INTEGRATION OF VERTICAL ELECTRICAL SOUNDING (VES) RESISTIVITY AND VERY LOW FREQUENCY ELECTROMAGNETIC (VLF-EM) METHODS IN GROUNDWATER EXPLORATION WITHIN AJAOKUTA AND ENVIRONS, NORTH CENTRAL, NIGERIA

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Abstract

The study involves integrating the geology, electrical resistivity, and electromagnetic methods i.e. Vertical Electrical Sounding (VES) and Very Low Frequency Electromagnetic (VLF-EM) respectively, in delineating groundwater potential zones. Geological field mapping carried out within the study area reveals the major rock types within the study area as fine to medium-grained granitic gneiss, porphyritic granite, and migmatite of the Precambrian Basement Complex of South-western Nigeria. The VES result showed that there are four to five geo-electric layers in the study area The layers with their respective range of resistivity and thickness values are the topsoil comprising of lateritic clay 6.3 - 320.8 Ωm and 0.5 - 11.0 m; weathered basement 1.5 - 2228.2 Ωm and 1.2-22.7 m; confining fairly weathered basement 41.0 - 3284.6 Ωm and 5.2 - 87.1 m; weathered/fractured basement aquifer; 63.1- 2145.1 Ωm and 5.3 - 69.5 m and fresh basement 406.8 - 31456.2 Ωm with undefined thickness. These results reveal two curve types, i.e. HA and HK, and further characterized the groundwater potential zones within the study area into three; good (western and southern part), moderate (north-eastern part), and poor (central part) groundwater prospect. Also, the VLF-EM results correlate with what was obtained from the VES data. This suggests that the groundwater potential zones consist of water-bearing strata in the overburdened materials and weathered basement, with targeted aquifer depths ranging from 40 - 90m, which are mainly located within the migmatite and porphyritic granite rocks in the study area.

Keyword: VES, VLF-EM, Integration, Groundwater Potentials, Ajaokuta, North Central

Introduction

Groundwater has been described as water that occurs in the vadose zones (Fitts, 2002) which filled the pore space of soil and fissure below the water table (Freeze and Cherry, 1979). It occurs in highly permeable geological formations known as aquifers which have properties that allow storage and movement of water (Eduvie, 2006) and can be extracted by drilling boreholes and hand-dug wells. Groundwater can be found both in sedimentary and basement terrain which forms the two broad geological terrains in Nigeria (Adeeko et al., 2019). Exploration of groundwater in sedimentary terrain can be of little or no complexity. However, Adeyeye et al. (2019) observed that in crystalline basement terrains, the occurrence of groundwater is complex and non-consistent.

Different geophysical and hydrogeological techniques which include electrical resistivity, seismic, magnetic, electromagnetic, ground probing radar, pumping test, and down-hole logging have been used to explore groundwater (Omamode et al., 2014; Oyedele and Olayinka, 2012, Bello et al., 2019; Azhar et al., 2019). According to Sundararajan et al (2007), in the absence of surface manifestations of structures favourable for groundwater occurrence, instead of depending on one particular geophysical method, an integrated geophysical strategy plays an indispensable role not only in mapping and understanding the nature of aquifers but also ensures a better success rate of exploration. Geoelectric parameter using the Schlumberger Vertical Electrical Sounding (VES) has been employed to evaluate groundwater accumulation potential in a Basement Complex terrain (Akor et al., 2017; Adeeko et al., 2019; Adagunodo et al., 2018). Like the electrical resistivity technique, the very low-frequency electromagnetic (VLF-EM) method is sensitive to groundwater (Sharma and Baranwal 2005) and conductive geological materials in the subsurface (Ohwoghere- Asuma et al. 2018). It has been described as the easiest to use of all known electromagnetic methods for subsurface exploration (Sharma and Baranwal 2005).

The main sources of water supply in the study area are surface water from River Niger and tributaries, rain and shallow wells which seem to be undependable and inadequate as most wells in the area dry up during the dry season and the river is far from the inhabitants, therefore, the potential supply of groundwater was recommended to be investigated (Samuel, 2014; Osadebe *et al.,* 2005). Within the study area, Samuel (2014), revealed that there are three major geoelectric layers, which are the topsoil, weathered or highly fractured layer, and crystalline basement. He further stated that from observed interpreted data structures such as fracturing, fissuring, joints, and weathered layers it is confirmed there is provision for secondary porosity which enhances groundwater potential as evident in it's extremely low basement resistivity values and thick overburden.

However, most of the previous studies done within the study area used only Vertical Electrical Sounding (VES) in groundwater prospecting. Therefore, this study involves integrating the geology, electrical resistivity, and electromagnetic methods (Vertical Electrical Sounding and Very Low Frequency Electromagnetic respectively), in delineating geological deep fissures that may allow accumulation of groundwater.

Location and Geologic Setting of the Study Area

The study area is within parts of sheet 247 Lokoja SW, Ajaokuta, and environs, located in Ajaokuta Local Government of Kogi State. It is about 42km south of Lokoja, Kogi state capital. It is between latitude 7° 32' 00'' to 7° 37' 07'' and Longitude 6° 35' 58'' to 6° 41' 57''. There is a major express road from the southwest, passing through Ajaokuta to Okene and linking the eastern part of the country. Another major road is the one that leads to Lokoja, which is a link to the northern part of the country.

The study area is part of the Southwestern Precambrian Basement complex of Nigeria (Jones and Hockey 1964, Kogbe, 1975, Rahaman, 1975) comprising migmatite, granite gneiss, and porphyritic granite (Figure 1). According to Dada (2006) and Obaje (2009), the basement rocks are believed to be the results of at least four major orogenic cycles of deformation, metamorphism, and remobilization corresponding to the Liberian (2,700 Ma), the Eburnean (2,000 Ma), the Kibaran (1,100 Ma), and the Pan-African cycles (600 Ma). The first three cycles were characterized by intense deformation and isoclinal folding accompanied by regional metamorphism, which was further followed by extensive migmatization. The Pan-African deformation was accompanied by regional metamorphism, migmatization, and extensive granitization and gneissification which produced syntectonic granites and homogeneous gneisses. Late tectonic emplacement of granites and granodiorites and associated contact metamorphism accompanied the end stages of this last deformation. The end of the orogeny was marked by faulting and fracturing. The rocks of the basement complex comprise migmatitic gneiss and granite gneiss, slightly migmatized to unmigmatized para schist and meta-igneous rock (Ajayi and Hassaan, 1990). Turner (1983) studied rocks of Western Nigeria and divided the rocks into three groups of which the Igarra-Kabba-Lokoja belt was prominent.

The rocks were intruded by the Mesozoic calc-alkaline ring complexes (Younger Granites) of the Jos Plateau and are unconformably overlain by Cretaceous and younger sediments (Obiora, 2005). Obaje (2009) was of the view that the Precambrian basement complex rocks are mostly gneiss and migmatite with older granite intrusives. He also noted mineral foliations defined by alternating biotite-rich and quartz feldspar rich which are common in the gneiss. Major foliation and fracture trends are in the N-S and NNE, SSW directions which correspond to the flow direction of the River Niger. Odigi (2000) indicated that the migmatitic-gneisses in the Okene-Lokoja area are meta-igneous rocks that show mildly alkaline characteristics and are calc-alkaline in nature suggesting they were derived from an ensialic calc-alkaline magma. Major rock types that occur within the study area are migmatites, augen gneiss, and biotite gneiss, there are minor occurrences of rock types like pegmatites and quartzo-feldspathic veins. Migmatites are the widest-spread rock type in the area and form the country rock in which all other rocks intruded (Imasuen *et al.*, 2013). Field geologic and petrographic studies of the marble and the associated rocks in Itobe and its environs by Onimisi and Daniel (2014) showed that the observed structures in the rocks include foliation, minor folds, joints, and fractures.

