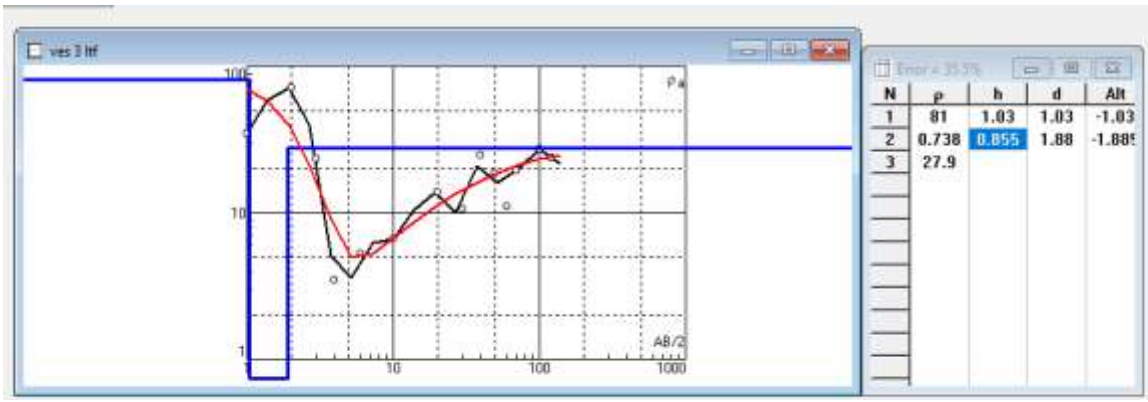

Fig. 8. VES station 3 shows graph of apparent resistivity against electrode spacing

Table 3 and the curve in Fig. 8 indicate 3 layers with the first layer having a resistivity of 81ohm-m, depth of 1.03 m, and a thickness of 1.03m, the second layer having a resistivity of 0.738ohm-m, depth of 1.88 m and a thickness of 0.855m, from the above interpretation, it is not advisable to drill or dig a well in this location as it does not show any viable potential for the presence of water. See Table 17.

VES 4: (LOCATION: Karaworo LONGITUDE: **6° 44' 29"** LATITUDE: **7° 48' 42.9"**, ELEVATION: **92.1m**)

Table 4. Field data for VES 4 showing apparent resistivity

Electrode position	Electrode spacing		Apparent Resistivity
	AB/2(m)	MN/2(m)	(Ohm-m)
1	1	0.5	19.22
2	2	0.5	12.09
3	3	0.5	13.08
4	4	0.5	12.25
5	6	0.5	13.18
6	6	1.0	13.52
7	10	1.0	13.24
8	20	1.0	13.00
9	30	1.0	10.98

Electrode position	Electrode spacing		Apparent Resistivity (Ohm-m)
	AB/2(m)	MN/2(m)	
10	40	1.0	17.24
11	40	2.5	19.32
12	50	2.5	24.35
13	60	2.5	21.62
14	70	2.5	7.28
15	70	5.0	15.87
16	100	5.0	20.56
17	120	5.0	23.59
18	140	5.0	30.67

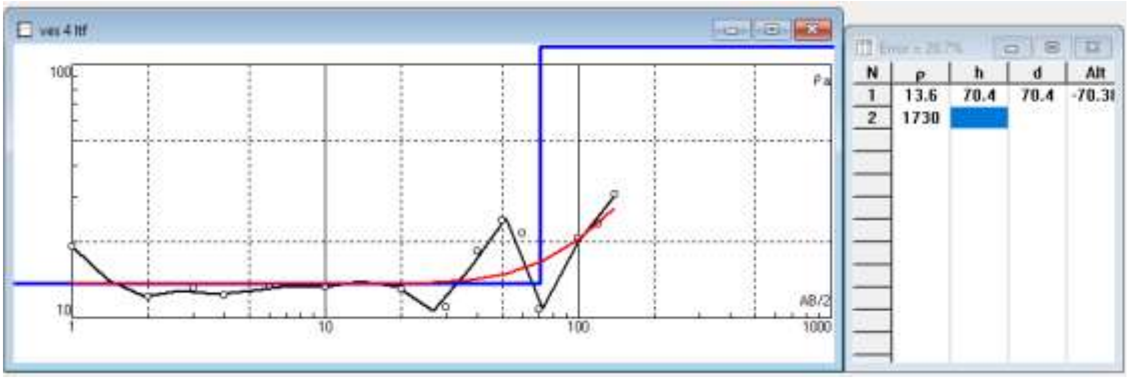

Fig. 9. VES station 4 shows graph of apparent resistivity against electrode spacing

The table and curve as seen above indicate that VES has 2 Layers, layer 1 is characterized by a resistivity of 13.60ohm-m, a depth of 70.4m and a thickness of 70.4m while the second layer has a resistivity of 1730 ohm-m its depth and thickness are at infinity. This particular location can probably be suggested for drilling because it has high resistivity with a reasonable depth, and the well should be drilled above 70 m. More details can be seen in Table 17.

