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ARTICLE

Characterization of Subsurface Lithology and Aquifer Parameters Using Vertical Electrical Sounding (VES) for Groundwater Development in Igbo-Imabana, Southern Nigeria

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ABSTRACT

Vertical Electrical Soundings (VES) using Schlumberger array was carried out at fifteen (15) different points to evaluate aquifer characteristics within Igbo-Imabana, Abi L.G.A of Cross River State. Resistivity meter and its accessories were used for data acquisition. The maximum current and potential electrode distance were 400 m and 20 m respectively. The field data were interpreted using Interpex software and three to five geo-electric layers encountered within the study area. The dominant curve type was H followed by K. From the result, geo-electric layers delineated were sandstone, clay, saturated sandstone, sandy shale, clayey shale, and shale with average apparent resistivity values of 2249.94 Ωm, 2.86 Ωm, 365.28 Ωm, 222.69 Ωm, 14.60 Ωm and 59.02 Ωm respectively. The top geo-electric layer was dominantly lateritic topsoil, with variation in degrees of compaction and having an average resistivity of 876.33 Ωm with depth and thickness generally less than 5 m. The calculated aquifer parameters hydraulic conductivity (K_c), transmissivity, longitudinal conductance, and transverse resistance from the VES results show ranges values; 3.86×10^{-4} to 4.69×10^{-2} m/day, 2.95×10^{-3} to 2.82 m^2/day, 2.95×10^{-3} to 2.81 Ωm and 484.33 to 19444.83 Ω^2m respectively. The aquifer thickness and depth values range from 3.60 m to 68.05 m and 5.20 m to 76 m respectively. The study reviewed that the area is made of heterolithic/heterogenous lithofacies, confined aquifer(s), shallow and deep aquifer. Also, from the models and aquifer parameters, the area is characterized by semi-pervious materials. This integrally explains why the area have have low transmissivity and majority of boreholes drilled in the area failed.

1. Introduction

Water is essential for life. It occurs as surface or groundwater. Many workers have emphasized on water and its use for domestic, industrial, agricultural, and aesthetics purposes [1-7]. Water is an important and necessary

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commodity to the sustenance of life (both plants and animals). Its shortage is of great concern especially during dry season to the people of Igbo-Imabana. Igbo-Imabana (Figure 2) is located between latitudes 5.50° N and 6.00° N of the Equator and longitudes 8.05° E and 8.12° E of the Greenwich Meridian within Cross River State, Nigeria. The area comprises of six villages; Mboti, Itaghoghor, Ebor, Lehangha (Igbo Beach) and Ikpalegwa. The shortage of water in these communities cannot be overemphasized. The indigenes have to trek long distances of about 4 km to rivers and streams which are often degraded in quality due to its exposure to physical, biological and chemical contaminants [8]. Also, the distance between Igbo-Imabana and Itigidi/Ediba Water Board Stations located in the Local Government Area has made it difficult to extend pipe-borne water to the community [8]. More deteriorating is the menaces of outbreak of cholera dysentry, typhoid fever and the transmission of certain viral diseases in the area has been traced to the consumption of water from the River Cross, which is a major source of water in the area [9]. Consequently, groundwater resource in Igbo-Imabana is the only source of potable water for domestic, industrial and other uses. However, efforts by government agencies like Rural Water and Sanitation (RUWATSA) to drill boreholes in the area have failed because of poor knowledge of the aquifer characteristics within the area. Moreover, these agencies drill without proper considerations of aquifer parameters and geophysical survey which have led to borehole failures in the area. In addition, most boreholes and hand dug wells have either partially or totally failed because of drilling (groundwater) was not supported by any professional prospecting for the location of water bearing horizon. Locally, no research has been published on the characterization of subsurface lithology to give adequate understanding of groundwater potential in the area. This work has derived the resistivity of the sub-surface geo-electric layers from their conductivities. Correlating the geo-electric sections at various sounding points aided evaluation of depth to the aquiferous units within the study area, hence giving an overview of groundwater trend in the area. As water-table may not apply in the area following geological constrains.

Electrical resistivity method(s) has become one of the most useful groundwater exploration techniques, following the sensitivity of rocks resistivity to their ionic content and fluid characteristics [10-13]. The method enables a quantitative assessment of groundwater by using a controlled source of specific dimensions which account for superiority over other electrical methods. Resistivity studies using Vertical Electrical Sounding (VES) have been employed by so many authors for delineating groundwater potentials [14-16]. The works of several researchers, are also supportive of the fact that electrical resistivity using VES can be used to locate water bearing formations which when exploited will yield sufficient volume of water for the people of Igbo-Imabana, hence the need for this research [8,17-25]. It is against this background that this research focused on providing the general knowledge about geology of the area. Combing it with geophysical approach aided defining aquifer units and aquifer characteristics like aquifer depth, thickness and transmissivity at some selected sites in the area. Hence, providing a comprehensive data of Igbo-Imabana area geologically and geophysically for subsequent exploitation of groundwater resources in order to meet the water needs of the people.

2. Geology, Physiography and Hydrogeological Settings

Regionally, Igbo-Imabana is located within the Ikom-Mamfe embayment [26]. The embayment is the Northwest to Southeast segment of the Northeast to Southwest trending Benue Trough [27]. It extends laterally into parts of Western Cameroon covering an area of about 2,016 km^2 [28]. The basin originated following failed arm (Aulacogen) during the separation of South America from Africa as the Atlantic Ocean opened at the site of an RRR junction [29-33]. After which the Trough was filled by sediment from the several depositional cycles which accumulated up to 6,000 m of fluvial, deltaic and marine sediments [31]. The sediments consist dominantly of Albian, Cenomanian and Turonian lithofacies and were affected by the Santonian Tectonic episode which resulted in folding, faulting, fracturing and igneous activity [32]. The sedimentation within the Benue Trough was controlled first by the progressive eustatic rise of sea level from the Albian, local diastrophism and the consequent widespread down warping of continental margins and the creation of vast interior seaways during the Cenomanian and Turonian [33]. These resulted in the transgressive-regressive cycles that characterized of deposition sediments in the Benue Trough [33]. The stratigraphy of the Trough was thus divided into three unconformities bounded depositional sequences. An Albianic–Cenomanian sequence includes the emplacement of the Abakiliki Pyroclastics and the deposition of the Asu River Group [35]. Secondly, the Turonian–Coniacian sequence which marked the folding and erosion of the Asu River Group, the deposition of the Eze-Aku Group, Agwu Shales and lateral equivalents followed by a period of Santonian folding. The Santonian deformation and magmatism was followed by the displacement of the Benue Trough westward leading to the subsidence of the Anambra Basin, the smaller Afikpo Syncline, and the Abakiliki Anticlinorium [31].

The three major lithostratigraphic units dominant around Ikom-Mamfe axis of the Trough comprised of Asu River Group (ARG), Eze Aku Group (EAG) and Post-Santonian Nkporo Group. These cretaceous lithostratigraphic units overlaid the Precambrian basement rocks around the area, with the ARG (Albian Age) directly overlie the Precambrian basement and is the oldest sedimentary rocks within the study area. The sediments within the ARG are made up impervious shales, limestones with intercalation of sandstone and ammonites. The sediments are marine to marginal marine in character [35,36].

The EAG overlies ARG comprising of thick flaggy impervious calcareous and non-calcareous shales, sandy shaly limestone and calcareous sandstone [35,36]. The EAG is overlain by the post Santonian Nkporo Group sediment (Shale) and the major lithologic units in the formation are sandstone, mudstone and shale [35,36].

Two principal climatic conditions, the wet and dry seasons are common in the area and portray a humid climatic condition with relative humidity of ~80%, annual precipitation of ~2,200 mm and temperatures dropping to as low as 23 °C in the wet season and rising to ~35 °C in the dry season [37]. The wet season begins in March when moisture-enriched tropical maritime air mass that originates from the Atlantic Ocean blows northward across the area. The air mass usually begins the gradual process of temporal termination of constant blowing activity in the area around October which symbolizes the end of the rainy season. The beginning of dry season in the area starts around November and it is marked by sudden increase in ambient temperature, heat and aridity, a condition that persist till march. This season is also characterized arrival of tropical air mass usually blowing southwards from Sahara Desert across the area [37,38].

3. Materials and Method

3.1 Data Acquisition

The VES conducted in area was done using Schlumberger electrode array for the data acquisition (Figure 1). Abem Terrameter (SAS 1000), four electrodes, four reels of Cables, Direct Current Source (12 Volts Car battery), hammers, field Survey Data sheet, global positioning system (GPS) and measuring tapes were all used for data acquisition. Resistivity soundings were performed at fifteen (15) different locations (Figure 2) with maximum current electrodes separation (A-B) of four hundred (400 m) meters and potential electrodes (M-N) 20 m, though it was less at some locations due to emplaced structures.

From Ohm's law which is stated numerically as:

$$V \alpha R \tag{1}$$

$$V = IR \tag{2}$$

where V is the electrical potential, I is the current and R is the material resistance to the flow of current. Electrical resistivity method was used by passing direct current (D.C.) into the ground through a pair of electrodes (current electrodes) while the resulting potential difference (Δv) arising from the current flow is measured through a pair of electrodes (potential electrodes). The field data acquisition and subsurface current interaction is schematically presented in Figure 1. The sensing efficacy of the current depends on depth of investigation which is function of the electrode spacing. The greater the spacing between the outer current electrodes, the deeper the electric current will flow in the earth, hence the greater the depth of investigation [14]. The ground responses are integral functions rock type, fluid content and hydrogeochemical component the fluid.

