Volume 15, Number 3, 2022. pp. 247-258

Jordan Journal of Physics

ARTICLE

Mapping and Delineation of Hard Rock Aquifers in Parts of the South-western Nigeria Basement Complex Using Integrated Geophysical Techniques

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Doi: **https://doi.org/10.47011/15.3.4**

Received on: 23/07/2020; *Accepted on: 24/02/2021*

Abstract: An integrated geophysical survey involving three different techniques; namely, VLF-EM, Seismic Refraction and Vertical Electrical Sounding (VES) has been carried out in parts of Eruwa, Ibarapa East LGA, Oyo State with a view of determining the structural characteristics of the subsurface geology and identifying suitable sites where viable borehole could be sited to reduce the problem associated with acute shortage of groundwater in the area. The area lies within the crystalline basement rock terrain of South-Western Nigeria and bounded by Latitude 7° 32' 59"N and Longitude 3° 25' 59"E. The VES results reveal that the area is made up of four major lithologic layers with the topmost layer being majorly laterites, the second layer being sandy clay, the third is weathered basement, while the fourth layer is fractured basement. The aquifer in the study area is mostly confined with curve responses of HA- and HKH-types. The 2-D pseudosection also showed that the fresh basement is very extensive laterally with undulating topography. The result of VLF-EM revealed high-amplitude anomalies. These anomalies are indicative of high conductive zones within the basement bedrock of the study area. The results of the seismic inversion reveals three lithologic layers; namely, the topmost layer / topsoil which is sandy (moderately loose) with an average velocity of 500 m/s, the middle layer can be sandy clay/laterite/caked clay with an average velocity of 1,149.33 m/s and the third layer can be said to be the beginning of the weathered/fresh basement with a velocity of 2,719 m/s. In conclusion, the three geophysical techniques have shown that the area is a hard-rock terrain with complicated geology with aquifers confined and the water bearing formation with low total longitudinal conductance.

Keywords: Basement terrain, Granitic masses, Aquifer, Topography, Curve types.

Introduction

Eruwa town, the administrative headquarter of Ibarapa East Local Government Area in Oyo State, Nigeria has average counts per head population of about 71,027 according to the 2006 National Population Census (NPC) exercise constituting about 60% of the population of the entire Local Government [1]. The high population density of the area is due to its new status of being the LG capital after the emergence of Osun State which was carved out from the old Oyo State in 1991. The area has therefore witnessed an influx of people from far and near due to the emergence of many industries, tertiary institutions and government agencies. Hence, the demand for a potable and consistent water supply by the people in the area

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for both domestic usage and industrial usage is becoming inherently high. Another alternative the people around have is borehole development which is perceived to be very expensive to dig and equip for the agrarian community. The second and more disturbing problem is associated with finance, where there is a problem of blind drilling (without pre-drilling survey), as many of the inhabitants are not aware of that it is always better to carry out a groundwater geophysical survey before drilling to narrow uncertainty, identify best spots for drilling, conserve available scarce resources (finance) and in the long run preserve the environment.

Location, Geology and Hydrogeology of the Study Area

The area of study, Eruwa, is located in South-western Nigeria and bounded with Latitude 7° 32' 59"N and Longitude 3° 25' 59"E (Fig. 1). It is characterized by a tropical wet savannah climate which serves as home to forest reserves on the West African tectonic plate. Eruwa is 72 km south-west of Ibadan and 60 km north of Abeokuta. It is bounded in the north by Iseyin, in the east by Ibadan and in the south by Ogun State. The geology of the area falls within the context of the South-western Nigeria Precambrian basement complex and is an extension of the Ilesha Schist belt. The main lithologies include amphibolites, migmatite gneisses, granites and pegmatites. Other important rock units are the schists, made up of biotite schist, quartzite schist, talc-tremolite schist and muscovite schists. The crystalline rocks have intruded into these schistose rocks. The Precambrian basement complex of South-western Nigeria underlies the area with local geology, essentially amphibolite, hornblende gneiss, granite gneisses and migmatite. [2] had earlier described the basement rocks in the area to be porphyritic granites and schist xenoliths with duplication of the Ilesha schist belt of South-western Nigeria and the rock samples in Ilesha were extended and used to generalize the underlying rocks of the South-western basement complex. The most remarkable geological feature in Eruwa is the chain of hills (both low-lying and outlying). Prominent amongst these hills are Adoko, Akolu, Andoro, Apanpa, Eetaka, Ilewu, Obaseeku, Ofere, Ogodo, Ojoko, Okele, Oluweri and Wee-wee-onigba-poro. The geo-diversity of the area and the whole Ibarapa sparks geological interest, particularly with the non-existence of adequate supply of potable water, which has made inhabitants seek for alternatives [1].

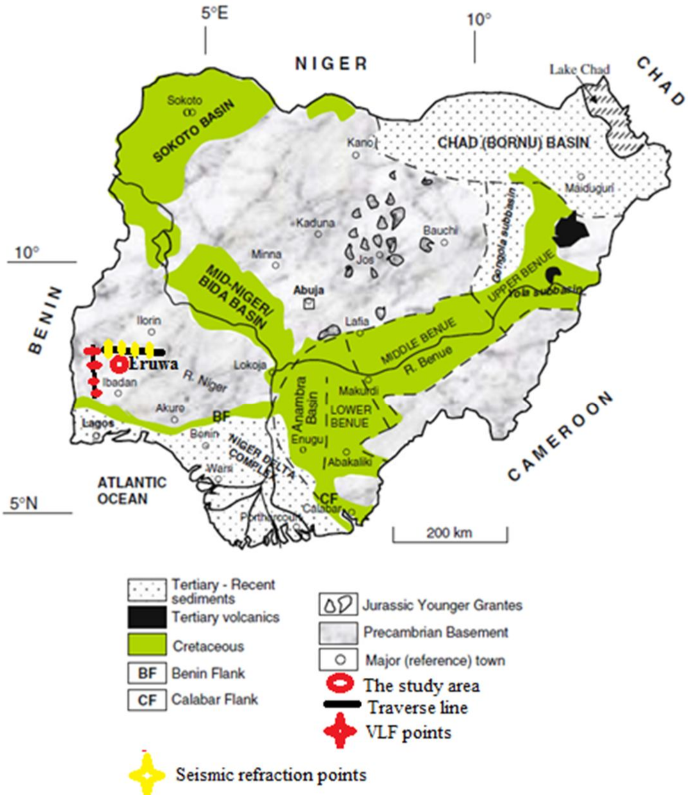

FIG. 1. Geological map of Nigeria showing the study area and some of the acquired data points.