Materials and Methods

Vertical Electrical Sounding (VES) Data Collection

Vertical Electrical Sounding (VES) using the Schlumberger array was carried out at twenty six (26) VES locations across the mapped area. The instrument used for the survey is a DDR3 Geo-sensor terrameter, a modern instrument which automatically displays the resistance readings at every VES point on the digital read-out screen. The displayed readings were jotted down in a hand book used for taking field notes and recording readings during the survey. Global Positioning System (GPS) was used to obtain the coordinate of each sounding point within the study area. Four electrodes were arranged based on Schlumberger electrode configuration and pegged to the ground using a hammer. The readings were recorded based on the prepared data sheet and the maximum current electrode spacing (AB/2) was 200m and that of potential electrode spacing (MN/2) was 15m. The observed field data were converted to apparent resistivity values using Equation 1 below. The apparent resistivity and current electrode spacing were used for plotting the curves and the partial curve matching follows. WINRESIST computer software was used to plot the graphs and delineate different layers with their respective resistivity, depth, and thickness.

$$\rho_a = \pi \left[\frac{\left(\frac{AB}{2}\right)^2 - \left(\frac{MN}{2}\right)^2}{\left(\frac{MN}{2}\right)} \right] R \qquad (1)$$

Where; ρ_a is Apparent resistivity, R is the resistance, AB/2 is current electrode spacing, and MN/2 is potential electrode spacing.

Very Low Frequency Electromagnetic (VLF-EM) Method

PQWT-TC300 meter high-accuracy water survey equipment was used to carry out twelve (12) geophysical surveys in selected VES locations. The two electrodes or probes were connected to the terminal which was further connected to the device. The two electrodes were pegged at ten meters (10 m) intervals along a straight profile line. The device was switched on and readings were taken by continually changing the electrode position at one meter (1 m) and still maintaining the 10 m interval or spacing. After the desired data was taken along the profile line, the data was processed immediately to obtain a profile in form of a graph. The profile was then stored in the device with a reference number to access it later. This procedure was used in all the locations. The profile was interpreted based on the ranges of different colours, the colours are blue, light blue, green, yellow, orange, and red indicating higher groundwater potential zones, moderate groundwater potential zones, low groundwater potential zones, very low groundwater potential zones and absence or poor groundwater potential zones respectively. The horizontal axis represents the profile line while the vertical axis represents the depth, both in meters.

Result and Discussion

The VES results shown in Table 1 reveals that there are four (4) to five (5) geo-electric layers within the study area (Figure 2). The layers are the topsoil with lateritic clay, weathered basement, confining/fairly weathered basement, weathered/fractured basement aquifer, and fresh basement. Two curve types were observed, and they are HA (for VES 1, 2, 3, 4, 5, 7, 8, 9, 11, 14, 15, 17, 18, 19, 20, 22, 23, 24, 25, and 26) and HK (for VES 6, 10, 13, 16, and 21), these are the possible types of four-layer model and characteristics of basement curve types as described by Sunmonu et al. (2015) and Adagunodo et al. (2018). The resistivity and thickness of the top soil with lateritic clay layer range from 6.3 - 320.8 Ωm and 0.5 - 11.0 m, that of the weathered basement layer has resistivity and thickness ranges from 1.5 - 2228.2 Ωm and 1.2 - 22.7 m, confining/fairly weathered basement has resistivity and thickness ranges from 41.0 - 3284.6 Ωm and 5.2 - 87.1 m, weathered/fractured basement aquifer has resistivity and thickness range from 63.1 - 2145.1 Ωm and 5.3 - 69.5 m. The fresh basement has resistivity ranges from 406.8 - 31456.2 Ωm having infinite thickness. However, Samuel (2014) delineated three (3) geo-electric layers with shallow aquifer depth within the area.

The aquifer resistivity ranges from 49.5 - 3284.6 Ωm with a mean value of 745.8 Ωm (Table 2). The groundwater potential of the study area was classified using the classification of resistivity range for lithological characterization and groundwater prospect of bedrock by David (1988) and Akanbi (2017) (table 3). Sixteen (16) of the VES points (VES 1, 2, 5, 6, 9, 10, 13, 15, 16, 18, 19, 20, 21, 22, 23, and 25) has good groundwater prospect, five (5) of the VES points (VES 3, 4, 7, 8, and 17) has moderate groundwater prospect and the remaining five (5) VES points (VES 11, 12, 14, 24, and 26) has poor groundwater prospect. From the aquifer resistivity map (Figure 3), it can be observed that the western and southern part has good groundwater potential as this area is dominated by migmatite and porphyritic granite, while the central part has poor groundwater potential due to the presence of granite gneiss and fairly weathered migmatite in the area. High, moderate, and low aquifer potential has been visualized within the basement complex of Nigeria Adagunodo et al., 2018; Fajana, 2020). Also, the resistivity values distinguish the aquifers into fractured aquifers and weathered basement aquifers with most of the area made up of fractured aquifers of which fractured bedrock has been the most promising factor for groundwater exploration in crystalline terrain (Obiabunmo et al., 2014). Since 80% of the VES points have good to moderate groundwater potential, the study area can be characterized by boreholes sustainable for domestic and industrial uses.

The aquifer thickness ranges from 5.2 - 69.5 m with an average value of 21.3 m, indicating that the thickness is suitable for drilling a borehole except for VES 3, 8, 11, 12, and 26 which do not have appreciable thickness. The mean value is suitable for groundwater development within the study area. The aquifer thickness map (Figure 4) correspond to what was observed in the resistivity map as areas with the higher thickness are concentrated in the western and south-western part of the study area.

The aquifer depth ranges from 8.9 - 125.7 m, with an average value of 55.3 m. The aquifer depth is widely distributed not minding the groundwater potential of the study area, the shallow aquifer depth is found within a small portion of the central and southern part (Figure 5). Shallow aquifer depth (< 40 m) has been delineated within the study area (Samuel, 2104) and the basement complex of Nigeria (Sunmonu et al., 2015; Adagunodo et al., 2018). However, this study further confirms the occurrence of groundwater within the basement at a high depth (> 40 m) and that the borehole should be drilled between 40 - 100 m within the basement complex as also stated by Adagunodo et al. (2018).

VLF-EM profiling was carried out around twelve (12) VES points as shown in figure 6 to figure 17. Omeje et al. (2021) stated that the EM method is cheaper, faster and of higher precision in identifying groundwater bearing formation and possible structural control of which the other techniques do not poses such attributes. The EM method has the attribute of enabling the user to view results in 3D format and this makes interpretation easier and more reliable.

The VES 1 point falls at line 8 in the EM profile (Figure 6) which reveals an overburden of about 10 m containing water, chances of having water are from 30m, and at about 90 m the highly resistive rock (fresh basement) begin, corresponds to what was observed from the VES result revealing the presence of water in the overburden and fracture basement at 70 m. The same trend was observed for the profile of VES 2 (Figure 7) and VES 6 (Figure 8) which fall at line 3 and 7 of the EM profile respectively, but better chances of having water in VES 2 and 6 is high as a result of thicker blue colour which indicates the presence of water. VES 7 falls at line 8 in its EM profile (Figure 9) and reveals the presence of water to about 120 m and this correlate with what the VES result showed, better chances of having water along the profile line in the area are high. VES 9 which falls at EM profile (Figure 10) line 3 also has a chance of having water from 40 – 50 m. VES 11 which falls on line 3 in the EM profile (Figure 11) has poor groundwater prospects and this can be correlated and ascribed to a continual increase in resistivity value shown by the VES data. EM profile line for VES 14 which falls in line 2 (Figure 12) has poor groundwater potential and this conforms with the VES result. The chance of having water within the VES points is low. Other EM profiles for VES 15, VES 16, VES 17, VES 18, and VES 19 (Figure 13-17) have the same pattern indicating the presence of water along the profile and conforming with their VES points. Generally, the VLF-EM result further confirmed that the water-bearing strata are in the overburdened materials/weathered basement and fracture basement aquifer, and aquifer depth for groundwater development should be targeted at 40-90 m.

Conclusion

Integration of Very Low Frequency Electromagnetic (VLF-EM) and Vertical Electrical Sounding (VES) Resistivity methods has shown to be more reliable with higher precision and accuracy in identifying groundwater potential zones and possible structural control within the subsurface. The VES result showed that there are four (4) to five (5) geo-electric layers in the study area, these layers are the topsoil with lateritic clay, weathered basement, confining/fairly weathered basement, weathered/fractured basement aquifer, and fresh basement. Two curve types were observed; they are HA and HK curve types. The aquifer resistivity map and the electromagnetic profile reveals that the eastern and southern portion of the study area which are mainly dominated by migmatite and porphyritic granite rocks are characterized as good groundwater potential zones, while the central portion which is mainly dominated by granite gneiss shows poor groundwater potential zones due its texture. They are mostly referred to groundwater low yield areas.