Sounding locations were randomly selected such that it covers the six (6) communities; Ebor, Mboti, Ilike, Itaghoghor, Lehangha (Igbo Beach) and Ikpalegwa that make up Igbo-Imabana and also based on the existing structures in the field as shown in the VES points map of the study area (Figure 2).

The resistivity of a rock material whose resistance is R and having a cross sectional area A and length L is expressed as [39]:

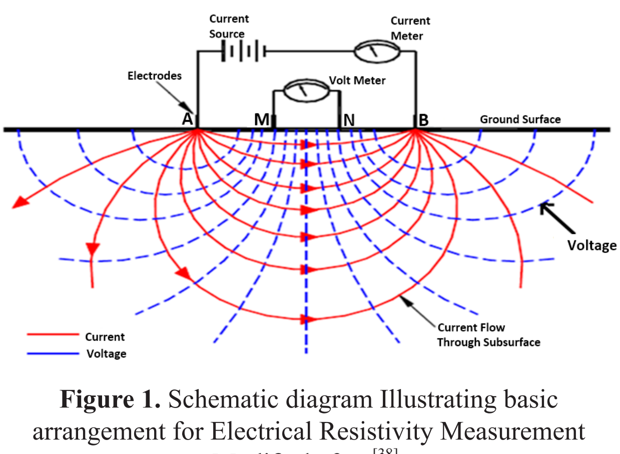


Figure 1. Schematic diagram Illustrating basic arrangement for Electrical Resistivity Measurement Modified after [38].

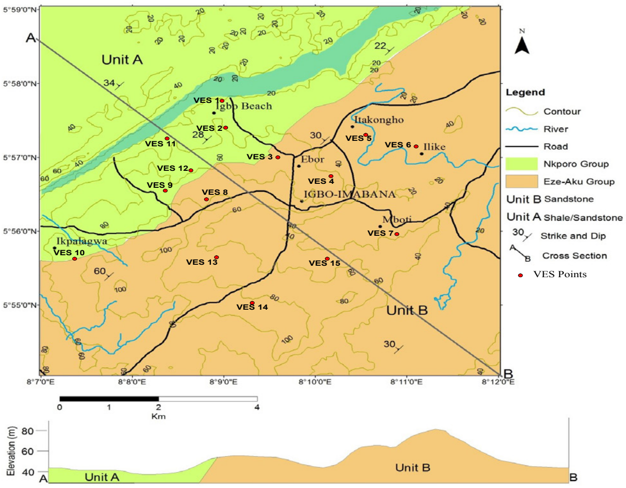


Figure 2. Geologic Map of the Study Area showing Lithostratigraphic unit and VES points of the study area.

$$\rho = \frac{AR}{L} \quad (3)$$

where,

R = the resistance measured between two equipotential surfaces;

L = distance separating the two equipotential surfaces.

3.2 Aquifer Parameters

The hydraulic characteristics of aquifers are important properties for both groundwater and contaminated land assessments and as well for safe construction of engineering structures [40]. Application of field hydrogeological method in aquifer parameter estimation is time consuming and capital intensive. In the alternative, surface geophysical method may provide rapid and effective techniques for groundwater exploration and aquifer evaluation. The resistivity readings were processed to produce geo-electric sections of the thickness and resistivity of subsurface electrical layers [41].

Hydraulic conductivity and aquifer depth are among the fundamental properties describing and characterizing subsurface hydrology. Many investigation techniques are commonly employed with the aim of estimation of spatial distribution of hydraulic parameters [42]. Field estimations of these parameters are always available and surface resistivity parameters extracted from surface electrical measurements can be highly effective not only for aquifer hydraulic conductivity estimation but also for group of hydraulic parameters. Correlation between hydraulic and electrical aquifer properties can be possible, as both properties are related to the pore space structure and heterogeneity of the medium under study [43-45].

Transverse resistance of the aquifer $R = h\rho$ (4)

and the

Longitudinal conductance $S = h/\rho$ (5)

ρ and h are the resistivity's and thicknesses of the individual layers respectively, the parameters S and R are commonly called Dar-Zarrouk parameters [46].

3.2.1 Hydraulic Conductivity

Hydraulic conductivity is symbolically represented as *K*, which is a property of rock that describes the ease with which water can move through pore spaces or fractures [42]. It depends on the intrinsic permeability of the material and on the degree of saturation. Saturated hydraulic conductivity, *Ksat*, describes water movement through saturated media.

$K_c=1/p$ (6)

where K_c is the calculated hydraulic conductivity, and *p* is the resistivity of the saturated layer from VES.

3.2.2 Transmissivity

Transmissivity is a measure of how much water can be transmitted horizontally. It is directly proportional to the hydraulic conductivity (K) and aquifer thickness (b). Expressing K in m/day or cm/s and b in m, the transmissivity (T) is found in units m^2/day or cm^2/s.

$T=Kb$ (7)

The transmissivity (T) of aquifer is related to the field hydraulic conductivity (K) by the equation above.

According to Niwas, S. and Singhal, D. C., in a porous medium transmissivity is calculated by;

$T_C = K_C b$ (8)

where,

T_C = Calculated transmissivity (m^2/day) from VES data.

K_C = Calculated hydraulic conductivity (m/day) from VES data.

b = Thickness of saturated layer (m) [47].

4. Discussion

The acquired resistivity values for the respective VES points were plotted and modelled as shown in the respective graphs (Figure 3 to Figure 17), geo-electric layers, apparent resistivities, depths, thickness and inferred lithologies (Table 1). The geo-electric correlation of the fifteen (15) VES points (Figure 18 (a & b)) revealed heterogeneous subsurface lithofacies in the study area. The geo-layers ranges from two (2) to five (5) across the study area. Apart from the apparent resistivity parameter, thickness and depth has critical impactful role to play on functionality of the borehole and otherwise. Usually, recorded variation in depths of aquifers from place to place is as a result of variation in geo-thermal and geo-structural occurrence, subsurface stratigraphic successions, aquiferious unit thickness, presence of impervious layers and past geodynamics (such as tectonic and magmatic events where such applied) [13]. Hence, delineation of aquiferous zone is integral function of thickness, depth and apparent resistivities of the subsurface geo-electric layers (Table 1). The top soil/first geo-electric layer is dominantly laterite rich in sand content, clay and shaley materials in order of abundance with an average apparent resistivities of 876.33 Ωm, 19.44 Ωm and 62.70 Ωm respectively. The thickness and depth ranges from 0.293 m to 4.193 m with an average 0.820 m (See Table 1). Basically six (6) geo-electric layers were found in the area are interlayering; clay, sandstone, shale, clayey shale, sandy shale and/or saturated sandstone. The summary of the average, minimum and maximum apparent resistivity, thickness and depth as presented in Table 2, show case troubling lithofacies (Aquicludes and Aquifuge) relative to groundwater accumulation following their porosity and permeability. Generally, the geo-electric layers thickness, depth, apparent resistivity and inferred lithologies (Table 1 and Figure 18) designated that the study area is underlain by heterolithic units/formations. Also, the thin (thickness) nature of the aquifer units in the study further impact negatively on the groundwater development of the area as indicated by some of the VES points.

Compositely, the confinement of most of the aquifer units as indicated by geo-electric model (Figure 18) will further accentuate potential failure rate of the borehole, as the aquifer will be limited to base flow as means of recharge where such is even obtainable. This implies that the probabilistic function of discharge exceeding recharge will be eminent via-z-via, drawdown, head loss and damaging of submersible pump will be at high echelon, hence frequent borehole failure as it has been the case in the study area. Keeping in mind that borehole failure is not only occasion by insufficiency of groundwater, though no doubt that it stands at front line of factors responsible for borehole failures.