VES 5 LOCATION: Karaworo (LONGITUDE: **6° 44' 39.9"** LATITUDE: **7° 48' 43"**, ELEVATION: **90.2m**

Table 5. Field data for VES 5

Electrode position	Electrode spacing		Apparent Resistivity (Ohm-m)
	AB/2(m)	MN/2(m)	
1	1	0.5	2.23
2	2	0.5	10.74
3	3	0.5	18.81
4	4	0.5	36.53
5	6	0.5	37.38
6	6	1.0	12.42
7	10	1.0	26.38
8	20	1.0	12.36
9	30	1.0	7.92
10	40	1.0	12.53
11	40	2.5	15.90
12	50	2.5	11.44
13	60	2.5	22.73
14	70	2.5	31.91
15	70	5.0	28.37
16	100	5.0	24.24
17	120	5.0	20.37
18	140	5.0	25.30

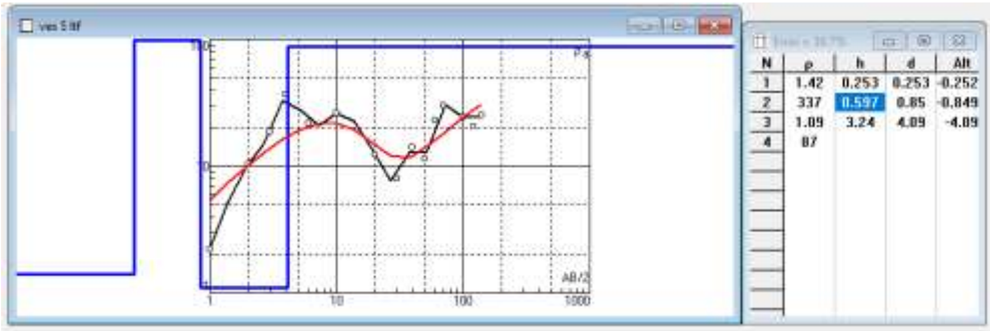

Fig. 10. VES station 5 showing the graph of apparent resistivity against electrode spacing

From the above table and curve, the VES has four (4) layers the first layer has a resistivity of 1.42ohm-m, a depth of 0.253m and a thickness of 0.253m, the second layer has a resistivity of 337ohm-m, a depth of 0.85m and a thickness of 0.597m, the third layer has a resistivity of 1.09ohm-m, depth 4.09m, and a thickness of 3.24m, while the fourth layer has a resistivity of 87ohm-m, with the depth and thickness at infinity. The probable suggestion of a hand-dug well might be considered at this location. More details are shown in Table 17.

VES 6 (LOCATION: Karaworo (LOGITUDE: **6° 44' 40.2"** LATITUDE: **7° 48' 41.4"**, ELEVATION: **69.8m**).

Table 6. Field data for VES 6 showing apparent resistivity

Electrode position	Electrode spacing		Apparent Resistivity (Ohm-m)
	AB/2(m)	MN/2(m)	
1	1	0.5	60.80
2	2	0.5	49.73
3	3	0.5	27.25
4	4	0.5	21.93
5	6	0.5	20.02
6	6	1.0	23.87
7	10	1.0	13.16
8	20	1.0	10.24
9	30	1.0	9.13
10	40	1.0	32.43
11	40	2.5	17.15
12	50	2.5	17.11
13	60	2.5	19.09
14	70	2.5	35.12
15	70	5.0	37.22
16	100	5.0	32.10
17	120	5.0	27.89
18	140	5.0	36.12

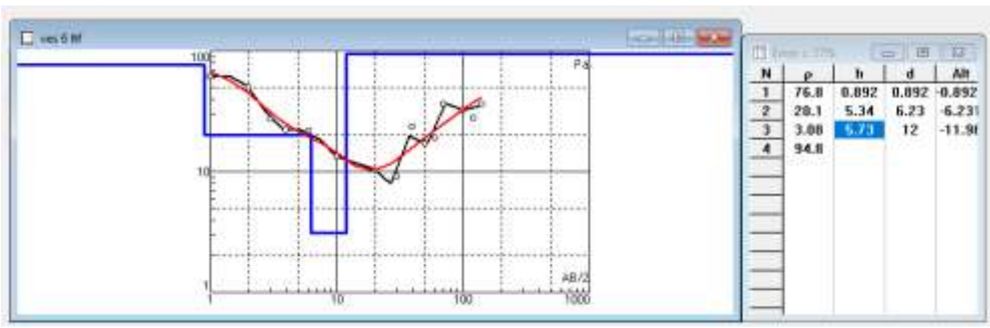

Fig. 11. VES station 6 showing the graph of apparent resistivity against electrode spacing

The VES has four (4) layers the first layer has a resistivity of 76.8ohm-m, depth of 0.892m and a thickness of 0.892, the second layer has a resistivity of 20.1ohm-m, depth of 6.23 and a thickness of 5.34m, the third layer has a resistivity of 3.08ohm-m, depth 12m, and a thickness of 5.73m, while the fourth layer has a resistivity of 94.8ohm-m, with the depth and thickness at infinity. The probable suggestion of a hand-dug well might be considered at this location as observed from the table and curve above. More details are shown in Table 17.

