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Geoelectric Assessment Of Groundwater Potentials In A Complex Basement Terrain Around Modomo Ile-Ife, Southwestern Nigeria

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Abstract
A geophysical investigation was conducted in the Modomo area of Ile-Ife, Osun State, to delineate the geoelectric properties of the Basement complex and assess its groundwater potential. The study employed the Very Low Frequency (VLF) electromagnetic method for initial reconnaissance and the Vertical Electrical Sounding (VES) technique for detailed analysis. The VLF method mapped potential geological structures, and its qualitative results informed the VES investigation. VLF-EM data were visualized as current density pseudo sections using Karous-Hjelt and Fraser filters. Electrical resistivity data from VES were interpreted using partial curve matching and 1-D computer iteration. The VES results, presented as geoelectric sections, showed the area comprises topsoil, a weathered/fractured layer, and fresh bedrock. Topsoil thickness ranged from 0.5 to 1.50 meters, with resistivity values between 154 and 1232 Ohm-m. The weathered/fractured layer's thickness ranged from 0.70 to 6.6 meters, with resistivity values between 76 and 500 Ohm-m. The fresh basement had resistivity values ranging from 459 to 3408 Ohm-m. The study also calculated the Dar-Zarrouk parameters—transverse unit resistance (T) and longitudinal unit conductance (S)—and derived the electrical anisotropy coefficients to create an anisotropy map. The combined VLF-EM and electrical resistivity methods effectively delineated the geoelectric characteristics of the Basement complex, identifying geological structures conducive to groundwater accumulation. It is recommended that boreholes be sited in high conductivity zones indicated by VES 2, 3, 5, 7, and 10, which are likely to contain aquifers. Boreholes should be drilled to depths of 20 to 25 meters to exploit basement fractures.

***Key Word**: Groundwater Potential, Dar-Zarrouk parameters, Electrical anisotropy, Borehole Drilling*

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I. Introduction

Geophysical investigations of the earth entail obtaining measurements at or near the surface of the earth that are impacted by its internal composition of physical attributes. Geophysical methods can be used to explore the subsurface geology of a given location. These methods are useful for groundwater research and development, as well as engineering and environmental site investigation. The selection of a certain geophysical method is based on the presence of a considerable contrast in the earth's properties being studied, such as resistance, elasticity, density, and magnetic susceptibility. Determining the thickness of the overburden, mapping the water table, identifying joints and fractures, and assessing the degree of connection between different geologic structures are all possible using geophysical methods. Groundwater is an extremely important supply source for a nation's socioeconomic development. It is crucial because it provides some populations with the water they need for industrial, agricultural, and home purposes. Rain naturally replenishes groundwater through percolating through the soil or via secondary pores in the subsurface rocks [1] Thus, climatic conditions, geology, the structural features found in subsurface rock, geomorphological features, land use type, and their interaction with hydrological features can all have an impact on the occurrence and distribution of groundwater in a given area [2,3,4]. Confirmed that groundwater provides 26% of the world's renewable freshwater resources. The conditions that led to groundwater's occurrence differ depending on the place. Numerous parameters have been used as indices in the research of groundwater resources. The observed lithologic unit in hard rock terrain consists of a fresh basement, a weathered/fractured unit, and a weathered layer [5]. The permeability and porosity of lithologies are contingent upon the nature of the geologic elements that comprise them [6]. A fractured basement will have greater pores and permeability than clay-based weathering layers. In the basement complex rock terrains, groundwater research is commonly conducted using very low frequency electromagnetic (VLF-EM) and vertical electrical sounding (VES) techniques [7]. In the basement complex terrains, groundwater exploration has also made considerable use of the electrical resistivity approach [8,9, 10,11,12,13]. In the hardrock terrain surrounding

Modomo area in Ile-Ife, southwest Nigeria, where water-saturated fractures are randomly distributed, the VLF electromagnetic (VLF-EM) method and the Electrical resistivity method (VES) were used to investigate for groundwater and offer solutions regarding the occurrence of acute water supply shortage (Fig 1). As a result, most boreholes and wells are either unproductive or occasionally have low yield. The resistance provided by subsurface layers can be used to locate good groundwater potential zones. The mineral content, texture, salinity, moisture content, fissures, and fractures of a geological formation are all important factors that affect how electrically resistive a formation is. The amount of secondary porosity found in worn zones, fractures, and joints has a bigger impact on how much rocks' resistivity values vary. The present research used vertical electrical sounding (VES) and VLF-EM to map the groundwater potential zones within the community. Geoelectric sections, when interpreted, show that the area is composed of fresh bedrock, a weathered/fractured layer, and topsoil. In order to identify and describe the groundwater potential zones in the region, the Dar-Zarrouk parameters were also computed from the results and their thematic maps were created. The results of this study will function as a roadmap for the community's future borehole development.