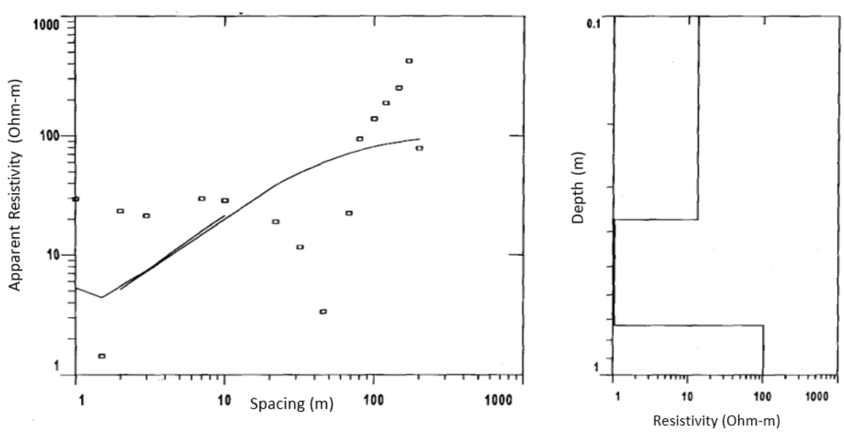


Figure 3. Sounding curve for VES 1 at PCN Prim. Sch. Lehangha, Igbo-Imabana

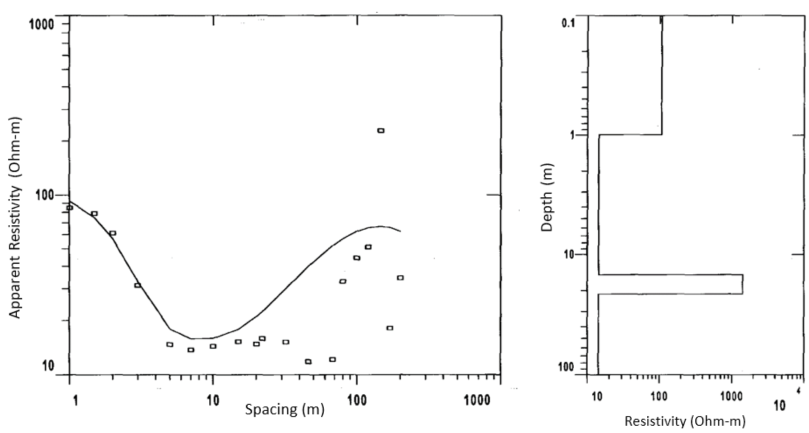


Figure 4. Sounding curve for VES 2 at Jehovah's Witness Church, Lehangha Road, Igbo-Imabana