Integration of the VLF-EM data and the VES data further correlates and confirmed that the water-bearing strata within the study area lie in the overburdened materials/weathered basement and fracture basement aquifer. Therefore, aquifer depth for groundwater development should be targeted at 40-90 m. It is recommended that the VLF-EM and the VES method should be used mostly in groundwater exploration, especially in areas with established cases of very low yield.

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Table 1: Geo-electrical Layer Result Obtained from the Plotted Graphs

VES No.	Coordinates	Resistivity (Ωm)	Thickness (m)	Depth (m)	Inferred Lithology	Curves Type
VES 1	N7°32’53’’	137.6	11.0	11.0	Top soil with lateritic clay	HA
	E6°40’21.4’’	82.2	2.4	13.3	Weathered basement	
		785.5	47.5	60.8	Confining fairly weathered basement	
		374.0	12.1	72.9	Fracture basement aquifer	
		1045.3			Fresh basement	
VES 2	N7°32’40.1’’	320.8	0.5	0.5	Top soil with lateritic clay	HA
	E6°40’49.2’’	36.8	22.7	23.2	Weathered basement	
		350.7	29.8	52.9	Confining fairly weathered basement	

		152.6 955.6	10.0	62.9	Fracture basement aquifer Fresh basement	
VES 3	N7°33’50.7’’ E6°41’34.3’’	44.9 144.5 639.2 53094.2	5.3 3.2 5.5	5.3 8.5 14.0	Top soil with lateritic clay Weathered basement weathered basement aquifer Fresh basement	HA
VES 4	N7°34’11.9’’ E6°38’53.6’’	317.3 55.7 1586.0 918.9 5369.5	0.7 11.0 30.0 16.3	0.7 11.7 41.7 57.9	Top soil with lateritic clay Weathered basement Confining fairly weathered basement weathered basement aquifer Fresh basement	HA
VES 5	N7°33’17.1’’ E6°39’19.7’’	28.3 1.5 41.0 63.1 5693.1	1.0 1.9 11.8 9.1	1.0 2.9 14.8 23.9	Top soil with lateritic clay Weathered basement Confining weathered basement Fracture basement aquifer Fresh basement	HA
VES 6	N7°33’24.9’’ E6°37’36.1’’	35.9 119.9 1801.8 323.7 452.6	6.9 3.6 54.9 28.4	6.9 10.4 65.4 93.7	Top soil with lateritic clay Weathered basement Confining fairly weathered basement Fracture basement aquifer Fresh basement	HK
VES 7	N7°33’13.6’’ E6°37’14.9’’	26.5 2228.2 11644.5 643.6 1173.4	5.3 8.3 87.1 25.0	5.3 13.6 100.7 125.7	Top soil with lateritic clay Fairly Weathered basement Confining fairly weathered basement weathered basement aquifer Fresh basement	HA
VES 8	N7°33’14’’ E6°36’36’’	10.6 110.9 1436.0 21321.6	2.5 1.2 9.2	2.5 3.7 8.9	Top soil with lateritic clay Weathered basement Weathered basement aquifer Fresh basement	HA
VES 9	N7°33’50.0’’	6.3	2.8	2.8	Top soil with lateritic clay	HA

	E6°36’19.2’’	47.1 141.6 150.6 1125.4	13.9 14.6 9.6	16.7 31.4 40.9	Weathered basement Confining weathered basement Fracture basement aquifer Fresh basement	
VES 10	N7°34’30.2’’ E6°36’49.0’’	30.8 638.8 3095.4 187.1 406.8	3.2 1.7 15.3 39.5	3.2 4.9 20.2 59.7	Top soil with lateritic clay Weathered basement Confining fairly weathered basement Fracture basement aquifer Fresh basement	HK
VES 11	N7°34’32’’ E6°37’59.1’’	259.1 13.0 1680.6 1891.2 38636.5	0.7 3.4 9.4 5.3	0.7 4.0 13.4 18.6	Top soil with lateritic clay Weathered basement Confining fairly weathered basement Poorly weathered basement aquifer Fresh basement	HA
VES 12	N7°35’05’’ E6°37’50’’	24.9 88.6 11696.6 2145.1 31456.2	4.8 1.6 27.3 5.9	4.8 6.4 33.7 39.6	Top soil with lateritic clay Weathered basement Confining fairly weathered basement Poorly basement aquifer Fresh basement	HA
VES 13	N7°36’11.9’’ E6°38’15.3’’	239.1 19.6 2115.0 116.3 467.3	0.8 4.1 25.8 69.5	0.8 4.8 30.7 100.2	Top soil with lateritic clay Weathered basement Confining fairly weathered basement Fracture basement aquifer Fresh basement	HK
VES 14	N7º33’40.1’’ E6º38’44.4’’	45.7 235.5 2803.2 3064.7	0.6 16.7 11.3	0.6 17.3 40.8	Top soil with lateritic clay Confining weathered basement Fresh basement aquifer Fresh basement	HA
VES 15	N7º33’41.3’’ E6º37’15’’	206.4 31.2 514.5	1.2 7.8 27.4	1.2 9.0 36.4	Top soil with lateritic clay Weathered basement Confining fairly weathered basement	HA

		102.2 786.3	32.4	68.8	Fracture basement aquifer Fresh basement	
VES 16	N 7^{O} 33' 37" E 6^{O} 36' 57"	165.6 8.5 59.3 120.4	2.8 13.6 28.4	2.8 16.4 44.8	Top soil with lateritic clay Confining weathered basement Fracture basement aquifer Fresh basement	HK
VES 17	N 7^{O} 33' 41.3" E 6^{O} 37' 19.9"	271.3 68.7 633.4 990.0	1.7 25.6 24.3	1.7 27.3 51.6	Top soil with lateritic clay Confining weathered basement Weathered basement aquifer Fresh basement	HA
VES 18	N 7^{0} 32' 45.9" E 6^{0} 40' 59.9"	29.1 11.2 435.3 6342.3	1.1 12.8 23.5	1.1 13.9 25.2	Top soil with lateritic clay Weathered basement Fracture basement aquifer Fresh basement	HA
VES 19	N 7^{0} 33' 11.0" E 6^{0} 38' 16.1"	1195.0 37.0 61.0 2767.5	0.8 12.3 34.6	0.8 13.1 47.7	Top soil with lateritic clay Confining weathered basement Fracture basement aquifer Fresh basement	HA
VES 20	N 7^{0} 32' 59.5" E 6^{0} 36' 21.7"	88.3 62.1 132.0 6542.1	3.2 11.3 42.4	3.2 14.5 23.7	Top soil with lateritic clay Weathered basement Fracture basement aquifer Fresh basement	HA
VES 21	N 7^{0} 34' 30" E 6^{0} 37' 20"	156.4 48.84 345.6 139.6 2342.3	2.8 12.6 33.6 19.8	2.8 15.4 49.0 68.8	Top soil with lateritic clay weathered basement Confining weathered basement Fracture basement aquifer Fresh basement	HK
VES 22	N 7^{0} 32' 42.2" E 6^{0} 40' 24.2"	254.2 55.0 1123.3 204.2	1.9 8.3 36.9 26.3	1.9 10.2 47.1 73.4	Top soil with lateritic clay weathered basement Confining weathered basement Fracture basement aquifer	HA

		986.9			Fresh basement	
VES 23	N 7^0 36’ 39.7”	50.2	3.2	3.2	Top soil with lateritic clay	HA
	E 6^0 38’ 21.2”	29.4	11.6	14.8	weathered basement	
		398.4	22.5	37.3	Confining weathered basement	
		102.4	14.5	51.8	Fracture basement aquifer	
		1324.4			Fresh basement	
VES 24	N 7º35’ 30.1”	381.2	2.1	2.1	Top soil with lateritic clay	HA
	E 6º38’13.4”	98.65	18.2	20.3	weathered basement	
		2342.2	11.3	31.6	Poorly basement aquifer	
		6896.3			Fresh basement	
VES 25	N 7^0 34’ 15.0”	13.3	1.3	1.3	Top soil with lateritic clay	HA
	E 6^0 36’ 24”	11.4	13.4	14.7	weathered basement	
		49.5	35.3	50.3	Fracture basement aquifer	
		744.4			Fresh basement	
VES 26	N 7^0 34’ 12.7”	91.0	3.5	3.5	Top soil with lateritic clay	HA
	E 6^0 40’ 5.2”	45.9	54.7	58.2	weathered basement	
		3284.6	5.2	100.6	Fresh basement aquifer	
		3284.6			Fresh basement	
		546.2				

