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Geo-electrical Method Applied to Evaluation of Groundwater Potential and Aquifer Protective Capacity of Overburden Units

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Authors' contributions

This work was carried out in collaboration between all authors. Author EEU designed the study. Authors NKA and BEE collected the data and correlated the results and made the draft. Author AI made the literature review and assessments. All authors read and approved the final manuscript.

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ABSTRACT

Aims: This study was designed to determine different subsurface Geo-electric layers, the aquifer units, determination of Dar-Zarrouk parameter (Longitudinal conductance(S) and Transverse resistance (R)) as well as identifying suitable areas with poor, weak, moderate and excellent aquifer protective capacity rating.
Study Design: The study area, Sabo in Kaduna state lies approximately between latitudes 10º25’N and 10º30’N and longitudes 7º25’E and 78º30’E covering an area of about 500,000m^2.
Methodology: A total of sixty-six (66) vertical electrical soundings (VES) using Schlumberger electrode array were acquired with a maximum electrode separation of AB/2=100 m, using the ABEM Terrameter SAS 300C.
Results: Maximum of five lithologies were identified namely, topmost layer which consists of lateritic clay, river sand and gravel, clayey sand, weathered transition zone/ fractured layer and the fresh basement. Qualitative interpretation indicates that the weathered layer and weathered/fractured basement constitutes the main aquifer units. These aquifers are characterized by thick overburden found within basement depressions with maximum value of 65 m and resistivity values between 10 ohm.m and 756 ohm.m.

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The Dar-Zarrouk parameters evaluated are total longitudinal unit conductance (S) and total transverse resistance (T) with values ranging from 0.005 – 0.65 mhos and 2000 – 32000 ohm.m^2.

Conclusion: The results show that the lithology of the aquifer is dominated by clay/clayey sand and sandy materials with attendant low and high transmissivity. About 80 % of the area has longitudinal conductance value greater than 0.3 mhos due to high content of clay/lateritic clay indicating moderate protective capacity rating, hence vulnerable to contamination.

Keywords: Schlumberger; dar-zarrouk; aquifer; contamination.

1. INTRODUCTION

Water is an essential commodity to mankind and it is found everywhere in the earth's ecosystem. However the water, which exists in such abundance on the earth, is unevenly distributed in both time and space and in circulation [1]. The search for groundwater has become quite intense in human history. This is due to the fact that government is unable to meet the ever-increasing water demand; inhabitants have had to look for alternative sources such as surface streams, shallow wells and boreholes. The amount of surface water available for domestic, industrial and agricultural use is insufficient to fulfill the current demand in the world. Therefore, exploration for groundwater is of vital importance. Groundwater is the water that lies beneath the ground surface, filling the pore spaces between grains in bodies of sediment and clastic sedimentary rock and filling cracks and crevices in all types of rock [2]. Kaduna is one of the largest urban centers in Nigeria with several settlements around it (Fig. 1), one of which is Sabo community where the research work was carried out. Groundwater exploration is gaining more and more importance in Kaduna owning to the ever increasing demand for water supply, especially in areas with inadequate pipe-borne and surface water supplies. With the advances in technology, hydrogeologists and geophysicists resorted to geophysical methods such as very low frequency, direct- current resistivity sounding, resistivity imaging, self-potential (SP) and magnetic methods to locate groundwater. The objectives of this study were designed to determine different subsurface Geo-electric layers, the aquifer units, determination of Dar-Zarrouk parameter (Longitudinal conductance(S) and Transverse resistance (R)) as well as identifying suitable areas with poor, weak, moderate and excellent aquifer protective capacity rating.

1.1 Study Area

The study area lies approximately between latitudes 10º25'N and 10º30'N and longitudes 7º25'E and 78º30'E covering an area of about 500,000m^2(Fig.1).Precambrian basement complex rocks underlie the entire area of Kaduna and they consist of migmatite gneiss complex, metasediments/metavulcanics (mostly schist, quartzite, amphibolites and banded iron formation, pan African granitoids and calc-alkaline granites, and volcanics of Jurassic age [3]. A stream which forms part of River Kaduna draining system cut across all the profiles. The relief of the area ranges between 370 and 650m [4,5]. Lower relief is occupied by the stream and river valley [6]. Groundwater in the area has not been adequately developed and as such data relating to their magnitude and mode of formation are lacking. However in the Basement complex, the permeability and storativity of the groundwater system are dependent on structural features such as the extent, and volume of fractures together with thickness of weathering [7,8]. The relatively high annual rainfall (1270mm) and temperature (32ºC) in Kaduna, which has resulted in the formation of deep weathered zone in addition to high density of fractures, have contributed tremendously to constituting large reservoirs of groundwater, good aquifers and high yields of boreholes [7]. Geophysical investigation and borehole drilling reports have clearly established two major aquifers. These are the overburden weathered aquifer and the fractured crystalline aquifer [7,9]. Both aquifers at some places are interconnected and form a hydro geological unit of water table surface.