VES 7 (LOCATION: Karaworo (LONGITUDE: **6° 44' 40.5"** LATITUDE: **7° 48' 42.2"**, ELEVATION: **72.0m**)

Table 7. Field data for VES 7 showing apparent resistivity

Electrode position	Electrode spacing		Apparent Resistivity (ohm-m)
	AB/2(m)	MN/2(m)	
1	1	0.5	5.64
2	2	0.5	5.03
3	3	0.5	5.24
4	4	0.5	5.19
5	6	0.5	6.45
6	6	1.0	5.86
7	10	1.0	9.11
8	20	1.0	5.94
9	30	1.0	3.82
10	40	1.0	4.44
11	40	2.5	12.72
12	50	2.5	15.29
13	60	2.5	15.90
14	70	2.5	19.68
15	70	5.0	16.40
16	100	5.0	20.40
17	120	5.0	21.35
18	140	5.0	17.51

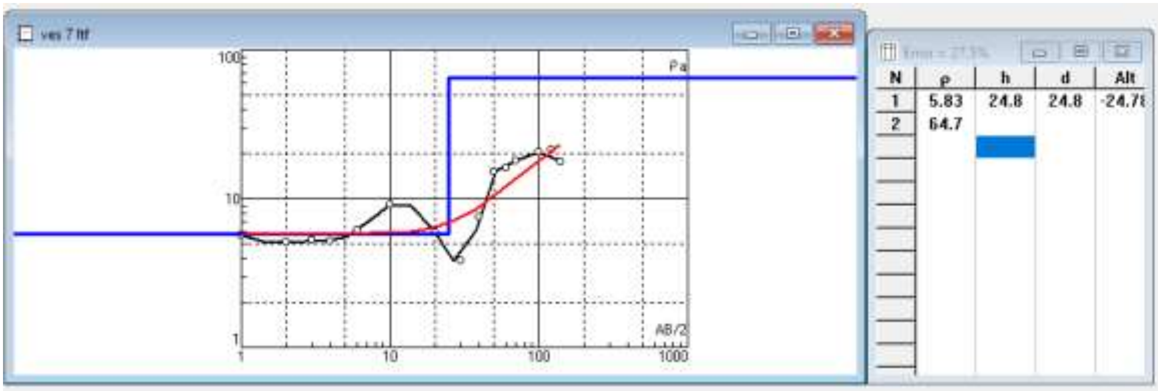

Fig. 12. VES station 7 showing graph of apparent resistivity against electrode spacing

The above curve recognizes two layers with the first layer having a resistivity of 5.38ohm-m, depth of 24.8m, and a thickness of 24.8m and the 2nd layer having a resistivity of 64.7ohm-m with a depth and thickness at infinity. With the above data we can suggest probably a hand-dug well at this location, and also a borehole, more details are shown in Table 17.

VES 8 (LOCATION: Karaworo LONGITUDE: **6° 44' 41.3"** LATITUDE: **7° 48' 81.00"**, ELEVATION: **77.1m**).

Table 8. Field data for VES 8 showing apparent resistivity

Electrode position	Electrode spacing		Apparent Resistivity
	AB/2(m)	MN/2(m)	(ohm-m)
1	1	0.5	7.41
2	2	0.5	6.23
3	3	0.5	5.70
4	4	0.5	6.02
5	6	0.5	6.95
6	6	1.0	9.59
7	10	1.0	13.12
8	20	1.0	16.56
9	30	1.0	20.57
10	40	1.0	31.34
11	40	2.5	20.91
12	50	2.5	22.64
13	60	2.5	28.68
14	70	2.5	34.46
15	70	5.0	30.08
16	100	5.0	29.81
17	120	5.0	33.02
18	150	5.0	21.08

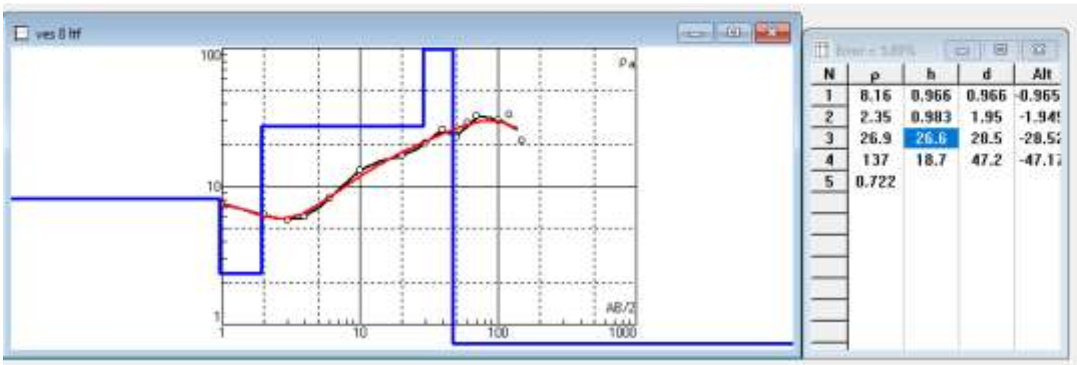

Fig. 13. VES station 8 shows graph of apparent resistivity against electrode spacing

There are 5 layers in this VES location the first layer has a resistivity of 8.16ohm-m, depth of 0.966m, and a thickness of 0.966m and the second layer has a resistivity of 2.35ohm-m, depth of 1.95m and a thickness of 0.983m and third layer has a resistivity of 26.9ohm-m, depth 28.5m and a thickness of 26.6m and the fourth layer has a resistivity of 137ohm-m, depth 47.2m, and a thickness of 18.7m and the fifth layer having a resistivity of 0.722ohm-m with a depth and thickness at infinity.