Table 2: Aquifer Characteristics and Interpreted Groundwater Potential of the Study Area

VES NO.	Coordinates	Resistivity (Ωm)	Thickness (m)	Depth (m)	Groundwater potential
VES 1	N7°32'53'' E6°40'21.4''	374.0	12.1	72.9	Good
VES 2	N7°32'40.1'' E6°40'49.2''	152.6	10.0	62.9	Good
VES 3	N7°33'50.7'' E6°41'34.3''	639.2	5.5	14.0	Moderate
VES 4	N7°34'11.9'' E6°38'53.6''	918.9	16.3	57.9	Moderate
VES 5	N7°33'17.1'' E6°39'19.7''	63.1	9.1	23.9	Good
VES 6	N7°33'24.9'' E6°37'36.1''	323.7	28.4	93.7	Good
VES 7	N7°33'13.6'' E6°37'14.9''	643.6	25.0	125.7	Moderate
VES 8	N7°33'14'' E6°36'36''	1436.0	9.2	8.9	Moderate
VES 9	N7°33'50.0'' E6°36'19.2''	150.6	9.6	40.9	Good
VES 10	N7°34'30.2'' E6°36'49.0''	187.1	39.5	59.5	Good
VES 11	N7°34'32'' E6°37'59.1''	1891.2	5.3	18.6	Poor
VES 12	N7°35'05'' E6°37'50''	2145.1	5.9	39.6	Poor

VES 13	N7°36’11.9’’ E6°38’15.3’’	116.3	69.5	100.2	Good
VES 14	N7º33’40.1’’ E6º38’44.4’’	2803.2	23.5	40.8	Poor
VES 15	N7º33’41.3’’ E6º37’15’’	102.2	32.4	68.8	Good
VES 16	N 7^{O} 33’ 37” E 6^{O} 36’ 57”	59.3	28.0	44.8	Good
VES 17	N 7^{O} 33’ 41.3” E 6^{O} 37’ 19.9”	633.4	24.3	51.6	Moderate
VES 18	N 7^{0} 32’ 45.9” E 6^{0} 40’ 59.9”	435.3	11.3	25.3	Good
VES 19	N 7^{0} 33’ 11.0” E 6^{0} 38’ 16.1”	61.0	34.6	47.1	Good
VES 20	N 7^{0} 32’ 59.5” E 6^{0} 36’ 21.7”	132.0	42.4	23.7	Good
VES 21	N 7^{0} 34’ 30” E 6^{0} 37’ 20”	139.6	19.8	68.8	Good
VES 22	N 7^{0} 32’ 42.2” E 6^{0} 40’ 24.2”	204.2	26.3	73.4	Good
VES 23	N 7^{0} 36’ 39.7” E 6^{0} 38’ 21.2”	102.4	14.5	51.8	Good
VES 24	N 7º35’ 30.1” E 6º38’13.4”	2342.2	11.3	31.6	Poor
VES 25	N 7^{0} 34’ 15.0” E 6^{0} 36’ 24”	49.5	35.3	50.3	Good
VES 26	N 7^{0} 34’ 12.7” E 6^{0} 40’ 5.2”	3284.6	5.2	100.6	Poor
	Minimum	49.5	5.2	8.9	
	Maximum	3284.6	69.5	125.7	
	Average	745.8	21.3	55.3	

Table 3: Range of Resistivity for Lithological Characterisation and Groundwater Prospect of Bedrock (David, 1988 and Akanbi, 2017)

Bedrock resistivity (Ωm)	Description of the bedrock	Groundwater prospect of bedrock
>1800	Fresh	Negligible
601–1800	Weak/slightly weathered	Moderate
< 600	Fractured	Good