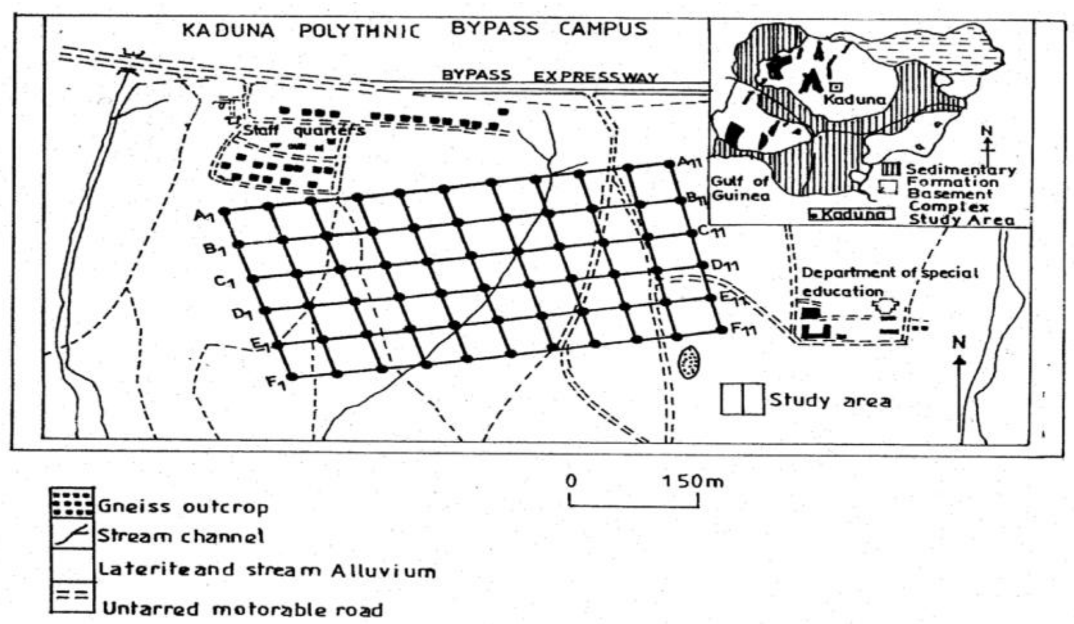
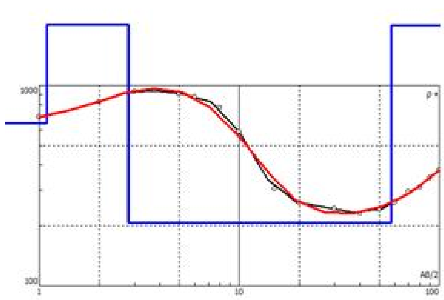


Fig. 1. Map of study area showing the profiles A – F

2. MATERIALS AND METHODS

2.1 Data Acquisition and Interpretation

Geophysical investigations consisting of 66 vertical electrical sounding (VES) using the Schlumberger four-electrode array were taken within the study area. Six profiles numbered A-F were established covering an area of 0.5km^2. A station interval of 100m was used to establish the various sounding points along each profile by wooden pegs marked as A1------F11. The electrode spread of AB/2 was varied from 1 to a maximum of100 m. The expected depth of investigation was (D) = 0.125 L, where L = AB/2 and AB the current electrode and the potential electrode MN changing correspondingly from 0.5-15m. The measurements were made with ABEM Terrameter units. Field resistivity structures of sounding data were determined by the software, IPIWIN (version 3.0.1) developed by the Geophysics Group Moscow State University for inverse interpretation [10]. Data were interpreted in terms of four and five layer structure (Fig. 2). The fit between model response and the field data for the VES points were generally lower than 10%.



N	ρ	h	d	Alt
1	1207	0.4205	0.4205	0.4204
2	500.1	12.79	13.21	-13.212
3	69.05	12.17	25.38	-25.383
4	27428			

Fig. 2. Typical VES curve and model description

The VES data were subsequently plotted as geo-electric sections (Figs. 5 - 9) to show the variations of resistivity and thickness values of layers within the depth penetrated in the study area at the indicated VES stations. The interpretation of the VES curves aided by lithological logs from boreholes (Fig. 3) enabled the derivation of maximum of five geologic sections. Qualitative interpretation indicates that the weathered/fractured basement constitutes the main aquifer unit. Isopach and iso-resistivity maps of weathered layer (Figs 10 and 11) were plotted to look at the thickness of overburden in the study area and the range of resistivity of the materials of the water bearing layer respectively. In addition, maps of longitudinal conductance and transverse resistance of the study area were produced for aquifer protective capacity rating and to define target areas of good groundwater potential (Figs. 12 and 13.) respectively. The longitudinal layer conductance (S) of the overburden at each station was obtained from the equation:

$$S = \sum_{i=1}^{n} \frac{h_i}{\rho_i} \tag{1}$$

While the transverse resistance (T) was obtained from the equation:

$$S = \sum_{i=1}^{n} \rho_i h_i \tag{2}$$

Where h_i is the layer thickness, ρ_i is layer resistivity while the number of layers from the surface to the top of aquifer varies from $i = 1 \ to \ n$.

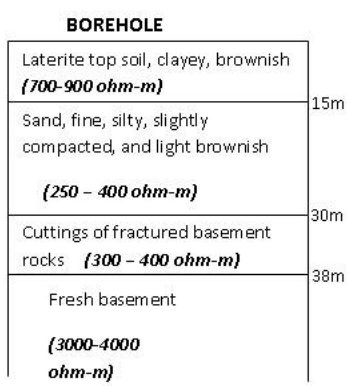


Fig. 3. Borehole lithology and interpretation modified from Aboh (2002).