The probability of this zone being a water-bearing zone is very high because of the low resistivity and appreciable depth at this location. More details are indicated in Table 17.

VES 9 (LOCATION: (Karaworo LONGITUDE: **6° 44' 41.7"** LATITUDE: **7° 48' 43.3"** ELEVATION: **73.3m**).

Table 9. Field data for VES showing apparent resistivity

Electrode position	Electrode spacing		Apparent Resistivity
	AB/2(m)	MN/2(m)	(ohm-m)
1	1	0.5	38.75
2	2	0.5	15.93
3	3	0.5	11.64
4	4	0.5	11.80

Electrode position	Electrode spacing		Apparent Resistivity (ohm-m)
	AB/2(m)	MN/2(m)	
5	6	0.5	11.12
6	6	1.0	11.46
7	10	1.0	11.73
8	20	1.0	24.81
dd	30	1.0	19.70
10	40	1.0	23.17
11	50	1.0	35.51
12	60	1.0	25.42
13	70	1.0	42.36
14	70	2.5	29.55
15	100	2.5	23.02
16	120	2.5	37.08
17	150	2.5	31.02

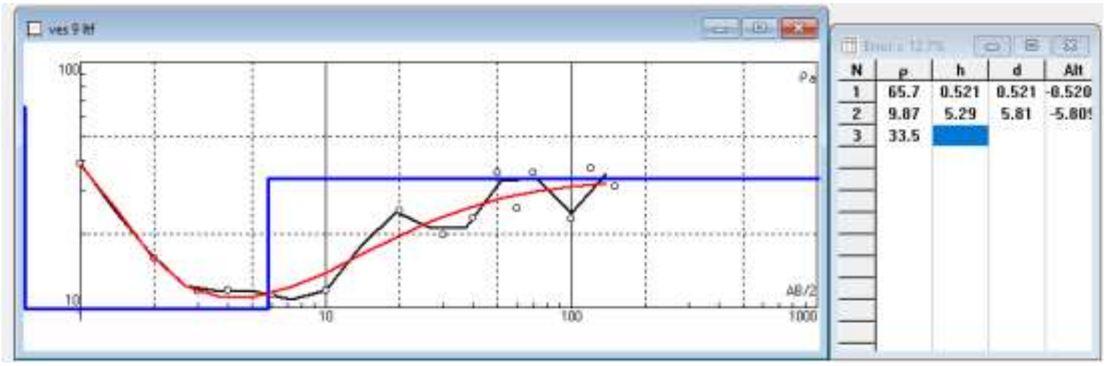

Fig. 14. VES station 9 showing the graph of apparent resistivity against electrode spacing

Three (3) layers were deducted from the curve above, the first layer has a resistivity of 65.7ohm-m, depth of 0.521m, and a thickness of 0.521 and the second layer has a resistivity of 9.87ohm-m, depth of 5.81m and a thickness of 5.29m and the third layer having a resistivity of 33.5ohm-m with its depth and thickness at infinity.

With the above information obtained from the interpretation, a probable hand-dug well can be drilled here if the community is in dire need of water, more details are shown in Table 17.

VES 10 (LOCATION: Karaworo LONGITUDE: **6°** 44’ **27.1**” LATITUDE: **7° 48’42.1”** ELEVATION**: 85.8m).**

Table 10. Field data for VES 10 showing apparent resistivity

Electrode position	Electrode spacing		Apparent Resistivity (ohm-m)
	AB/2(m)	MN/2(m)	
1	1	0.5	6.21
2	2	0.5	6.33
3	3	0.5	6.60
4	4	0.5	6.68
5	6	0.5	7.69
6	6	1.0	7.84
7	10	1.0	8.09
8	20	1.0	8.96
9	30	1.0	6.29
10	40	1.0	10.44
11	40	2.5	18.71
12	50	2.5	9.97
13	60	2.5	5.88

Electrode position	Electrode spacing		Apparent Resistivity (ohm-m)
	AB/2(m)	MN/2(m)	
14	70	2.5	3.16
15	70	5.0	4.15
16	100	5.0	6.11
17	120	5.0	10.10
18	140	5.0	9.40

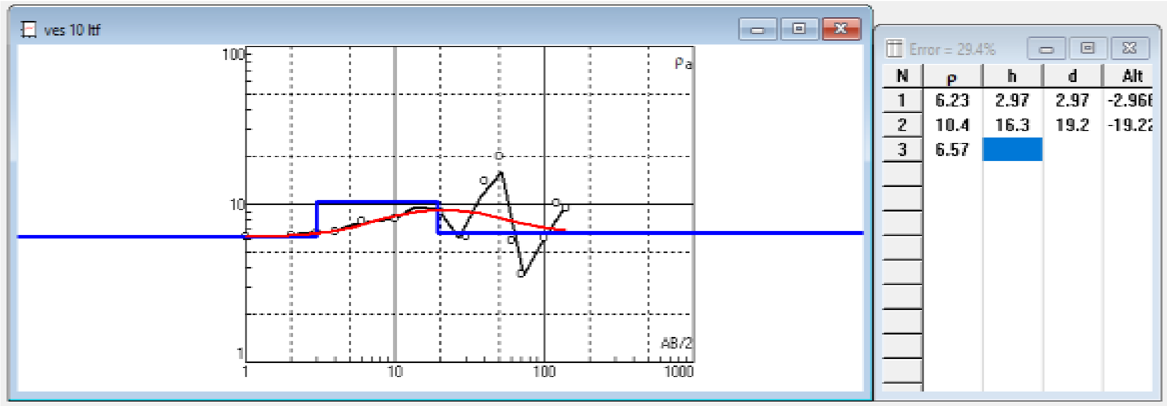

Fig. 15. VES station 10 showing the graph of apparent resistivity against electrode spacing