II. Location And Geology Of The Study Area

The research area is in the Modomo area of Ile-ife Osun State, southwestern Nigeria. The survey site is located at latitudes $7^{0}28$ N and $7^{0}30$ N, and longitudes $4^{0}30$ E and $4^{0}32$ E, respectively (Fig 1). The Study Area is accessible by a network of roads and well-developed walkways. The study area's topography is predominantly made up of lowlands, and its features (landforms and drainage pattern) are the result of the interaction of erosion, weathering, and geological processes. Furthermore, the research region (on a scale of 1:50,000) is mostly drained by the River Opa, which flows NE-SW, and certain streams thought to be its tributaries. These tributaries are streams, some of which are seasonal, and contribute to the area's dendritic drainage pattern (Fig 1). The study region is located in Nigeria's tropical rain forest and has two different seasons: the wet season, which lasts from April to October, and the dry season, which runs from November to March. The annual mean rainfall is around 1,000 - 1,250 mm [14], while the average annual temperature is around 27^{0}C [15]. Due to high rainfall, evaporation is normally at its lowest between June and September, encouraging penetration to the water table. Geologically, the research region (Fig 2) is located within Nigeria's crystalline basement complex, which includes early Proterozoic (2200 My) granite-gneiss, gneisses, and schists. The basement complex rocks in the research area are classified as mildly migmatised to non-migmatised meta-sedimentary and meta-igneous rocks, commonly known as Schist belts. The schists are made up of mica-garnet containing rocks that are inextricably linked to mafic to ultramafic rocks. Several writers have carefully investigated and characterized these rocks [16,17]. Granite gneiss is the dominant rock type that makes up the local geology in the area

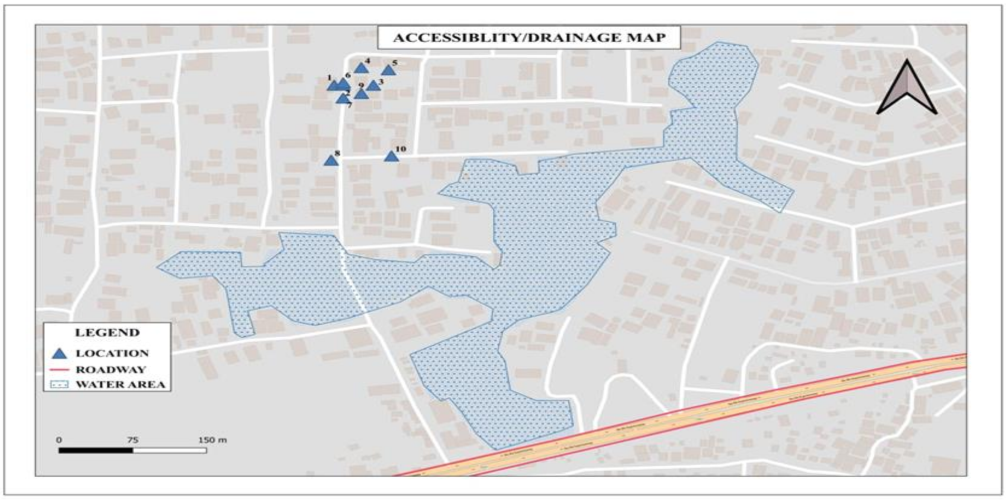


Figure 1: Location, Accessibility and Drainage map of the study Area

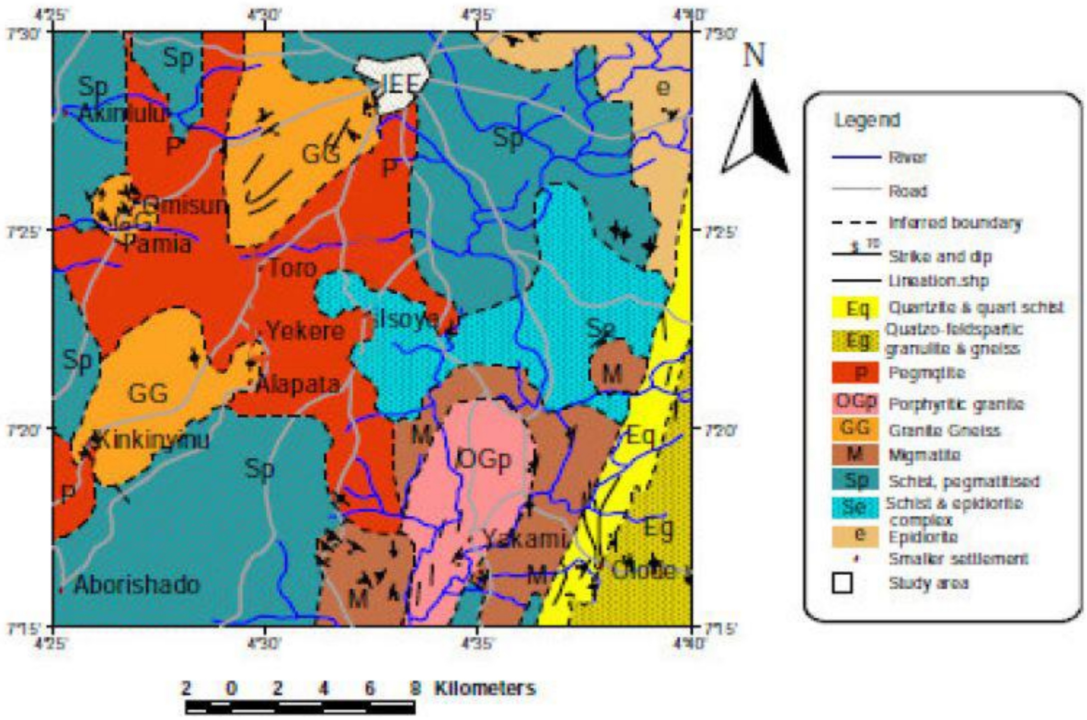


Figure 2: Geologic Map of the Study Area and its environs (After Geological Survey of Nigeria, Iwo sheet 60, 1966)