3. RESULTS AND DISCUSSION

3.1 Interpretation of VES A_1- A_{10}

Fig. 4 shows the resistivity cross-section constructed for VES points A_1 – A_{10}. The figure delineates four to five layers along this profile. From the figure, the first layer has resistivity ranging from 268 ohm– m to 2291 ohm – m. Going by the characteristic resistivity values for the earth materials found within the study area and the lithologies of the borehole log discussed above (Fig. 3.), this layer most likely consist of laterite, River sand and gravel. The high resistivity end (2291ohm–m) typifies the hard indurated red laterite usually found on foot path while the low resistivity zone (268 ohm–m) is the River sand and gravel found at VES A_8 which is 3m away from stream. The thickness of this layer varies from 0.5 m to 1.3 m. The second layer consists of clayey sand with maximum resistivity value of 497 ohm–m. The thickness of this layer varies from 0.6 m to 13 m. The resistivity values of the third layer which vary from 5 ohm-m to 1314 ohm-mare considered as the weathered basement for the four layer case. This layer has a mean thickness of about 44 m. For the five layer case, its resistivity varies from 358 ohm-m to 1314 ohm-m with a mean thickness of 8.3 m. Fresh basement rocks with resistivity values ranging from 1227 ohm-m to 59413 ohm are found beneath the four layer case. The thickness is infinite. There is a thick pre-basement horizon with a resistivity value ranging from 60-361 ohm–m and mean thickness of 32 m beneath the five layer case (VES A_4, A_5, and A_7). This most probably represents a fractured bedrock sequences. The fifth layer with an infinite thickness is the Fresh basement. The resistivity of this layer is > 1800 ohm-m.

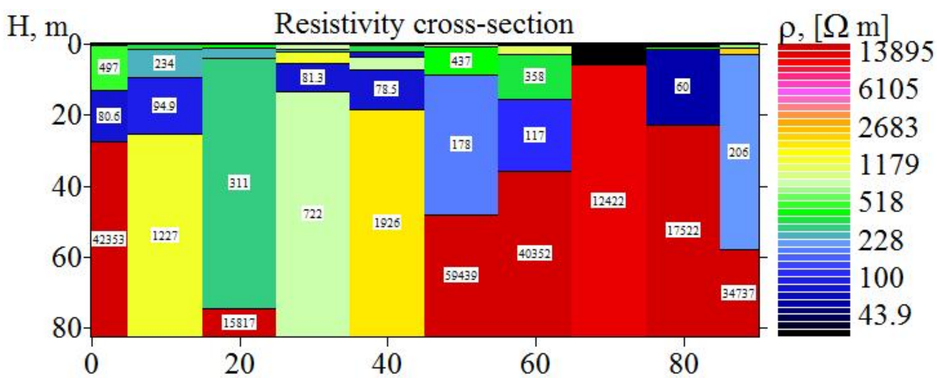


Fig. 4. Resistivity cross-section for VES A_1- A_{11}

3.2 Interpretation of VES B_1- B_{10}

The resistivity cross-section for VES points B_1 to B_{10} (Fig. 5.) is dominated by five layers. The figure suggests that the first layer most likely consists of River sand, gravel and laterite. The resistivity value varies from182 ohm-m to 1179 ohm–m. The thickness of this layer ranges from 0.5 m to 1.4 m. The second layer with maximum resistivity value of 694 ohm-m is the clayey sand. Its thickness varies from 1.8 m to 10 m. The material beneath the third layer case (VES B_8) with resistivity value > 15000 ohm is the fresh basement. Its thickness is infinite. The weathered basement formed the third layer with mean thickness of about 36 m for the four layer case. The maximum resistivity of this layer is 300 ohm-m. The third layer beneath VES points which show five electrostatigraphic units, the resistivity and thickness ranged from 60 ohm- m to 1438 ohm–m and 4 m to 10 m respectively. The low resistivity is due to sandy clay while the high resistivity is due to coarse sand mixed with gravels or pebbles. A pre-basement horizon, which probably represents a fractured basement bedrock sequence, with mean thickness of about 28m, underlay the VES points with five electrostatigraphic units. The resistivity of this fractured basement ranges from 43 ohm–m to 290 ohm-m. The Fresh basement with an infinite thickness forms the fourth layer beneath the remaining VES points. The resistivity is >20,000 ohm-m except at VES B_1 which has a resistivity of 536 ohm-m characteristics of fractured bedrock. With an infinite thickness, the resistivity of the fifth layer ranged from 270 ohm-m to 30,000 ohm-m. Low resistivity value (< 1000 ohm-m) in the bedrock denotes fractured basement.