Materials and Methods

The mapping involves three different geophysical techniques; namely, VLF, seismic refraction and vertical electrical sounding methods, which were conducted with the aim of identifying the suitable point where a viable borehole could be sited and determining the subsurface structural characteristics of the area. The total mapped area lies between Lat. 7.537299ºN / Long. 3.432098ºE and Lat. 7.548944ºN / Long. 3.458127ºE.

VLF-EM is an inductive exploration technique that utilizes radio signals in the range of 15 to 30 kilohertz (kHz). It has been used extensively in mapping shallow subsurface structures and detecting long, straight electrical conductors [3]. The instrument used compares the field componet of the transmitted signal to the secondary signal. When the subsurface conductor is not present in the coil, the transmitted signal is horizontal and linearly polarized [4]. When a conductor is crossed, the field becomes elliptically polarized and the major axis of the ellipse tilts with respect to the horizontal direction. Therefore, a total of 42 station positions (21 each on two different traverses) were occupied for VLF-EM using EM16 VLF receiver with a station spacing of 5 m. Although both the real and quadrature components of the VLF-EM were measured, the real component data, which is usually more diagnostic of linear features, was processed for qualitative interpretation. Seismic refraction data was acquired along a traverse with constant geophone spacing (2.5 m) with a 24-channel ABEM seismograph (MK8 Terraloc seismometer). The larger the geophone – to – geophone spacing and the offset employed, the larger the depth of investigation. As many layers as possible can be mapped.

The electrical resistivity technique measures both lateral and vertical variations in ground resistivity from different points on the earth's surface. The resistivity of the ground is measured by sending current into the ground at the current electrodes and the corresponding potential difference is measured at the potential electrodes, which is then converted into apparent resistivity value by multiplying with an appropriate geometrical factor. The Schlumberger array was used to collect VES data for eight (8) sounding points with a maximum electrode spacing of 100 m.

In addition, to have a clear understanding of parameters used to define the target areas of groundwater potential, the total longitudinal conductance (S) as developed by "Dar- Zarrouk Parameters" was used extensively by many authors, such as [7, 8]. These parameters were used to classify each VES point into poor, weak, moderate, good and excellent aquifers depending on the numerical value obtained to each VES point. Mathematically, the total longitudinal conductance (S) is given as:

$$S = \sum_{i=1}^{n} \frac{h_i}{\rho_i} = \frac{h_1}{\rho_1} + \frac{h_2}{\rho_2} + \frac{h_3}{\rho_3} + \ldots\ldots\ldots + \frac{h_n}{\rho_n} \quad (1)$$

where h_i is the saturated thickness of each layer and (ρ_t) is its true resistivity. The higher values of S are an indication of relatively thick succession and should be accorded the highest priority in terms of groundwater potential and *vice versa* [7]. Table 1 below shows longitudinal conductance ratings based on the values obtained from the field.

TABLE 1. Ratings of longitudinal conductance.

Range of S	Indication
S > 10	Excellent
5 < S < 10	Very good
0.7< S < 4.9	Good
0.2 < S < 0.69	Moderate
0.1 < S < 0.19	Weak
S < 0.1	Poor

Results and Discussion

The results of the three geophysical methods have been divided into sections as described below. For the VLF-EM profile plots, the two traverses surveyed within the area reveal plots of real and filtered value (Q-factor) against distance which is 100 m at maximum. The first traverse plot shown in Fig. 2a reveals real filtered anomaly of both negative and positive peaks with multiple positive peaks to be mostly predominant. These positive peaks coincide with the S-shaped anomaly of the un-filitered data. It can also be observed from the plot that these peaks are located at varying distances of 18 m, 35 m, 72 m and 88 m, respectively.

The second traverse plot shown in Fig. 2a also reveals both positive and negative anomalies, with positive peaks found in majority. These positive peak anomalies are found at varying distances raging from 28 m, 48 m and 78 m, while negative anomalies are found at distances 38 m, 58 m, 62 m and 88 m, respectively. These high positive peak anomalies are indicative of high conductive zones within the basement bedrock and the minor/low amplitude positive peak anomalies are also indicative of medium to low conductive zones within the basement and/or near-surface conductive zones [5]. These conductive zones represent structural features, such as joints, faults or fractures.

In addition to the profile plots shown in Fig. 2a and Fig. 3a, we also plotted pseudo-sections as shown in Fig. 2b and Fig. 3b. These 2D pseudo-section plots were carried out on Karous-Hjelt 2D model. The model shows regions of conductive and resistive features of varying degrees, where deep orange color is delinated as of conductivity zones trending in different directions, while other colors, such as green and yellow, are resistive zones.

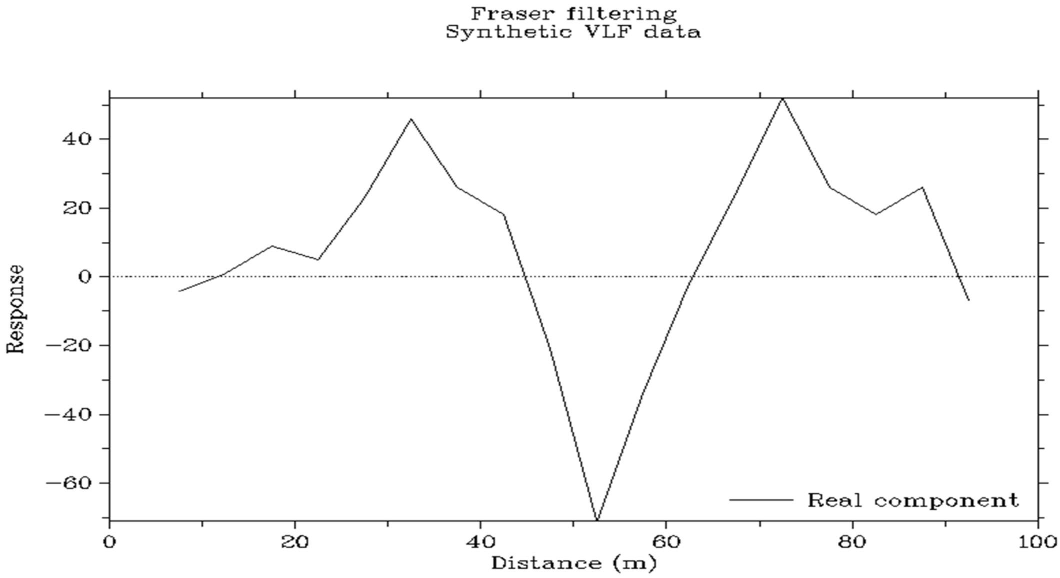

FIG. 2a. Frazer filter along traverse 1.