As observed above, 3 layers were identified from a curve, the first layer has a resistivity of 6.23ohm-m, a depth of 2.97m and a thickness of 2.97 m, the second layer has a resistivity of 10.4 Ohm-m, a depth of 19.2m and a thickness of 16.3m, the 3rd layer has a resistivity of 6.57ohm-m with its depth and thickness at infinity. Hand-dug well can probably be suggested in this zone. More details can be seen in Table 17.

VES 11 (LOCATION: Karaworo LONGITUDE: **6° 44' 27.9"** LATITUDE: **7° 48' 42.1"** ELEVATION: **83.3m**)

Table 11. Field data for VES 11 showing apparent resistivity

Electrode position	Electrode spacing		Apparent Resistivity (ohm-m)
	AB/2(m)	MN/2(m)	
1	1	0.5	17.58
2	2	0.5	8.51
3	3	0.5	8.03
4	4	0.5	7.75
5	6	0.5	8.79
6	6	1.0	10.30
7	10	1.0	12.35
8	20	1.0	13.05
9	30	1.0	15.89
10	40	1.0	18.61
11	50	1.0	22.86
12	60	1.0	23.38
13	70	1.0	34.62
14	70	2.5	31.46
15	100	2.5	28.45
16	120	2.5	35.11
17	140	2.5	25.12

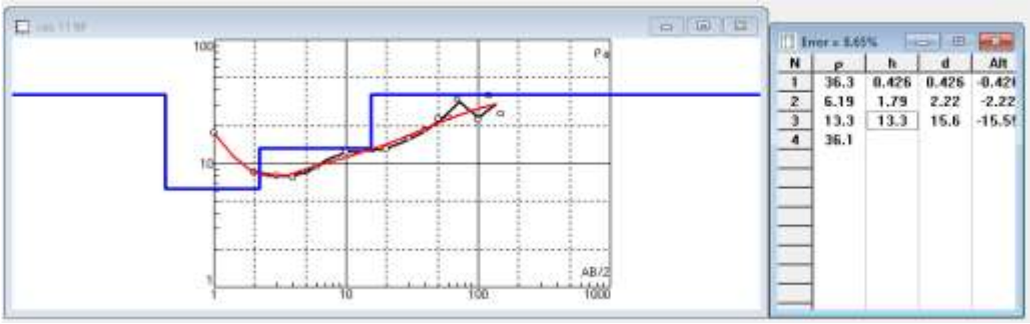

Fig. 16. VES station 11 shows graph of apparent resistivity against electrode spacing

Four (4) layers were identified, the first (1) layer has a resistivity of 36.3ohm-m, with a depth of 0.426m and a thickness of 0.426m. The second layer has a resistivity of 1.79ohm-m, a depth of 2.22m and a thickness of 1.79m, the third layer has a resistivity of 13.3ohm-m, a depth of 15.6m and a thickness of 13.3m, while the final layer has a resistivity of 36.1ohm-m with the depth and thickness at infinity. A hand-bore well can probably be dug at this point; more details are shown in Table 17.

VES 12 (LOCATION: Karaworo LONGITUDE: **6° 44' 28.2"** LATITUDE: **7° 48' 42.2"** ELEVATION: **82.8m**).

Table 12. Field data for VES 12 showing apparent resistivity

Electrode spacing	Electrode spacing		Apparent Resistivity (ohm-m)
	AB/2(m)	MN/2(m)	
1	1	0.5	13.80
2	2	0.5	17.91
3	3	0.5	19.13
4	4	0.5	18.97
5	6	0.5	18.70
6	10	0.5	13.78
7	20	0.5	17.08
8	30	0.5	18.51
9	40	0.5	20.28
10	40	1.0	51.06
11	50	1.0	55.78
12	60	1.0	81.19
13	70	1.0	30.03
14	70	2.5	29.63
15	100	2.5	35.02
16	120	2.5	23.51
17	150	2.5	40.12
18	180	2.5	27.32

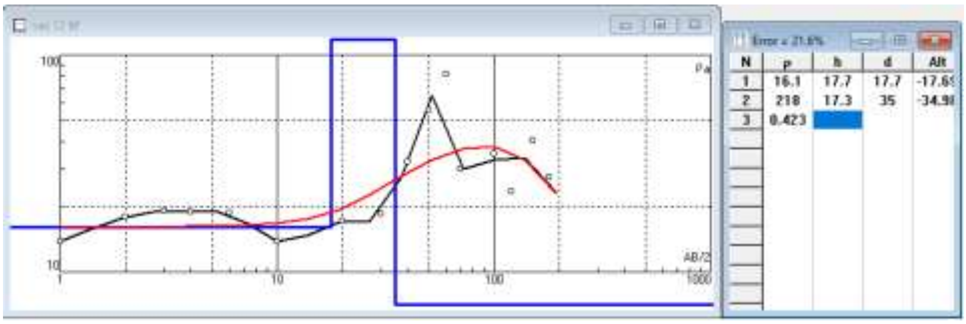

Fig. 17. VES station 12 showing the graph of apparent resistivity against electrode spacing

From the table and curve above, three layers were identified, the first layer has a resistivity of 16.1ohm-m, a depth of 17.7m and a thickness of 17.7m. The second layer has a resistivity of 218ohm-m, a depth of 35m and a thickness of 17.3m and the third layer has a resistivity of 0.423ohm-m with the depth and thickness at infinity. There is probably an aquifer at this depth so, a borehole is suggested for this point, more details can be seen in Table 17.