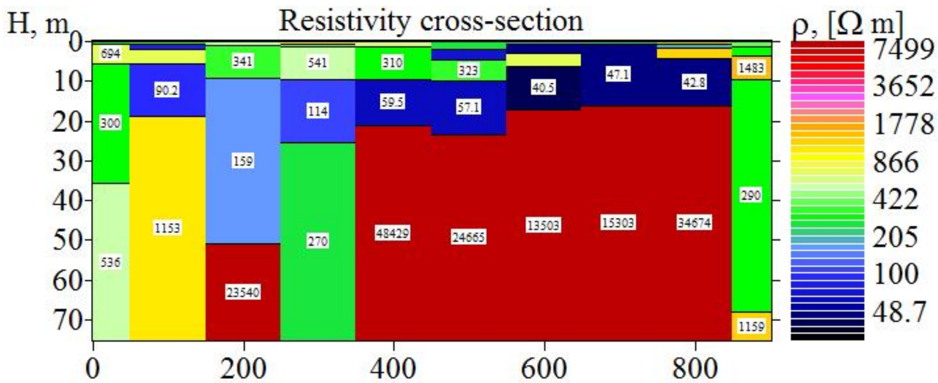


Fig. 5. Resistivity cross-section for VES B_1- B_{10}

3.3 Interpretation of VES C_1- C_{10}

Fig. 6 shows the resistivity cross sections of profile C. Maximum of Five geologic sections are delineated for this profile. The first geo-electric layer with apparent resistivity values that varies from 318 ohm-m to 2600 ohm-m is entirely laterite. It is reddish brown in color. The maximum thickness of this layer is about 3m. Underlying this layer is the clayey sand beneath the four and five electrostatigraphic units. The resistivity and thickness of this layer varies from 20 ohm-m to1633 ohm-m and 0.6 m to 11 m respectively. The second layer beneath VES $C_7$with three electrostatigraphic units has resistivity value of 81 ohm-m and thickness of 25 m. This probably constitutes the weathered basement rocks (saprolite) and is characteristic of clay. While the third layer constitutes fresh basement beneath VES $C_{7,}$ it is the weathered basement beneath VES points with four electrostatigraphic units. The thickness beneath VES C_7 is infinite and varies from 32 m to 53 m beneath the VES points with four electrostatigraphic units. Pre- basement horizon which represents fractured bed rock sequence with a mean thickness of 34 m forms the fourth geo-electric layer beneath the five electrostatigraphic units. The resistivity of the fractured bedrock varies from95 ohm-m to 151 ohm-m. Fresh / fractured basement constitute the last geo-electric layer for the VES points with four and five electrostatigraphic units. This layer with an infinite thickness has resistivity value that ranges from 661 to 61,835 ohm-m. The lower end of the range is diagnostic of fractured bedrock.

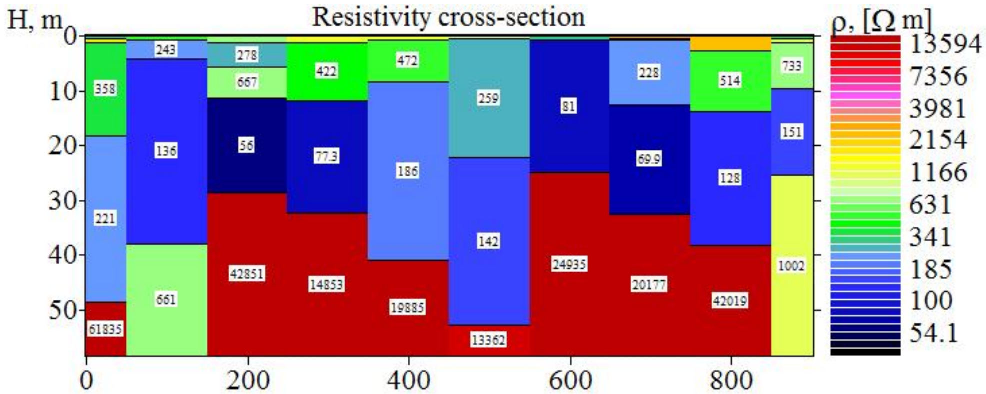


Fig. 6. Resistivity cross-section for VES C_1- C_{10}

3.4 Interpretation of VES D_1- D_{10}

The deduced resistivity cross-section for the study area of profile D is shown in Fig. 7. The resistivity cross sections show a maximum of four geologic units. The first layer which typifies laterite has resistivity and thickness values ranging from 210 ohm-m to 5298 ohm-m and 0.9 m to 26 m respectively. The high resistivity end is characteristics of the indurated hard red laterite usually found on foot path. Coarse sand mixed with gravels or pebbles with maximum resistivity value of 2330 ohm-m forms the second layer except at VES points $D_{6,}$ D_{10} & D_{11} which consist of weathered basement. Its thickness varies from1.5 m at VES D_4 to 16 m at VES D_3. The third layer does not consists of the same material throughout the entire profile, while it is fractured/fresh basement beneath VES points $D_{6,}$ & D_{10} with resistivity value of 383 – 38743 ohm-m and infinite thickness, it is weathered basement beneath the remaining VES points. The resistivity of the weathered basement varies from 33 ohm-m to 660 ohm-m with a mean thickness of 19m.The lower end of the range is due to higher percentage of clay admixture. The fourth layer with resistivity value >1000 ohm-m is considered as the fresh basement and has infinite thickness.