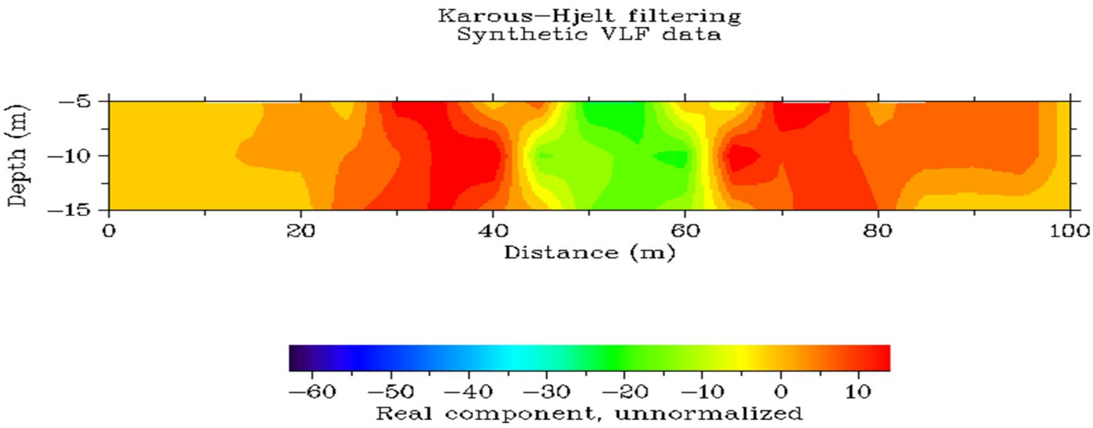

FIG. 2b. Karous – Hjelt current density plot for VLF – EM profile 1.

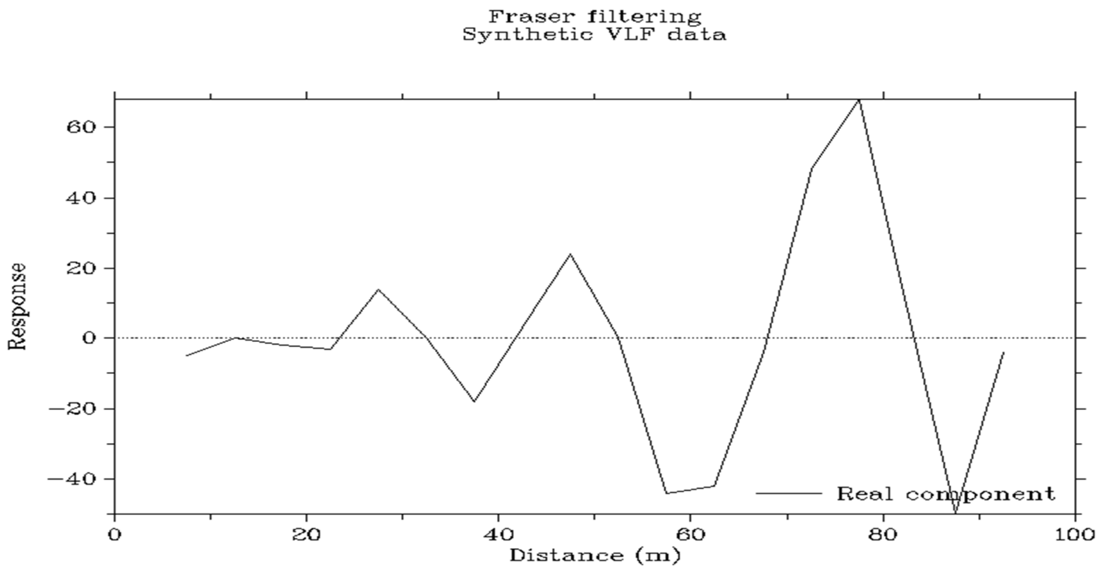

FIG. 3a. Frazer filter along traverse 2.

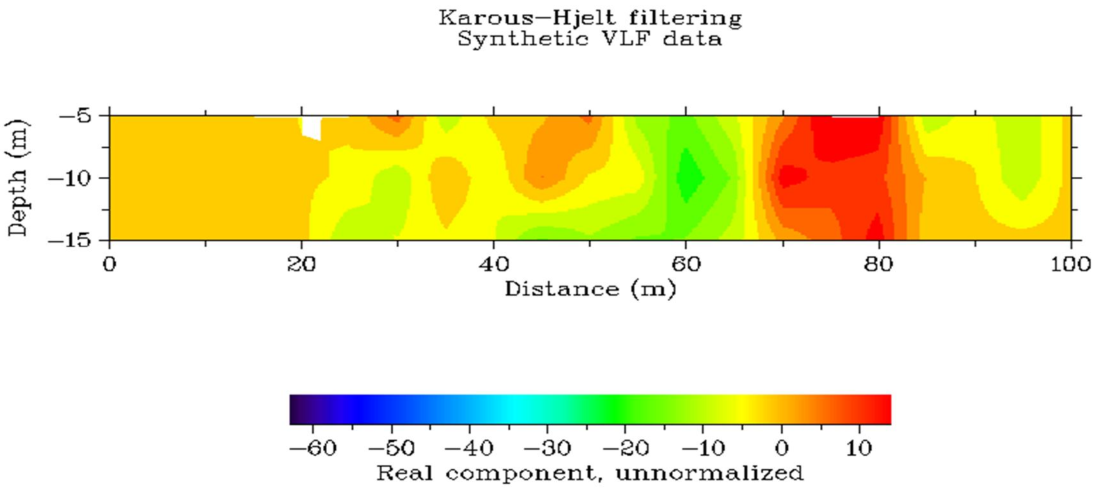

FIG. 3b. Karous – Hjelt current density plots for VLF – EM profile 2.