VES 13 (LOCATION: Karaworo (LONGITUDE: **6° 44' 28.4"** LATITUDE: **7° 48' 42.4"** ELEVATION: **82.4m**).

Table 13. Field data for VES 13 showing apparent resistivity

Electrode position	Electrode spacing		Apparent Resistivity (Ohm-m)
	AB/2(m)	MN/2(m)	
1	1	0.5	4.8
2	2	0.5	21.40
3	3	0.5	15.92
4	4	0.5	13.23
5	6	0.5	12.54
6	6	1.0	14.97
7	10	1.0	18.81
8	20	1.0	16.49
9	30	1.0	20.58
10	40	1.0	24.80
11	50	1.0	27.76
12	60	1.0	30.56
13	70	1.0	33.64
14	70	2.5	31.33
15	100	2.5	18.11
16	120	2.5	25.39
17	150	2.5	19.18
18	180	2.5	30.98

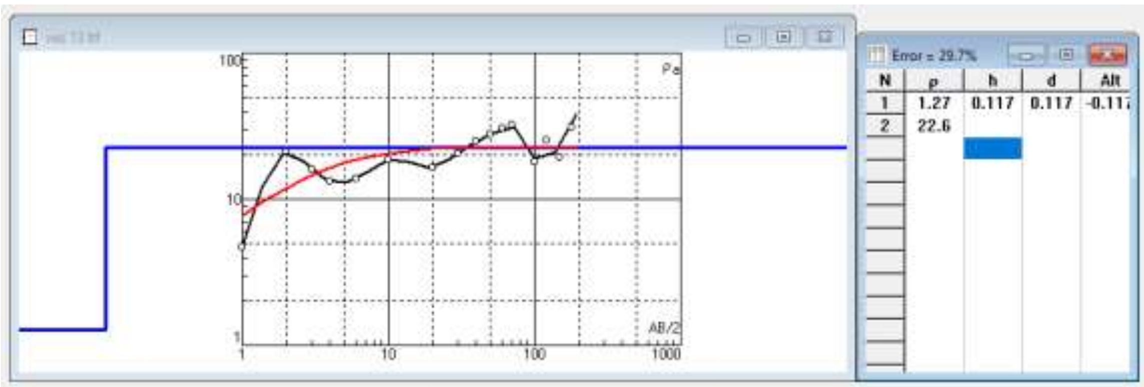

Fig. 18. VES station 13 showing graph of apparent resistivity against electrode spacing

From the table and curve, two can be identified two layers, the first layer has a resistivity of 1.27ohm-m, a depth of 0.117m and a thickness of 0.117m and the second layer has a resistivity of 22.6ohm-m with a depth and thickness at infinity. There is no probability of an aquifer in this zone as it is characterized by the presence of clay. More details as deduced from Table 17.

VES 14 (LOCATION: Karaworo LONGITUDE: **6° 44' 43.0"** LATITUDE**: 7° 49' 01.4"** ELEVATION: **83.1m**).

Table 14. Field data for VES 14 showing apparent resistivity

Electrode position	Electrode spacing		Apparent Resistivity (ohm-m)
	AB/2(m)	MN/2(m)	
1	1	0.5	18.93
2	2	0.5	2.68
3	3	0.5	2.05
4	4	0.5	1.10
5	6	0.5	0.634
6	6	1.0	0.46
7	10	1.0	7.19
8	20	1.0	37.62
9	30	1.0	80.11
10	40	1.0	86.49
11	50	1.0	95.76
12	60	1.0	188.15
13	70	1.0	274.07
14	70	2.5	149.42
15	100	2.5	48.10
16	100	5.0	60.63
17	120	5.0	53.19

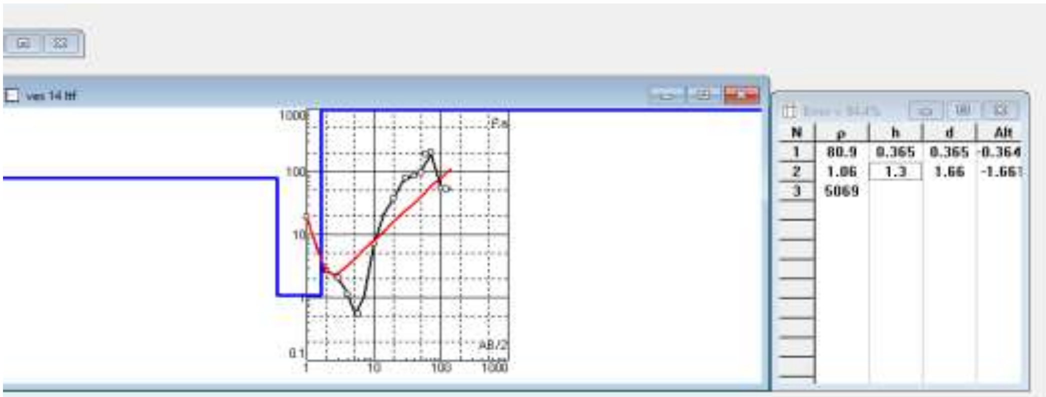

Fig. 19. VES station 14 showing the graph of apparent resistivity against electrode spacing