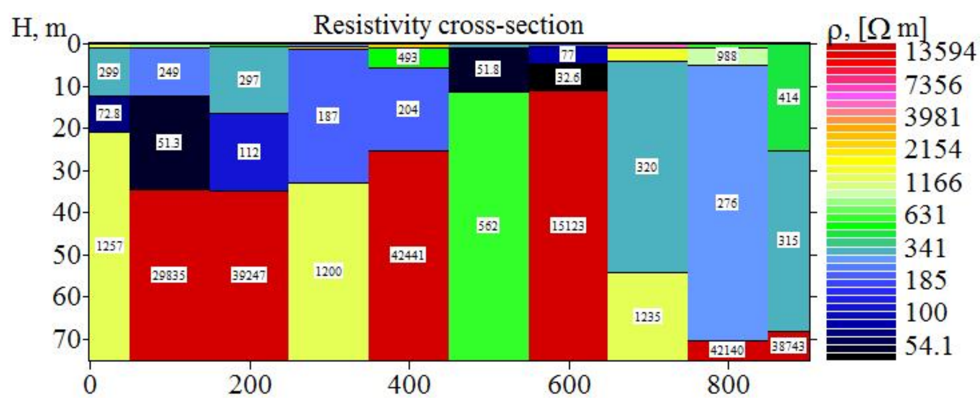


Fig. 7. Resistivity cross-section for VES D_1- D_{10}

3.5 Interpretation of VES E_1- E_{10}

The resistivity section through this profile is shown in Fig. 8. A maximum of four geologic sections is delineated for this profile. The first layer with resistivity ranging from 163 ohm-m to 1549 ohm–m and mean thickness of about 2.2 m represents the top soil formation characteristics of laterite. The second layer consist of different materials, while it is the weathered basement beneath VES E_4, $E_{5,}E_9$ and $E_{10,}$with maximum resistivity value of 101 ohm-m and mean thickness of 10 m, it is sand mixed with pebbles or gravels for the remaining VES points. The maximum resistivity value of the sand material is 2021 ohm-m and the thickness varies from 0.8 m to 16 m. The third layer for VES E_4, $E_{5,}E_9$ and E_{10} is considered as the Fresh basement with resistivity value > 1000 ohm-m. For other sections beneath this profile, the third layer is the weathered basement with range of resistivity and thickness values from 56 ohm–m to 223 ohm-m and 4 m to 39 m respectively. The fourth layer beneath the VES points with four geo-electric layers is the fresh basement with a maximum resistivity value of 43000 ohm-m and infinite thickness.

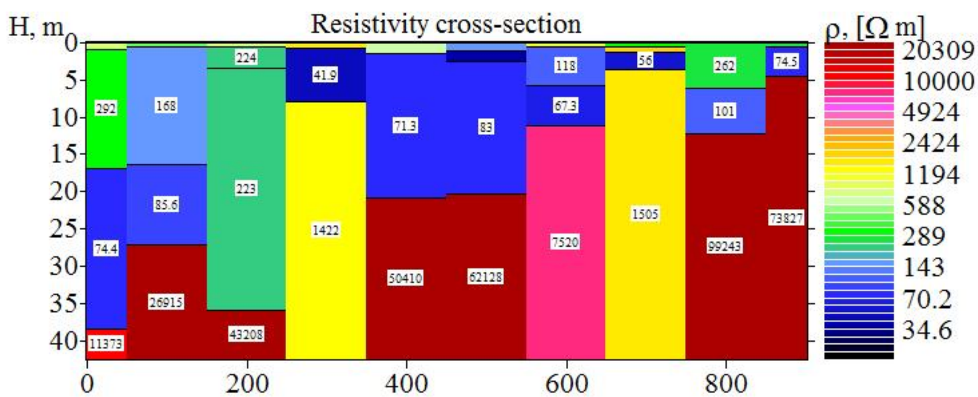


Fig. 8. Resistivity cross-section for VES E_1- E_{11}

3.6 Interpretation of VES F_1- F_{10}

The resistivity sections for profile F is shown in Fig. 9. Four and three geologic units are suggested for this profile. The first layer has resistivity value between 134-3096 ohm-m. The high resistivity value is due to an outcrop of gneiss rock two meters from VES F_{10}. The lower resistivity value signified laterite, River sand and gravel. The thickness of this layer is thin and has a mean of 1.02m. The second layer does not consist of the same materials across the entire profile. While it is considered as the weathered basement beneath VES F_1 – F_6, and F_{11} it is clayey sand for the remaining VES points. The weathered basement has a range of resistivity value of 10 ohm-m to 785 ohm-m and thickness which varies from 2.3 m and 45 m, while the clayey sand with a mean thickness of 1.6 m has maximum resistivity value of 400 ohm-m. The third layer beneath VES points F_7, F_8&F_{10} is considered as the weathered basement with maximum resistivity value of 1713 ohm-m and thickness of about 5 m. The third layer beneath other sections of this profile is the Fresh basement with an infinite thickness and maximum resistivity value of about 70292 ohm-m. The fourth layer beneath VES points F_7, F_8 & F_{10} is the fresh basement with resistivity value > 10,000 ohm-m.