The results of the near-surface seismic models show six (6) (Fig. 4 (a - f)) profiles spread over two (2) traverses at two different points of the study area. Three (3) seismic layers were delineated, the topmost layer with an average velocity of $500ms^{-1}$, the middle layer with an average velocity of $1{,}149.33ms^{-1}$ and the deeper layer with an average velocity of $2{,}719.67ms^{-1}$. The maximum depth obtained is 19.0 m, which could be due to the offset used in the survey, which was 2.5 m.The seismic layer models have helped in the consolidation of the layers, being compacted with depth, since higher velocity indicates more compacted lithology. Also, areas of thin velocity layers are shown as in Figs. 4b, e and f. The implication of this for groundwater prospecting is that only one aqcuifer unit can be obtained. By lithology, it can be deduced from the plots that the topmost layer is sandy which is an indication of being moderately loose, the middle layer can be sandy clay/laterite/caked clay and the third layer can be said to be the beginning of the weathered/fresh basement. The maximum depth reached is also due to the energy source used, which is not strong enough to image deeper horizons [6].

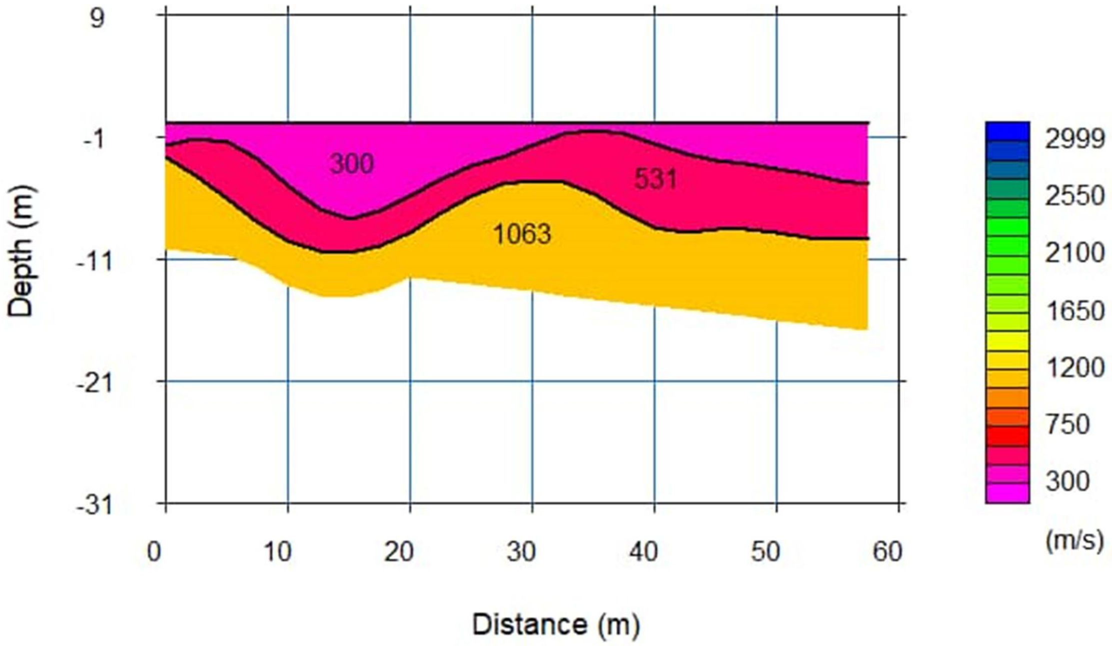

FIG. 4a. Delineated layered models from seismic inversion for profile 1.

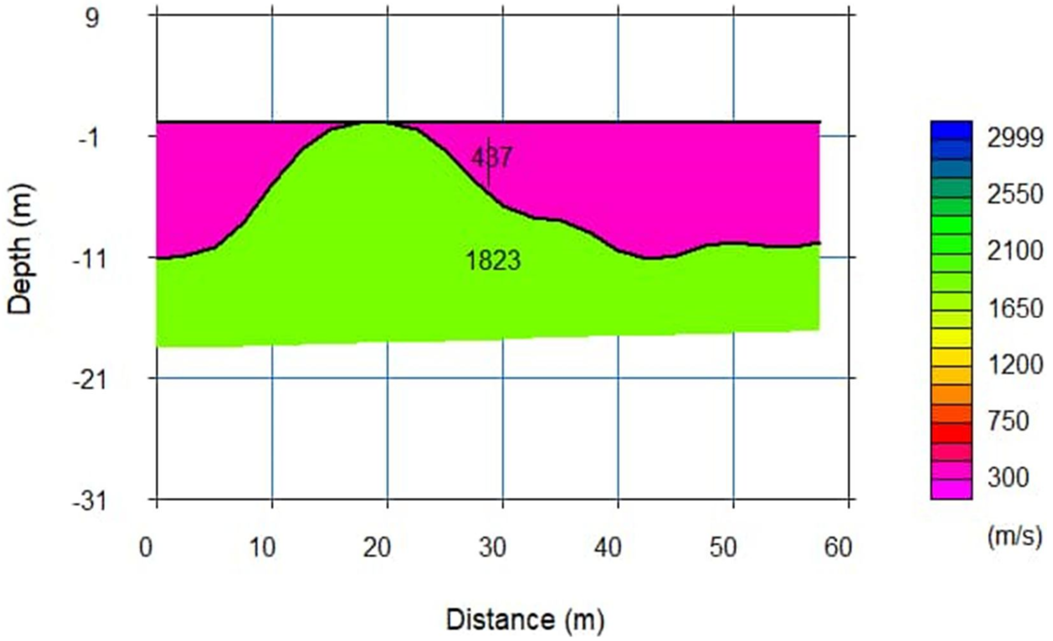

FIG. 4b. Delineated layered models from seismic inversion for profile 2.