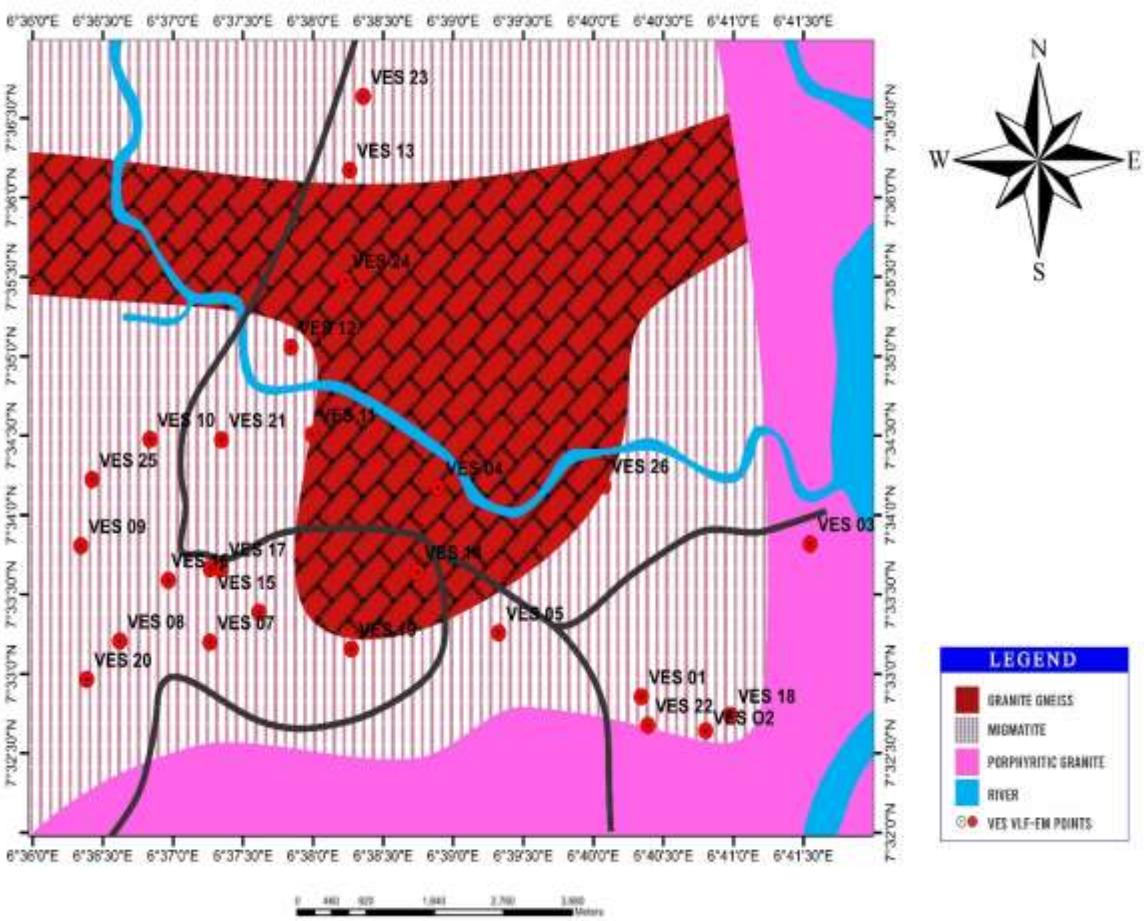

Figure 1: Geological and Location Map of the Study Area

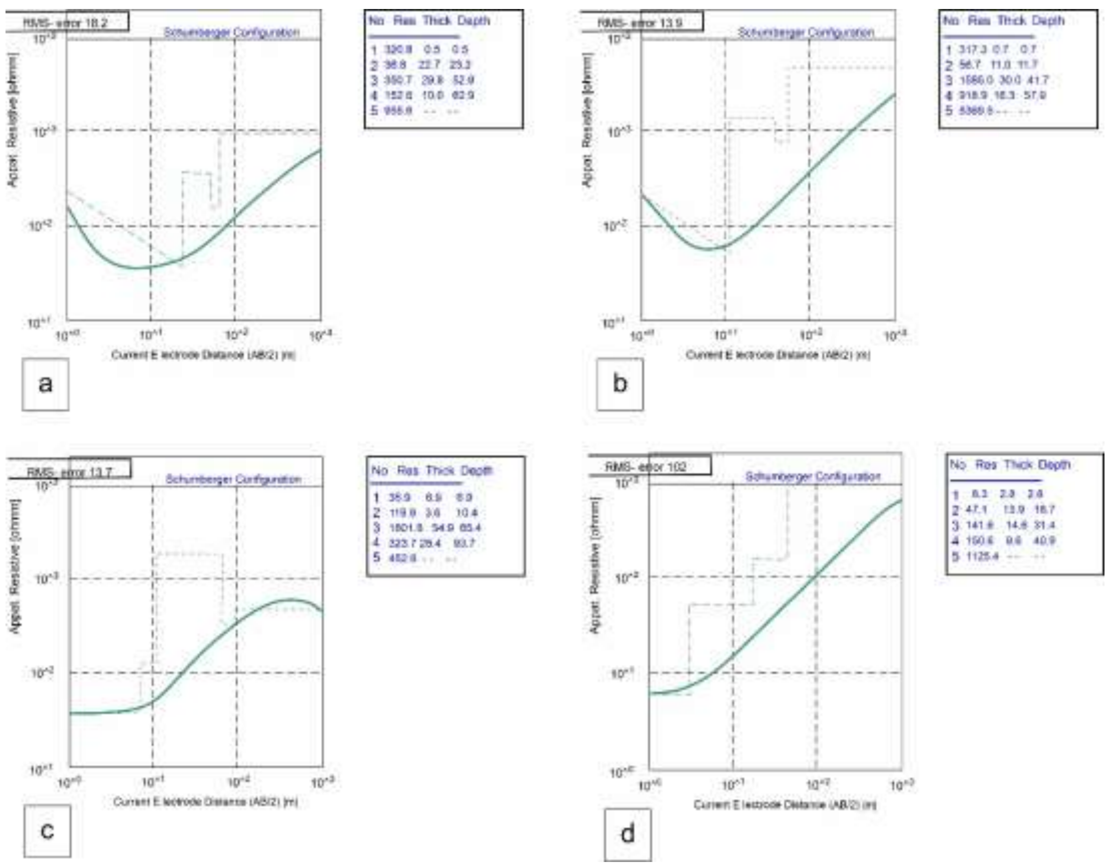

Figure 2: Geo-electric Curves for (a) VES 2, (b) VES 4, (c) VES 6, and (d) VES 9

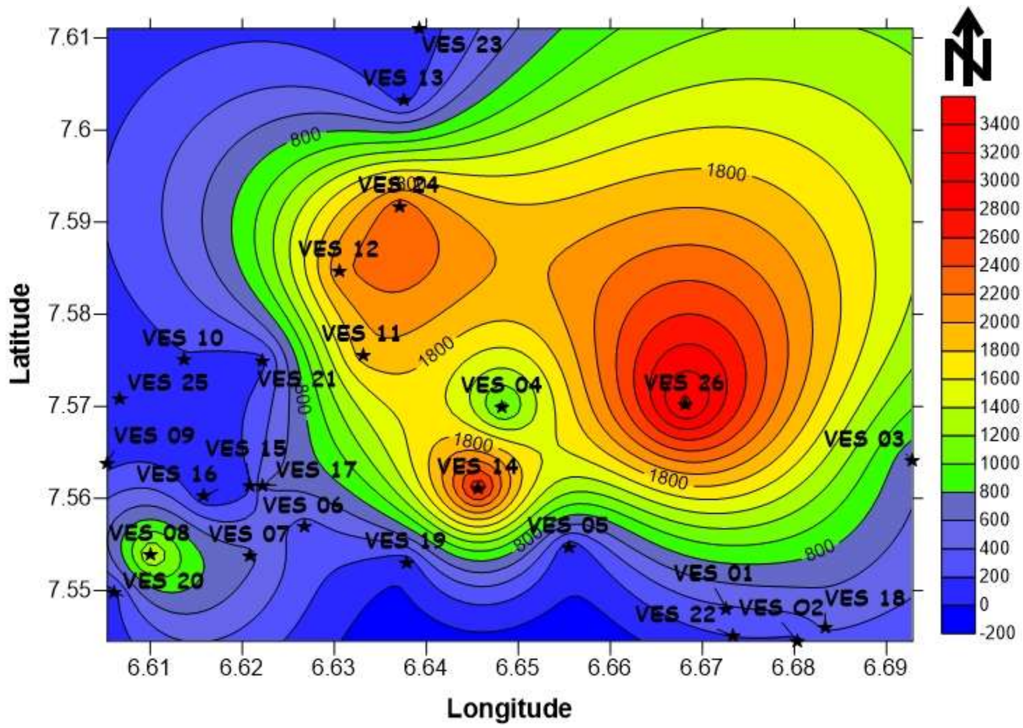

Figure 3: Map of the Study Area Showing Aquifer Resistivity

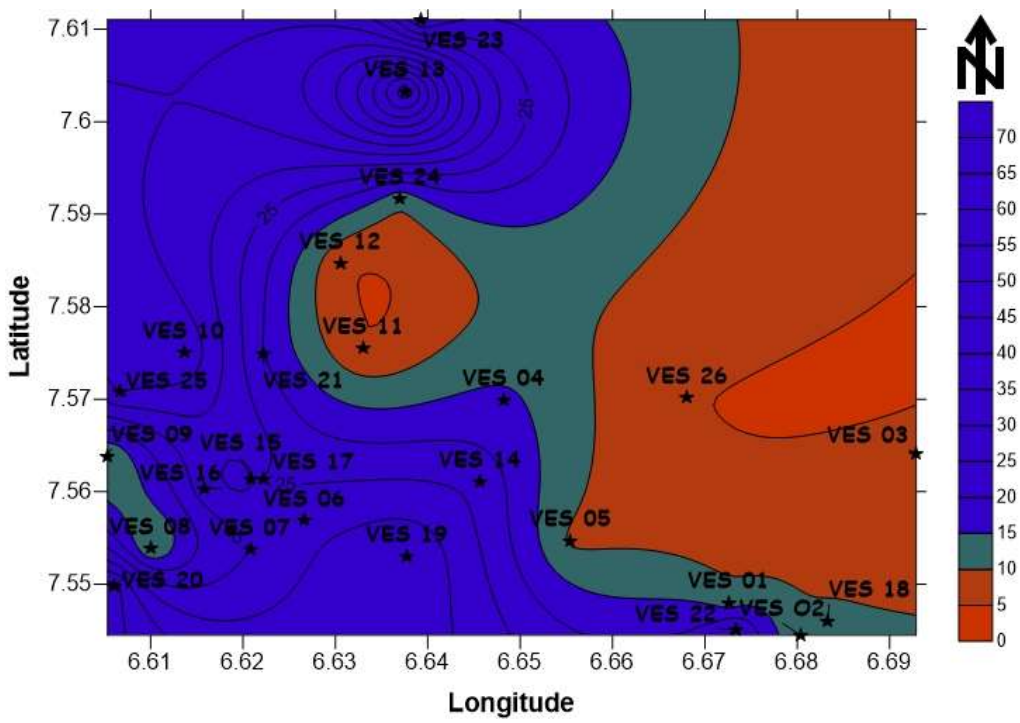