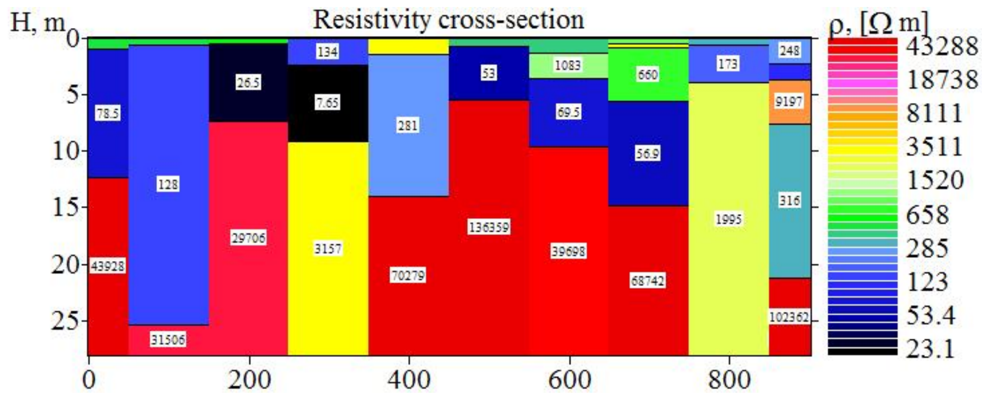


Fig. 9. Resistivity cross-section for VES F_1- F_{10}

3.7 The Isopach Map of the Overburden

Fig. 10 shows the depth–to-basement map. The map was produced by first summing the thickness of various layers underlying a particular VES points. This gives the depth-to the basement from the ground surface at that point. This depth determination was done for all the sounding points on the six profiles established. It varies between 5 m at F_{10}, which correspond to basement highs (F_{10} is 2m away from where the basement outcropped) to 65 m at A_3, A_{10} and D_{10}; the deepest points in the study area which corresponds to basement depression. Similar results of 4.3 – 64m depth were reported by [9].The overburden is deep in the north central, northwest and upper southeastern sections of the study area. The average depth-to-basement in these zones is about 40 m. The overburden in the Southeast of the study area is shallow with an average depth of 12m. The deepest sections of the study area (VES A_3, A_{10} and D_{10}) might be buried valleys or underground structural traps. Generally, areas with thick weathering and low percentage of clay are known to have high groundwater potential in the basement complex [11].

3.8 The Iso-resistivity Map of the Weathered Basement Layer

According to [12], the thick weathered basement layer (containing less percentage of clay) above the basement rock constitutes a water-bearing layer. Optimum aquifer potential is attained in the mid-range of saprolite resistivity (100 to 400 ohm-m) while resistivity values less than 80 ohm- m indicate clays [13]. Based on this, the weathered basement layer which either forms the second or third layer was considered as the aquifer units in the study area. The resistivity map of the weathered layer Fig. 11 shows the resistivity values, ranging from 50 to 700 ohm-m, while the most frequently occurring resistivity values are between 50 and 100 ohm-m. This revealed the highly heterogeneous variation in the composition of the weathered basement from clay, sandy clay, and clayey sand. According to [14], the electrical resistivity of this layer which forms the water bearing zone depends on the sand to clay ratio and degree of saturation. The zones with resistivity > 100 ohm-m is characteristics of clayey-sand and sand and it indicates good aquifer formation while the lower end (<100 ohm-m) typifies clay which lowers the aquifer potentials.