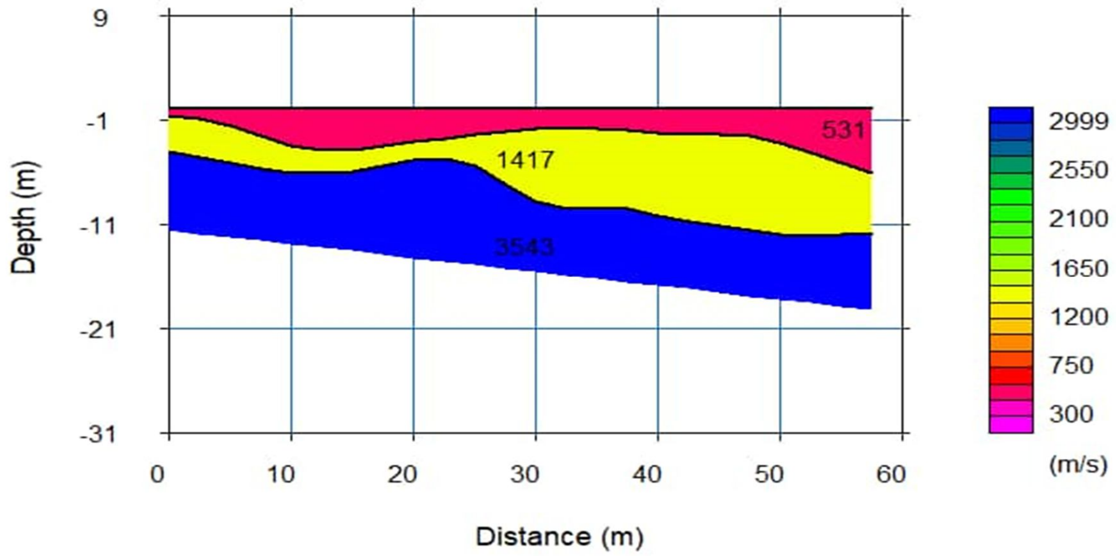

FIG. 4c. Delineated layered models from seismic inversion for profile 3.

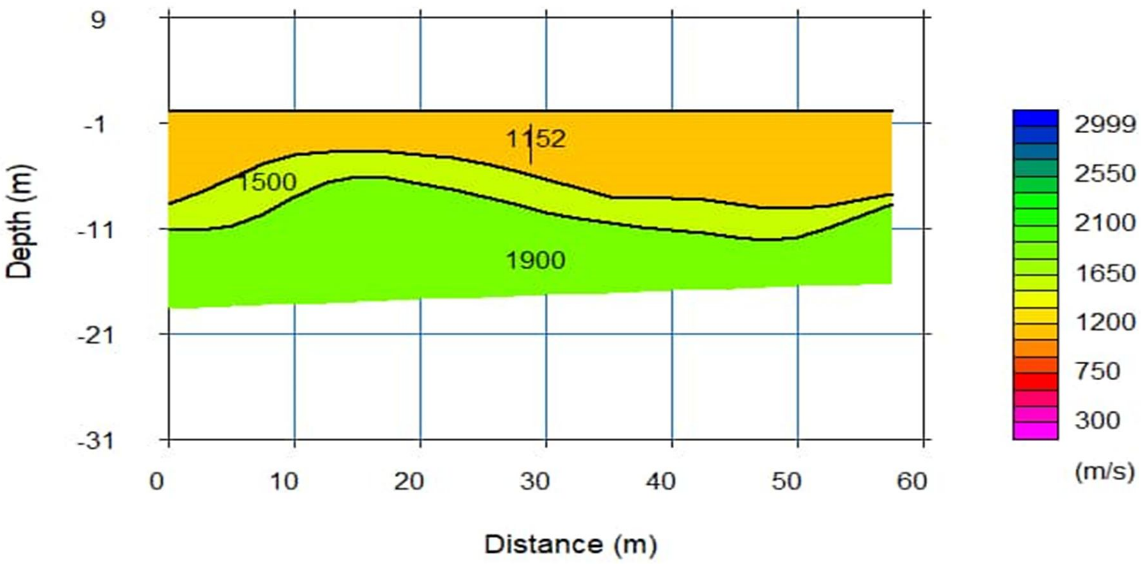

FIG. 4d. Delineated layered models from seismic inversion for profile 4.

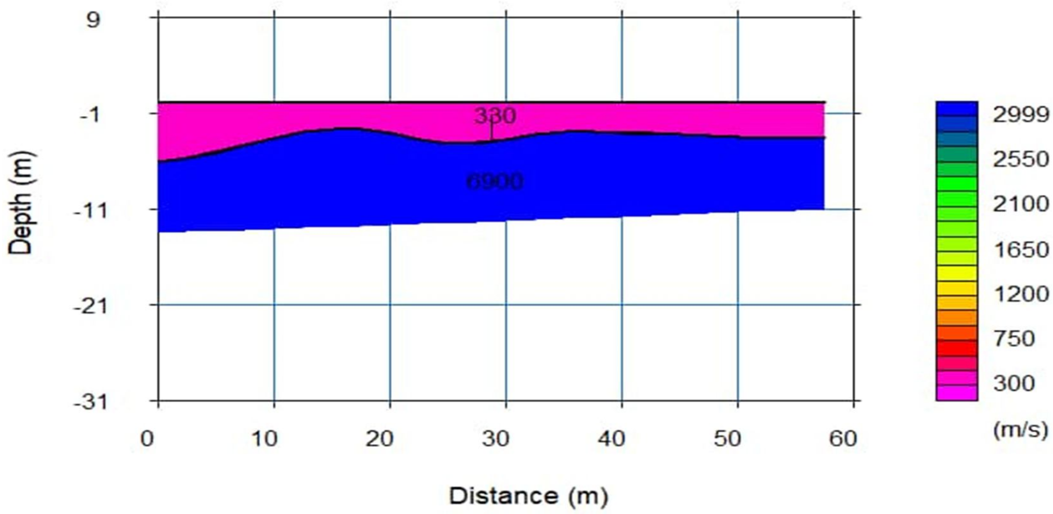

FIG. 4e. Delineated layered models from seismic inversion for profile 5.