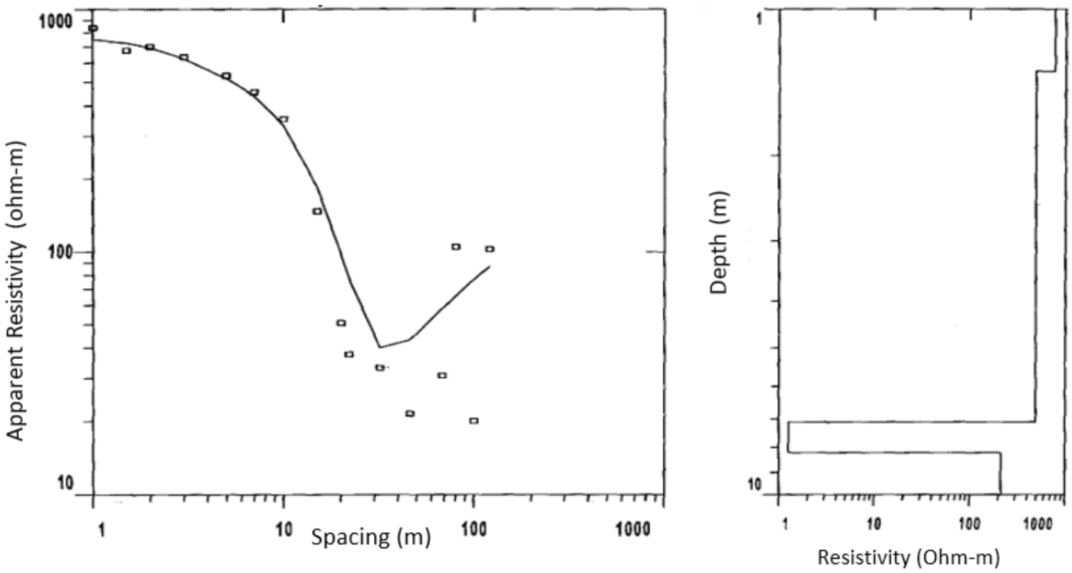


Figure 5. Sounding curve for VES 3 at PCN Prim. Sch. Ebor, Igbo-Imabana

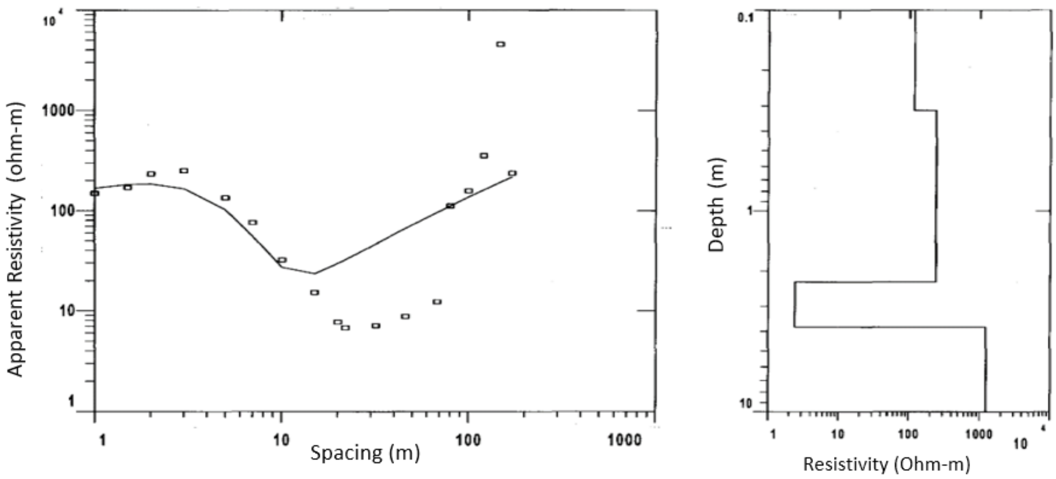


Figure 6. Sounding curve for VES 4 at Ebor Playground, Igbo-Imabana

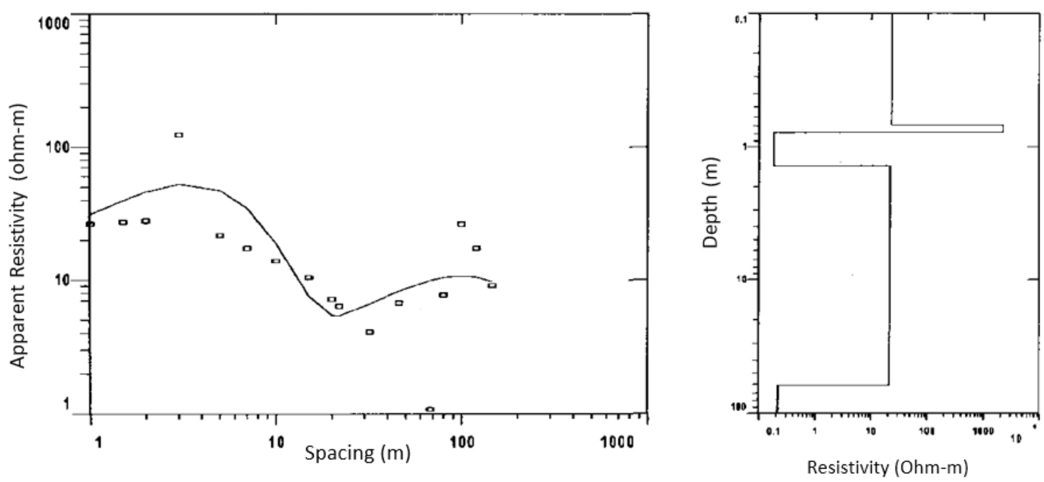


Figure 7. Sounding curve for VES 5 at Itakongho Prim. Sch., Igbo-Imabana

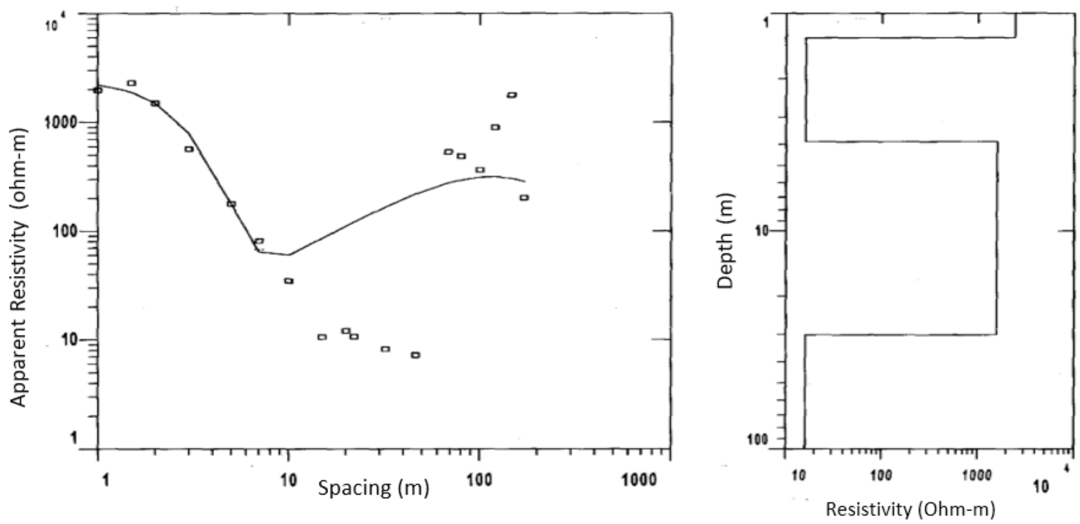


Figure 8. Sounding curve for VES 6 at Ilike Playground, Igbo-Imabana

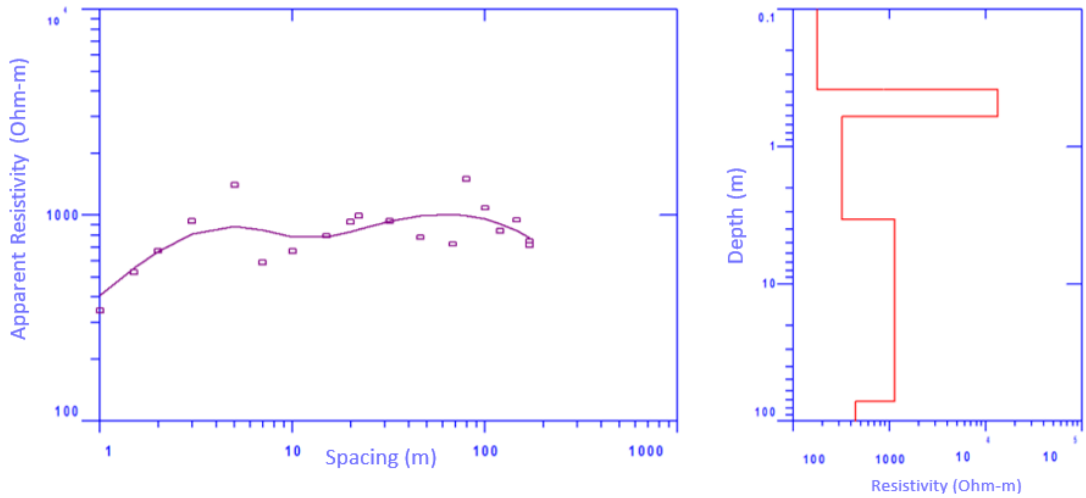


Figure 9. Sounding curve for VES 7 at Mboti Prim. Sch., Igbo-Imabana

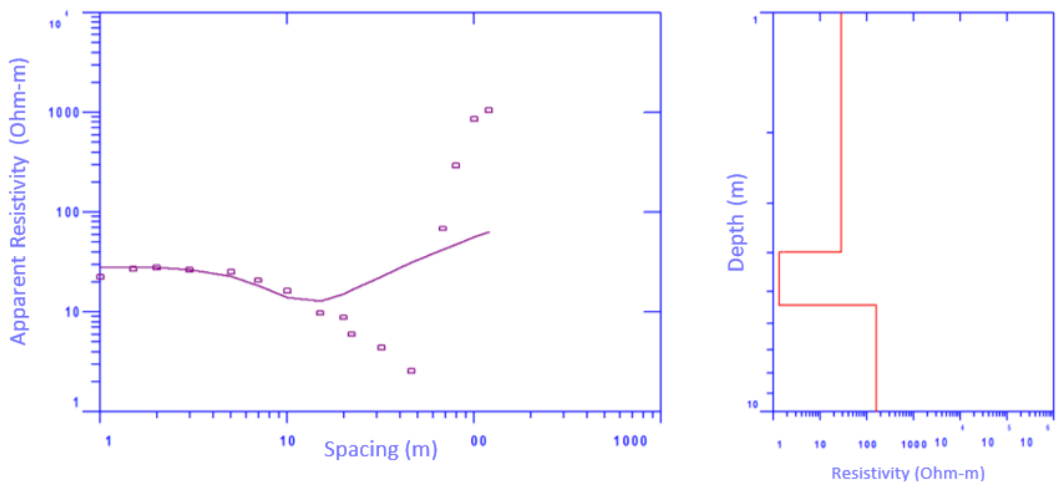


Figure 10. Sounding curve for VES 8 at Community Sec. Sch., Igbo-Imabana

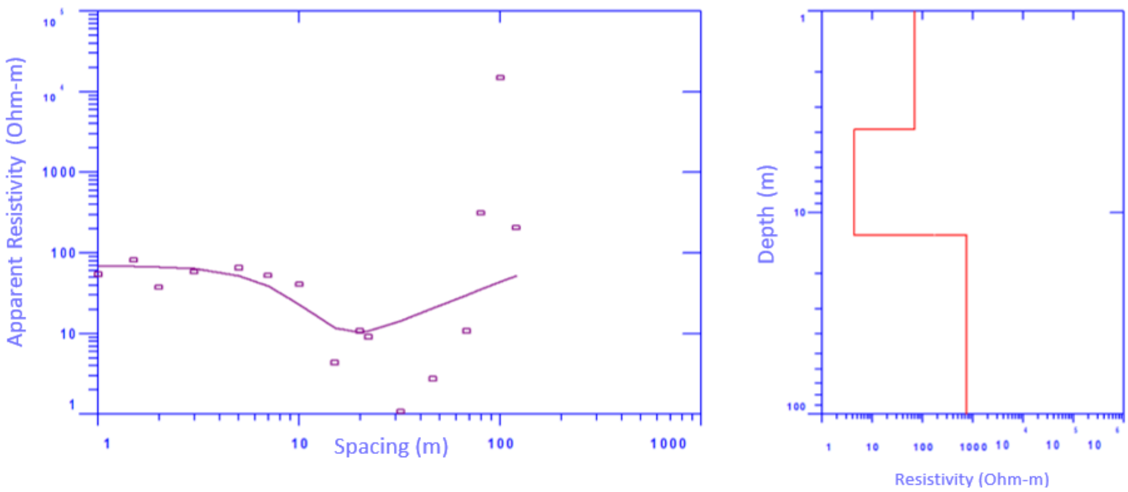


Figure 11. Sounding curve for VES 9 at New Layout, Ikpalegwa Road, Igbo-Imabana

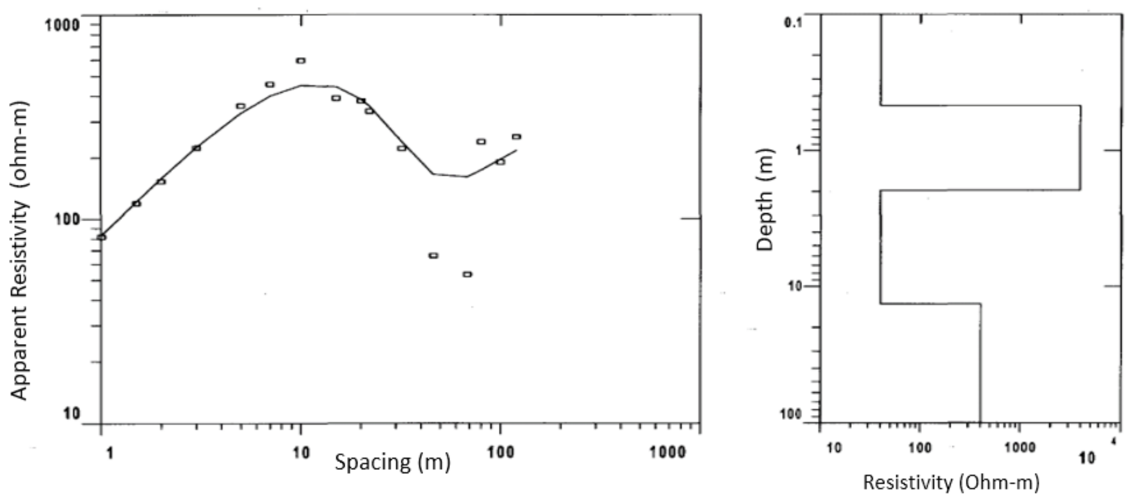


Figure 12. Sounding curve for VES 10 at Community Prim. Sch., Ikpalegwa, Igbo-Imabana