III. Materials And Methods

The Geonics EM 16 VLF equipment was utilized for these electromagnetic surveys, which measure both the real and imaginary components of the earth's field in % near electrically conducting objects (probably a rock fracture zone). The VLF-EM profiling took up a total of five traverses, with the traverses-oriented W-E and the base line-oriented N-S. The lengths of traverses one, four, and five are 110m apiece, while three and the baseline are 100 and 300m, respectively. Data were collected at 151 locations, each separated by 5m along the traverses. The VLF-EM profiling technique assessed the ratio of primary and secondary EM fields. The raw real component data of VLF-EM profiles were iterated using Karous-Hjelt filtering and computed Q-factor values. For this investigation, the ABEM SAS 300C terrameter was utilized to collect VES data on traverses one, two, four, and the baseline based on VLF-EM results, with half electrode spacing (AB/2) ranging from 1 to 100m. Ten (10) VES were spatially obtained across the investigated area, with an observed error of less than 2.0%. VES 4 and 5 are on traverse one, VES 1, 2, and 3 are on traverse two, VES 8, 9, and 10 are on traverse four, and VES 6 and 7 are on traverse 5. The VES data collected during this work were plotted on a log-log paper. The apparent resistivity values were plotted along the ordinate (y-axis), and the electrode spacing along the abscissa (x-axis). The resulting curves are referred to as depth sounding curves. The quantitative interpretation technique was used to determine the resistivities and thicknesses of the subsurface layers using partial curve matching techniques with master curves created for horizontally stacked earth models. The partial curve matching interpretation findings were then analyzed with the software WINRESIST. The EM data (vertical and horizontal coil resolutions) were displayed as conductivity profiles plotted against station intervals. The section displays field gradient graphs against station sites, along with their accompanying pseudo-sections. The EM profiles were qualitatively evaluated. The qualitative analysis allowed for the identification of vertical dipole inflection sites, which were deemed critical for vertical electrical sounding purposes.

IV. Results And Discussion

The findings of the EM and VES data interpretation are presented as geoelectric sections, profiles, and maps.

VLF-EM Results

The VLF electromagnetic profiling data are plotted as conductivity (mS/m) against station intervals (m). Figure 3 (a-e) shows typical EM profiles from the research area along traverses one through five. The EM anomalies vary greatly; some are acute, while others are broad [18]. Zones with peak positive vertical dipole anomalies are assumed to be conductive, which is typical of water-filled fissures [19] or the result of significant weathering [20]. The greater the peak, the deeper the rock fragmented [21]. When it comes to depth sounding, these zones are prioritized. The raw VLF data acquired by Traverse 1 is displayed in Figure 3a. The value of the Real(R) component vary from -25% to 15% while the value of the imaginary component(I) varies from -30% to 40%. The in-phase component is highly variable with two distinctive lows occurring at stations 20m and 40m respectively. The profile of the filtered real shows two positive peaks at 35m and 70m.These peaks suggest the possibility of a conductor in this area, and these points show up as zones of relatively high conductivity on the current density pseudo sections. Figure 3b shows the unfiltered VLF data obtained along traverse two. The value of the Real components varies from -25% to 11% while the value of the Imaginary components vary from -30% to 30%. The profile of the filtered data shows a minimum point at 58m.The profile of the filtered real also shows three positive peaks at 30m, 70m and 85m, which have been interpreted as conductors. These zones are also confirmed from the current density pseudo section. Figure 3c shows the unfiltered VLF data obtained along traverse three. The Real component vary from -25% to 5% and the Imaginary component vary from -35% to 20%. On this traverse the maximum positive value is at station 70m.The profile of the filtered Real shows two peaks at 20m and 50m, at these peaks there is possibility of a conductor. The unfiltered VLF data obtained along traverse four are shown in Figure 3d. The Real component vary from -22% to 11% and the Imaginary component vary from -30% to 35%. The profile of the filtered Real shows three positive peaks at 22m,52m and 78m respectively. These peaks correspond to zones of relatively high conductivity on the current density pseudo sections. Figure 3e shows the unfiltered VLF data obtained along traverse five. The Real component vary from -15% to 25% and the Imaginary component vary from -37% to 24%. The profile of the filtered data shows a minimum point at 250m and also shows three positive peaks at 50m,125m and 175m respectively. These peaks suggest the possibility of conductors along this traverse. At 250m the profile of the filtered Real is seen to be resistive as confirmed by the distinctive low at this station position which is confirmed by the current density pseudo section. Ten major linear features (suspected fracture zones) with positive filtered Real amplitudes were delineated using characteristic feature of coincident inflexions (for the real components) and cross-over points (for the real and imaginary components) with positive peaks on filtered real anomaly curves. These features suspected to be basement fractures are prominent along traverses one(35m,70m), traverse two(30m,70m,85m), traverse four(52m,78m) and traverse five(50m,125m,175m) respectively. The inversion of the VLF-EM Fraser filtered real component resulted in current-density pseudosections. High conductivity zones, which are possible zones of groundwater accumulation, are represented by bright (yellow-red) color relative to the colored scale on the current density pseudo sections. Closer observations of the current density pseudo sections for all the five traverses show continuity of these high conductivity zones in the N-S direction for all the traverses except for traverse five which trends in NE-SW direction. The VLF-EM results suggest that the rocks in the area are fractured. The subsurface model delineated along these traverses shows the conductive patterns from the surface to a maximum depth of 30 m, but it is seen to extend beyond, especially on the baseline. The Karous-Hjelt filter automatically removes the effect of overburden. It is best to prospect for groundwater in these high conductivity zones which correspond to the suspected fracture zones. The zones of high conductivity occur at distances varying between 30 – 100 m on traverses one to four. However, on traverse five, the high conductivity zones extend from 50 – 225 m.