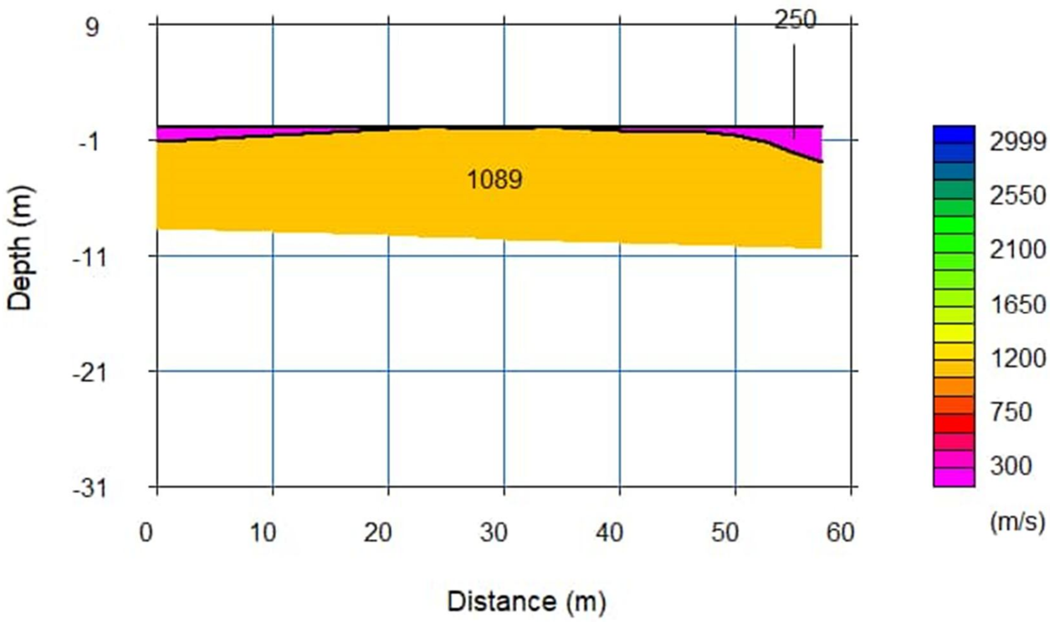

FIG. 4f. Delineated layered models from seismic inversion for profile 6.

The VES curves of the field data were obtained by plotting observed apparent resistivities against their corresponding half Schlumberger current electrode spacings plotted against each other on a scale (log-log scale) with the observed resistivity (ρ_o) on the y axis and the electrode spacing (AB/2) on the x axis using a computer software known as DC INVERSE. The results of the partial curve matching reveals the layers of the VES points, the apparent resistivity (ρ_a) of each layer, the thickness (h) of each layer and the total depth of overburden to the aquiferous zones. These parameters (layers of the VES points, the apparent resistivity (ρ_a) of each layer, the thickness (h) of each layer and the total depth of overburden to the aquiferous zones) were then iterated using IP2win software using minimized root mean square error to get the sounding curves, the true resistivity (ρ_t) of each layer, the real thickness of the saturated aquifer (h) and the true aquiferous depth to the overburden in the area. From this iteration, the study area has majorly HA- and HKH–curve types (Fig. 5a - f). Generally, for H-type geo-electric curves, the thickness of the middle layer is at least three times the thickness of the first layer ($h_2 > 3h_1$). H-type curves are characteristic of confined aquifers, where the topsoil is not so porous, but the middle layer is weathered or saturated with water, followed by a highly resistive layer acting as the third or final layer. A-type curve is typical for hard rock terrain, where thin topsoil is followed by harder formations. K-type curves show a trend of initial increasing resistivity, then after reaching a maximum peak, it descends. The combinations of the HA and HKH curves show that the area is complex and complicated, especially the HKH curve type which occurs in rare cases and represents multiple layers [7]. Also, to have a clear understanding of parameters used to define the target areas of groundwater potential, Eq. (1) was used to obtain the longitudinal conductance shown in Table 2. Table 2 shows the results obtained and it is observed that all the VES points are poor in terms of longitudinal conductance. This means that the area may not be good for groundwater prospectivity.

The 2-D resistivity pseudo-sections show a continuous extent of fresh basement underlying the study area. Traverse one (Fig. 6) shows that the basement at that point is either fractured or containing some mineralization or both. Traverse two shows that the fresh basement is highly resistive and this zone poses a serious threat (Fig 7). Above the fresh basement are layers of weathered basement and clay/ clayey sand / sandy clay overburden reaching a depth of around 6.0 m-10.0 m from the ground surface. The 2-D pseudo-sections show the lateral variation of resistivity with shallow depth, giving information about the lateral extent of subsurface geology. It also gives a new insight into the subsurface topography which is uniformly undulating on the first traverse and undefined on the second, as can be confirmed from the traverses.