Figure 4: Map of the Study Area Showing the Aquifer Thickness

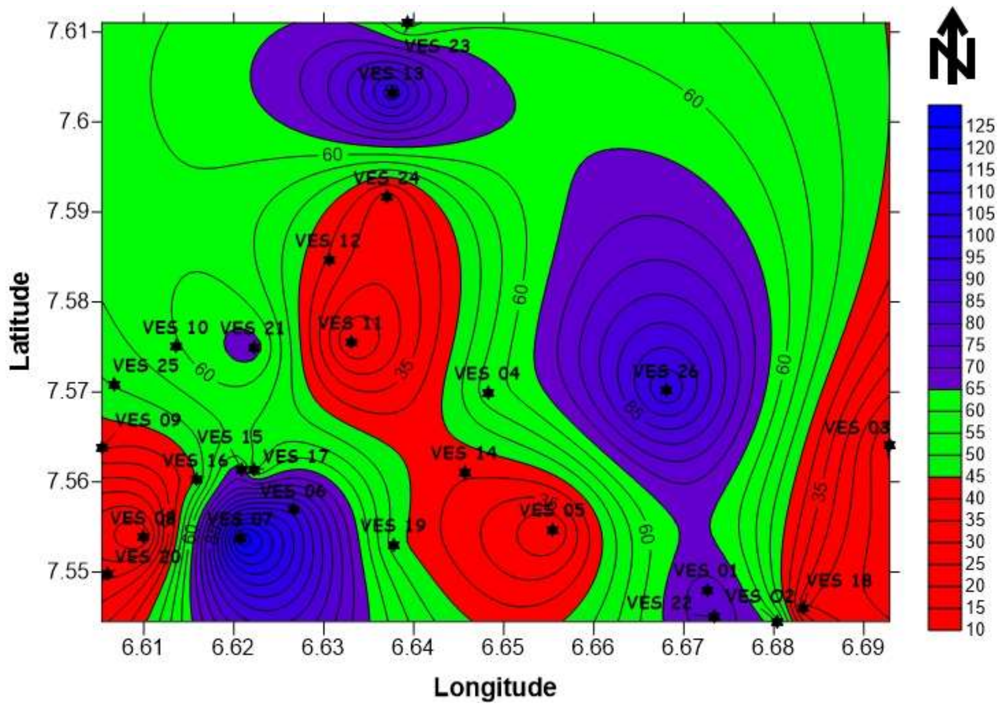

Figure 5: Map of the Study Area Showing the Aquifer Depth

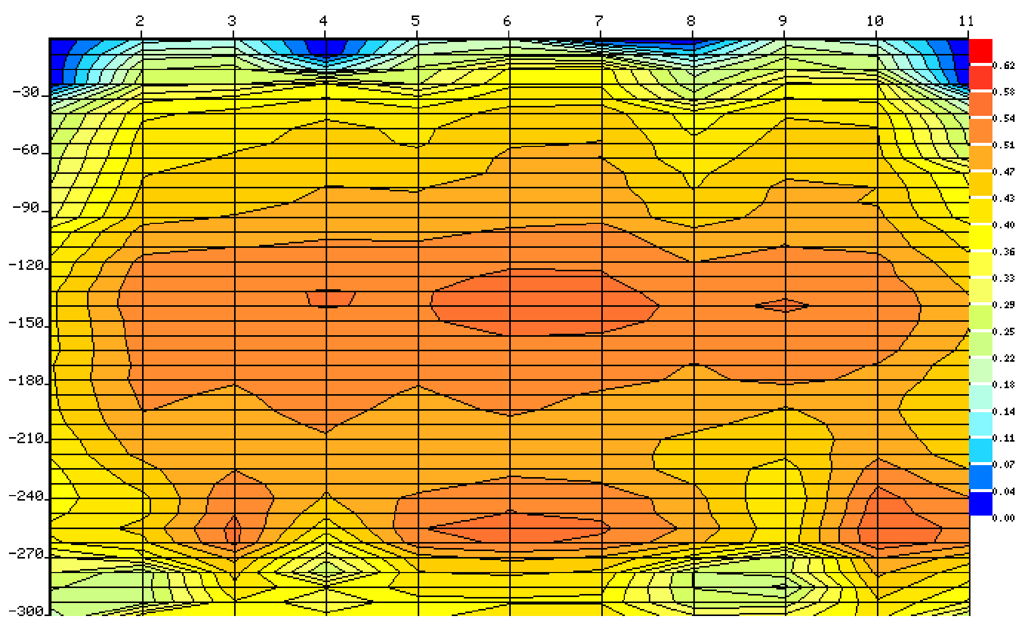

Figure 6: VLF-EM Profile in VES 1 Location

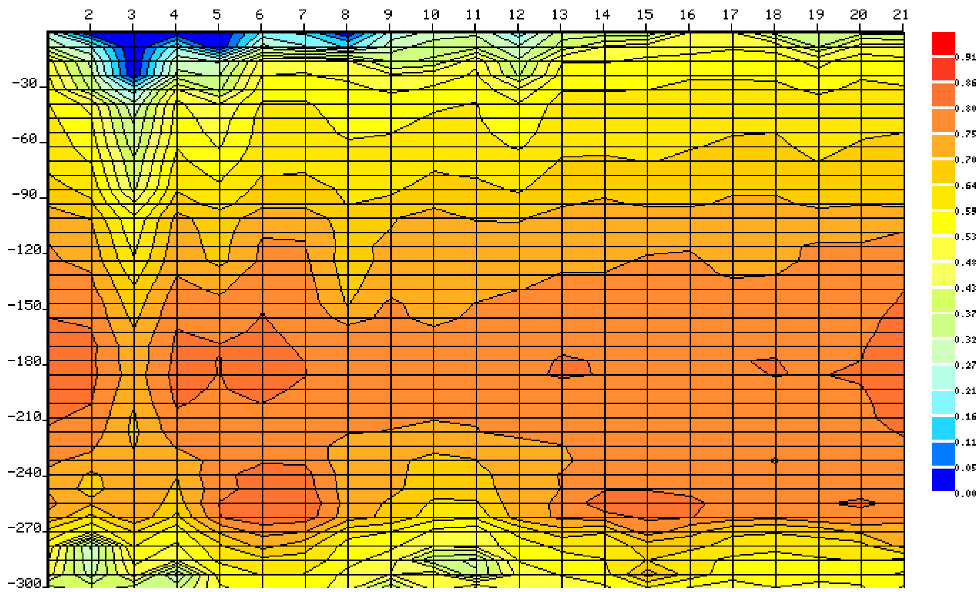

Figure 7: VLF-EM Profile in VES 3 Location

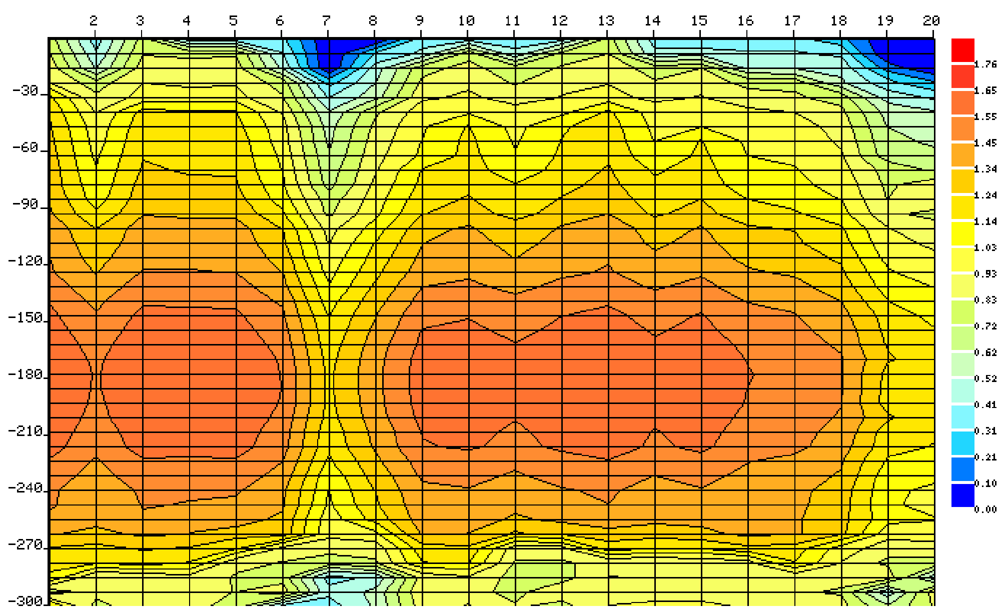

Figure 8: VLF-EM Profile in VES 4 Location