Resistivity Sounding Results

A total of ten (10) vertical electrical sounding were acquired within the investigated area. Four representative sample of the curve types found within the study area are shown in (fig 4). The sounding curves obtained from this area ranges from 3 to 4 layers with H curve type dominating. Varied sounding curves were obtained from the study area. The curve types obtained from this investigation are typical of basement curves which are A (10%), H (80%), QH (10%), HA (10%) and KA (10%) The summary VES interpretation is given in table 1. [22] showed that field curves often mirror image geo-electrically the nature of the successive lithologic sequence in an area and hence can be used qualitatively to assess the groundwater prospect of an area. The H and HA curves which are often associated with groundwater possibilities [23] are pertinent to the study area. The interpretations of the VES curves were used to prepare geoelectric sections (fig 5).

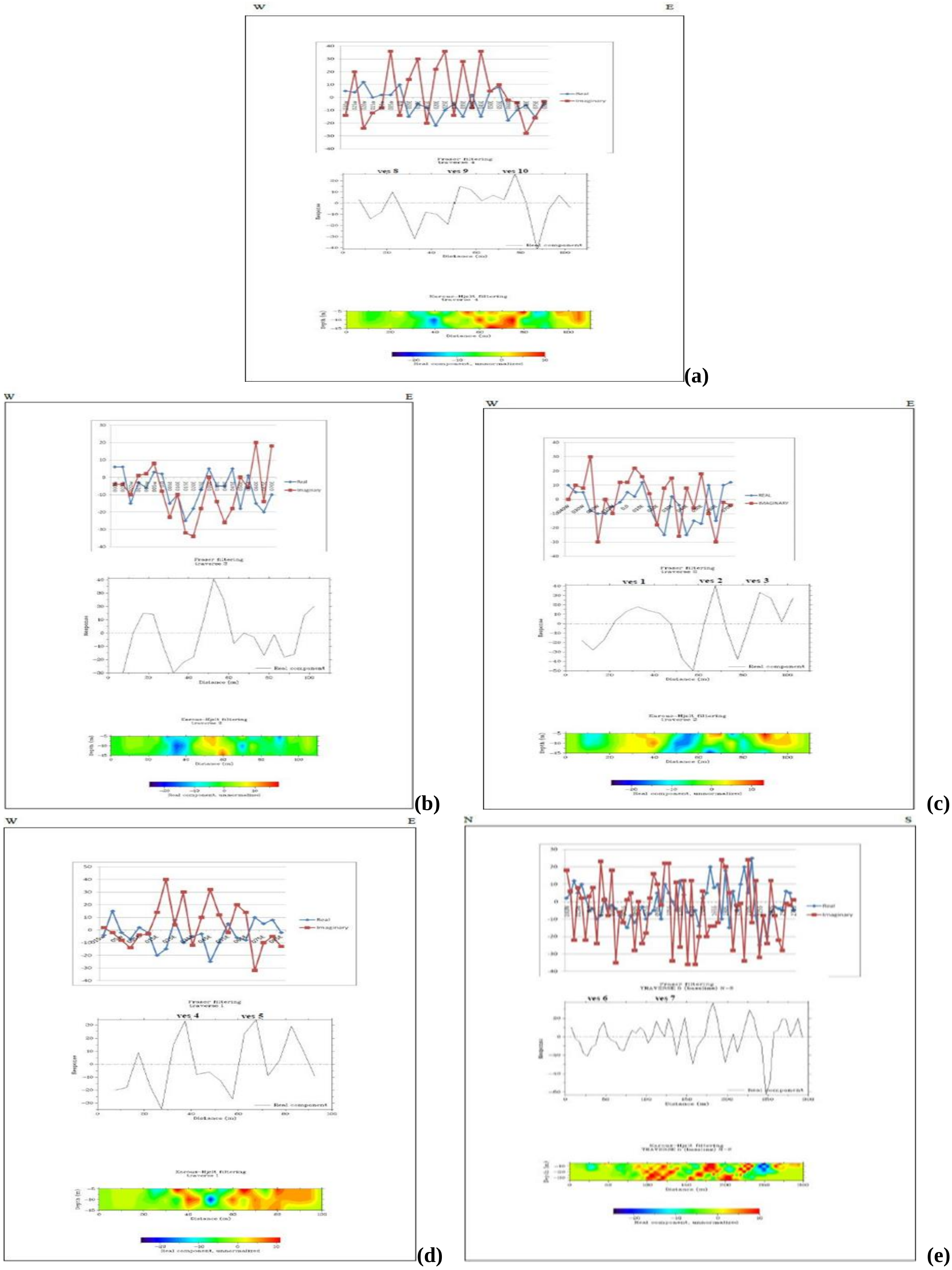


Figure 3: Filtered Real and Filtered Imaginary Profiles of Modomo (Traverse 1- 5)

The geo-electric parameters of the lithologic units were delineated from the interpreted sounding curves and shown on Table 1. The geoelectric sections show three subsurface geologic sequence which include the topsoil, the weathered/fractured layer and the fresh basement bedrock. The sections depict an area with an overburden thickness with range from 4.2 – 7.1 m.