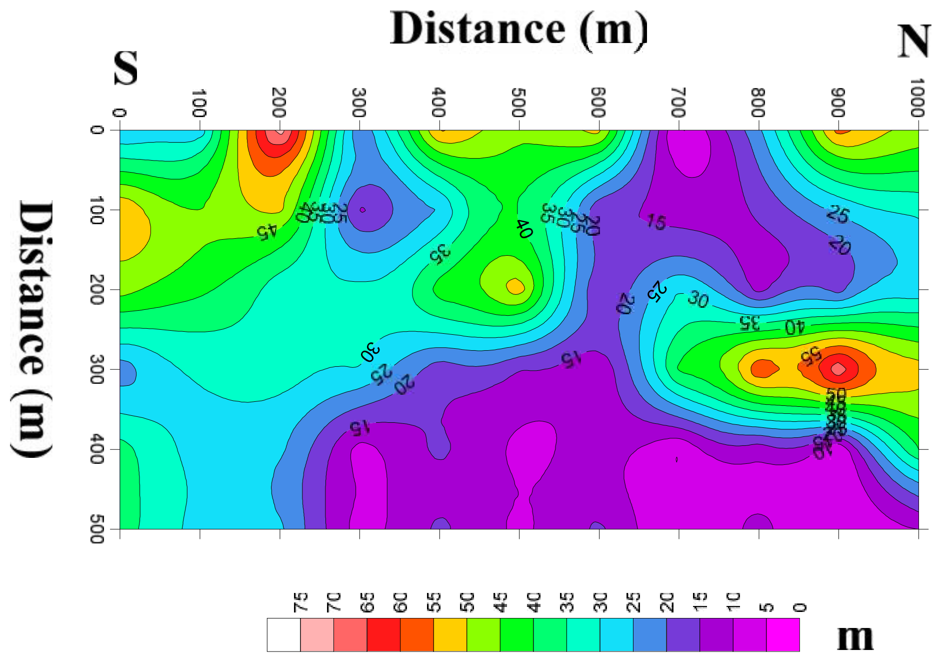


Fig 10. Isopach map of overburden

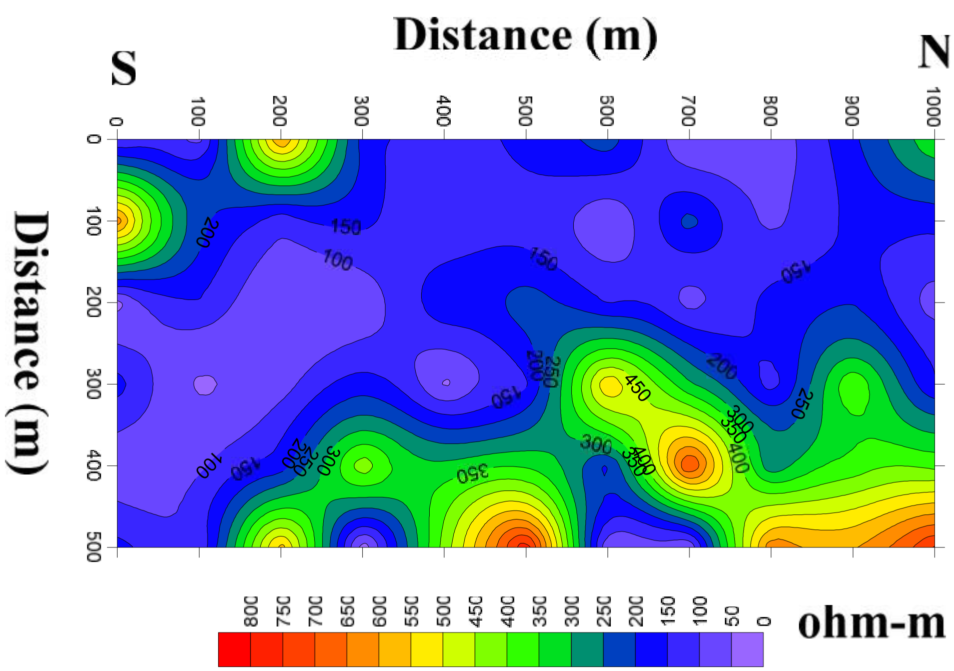


Fig. 11. Weathered basement map

3.9 Aquifer Protective Capacity Evaluation

The characteristic longitudinal unit conductance map (Fig. 12), prepared from equation 1, was used for the overburden protective capacity rating of the study area. The total longitudinal unit conductance values can be utilized in evaluating overburden protective capacity in an area. This is because the earth medium acts as a natural filter to percolating fluid. Its ability to retard and filter percolating ground surface polluting fluid is a measure of its protective capacity [15].The aquifer protective capacity characterization is based on the values of the longitudinal unit conductance of the overburden rock units in the area. The longitudinal unit conductance (S) values obtained from the study area, ranging from 0.005 to 0.65 mhos, were used to generate the longitudinal unit conductance map (Fig. 12). According to [16], Table 1, the protective capacity of the overburden could be zoned into good, moderate, weak, and poor protective capacity. Largely, the study area has revealed that the overburden materials in the area around the north central, southwest portions have moderate to good protective capacity. The longitudinal conductance in these areas ranged from 0.25 mhos to 0.65 mhos. Weak and poor protective capacity rating characterized the overburden materials above the saprolite (aquifer) in the eastern, east central and some portions in the southern parts of the study area. The longitudinal conductance in these zones is < 0.2 mhos.

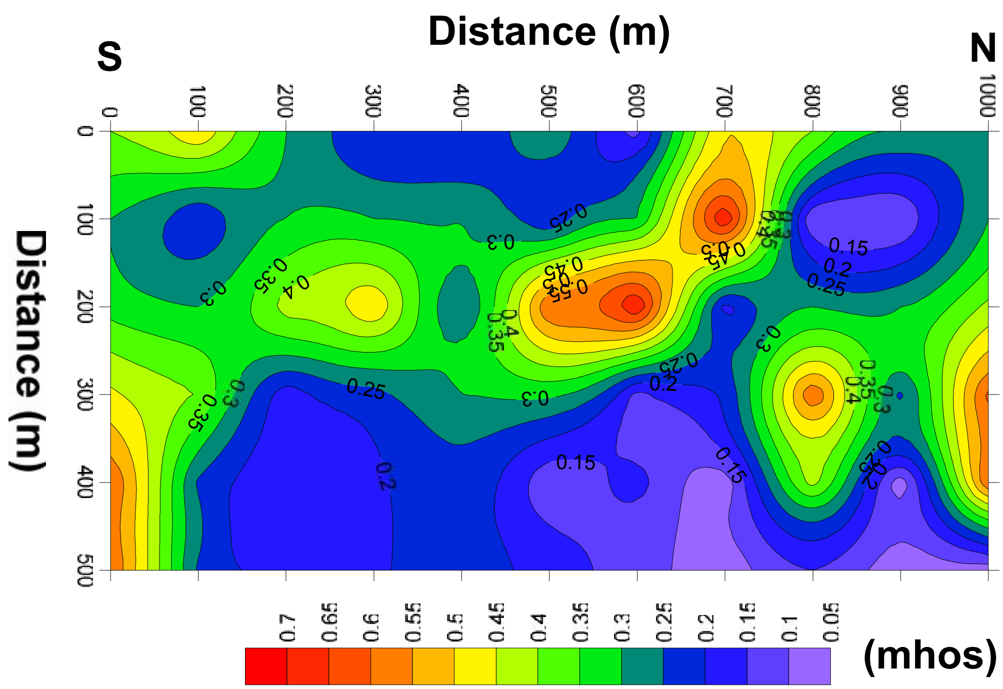


Fig. 12. Longitudinal conductance map

3.10 Transverse Resistance Map

The total transverse resistance (T) is one of the parameters used to define target areas of good groundwater potential. On a purely empirical basis, it can be admitted that the transmissivity of an aquifer is directly proportional to its transverse resistance i.e. the highest

