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EVALUATION OF THE PROTECTION AND HYDRAULIC CHARACTERISTICS OF THE AQUIFER FORMATION USING SECOND ORDER GEOELECTRIC INDICES AND PUMPING TEST IN AGHALOKPE, NIGERIA

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ABSTRACT
In this work, the vertical electrical sounding method and the borehole pumping test analysis were used to investigate the study area and to assess the geoelectrohydraulic parameters and aquifer protective capacity. Fifteen (15) Vertical electrical sounding (VES) stations spread across the study area with a maximum electrode separation, AB/2 of 200 m were occupied. The results provide information on aquifer electrical and hydraulic properties which included the aquifer resistivity, aquifer thickness and depth, longitudinal unit conductance, transverse resistance, hydraulic conductivity and transmissivity. The aquifer resistivity values ranged from 503–18914 Ωm, with a depth for adequate water production given as 14 m to a maximum of 22 m. The calculated longitudinal conductance and inferred protective capacity ranged from 0.0141 - 0.167 mho, indicating weak to moderate capacity. The borehole pumping test data was analysed using the Cooper-Jacob method in determining the aquifer parameters. The hydraulic conductivity (K) value mea sured from a reference well was combined with Dar-Zarrouk parameters to estimate the transmissivity and hydraulic conductivity values of the aquifer across the area. The results showed that the aquifer transmissivity values varied from 198.8 m^2/day to 1473.6 m^2/day with an average of 459.8 m^2/day, while hydraulic conductivity values varied from 5.7 m/day to 66.7 m/day, with an average of 31.1 m/day. These estimated parameters indicate that even though the area has high aquifer potential due to its transmissivity and hydraulic conductivity values, it is prone to contamination due to its poor protective capacity.

Keywords: Geoelectric indices, Aghalokpe, Aquifer parameters, Pumping test, Dar- Zarrouk

INTRODUCTION
Groundwater entails water existing underneath the surface of the earth and are contained in sustainable amount in the geologic formation called aquifers (Bierkens and Wada, 2019). Prospecting for prolific aquiferous zones for groundwater resource development has over the years been done by employing diverse means ranging from conventional physical observations to surface geophysical techniques (Todd and Mays 2005). These geophysical techniques detect variations of physical properties such as density, magnetic susceptibility, elasticity, and electrical resistivity and conductivity within the earth crust (Todd and Mays 2005). Electrical resistivity methods employing principally the vertical electrical sounding have been preferred and widely used in groundwater and environmental studies when compared to other geophysical survey techniques. This is because the method provides portability of

equipment, quick measurement of electrical resistivity, and slighter uncertainty in interpretations of results. The hydraulic indices of subsurface aquiferous units are important characteristics for both groundwater and the delineation of contaminant and contaminant flow and land assessments (Oroji, 2019). Therefore, the knowledge of hydraulic conductivity and transmissivity is crucial for the determination of natural water and contaminant flow through an aquifer (Timms et al., 2014). Unfortunately, the model techniques for the determination of aquifer hydraulic indices such as well tests, permeability measurements and grain size analysis are invasive, relatively costly and either integrate over a large volume or only offer information in the neighbourhood of the borehole (Niwas et al., 2011; Ubani et al., 2018). Conventional techniques for borehole data acquisition such as flowmeter and slug tests are expensive, time consuming, and invasive; therefore, electrical resistivity method using the vertical electrical sounding technique has been undertaken to compensate for the paucity of in situ hydrological measurements (Hubbard and Rubin, 2005). Therefore in areas with few pumping tests, the spatial distribution of aquifer properties cannot be confidently calculated. This research is focused on the applicability of geophysical measurements for the determination of aquifer transmitting properties of hydraulic conductivity and transmissivity. The results of this study can be used to improve the quality of groundwater flow simulation models and enhance groundwater resource development in the area and areas with similar geology.

DESCRIPTION AND GEOLOGY OF STUDY AREA

Aghalokpe is a populated place and is located in Delta State, Nigeria. The estimated terrain elevation above sea level is 11 m. Aghalokpe displays the description of the Sombriero-Warri deltaic plain deposits characterized by silts, fine and medium to coarse grained sand formations. It also has clay bands that are not uniform in thickness. It is in the Niger-Delta basin and lies within Latitudes 050 36^1 N and 050 42^1N and Longitudes 050 30^1E and 050 31^1 E (Figures 1 and 2). The Niger Delta basin has three predominant formations, which are the Benin, Agbada and Akata Formations. The Benin Formation is the youngest and contains the productive aquifer for urban and industrial water needs of the area. The vegetative cover is of rain forest and has equatorial climate of two main seasons (raining and dry seasons). The raining season begins in late March and extends to late September while the dry season starts in October and end in early March. Aghalokpe is close to Orerokpe which is the Headquarter of Okpe Local Government Area and has an area of about 291.37 sq. km.