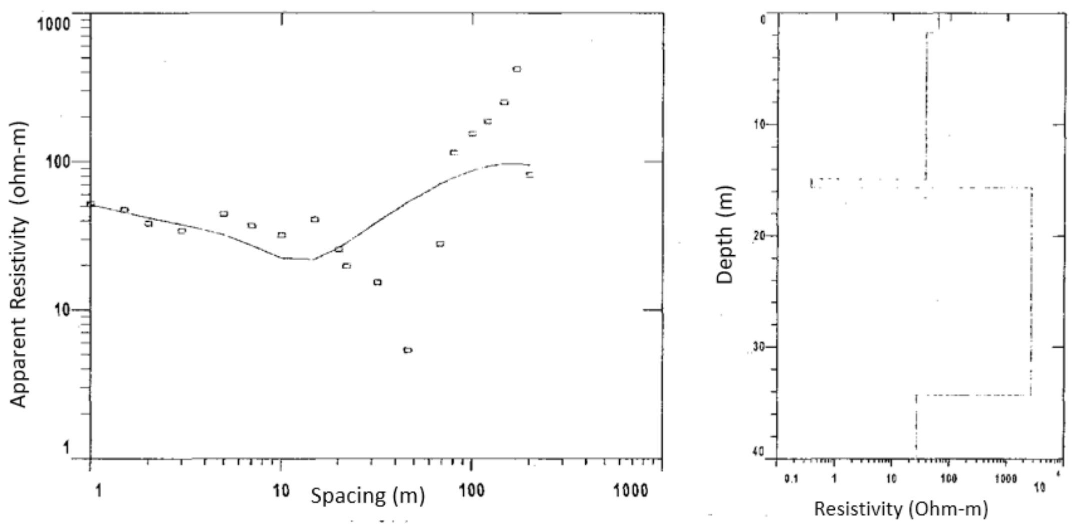


Figure 13. Sounding curve for VES 11 at Egbakili, Igbo-Imabana

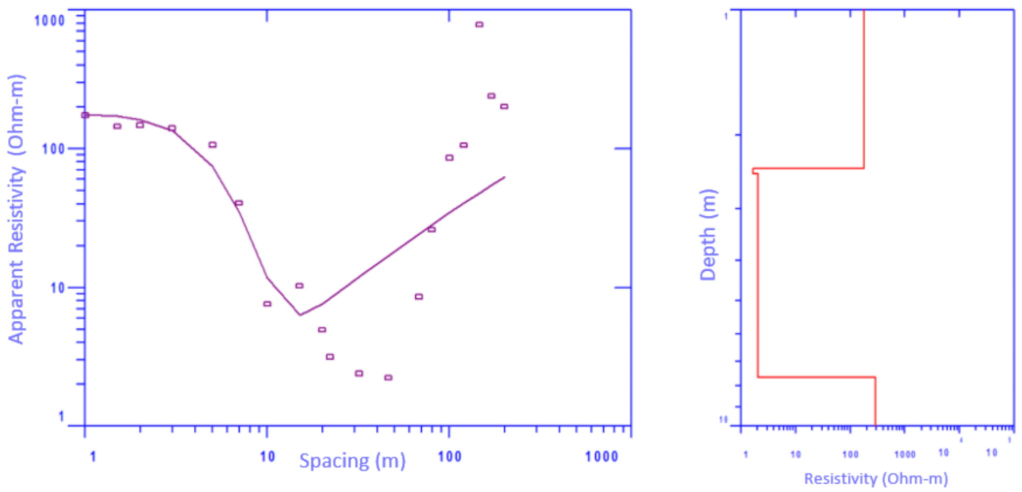


Figure 14. Sounding curve for VES 12 Behind Sec. Sch., Igbo-Imabana

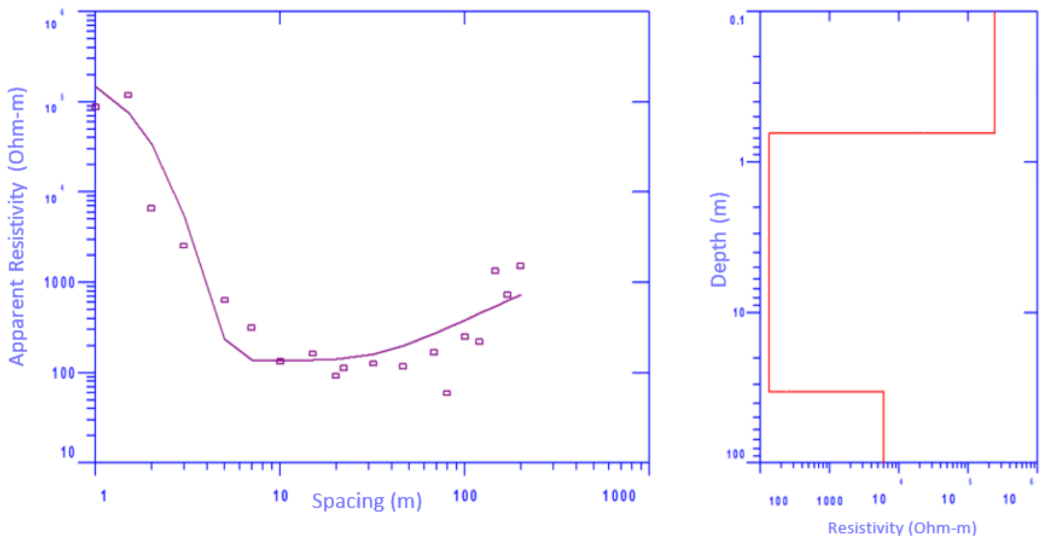


Figure 15. Sounding curve for VES 13 at Ozomozo, Igbo-Imabana

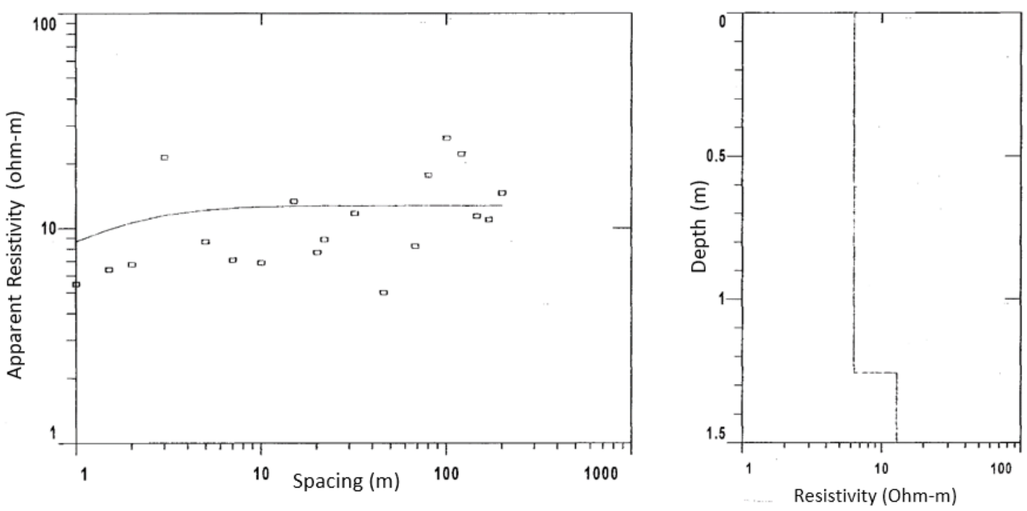


Figure 16. Sounding curve for VES 14 at Litakpa, Igbo-Imabana

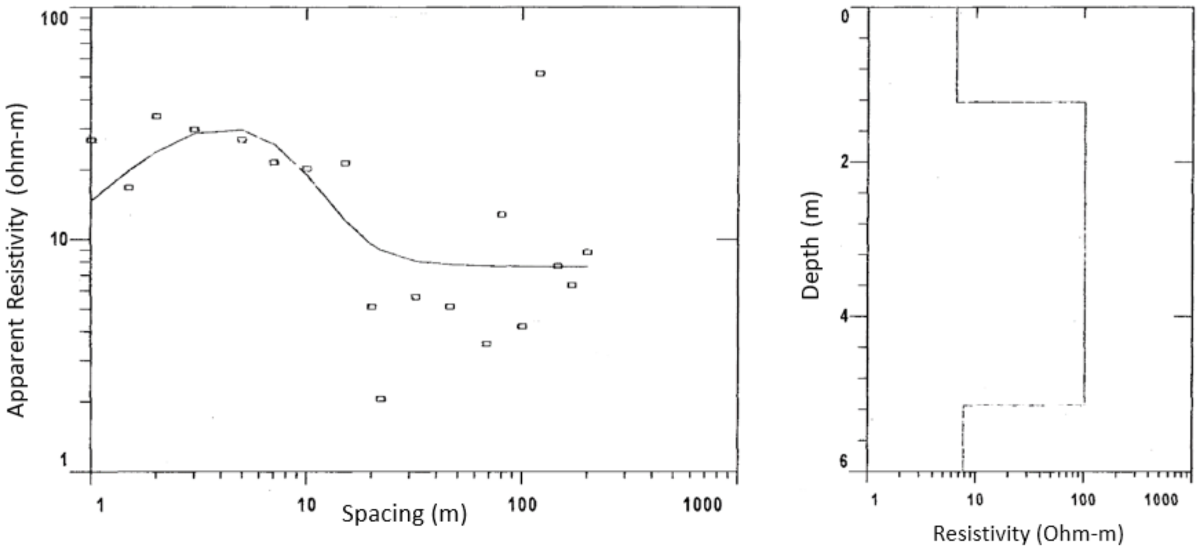


Figure 17. Sounding curve for VES 15 at Lehoma, Igbo-Imabana.

4.1 Correlation of the VES Point and Their Parameters in the Study Area

The geo-electric correlation sections (Figure 18) alongside with other aquifer parameters (Table 2) showed vertical and lateral variations in layer resistivity and thickness, which is a revelation of the lateral and vertical lithological changes in the study area varies significantly. Three to six subsurface layers were identified from geo-electric layer section. Virtually all the VES points have clay layer except for VES 7, 10 and 13. It is difficult to assign a specific depth point to groundwater occurrence in the area following the non-uniformity and contrasting heterogenous subsurface lithofacies. It was also observed that not all the VES points have litho-unit that has textural characteristics that enhance accumulation and discharge of groundwater. Such as it were case at VES 1, 5, 14 and 15. The aquifers across the area was found basically to be sandy shale/shaly-sand and sandstone. The sandy shale average apparent resistivity value of 222.69 Ωm, the sandstone is of two categories in the area with average apparent resistivity values of 365.28 Ωm and 2249.94 Ωm for saturated sandstone and unsaturated/fresh water bearing sandstone respectively. The presence and impact of shale litho-facie within sandy-shale aquiferous unit in some locations is highly suggestive that primary porosity will be very low such that water transmission and storage will be very poor [48]. Whereas the sands are usually saturated with water and forms dependable aquifer [49,50].

4.2 Curve Types

Following the three layers subsurface classification model on basis of apparent resistivity contrast the curve types were established [51]. The VES curve types identified in the study area include K, H, A, QHK, KH, QK, HK, HA and KHK. The curve H type is the most frequent sounding curve type in the study area followed by K curve type (Table 3 and Figure 19). The diversity in curve types also affirms the heterogeneity of the subsurface litho-units in the area.