Three layers were identified above from the curve, the first layer has a resistivity of 80.9ohm-m, a depth of 0.365m and a thickness of 0.365m, the second layer has a resistivity of 1.06ohm-m, a depth of 1.66m and a thickness 1.3m and the third layer has resistivity of 5069ohm-m, there is no presence of water from the resistivity difference seen above and this is due to high presence of clay. Details are shown in Table 17.

VES 15 LOCATION: Karaworo (LONGITUDE: **6° 44' 42.6"** LATITUDE: **7° 49' 00.6"** ELEVATION: **92.8m**).

Table 15. Field data for VES 15

Electrode position	Electrode spacing		Apparent Resistivity (Ohm-m)
	AB/2 (m)	MN/2 (m)	
1	1	0.5	55.48
2	2	0.5	30.54
3	3	0.5	15.17
4	4	0.5	6.07
5	6	0.5	5.05
6	6	1.0	3.53
7	10	1.0	16.53

Electrode position	Electrode spacing		Apparent Resistivity (Ohm-m)
	AB/2 (m)	MN/2 (m)	
8	20	1.0	55.63
9	30	1.0	53.68
10	40	1.0	141.72
11	50	1.0	169.94
12	60	1.0	249.98
13	70	1.0	63.32
14	70	1.0	42.62
15	100	2.5	56.93
16	120	2.5	37.82
17	120	5.0	30.17
18	140	5.0	34.10
19	140	7.5	40.45
20	160	7.5	52.12
21	200	7.5	33.17

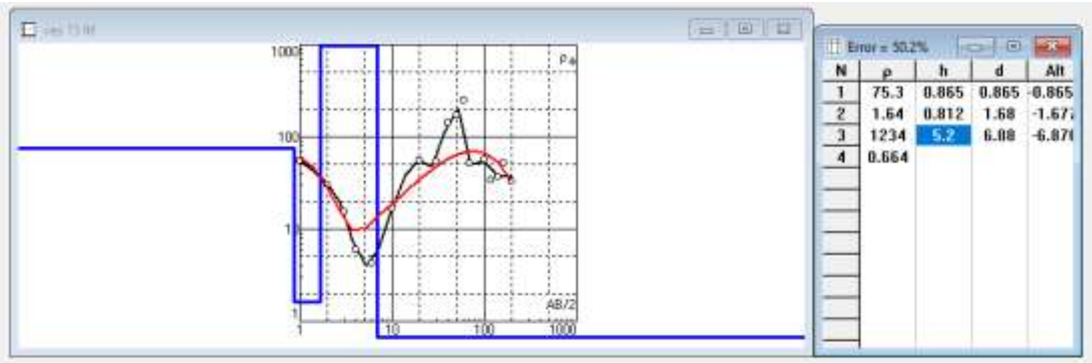

Fig. 20. VES station 15 showing the graph of apparent resistivity against electrode spacing

Four layers were recognized from the above, the first layer has a resistivity of 75.3ohm-m, a depth of 0.865 and a thickness of 0.865, the second layer has a resistivity of 1.64ohm-m, a depth of 1.68m and a thickness of 0.812m, the third layer has a resistivity of 1234 and a depth of 6.88m and a thickness of 5.2m, the fourth layer has a resistivity of 0.664ohm-m with its depth and thickness at infinity. Details as observed in Table 17.

4.2 Interpretation of the Curve Types

Resistivity curves are classified based on the number of layers in the curve. There are four major types of curves and a combination of two curves may also occur. The four (4) main types of curves and their trend of resistivity values are shown below: Table 16.

From the below curves, it can be seen that VES 1,2,3,5,6,8,9,10,11,12,14 and 15 are three-layered curves respectively, while VES 4,7 and 13 are two-layered curves respectively. The curve types include H-type, K-type, HK-type, HAK-type, QH-type etc.

Table 16. Resistivity curve types

Curves type	Resistivity value
Q	R1> R2> R3
H	R1> R2< R3
A	R1< R2< R3
K	R1< R2> R3

5. DISCUSSION

The study area is classified into three different formations which include Lokoja Formation, Patti Formation, Agbaja Ironstone etc. which are overlying each other. Sandstone, claystone and siltstone are the lithologies found at the location with angular to sub-rounded cobbles and pebbles which corresponds to the previous studies [21]. Fifteen (15) VES were taken at the study area with varying resistivity, depth and thickness. The low resistivity in the area as observed from the resistivity reading was found to be associated with the presence of lateritic clay and clay-sandstone. Most of the possible aquifers are found in the Patti Formation with just a few around the boundary between Patti and Agbaja Ironstone.