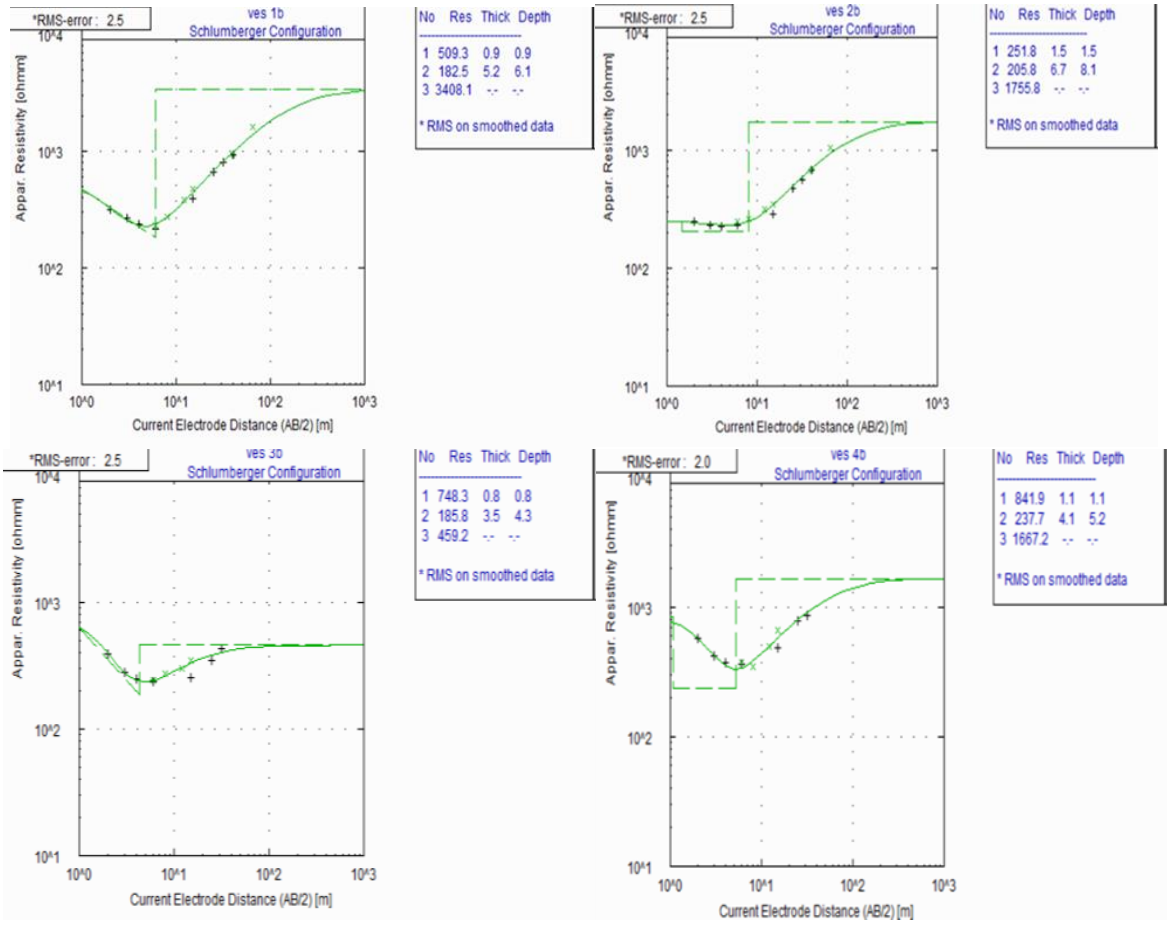


Figure 4: Typical Ves curves obtained in the study area

Table 1: Summary of Geo-electrical parameter of the VES curves

Ves Station No	Layer Resistivity (Ωm)				Layer Thickness (m)			Lithology	Curve type
	ρ_i	ρ_{ii}	ρ_{iii}	ρ_{iv}	hi	hii	hiii		
1	509	183	3408		0.9	5.2		Topsoil	
								Weathered layer	H
								Fresh bedrock	
2	251.8	205.8	1755.8		1.5	6.7		Topsoil	
								Weathered layer	H
								Fresh bedrock	
3	748.3	185.8	459.2		0.8	3.5		Topsoil	
								Weathered layer	H
								Fresh bedrock	
4	841.19	237.7	1667.2		1.1	4.1		Topsoil	
								Weathered layer	H
								Fresh bedrock	
5	539.8	76	498.3		1.2	3.5		Topsoil	
								Weathered layer	H
								Fresh bedrock	
6	1232.3	504.5	161.8	941.4	0.5	0.7	2.9	Topsoil	
								Weathered layer	
								Partly weathered/fractured layer	QH
								Fresh bedrock	
7	154.3	196.9	325.8	899.3	0.7	3.9	1.5	Topsoil	
								Weathered layer	
								Partly weathered/fractured layer	A
								Fresh bedrock	
8	966.9	196.9	1540.1		0.6	3.6		Topsoil	
								Weathered layer	H

								Fresh bedrock	
9	346.2	176.8	444.1	949.8	0.8	2	1.8	Topsoil	
								Weathered layer	
								Partly weathered/fractured layer	
								Fresh bedrock	HA
10	258.5	442.7	1209	726.9	1.1	1.8	2.9	Topsoil	
								Weathered layer	
								Partly weathered/fractured layer	KA
								Fresh bedrock	

Geoelectric sections

Electrical methods primarily reflect variations in ground resistivity. The electrical resistivity contrasts existing between lithological sequences [24,25] in the subsurface are often adequate to enable the delineation of geoelectric layers and identification of aquiferous or non-aquiferous layers [26]. Four geoelectric sections (Figures 5 a-d) were drawn for the survey area as a means of providing an insight into the subsurface sequence and the structural disposition. On the basis of the VES results three distinctive geoelectric layers were identified these include the topsoil, weathered/fractured layer and the highly resistive bedrock. Figure 5(a) shows a W-E geoelectric section (VES 1,6,2,3). The geoelectric section reveals three subsurface layers. The first layer constitutes the topsoil. It is composed of sandy clay/clayey sand with laterites in some places. Its resistivity value ranges from 509 - 1232 ohm-m. The layer thickness varies from 1.1 - 1.2m. Below this layer is a weathered layer which is composed of clay/sandy clay and has resistivity value that range from 183 to 206 ohm-m with thickness from 2.2 to 5.2m. This layer is underlain by the fresh basement with resistivity of 459 -3408 ohm-m. The