4.3 Aquifer Parameters Characterization of the Study Area

The aquifer parameters/hydraulic characteristics of the study area were established using the concept of Dar-Zarrouk parameter. The aquifer hydraulic conductivity obtained from the study area (Figure 20(a) and Table 4) ranges from 3.86×10^{-4} to 4.69×10^{-2} m/day with average of 6.42×10^{-3}m/day. From the values obtained, the area are characterized by semi-pervious relative permeability according to Bear, J. classification [52]. Its further portrays that area is dominantly underlain by fine-very sand, silt and shale such that aquifer attribute/yield will likely be good to poor in term of water discharge. This lithology characteristics might have affected the hydraulic conductivity of a porous rock varying with the volume (thickness) and arrangement of the pores (textural characteristics of layer) as well as amount of fluid contain. Here, mineral content (mostly clay minerals) and pore size distributions will be very impactful on indirect/direct aquifer characterization.

The apparent resistivity contrast of the aquiferous zone ranges from 21.31 Ωm to 2588.7 Ωm and an average of

786.04 Ωm. These units are indicated in the geoelectrical model of subsurface layers and apparent resistivity contouring (Table 4, Figures 18 and 20(d)) characteristic of aquifer materials ranging from saturated fine sand, medium, to very coarse sand with vary degree of fluid saturation. The variation in conductivity of these saturated zones may be due to the varying concentration of dissolved impurities, and high water resistivities and small grain sizes, knowing that electrical current is not only conducted by the pore fluid but also by the grain matrix [53,54].

Table 1. Summary of Interpreted VES Data

No. of Layers	Thickness (m)	Depth (m)	Apparent Resistivity (Ωm)	Inferred Lithology
VES 1				
1	0.37	0.37	13.29	Clayey top soil
2	0.359	0.729	1.02	Clay
3	ND	ND	101.1	Shale
VES 2				
1	0.989	0.989	105.8	Lateritic top Soil
2	13.72	14.71	14.19	Clay/Shale
3	6.62	21.34	1405.1	Sandstone
4	ND	ND	14.19	Clay/Shale
VES 3				
1	1.34	1.34	764	Sandstone
2	5.76	7.1	484.3	Saturated Sandstone
3	1.09	8.2	1.24	Clay
4	ND	ND	210.7	Sandy Shale
VES 4				
1	0.316	0.316	115.7	Lateritic Top soil
2	1.95	2.26	236.4	Sandy Shale
3	1.53	3.8	2.38	Clay
4	ND	ND	1219.5	Sandstone
VES 5				
1	0.689	0.689	22.54	Clayey top soil
2	0.0886	0.778	2232.3	Compacted laterite
3	0.612	1.39	0.177	Clay
4	60.04	61.43	21.31	Shale
5	ND	ND	0.215	Clay
VES 6				
1	1.29	1.29	2398.2	Compacted Lateritic Soil
2	2.59	3.89	15.89	Clay/Shale
3	26.26	30.15	1573.7	Sandstone
4	ND	ND	15.89	Clay/Shale
VES 7				
1	0.3863	0.3863	176.44	Sandy Soil
2	0.222	0.608	23853.4	Dry Sandstone
3	2.793	3.401	65.48	Shale

Table 1 continued

No. of Layers	Thickness (m)	Depth (m)	Apparent Resistivity (Ωm)	Inferred Lithology
VES 7				
4	68.29	71.69	1131.4	Sandstone
5	ND	ND	446.08	Saturated Sandstone
VES 8				
1	0.39	0.39	28.38	Clayey Top soil
2	5.26	5.65	1.334	Clay
3	ND	ND	157.91	Sandy Shale
VES 9				
1	4.193	4.193	65.68	Shaley Top Soil
2	11.13	15.32	4.916	Clay
3	ND	ND	719.78	Sandstone
VES 10				
1	0.468	0.468	39.7	Clayey Top soil
2	1.49	1.96	3930.4	Sandstone
3	11.49	13.45	39.7	Shale
4	ND	ND	396.4	Saturated sandstone
VES 11				
1	0.545	0.545	59.71	Shaley Top soil
2	13.99	14.54	13.99	Clayey/Shale
3	0.43	14.97	0.37	Clay
4	19.49	34.46	2588.7	Sandstone
5	ND	ND	26.14	Shale
VES 12				
1	0.293	0.293	179.19	Lateritic Top Soil
	7.429	7.722	1.643	Clay
2	0.232	7.954	2.046	Clay
3	ND	ND	285.76	Sandy/Shale
VES 13				
1	0.643	0.643	239950	Dry Sandy Soil
2	32.96	33.6	134.33	Saturated Sandstone
3	ND	ND	6072	consolidated Sandstone
VES 14				
1	0.383	0.383	6.26	Clay Soil
2	ND	ND	12.72	Clay/Shale
VES 15				
1	0.374	0.374	6.46	Clay Soil
2	4.826	5.2	100.4	Shale
3	ND	ND	6.8	Clay

The aquifer transmissivity ranges from 2.95×10^{-3} to 2.82 m^2/day with an average value of 2.78×10^{-1} m^2/day (Table 4 and Figure 20(b)). At the minimum depth of aquifer unit in the area (about 5 m), the boreholes have high likelihood of failing mostly when the thickness is below 5m also accentuated by confining nature of most of the aquifers. This defines the aquifer yield relationship to be proportionate to thickness and hydraulic conductivity (See Equation (8)). Compering Figure 20(a-c) shows that the contour map of transmissivity is much more similar to that of aquifer thickness, which is an indicative that transmissivity in confined aquifer (like the study area) is much more related to aquifer thickness than hydraulic conductivity. These are indicative of the productive potential of the aquifers. Relatively, aquifer depth varies from 5.20 m to 76 m and thickness range of 3.60 m to 68.05 m with an average of 27. 29 m. The depth range is suggestive of occurrence of both shallow and deep aquifer in the area, this further explained reasons for borehole failures as the shallow aquifer(s) thickness are small hence borehole has high likelihood of failing in such scenario. The transverse resistance varies from 484.33 Ω^2m to 19444.83 Ω^2m having an average of 47192.76 Ω^2m in the area (Figure 20 (f)).

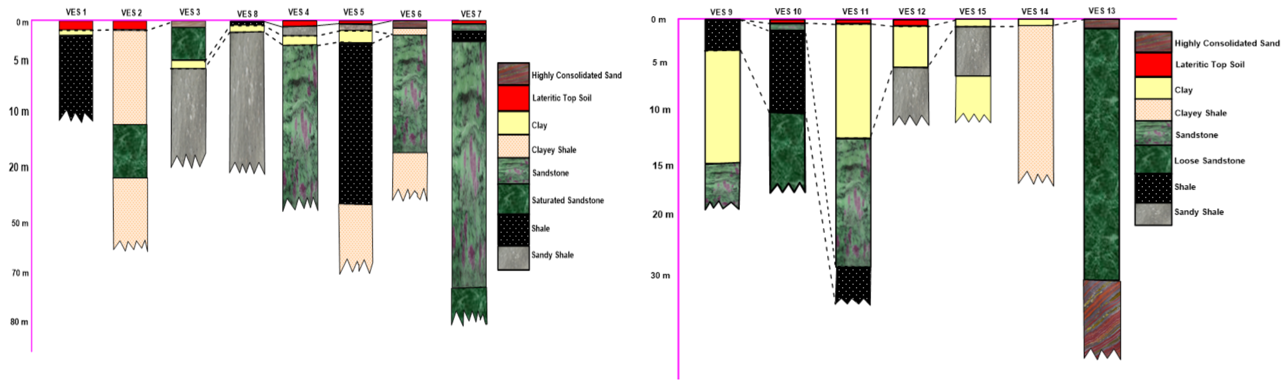
These hydro-geophysical isopach maps of the aquiferous layer (Figure 20 (a-f)) shows that one major significant fact why majority of boreholes drilled in the area fails anchors on heterogeneity of the subsurface litho-units and aquifer thickness which are high variability in the study area. Following this, water transmission and percolation into the underlying aquiferous units in the area will be low. Presence of clay also implies that the underlying aquiferous units are vulnerable to contamination due to the seemingly low values of the aquifer longitudinal conductance which is far less than unity (S < 1) except for VES 5 whose longitudinal conductance ranging from 2.95×10^{-3} to 2.81 Ohm^{-1}, having an average of 0.278 Ohm^{-1} and also clay at the top and bottom which acts as protective cover. Such that the lithologies encountered very much changes laterally and vertically from one VES point to another.

The summary of the study area groundwater supply/productive potential, protective capacity rating, transmissivity and percentage area coverage is presented in Table 5 (a-c), modified after specified standards [55-59].