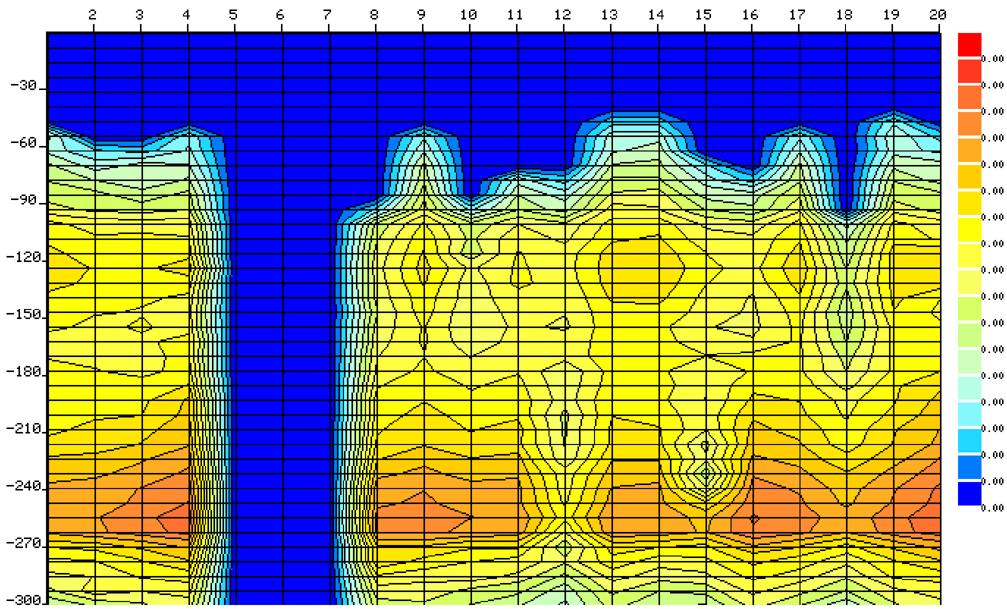

Figure 9: VLF-EM Profile in VES 7 Location

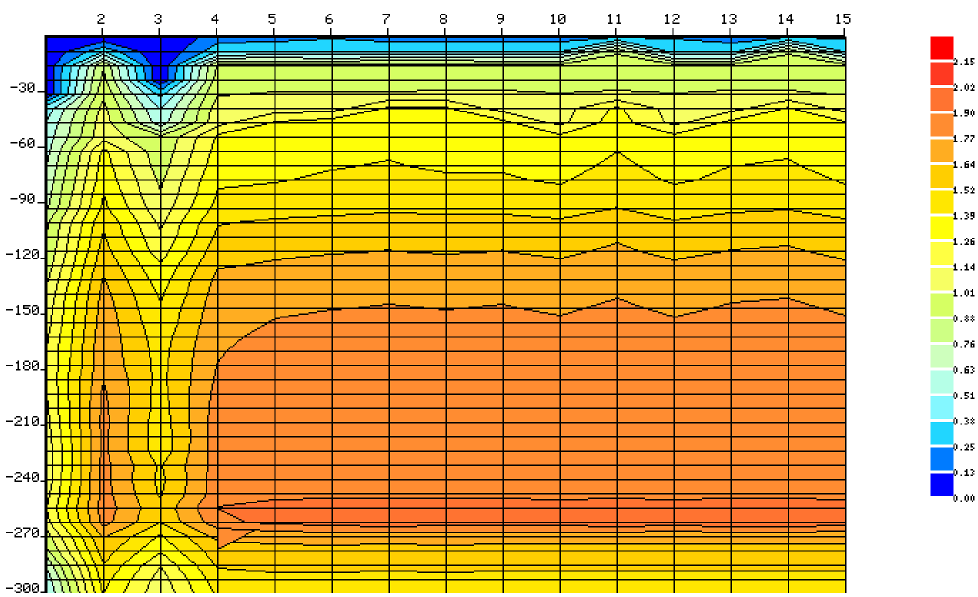

Figure 10: VLF-EM Profile in VES 9 Location

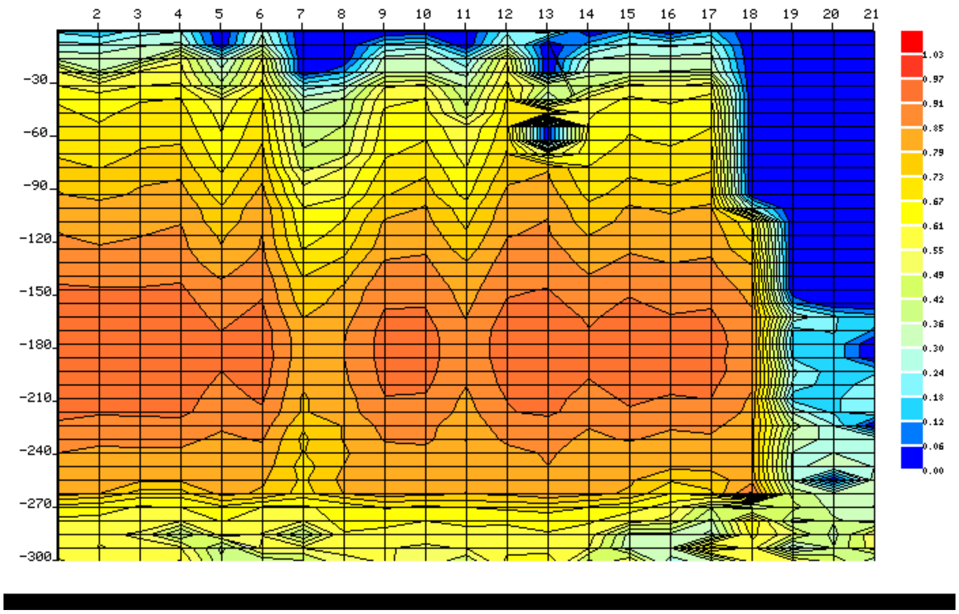

Figure 11: VLF-EM Profile in VES 11 Location

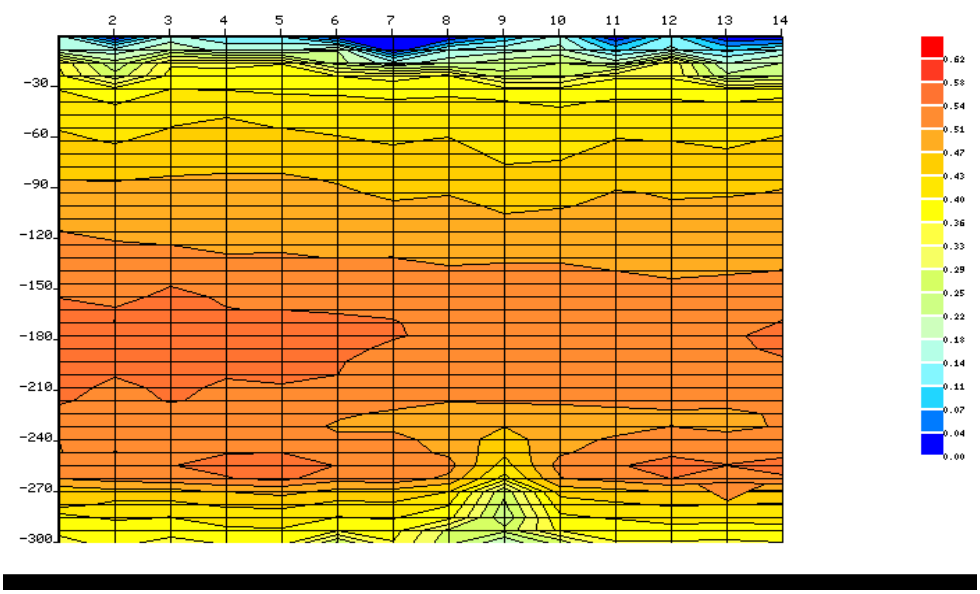

Figure 12: VLF-EM Profile in VES 14 Location

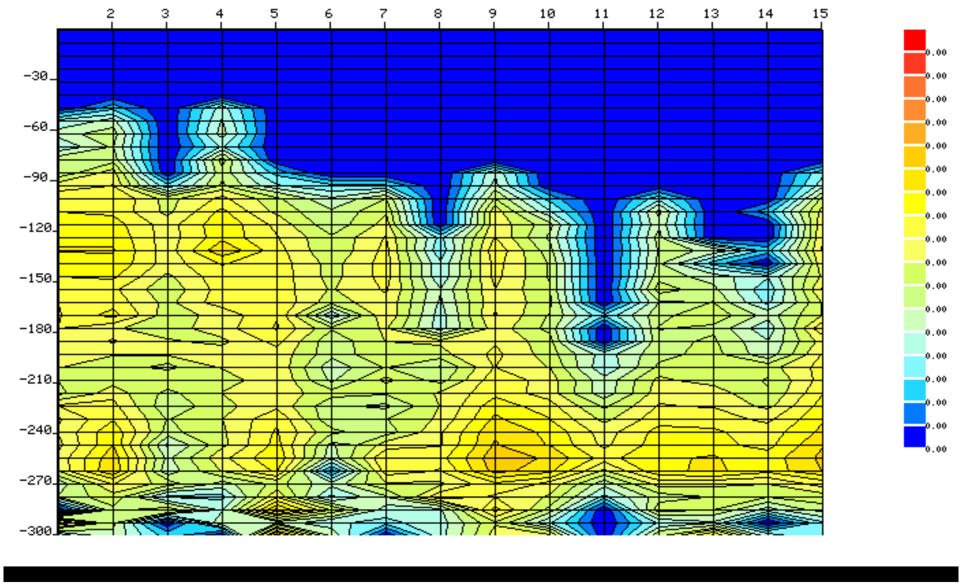