T values reflect most likely the highest transmissivity values of the aquifers or aquiferous zones and vice versa [17,18].The transverse resistance map and hence, the transmissivity of this aquiferous zones vary from 2000 ohm-m^2 to 40,000 ohm - m^2 (Fig. 13). The high end (>18,000 ohm-m^2) correspond to zones where the thicknesses and resistivities of the aquifer are large. The high transmissivities suggest that the aquifer materials are highly permeable to fluid movement within the aquifer, which possibly may enhance the migration and circulation of contaminants in the groundwater aquifer system while low transmissivities which dominates the map is suggestive of high percentage of impervious clay, hence retarding fluid movement within the aquifer.

Table 1. Modified longitudinal conductance/ Protective rating (Oladipo & Akintoranwa, 2007)

Longitudinal conductance (mhos)	Protective capacity rating
>10	Excellent
5 - 10	Very Good
0.7 – 4.9	Good
0.2 -0.69	Moderate
0.1 – 0.19	Weak
<0.1	Poor

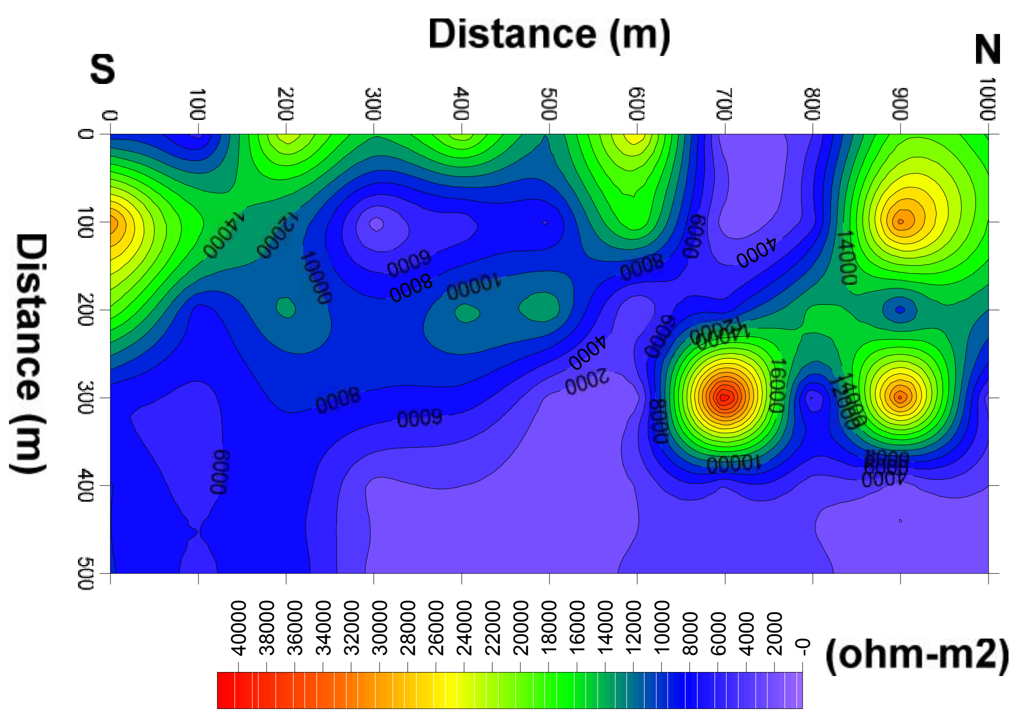


Fig. 13. Transverse resistance map

4. CONCLUSION

In this present work, we have presented the results from geo-electric sounding for groundwater evaluation and aquifer protection studies in the crystalline basement terrain around Sabo area in Kaduna state North western Nigeria. The results delineated three to five electrostatigraphic units in the study area, namely: the topsoil which consists of laterite, gravels and river sand, sand mixed with gravels or pebbles, weathered basement rock, fractured basement rock and fresh basement. The weathered and / fractured basement rocks constitute the aquifers or aquiferous zones in the area with the weathered basement as the most occurring. The geo-electric parameters determined from the VES data interpretation were employed to generate different hydro-resistivity maps such as depth-to-basement map, weathered resistivity map, total longitudinal conductance map and total transverse resistance map. Integrating all the geo-electric parameters determined, the results show that the lithology of the aquifer is dominated by clay/clayey sand and sandy materials with attendant low and high transmissivity. Generally, the study area has longitudinal conductance value greater than 0.3 mhos due to high content of clay/lateritic clay indicating moderate protective capacity rating, hence vulnerable to contamination.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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