Table 2. Geo-electric layers and their Average parameters for Aquifer Delineations

Parameter	C	Sst/Sh	C/Sh	Sst	Sat. Sst	Sh
Average ρ values (Ωm)	2.862	222.69	14.60	2249.94	365.28	59.022
Average depth (m)	5.115	NA	10.87	26.82	20.35	20.87
Average thickness (m)	1.630	NA	10.10	20.58	19.36	19.70
Minimum ρ (Ωm)	0.177	285.76	12.72	716.78	134.33	21.31
Maximum ρ (Ωm)	6.80	157.91	15.89	6072	484.3	101.1
Minimum depth (m)	0.37	2.26	3.89	1.340	7.1	3.401
Maximum depth (m)	15.32	NA	14.97	71.69	33.6	61.43
Minimum Thickness (m)	0.232	1.95	2.59	1.340	5.76	2.79
Maximum thickness (m)	11.13	NA	3.89	68.29	32.96	60.04
VES with Unknown depth and thickness	5&15	3,8&12	2,6&14	4,9&13	7 & 10	1&11

C =Clay, Sst/Sh = Sandy Shale, C/Sh = Clayey shale, Sst = Sandstone, Sat. Sst = Saturated sandstone, Sh = Shale, NA = Not Applicable



a b

Figure 18. a: Geo-electric correlation of VES 1 to VES 8; b: Geo-electric correlation of VES 9 to VES 15

Table 3. Classification of VES Curve Types in the Study Area

S/N	VES Curve type	VES N0	VES curve characteristic	Frequency	% Values
1	K	15	$\rho_1<\rho_2>\rho_3$	1	6.67
2	H	1,8,9,13	$\rho_1>\rho_2<\rho_3$	4	26.67
3	A	14	$\rho_1<\rho 2<\rho_3$	1	6.67
4	QHK	11	$\rho_1>\rho_2>\rho_3<\rho_4>\rho_5$	1	6.67
5	KH	4, 10	$\rho_1<\rho 2>\rho_3<\rho_4$	2	13.33
6	QK	3	$\rho_1<\rho_2>\rho_3<\rho_4$	1	6.67
7	KHK	5, 7	$\rho_1<\rho_2>\rho_3<\rho_4> \rho_5$	2	13.33
8	HK	2,6	$\rho_1>\rho 2<\rho_3>\rho_4$	2	13.33
9	HA	12	$\rho_1>\rho 2<\rho_3>\rho_4$	1	6.67

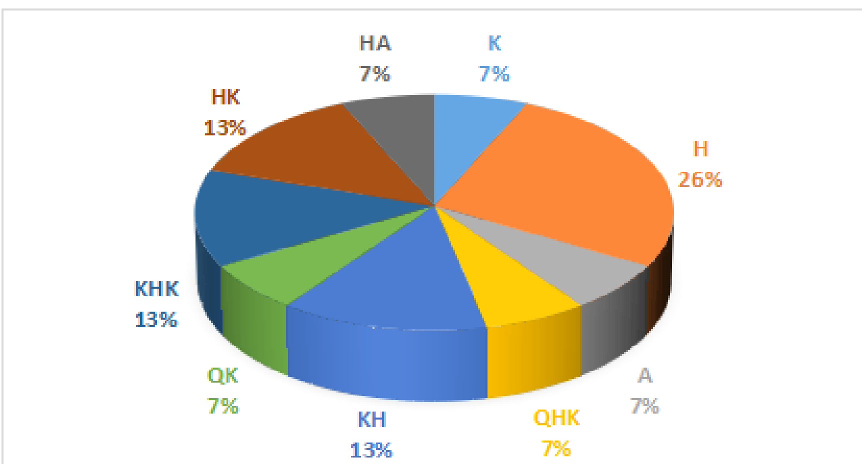
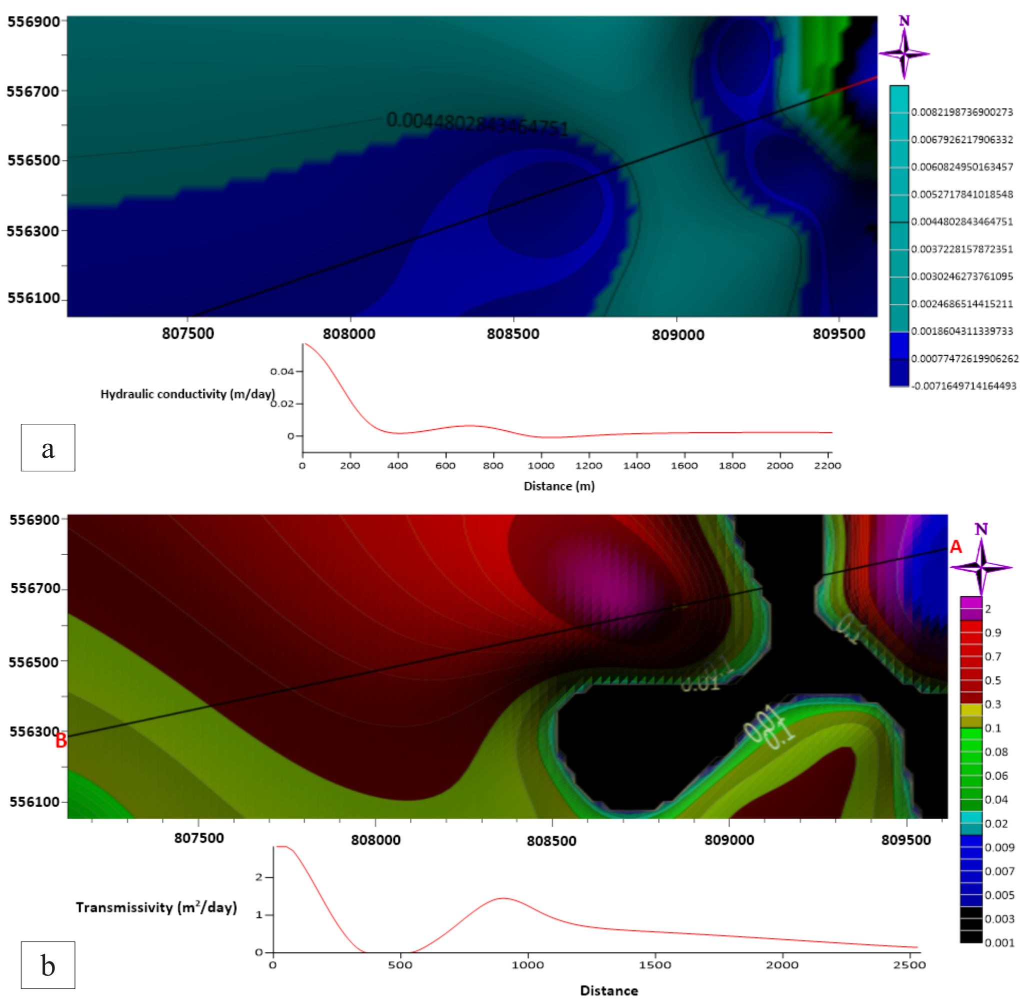


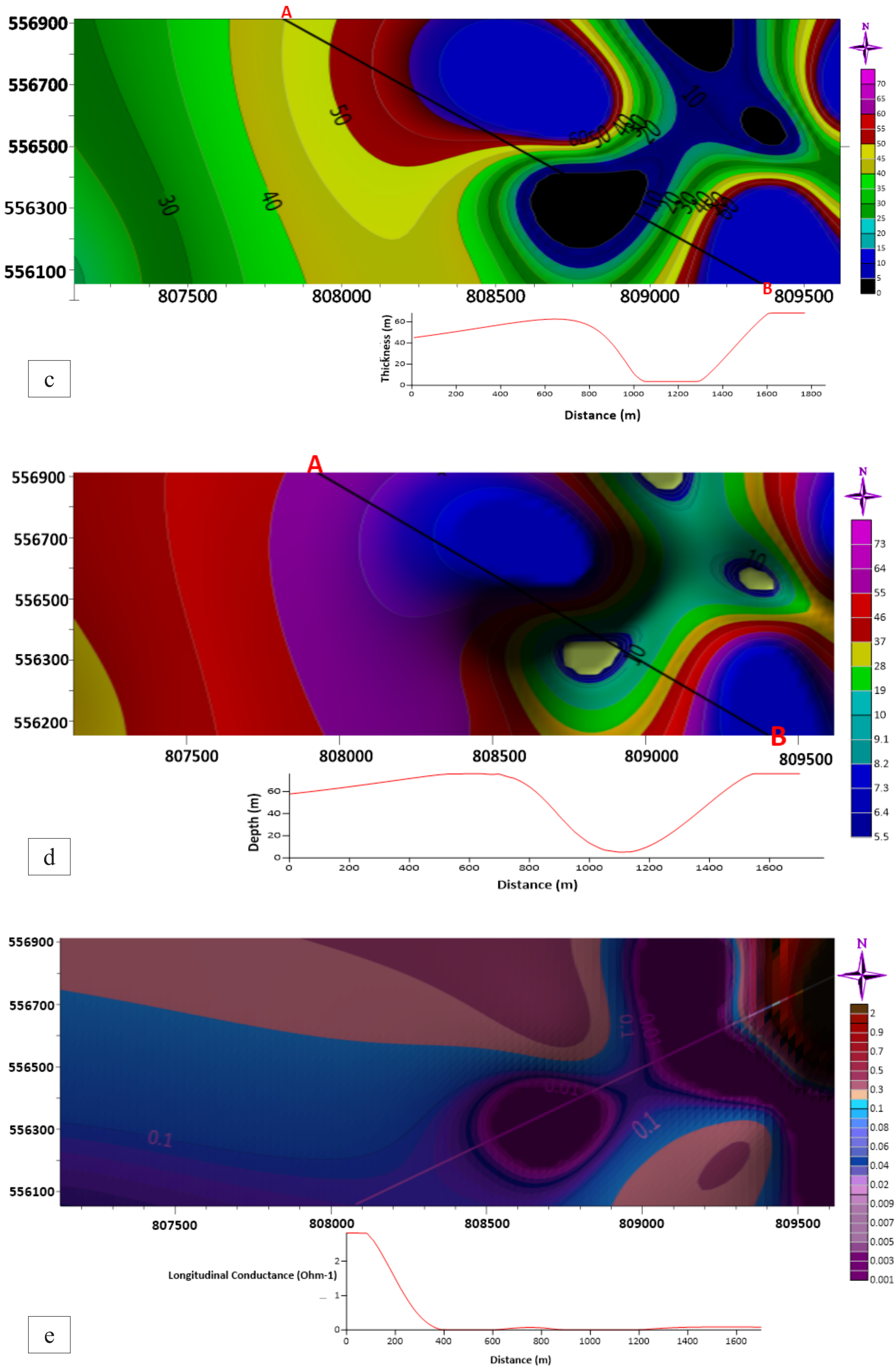
Figure 19. Pie Chart Classification of Vertical Electrical Sounding (VES) Curve type of study Area