depth to fresh rock varies between 4.1-8.1m. The recognizable structural features along this section are the bedrock ridge and depression beneath VES 6 and 2 respectively. Figure 5(b) shows the geoelectric section joining 4,6,7 and 8 trending in the W-E direction. Three geoelectric layers have been identified across this section. The first layer is the topsoil with resistivity values ranging from 154 to 1232 ohm-m and thickness from 0.8 to 1.5 m. It is composed of clayey sand/laterite. This layer is underlain by the weathered/fractured layer. It is characterized by layer resistivity values from 183 to 206 ohm-m with thickness between 2.9 to 6.6m. This is underlain by a fresh basement rock with resistivity values of 941 -2520 ohm-m and a depth to fresh rock of 4.1-7.1m. The geoelectric section of Figure 5(c) shows three subsurface layers. It covers VES 8, 9 and 10 and trends in the W-E direction. The first layer which is the topsoil is composed of clayey sand /laterite and has resistivity values between 250 - 800 ohm-m and thickness between 0.5 – 1.1 m. The layer is underlain by the weathered layer which is composed of sandy clay/ clayey sand and fractured basement for VES 10. Its resistivity values vary from 127 – 500 ohm-m. Its thickness ranges from 1.8 – 6.6 m. The layer is underlain by the fresh bedrock with resistivity values of 513-2520 ohm-m and a depth to fresh rock of 4.31-7.1m. The recognizable structural features along this section are the bedrock ridge and fracture beneath VES 9 and 10 respectively. Figure 5(d) presents the geoelectric section trending in the NE –SW direction. This section relates VES 5,2,7 and 8. The section reveals three subsurface layers. The first layer is basically topsoil with thickness and resistivity range between 0.5 - 1.0 m and 154 – 800 ohm-m respectively. It is characterized by clay and laterite. Below this layer is a weathered/fractured layer which is composed of clayey sand and fractured basement for VES 7 with thickness ranging from 2.3 - 7.1 m and resistivity values between 162 -326 ohm-m. The last layer is the fresh bedrock with resistivity values between 498-2520 ohm-m. The depth to fresh rock ranges between 4.2 -8.1m. The recognizable structural features along this section are the bedrock ridge and depression beneath VES 7 and respectively. Based on the geoelectric characteristic of the subsurface layers and the information obtained from the VES. Three major aquifer types were delineated in the study area which are: weathered layer, Weathered/fractured (unconfined) aquifer and Weathered/Fractured (confined) aquifer.