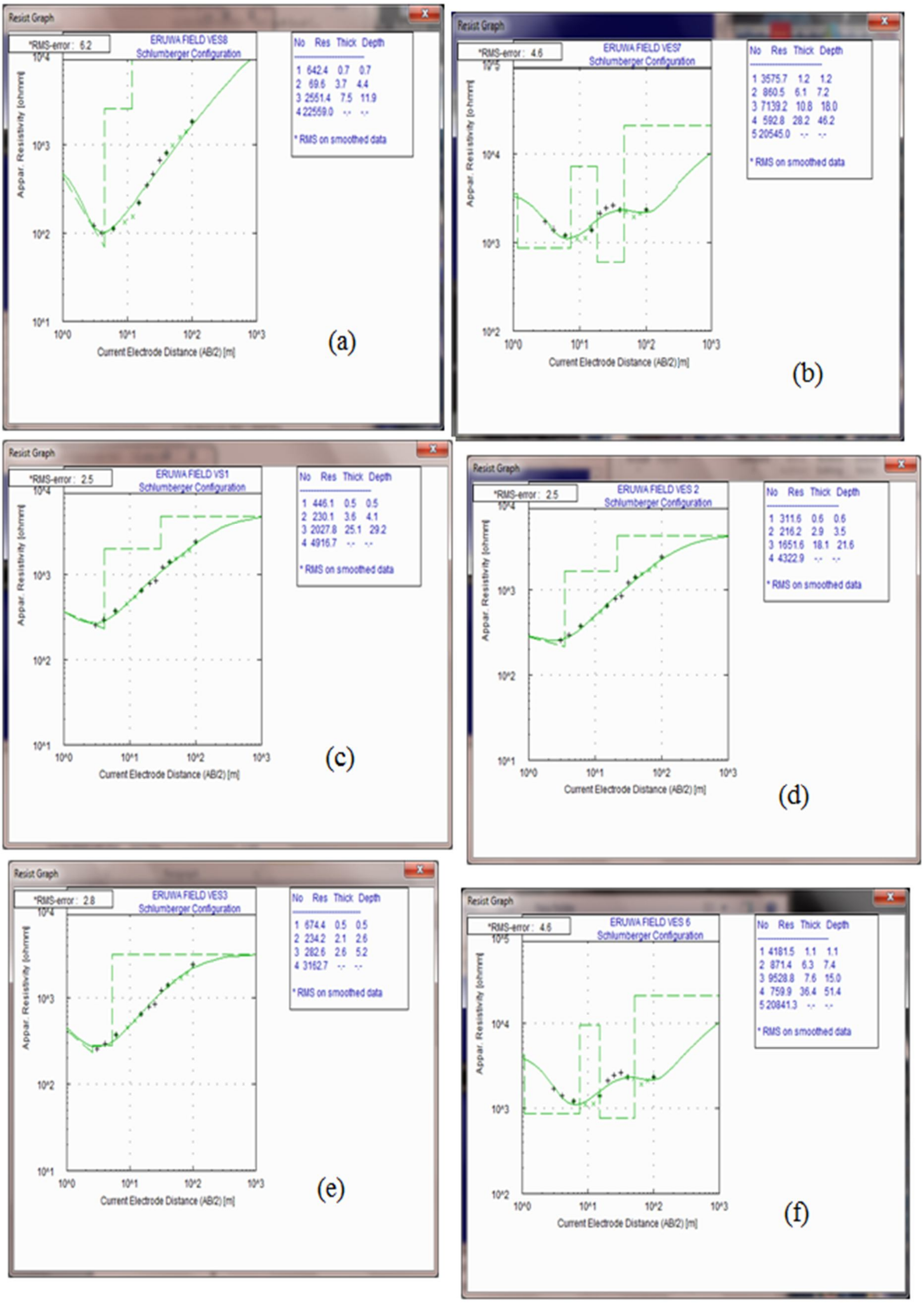

FIG. 5. Resistivity plots for each VES point.

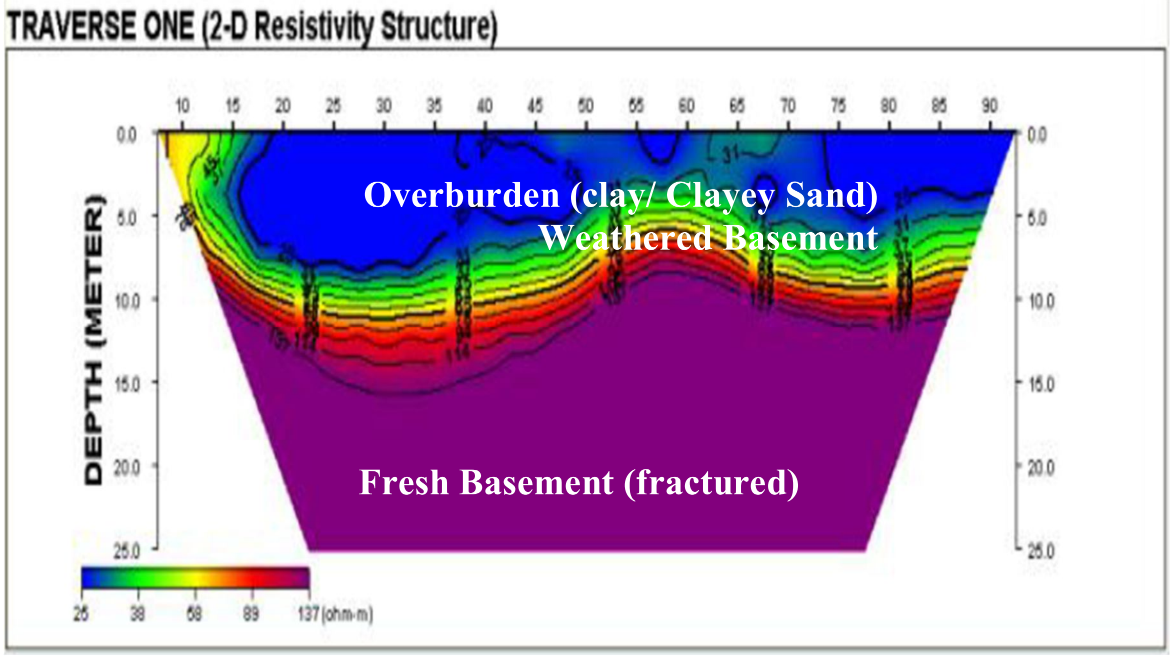

FIG. 6. 2D-pseudosection along traverse 1.