Table 4. Summary of Results of the aquifer Parameters Integrated from the Geo-electric Sections in the Study Area

VES NO	Depth to Aquifer (m)	Aquifer thickness (m)	Apparent resistivity (Ohm-m)	Transverse resistance (Ohm-m^2)	Longitudinal Conductance (Ohm^{-1})	Hydraulic conductivity (m/day)	Transmissivity (m^2/day)
1	ND	ND	ND	ND	ND	ND	ND
2	21.34	6.62	1405.1	9301.76	0.00471	7.12×10^{-4}	4.71×10^{-3}
3	7.10	5.76	484.3	2789.57	0.0119	2.07×10^{-3}	1.19×10^{-2}
4	7.4	3.6	1219.5	4390.2	0.00295	8.20×10^{-4}	2.95×10^{-3}
5	61.43	60.04	213.1	1279.45	2.82	4.69×10^{-2}	2.82
6	30.15	26.26	1573.7	41325.36	0.0167	6.36×10^{-4}	1.67×10^{-2}
7	71.69	68.29	1131.4	77263.31	0.0604	8.84×10^{-4}	6.04×10^{-2}
8	15.8	10.15	157.91	1602.79	0.0643	6.33×10^{-3}	6.43×10^{-2}
9	45.21	29.41	719.70	21168.73	0.0409	1.39×10^{-3}	4.09×10^{-2}
10	32.81	19.36	396.4	7674.304	0.0488	2.52×10^{-3}	4.88×10^{-2}
11	34.46	19.49	2588.7	50453.76	0.00753	3.86×10^{-4}	7.53×10^{-3}
12	76.00	68.05	285.76	19444.83	0.238	3.45×10^{-3}	92.38×10^{-1}
13	33.6	32.96	134.33	4427.52	0.245	7.44×10^{-3}	245×10^{-1}
14	ND	ND	ND	ND	ND	ND	ND
15	5.20	4.826	100.4	484.33	0.0481	9.96×10^{-3}	4.81×10^{-2}

ND = Not Determined




c
Thickness (m)
Distance (m)
d
Depth (m)
Distance (m)
e
Longitudinal Conductance (Ohm-1)
Distance (m)
A
B
N

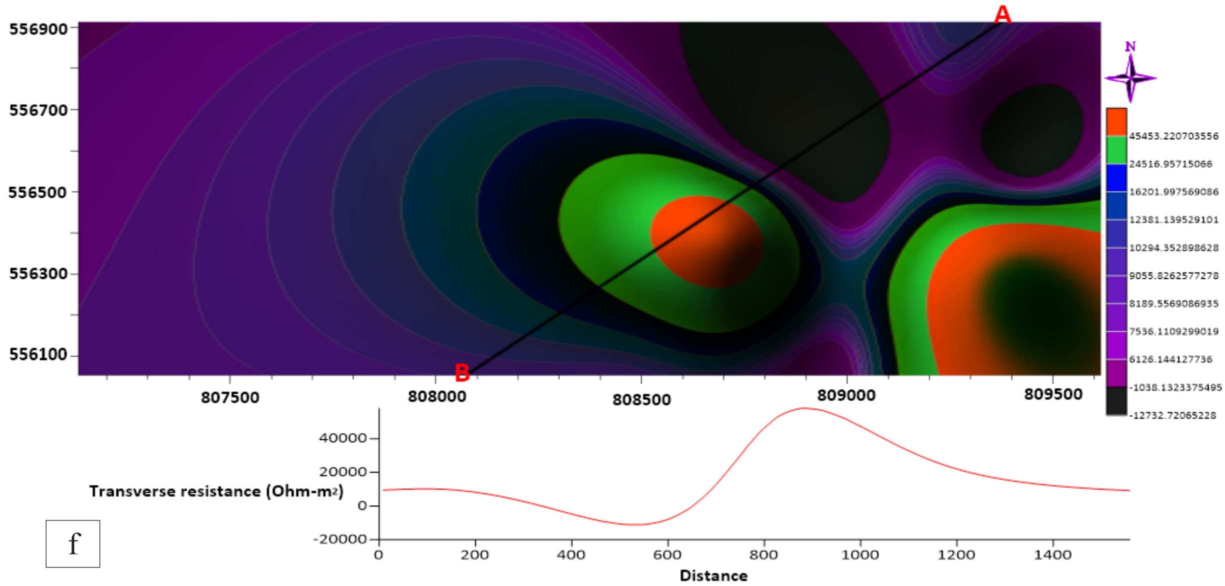


Figure 20. (a) Aquifer Hydraulic Conductivity Map, (b) Aquifer Transmissivity Map (c) Aquifer Thickness Map, (d) Aquifer Depth Map, (e) Aquifer Longitudinal Conductivity Map, (f) Aquifer Transverse Resistance of the study area.

Table 5a. Characterization of Aquifer Transmissivity Potentials of the area (after Standard of [55])

Transmissivity Rate	Transmissivity Potentials	VES Locations	Percentage (%)
> 500	High Potential	-	0
50 – 500	Medium Potential	-	0
5 – 50	Low Potential	12, 13	13.33
0.5 – 5	Very Low Potential	5	6.67
< 0.5	Negligible	1, 2, 3, 4, 6, 7, 8, 9, 10, 11, 13 & 15	80

Table 5b. Aquifer Transmissivity and Longitudinal Conductance Standard for Groundwater Characterization **(**Modified Aquifer Transmissivity Standard [56])

Transmissivity (m^2/day)	Designation	Groundwater Supply potential	VES Location	Percentage (%)
>1000	Very High	Withdrawal of great regional importance	-	-
100 -1000	High	Withdrawal of lesser regional importance	-	-
10 – 100	Intermediate	Withdrawal of local water supply (small Communities)	13	6.67
1 – 10	Low	Smaller withdrawal for local water supply (private Consumption)	12, 5	13.33
0.1 – 1	Very Low	Withdrawal for local water supply with limited Consumption	-	-
< 0.1	Impermeable	Source for Local water supply are difficult, if possible, to ensure	1, 2, 3, 4, 6, 7, 8, 9, 10, 11, 14, & 15	80

Table 5c. Modified Aquifer Productive Capacity Rating [57-59]

Longitudinal conductance (Ωm)	Protective Capacity Rating	VES Locations	Percentage (%)
>10	Excellent	-	-
5 – 10	Very Good	-	-
0.7 – 4.9	Good	5	6.67
0.2 – 0.69	Moderate	12, 13	13.33
0.1 – 0.19	Weak	-	-
< 0.1	Poor	1, 2, 3, 4, 6, 7, 8, 9, 10, 11, 14, & 15	80

5. Conclusions

The identification of aquiferous layers and aquifer parameter functions (conductivity, transmissivity, thickness, depth etc.) in the study area can be made possible through application of vertical electrical sounding (VES) method which in turn has been used to characterize the area. Finding of this research indicated that Igbo-Imabana area has generally low to impermeable lithologic units, which can only sustain borehole drilled for the purpose Withdrawal of local water supply (small Communities) and withdrawal for local water supply with limited consumption. Larger part of the area has difficult source for local water supply, if possible. The transmissivity potential of the area is relatively moderate to negligible, having weak to poor protective capacity. Aside the heterogeneity of subsurface lithology in the area, diagenetic processes, porosity alterations, tectonic events within the area also altered the primary porosity and permeability of the rocks in the past, hence semi-impervious nature of rock units dominate the area. Very high variation in lithologies, as depicted by geo-electric correlation, has impacted significantly, laterally and vertically on the porosity and permeability of the subsurface units (rock) in the area. This enhances heterogeneity of the lithology of the area. The depth to aquiferous units within the area is not precise (because from the result there is no uniform depth and thickness for the aquiferous units across the VES). There are also interlayering of shale, sandy-shale, clay and sandstone at the subsurface which was not evenly distributed. However, integrated geophysical approach still stands better ground of aquifer delineation in the study area. Hence geophysical survey has to precede borehole drilling in the area as far as drilling of sustainable productive borehole remains the cardinal priority.

Conflict of Interest

The authors declare that they have no competing interests.

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