Determination of Electrical anisotropy coefficient

The Basement Complex rocks in southeastern Nigeria are anisotropic [27]. Electrical anisotropy is caused by inhomogeneities, which come from varying degrees and depths of weathering as well as brittle deformation such as fractured zones, faults, and joints in rocks. [28,29] demonstrated how to determine the anisotropy coefficient using geoelectric data (layer resistivity (ρ) and thickness (h).

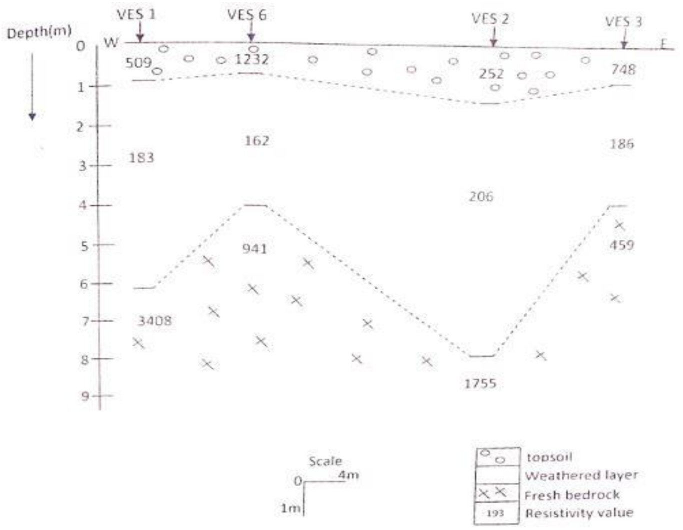


Figure 5(a):W-E Geoelectric Section VES 1, 6, 2 and 3

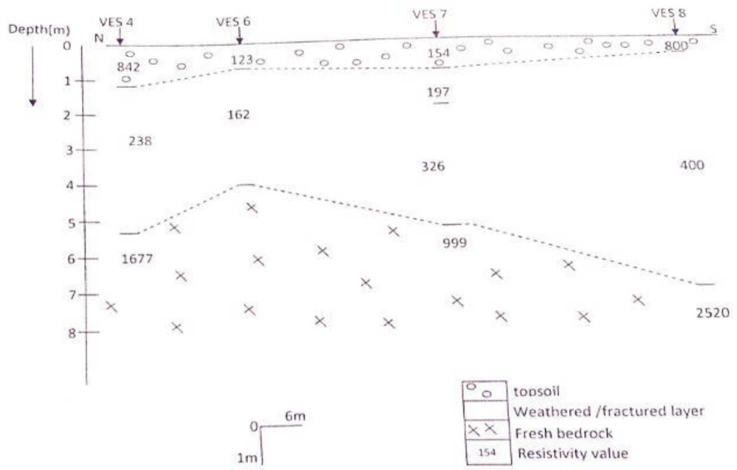
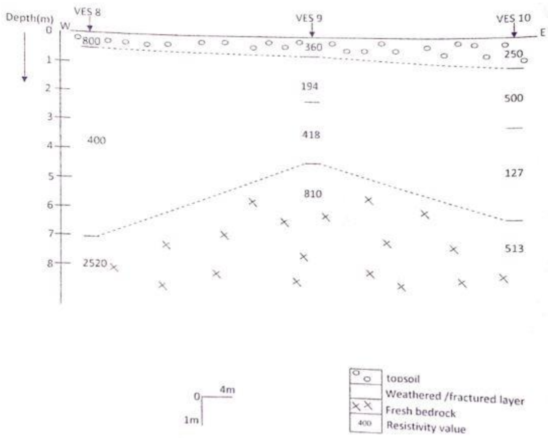


Figure 5(b): N-S Geoelectric Section for VES 4, 6, 7 and 8.



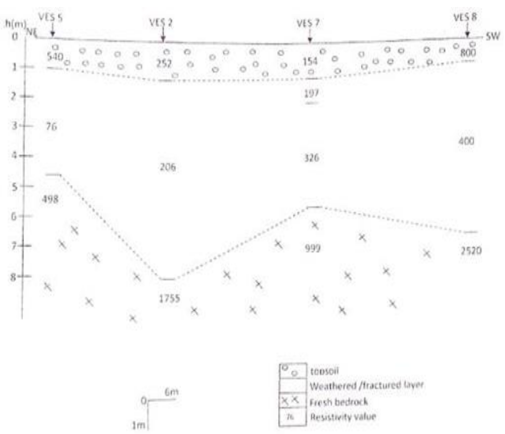


Figure 5(c): W-E Geoelectric Section for VES 8, 9 and 10.
Figure 5(d):NE-SW Geoelectric Section for VES 5, 2, 7 and 8.

$$\lambda = \sqrt{TS/H}$$

where λ = anisotropy coefficient,

T (Transverse resistance) $= \sum_i^n h\rho$

S (longitudinal conductance) $= \sum_i^n h/\rho$

H = summation of thicknesses

From this formula, the Dar Zarrouk parameters were generated and were used to generate an anisotropy map (Fig 6). For this work λ values were calculated from layer resistivities and thicknesses obtained from the quantitative interpretation of the VES data. Dar Zarrouk parameters are related to borehole yield as the highest transverse resistance (T) corresponds to zones with highest borehole yield [30]. Also, the higher the anisotropy coefficient, the higher the groundwater yield in the basement complex area of southwestern Nigeria [31]. The values of the Electrical anisotropy coefficient obtained were presented in Table 2 and were used to generate the anisotropy map. The values of the anisotropy coefficient obtained (0.65 to 1.40) show that the potential for groundwater occurrence in the study area ranges from low to medium level rating.