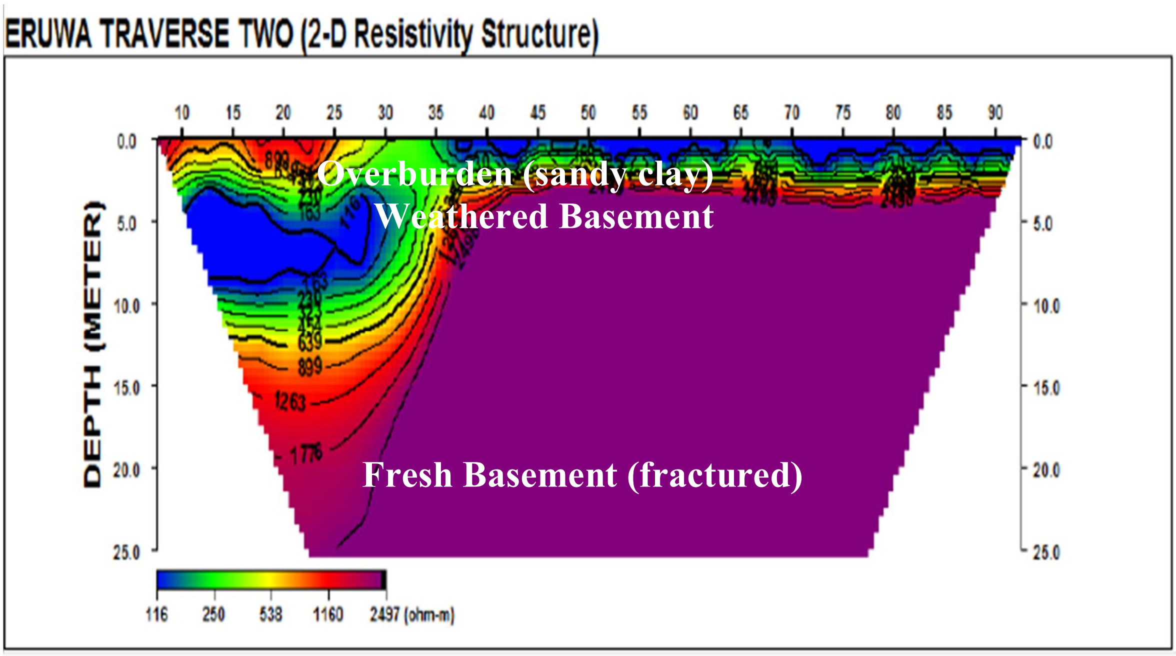

FIG. 7. 2D-pseudosection along traverse 2.

TABLE 2. Geoelectrical parameters, lithologic delineation and protective capacity of the study area.

VES	LAYERS	RESISTIVITY (Ωm)	THICKNESS (m)	LITHOLOGY	S	REMARK
VES 1	1	446.1	0.5	Sandy Topsoil	0.03	POOR
	2	230.1	3.6	Sandy Clay		
	3	2027.8	25.1	Weathered Basement		
	4	4916.7	∞	Fresh Basement		
VES 2	1	311.6	0.6	Sandy Topsoil	0.03	POOR
	2	216.2	2.9	Sandy Clay		
	3	1651.6	18.1	Weathered Basement		
	4	4322.9	∞	Fresh Basement		
VES 3	1	674.4	0.5	Sandy Topsoil	0.02	POOR
	2	234.2	2.1	Sandy Clay		
	3	282.6	2.6	Gravel		
	4	3182.7	∞	Fresh Basement		
VES 4	1	826.2	0.5	Sandy Topsoil	0.03	POOR
	2	221.8	3.4	Sandy Clay		
	3	1783.1	28.2	Weathered Basement		
	4	6939.5	∞	Fresh Basement		
VES 5	1	5666.1	0.9	Granitic Outcrop Extension	0.06	POOR
	2	922.0	6.7	Sandy Layer / Laterite		
	3	7522.7	9.5	Granitic Basement		
	4	870.0	45.1	Sand-Gravel Intercalation		
	5	58146.4	∞	Fresh Basement		
VES 6	1	4181.5	1.1	Granitic Outcrop Extension	0.06	POOR
	2	871.4	6.3	Sandy Layer / Laterite		
	3	9528.8	7.6	Granitic Basement		
	4	759.9	36.4	Sand-Gravel Intercalation		
	5	20841.3	∞	Fresh Basement		
VES 7	1	3575.7	1.2	Granitic Outcrop Extension	0.06	POOR
	2	860.5	6.1	Sandy Layer / Laterite		
	3	7139.2	10.8	Granitic Basement		
	4	592.8	28.2	Sand-Gravel Intercalation		
	5	20545.0	∞	Fresh Basement		
VES 8	1	642.4	0.7	Sandy Topsoil	0.06	POOR
	2	69.6	3.7	Clay		
	3	2551.4	7.5	Weathered Basement		
	4	22559.0	∞	Fresh Basement		

Discussion

All the three geophysical techniques carried out within the same grid have narrowed down the ambiguity and reduced the problem of alternative interpretation in the study area. The results of the study have shown that the area is truly a hard-rock terrain with complicated geology [9]. The Dar Zarrouk parameters and curve types analysis showed that most of the aquifers in the area sampled are confined with the water bearing formation having low total longitudinal conductance [7]. The overburden material on top of the weathered basement always has a clayey element, which further confirms poor aquifer rating, as shown in Table

2. It was also observed that the area has four lithologic layers. The depth to water table is shallow at relatively 20.0 m in average, while areas with five layers have depths at around 35.0 m. From the investigation, it can be observed that the positive peaks in the VLF are indicative of conductive zones in the subsurface, which are likely geological structures like faults and fractures and this is synonymous to what was obtained using VES technique. These points display basement depressions corroborated by the undulating nature of the subsurface geologies shown in the 2-D transverse section. The seismic models gave an insight into how compact the subsurface lithologies are (to a very shallow depth), while the VES interpretation has helped in delineating the subsurface lithologies by giving overburden thicknesses and depths to fresh basement. It is important to note that groundwater potential in the area is in a poor aquifer zone [10], but in the case of necessity where water must be drilled in the zone [9], it is pertinent to state that the water would be clean and not vulnerable to surface contaminants. In fact, [9] concluded with fear that the study area does not have enough groundwater potential that makes it worth to expend amounts of money for bore holes. This statement has corroborated our findings after using three geophysical techniques.

Conclusion

The combined result of the curve types' interpretation and Dar Zarrouk parameters (longitudinal conductance S) revealed that the mapped area has poor protective capacity due to the relatively thin succession of overlying geologies. The aquifers in the zone are largely confined and a high-power pump would be needed. However, in terms of vulnerability to contaminants or pollutants, the confined nature of the aquifer will make the water clean and protected against contamination. Therefore, groundwater, if found in the area, is most likely to be fresh water with little surface contaminants. It is therefore recommended that other areas in Eruwa town also be investigated using the same geophysical techniques. Also, Opeki Dam should be maintained to ensure regular and adequate supply of water to the entire people in the area.

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