Table 17. Tabular analysis of the field result

VES	Layers	Resistivity (Ohm-m)	Thickness (m)	Depth (m)	Zones	Curve Type	Groundwater prospect
1	1	87.6	0.505	0.505	Topsoil	H-type	Poor
	2	2.11	0.236	0.741	Claystone		
	3	37.7			Siltstone		
2	1	72.2	0.406	0.406	Claystone	H-type	Moderate
	2	6.03	7.35	7.75	Siltstone		
	3	24.4			Silty-sandstone		
3	1	81	1.03	1.03	Top soil	H-type	Poor
	2	0.738	0.855	1.88	Claystone		
	3	27.9			Silty sandstone		
4	1	13.6	70.4	70.4	Top soil		Good
	2	1730			Lateritic clay		
5	1	1.42	0.253	0.253	Top soil	KH-type	Moderate
	2	337	0.597	0.85	Claystone		
	3	1.09	3.24	4.09	Siltstone		
	4	87			Sand/sandstone		
6	1	76.8	0.892	0.892	Topsoil	QH-type	Moderate
	2	20.1	5.34	6.23	Claystone		
	3	3.08	5.73	12	Siltstone		
	4	94.8			Sand/sandstone		
7	1	5.83	24.8	24.8	Top soil		Moderate
	2	64.7			Lateritic clay		
8	1	8.16	0.966	0.966	Top soil	HAK-type	Moderate
	2	2.35	0.983	1.95	Lateritic clay		
	3	26.9	26.6	28.5	Claystone		
	4	13.7	18.7	47.2	Siltstone		
	5	0.722			Sand/sandstone		
9	1	65.7	0.521	0.521	Top soil	H-type	Moderate
	2	9.87	5.29	5.81	Lateritic clay		
	3	33.5			Silty sandstone		
10	1	6.23	2.97	2.97	Topsoil	K-type	Moderate
	2	10.4	16.3	19.2	Claystone		

VES	Layers	Resistivity (Ohm-m)	Thickness (m)	Depth (m)	Zones	Curve Type	Groundwater prospect
	3	6.57			Silty sandstone		
11	1	36.3	0.426	0.426	Topsoil	HA-type	Moderate
	2	6.19	1.79	2.22	Lateritic clay		
	3	13.3	13.3	15.6	Siltstone		
	4	36.1			Sandstone		
12	1	16.1	17.7	17.7	Topsoil	K-type	Moderate
	2	21.8	17.3	35	Claystone		
	3	0.423			Siltstone		
13	1	1.27	0.117	0.117	Topsoil	A-type	Poor
	2	22.6			Lateritic clay		
14	1	80.9	0.365	0.365	Topsoil	H-type	Poor
	2	1.06	1.3	1.66	Lateritic clay		
	3	5069			Silty sandstone		
15	1	75.3	0.865	0.865	Topsoil	HK-type	Poor
	2	1.64	0.812	1.68	Claystone		
	3	1234	5.2	6.88	Siltstone		
	4	0.664			Sand/sandstone		

The VES points found around the boundary between the Patti Formation and Agbaja Ironstone have low resistivity and no considerable depth, the low resistivity can be associated with the presence of lateritic clay and the oolitic ironstone of the Agbaja Formation, so this point can be suggested for a hand dug well. But those VES points found around the boundary between Patti and Lokoja Formation have very low resistivity readings and appreciable depth than the former and that can support drilling of a borehole and borehole drilling was suggested for those VES points. The VES points found in the Patti Formation have higher resistivity readings with very low depths which cannot support even a hand-dug well for it can dry out with time if dug. The maximum depth of the aquifers suggested for drilling is 70m with 35m as the minimum depth, with a maximum resistivity of 137ohm-m and 13.6ohm-m as the minimum resistivity of the aquifers. The maximum depth of the VES points suggested for a hand-dug well is 19.2m and 5.81m as the minimum depth with a maximum resistivity of 36.1 ohm-m and 6.57 ohm-m as the minimum resistivity.

From the analysis made so far, the borehole can be drilled at VES point 4,7,8 and12 while hand dug well can be dug at VES point 2, 6, 9, 10 and 11 etc.

6. CONCLUSION

The result and interpretation of the project work show that the electrical resistivity method fits the purpose of the search for conductive materials and groundwater within the subsurface. The subsurface layers delineated within the study area comprise the topsoil, lateritic clay, siltstone and sandstone, the curve types include K-type, HA-type, A-type, QH-type and HAK-type curves. It can be concluded that due to the low resistivity of the zones and the low thickness, the aquifer in some areas is characterized by lateritic claystone. Also, the thickness of the aquifer in some areas is reasonable enough to support a continuous supply of water to any borehole and some to hand-dug well within the area.

This investigation will serve as an opportunity to provide safe drinking water to the entire community around the study area via groundwater by the necessary bodies or individuals. Also, the aquifer resistivity, thickness and depth revealed that the study is good for groundwater development but there is a need for proper investigation before doing that.

7. RECOMMENDATION

Based on the result obtained it is recommended that boreholes should be drilled to a substantial depth of about 40m and above in order to obtain a better ground water yield.

More research should be carried out in the study area using other geophysical methods such as the Electromagnetic Method, induce polarization Method and Remote Sensing Method including both airborne and ground platform/LANDSAT etc. to get more information about the subsurface geology in the study area.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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