Table 2: Anisotropy coefficient values of the overburden.

Ves Stations	Anisotropy coefficient values
1	1.0357
2	1.01179
3	1.13304
4	1.0975
5	1.21129
6	1.3673
7	0.6516
8	1.01525
9	1.08725
10	1.2453

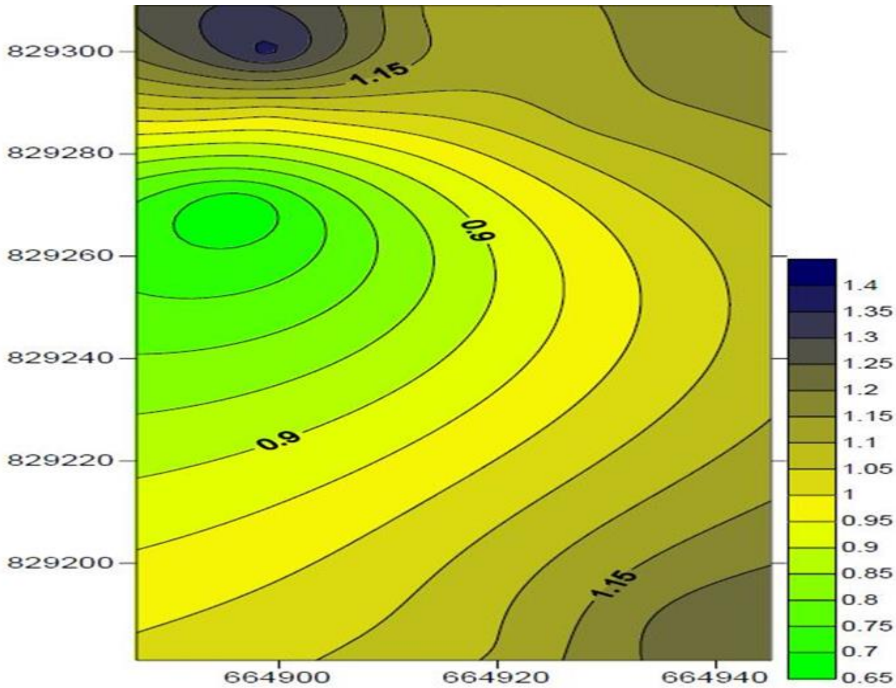


Figure 6: Anisotropy map obtained from the study area

V. Conclusions And Recommendations

Geological structures suspected of being basement fractures based on VLF-EM anomaly curves were validated by geoelectric subsurface pictures created from vertical electrical sounding interpretation findings. The VES interpretation results suggest that the survey region is made up of three geoelectric layers, which were identified as topsoil, weathered/fractured layer, and fresh bedrock. Topsoil resistivity values range from 154 to

1232 ohm/m, with thicknesses ranging from 0.5 to 1.5 m. The weathered/fractured layer ranges in thickness from 0.7 to 6.60 meters, with resistivity values ranging from 76 to 500 ohm-meter. The fresh bedrock is extremely resistant, with values ranging from 459 to 3408 ohm/m. The depth to bedrock ranges from 4.1 to 8.1 meters. The weathered layer is primarily clayey/sandy clay, which could be the result of pegmatite weathering, as evidenced by the area's geology. This indicates that the area has high porosity but poor permeability. The fractured layer is porous and permeable, making groundwater exploitation more possible in this aquifer unit. The anisotropy map indicates that the groundwater potential is low to medium. As a result, groundwater exploration requires drilling to the weathered layer in some areas and to the basement in others in order to tap the reserves within the fractured zones. Research has revealed that successfully sited boreholes that penetrate a fracture zone have long-term high productivity; thus, based on this project work, it is advised that boreholes be sited in high conductivity zones as shown by VES 2, 3, 5, 7, and 10, which form probable aquifers. VES 2 is recommended due to the substantial overburden. To take advantage of basement fractures, any borehole in this location should be 20 to 25 meters deep. To maximize yield from boreholes, the overburden must be adequately cased, screened, and gravel packed at appropriate parts, as well as hammering the cracked bedrock. Drilling rigs with down-the-hole hammering can be utilized to create the borehole. For a more extensive examination, test boreholes can be dug to further describe the aquifer and corroborate the results of the VLF-EM and VES surveys. Other geophysical approaches, such as seismic refraction and Dipole-dipole electrical resistivity surveys, can be utilized to supplement the methods used in this study.

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