Figure 13: VLF-EM Profile in VES 15 Location

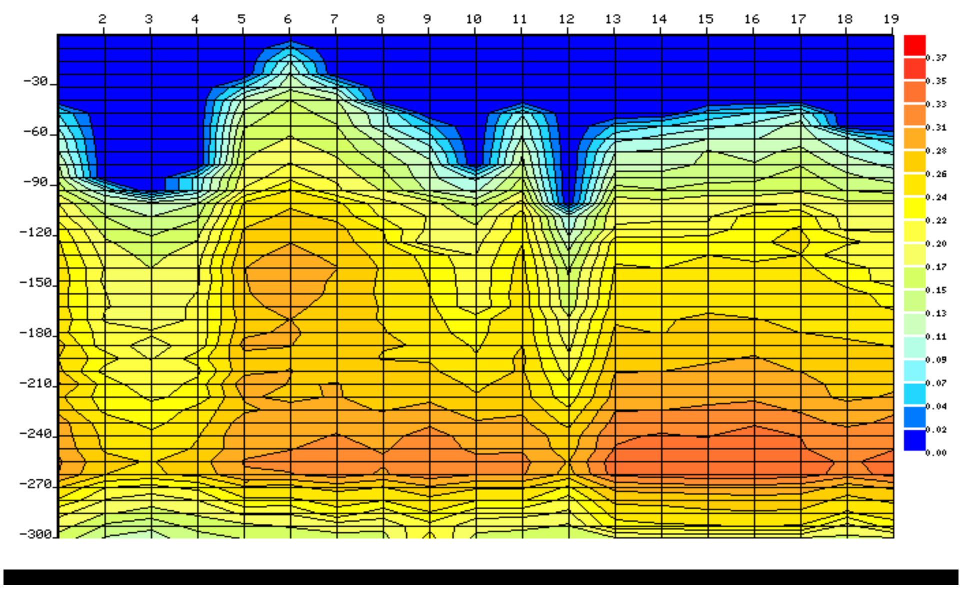

Figure 14: VLF-EM Profile in VES 16 Location

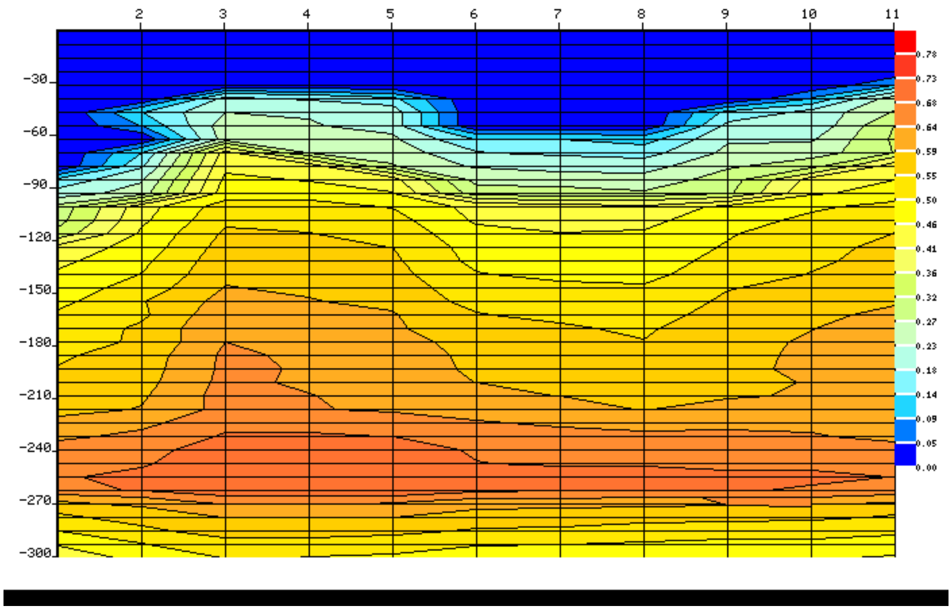

Figure 15: VLF-EM Profile in VES 17 Location

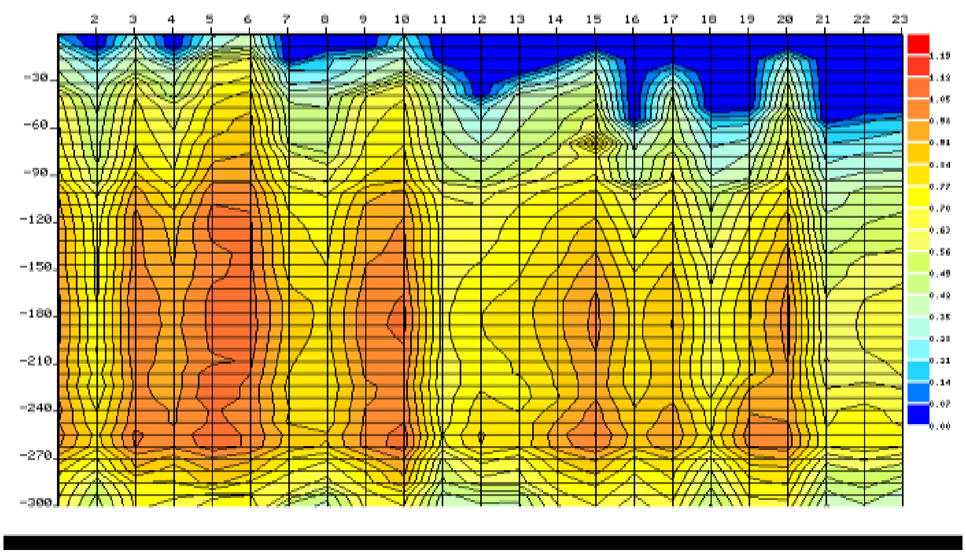

Figure 16: VLF-EM Profile in VES 18 Location

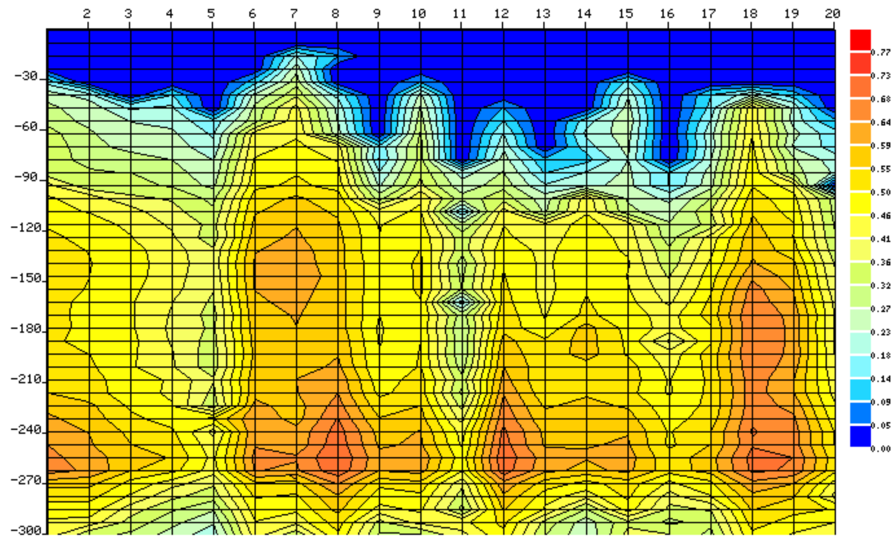

Figure 17: VLF-EM Profile in VES 19 Location