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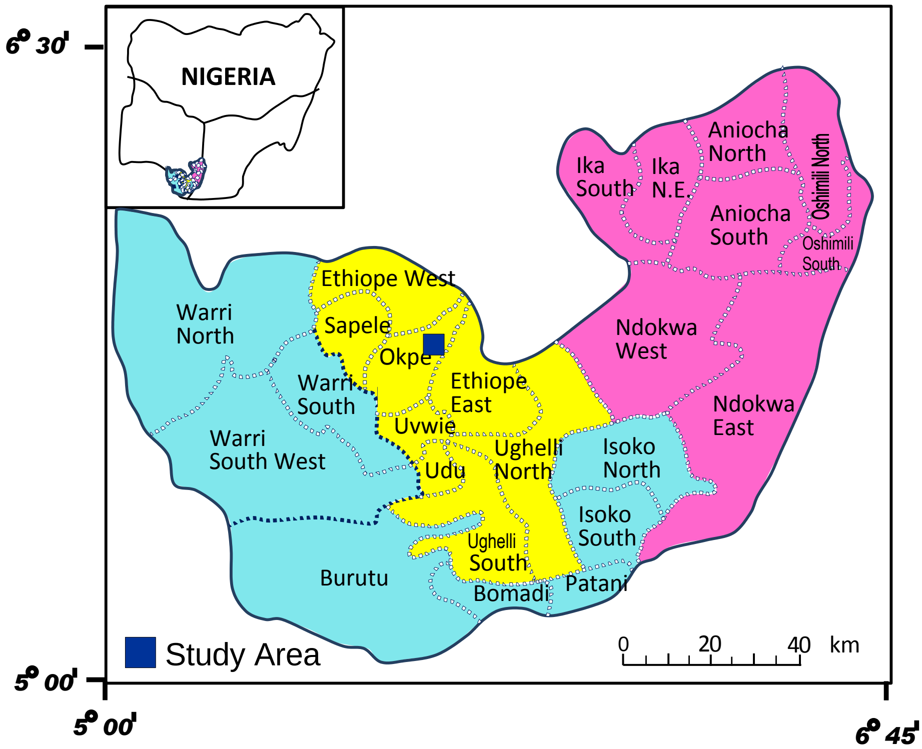

Figure 1: Map of Delta state showing the study area

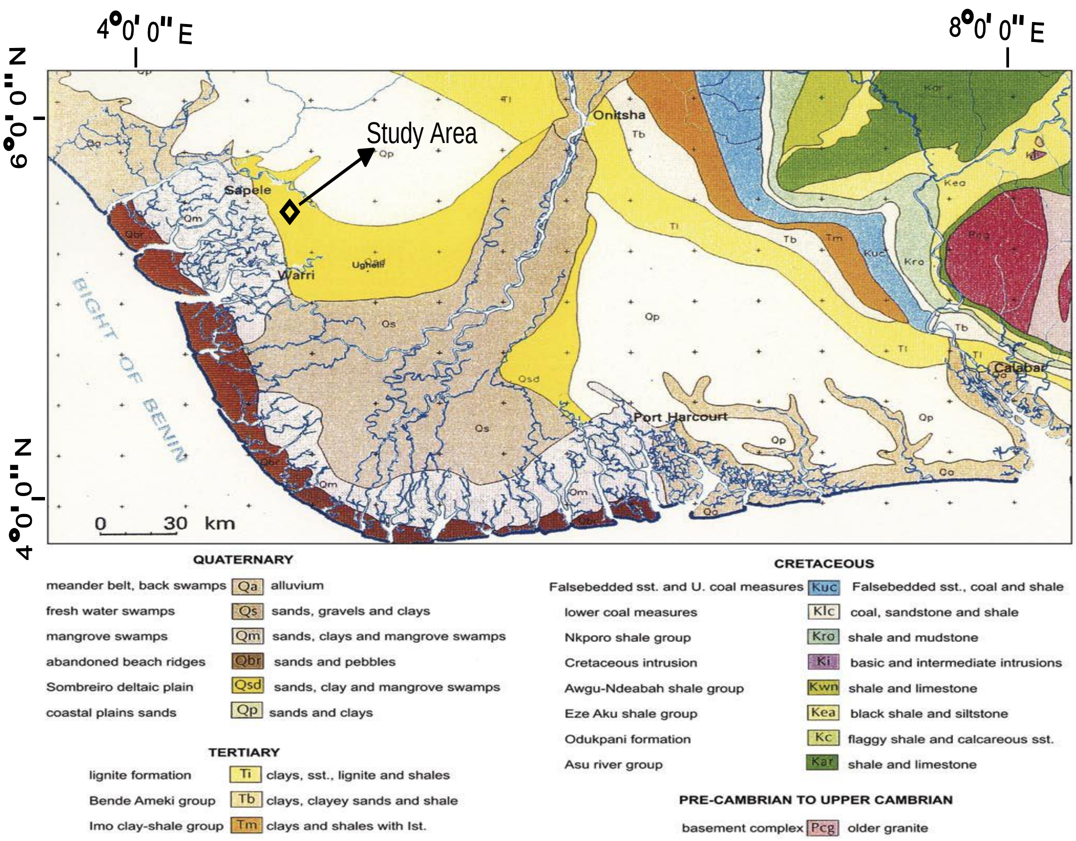

Figure 2: Geological map of the Niger Delta showing the study area (After Reijers, 2011)

METHOD OF STUDY

Vertical Electrical Sounding Measurement

In this study, Fifteen (15) VES stations spread across the study area were occupied (Figure 3). Geoelectric soundings were taken along roads and open spaces with a maximum electrode separation, AB/2 of 200 m. In the VES survey, two pairs of electrodes with the ABEM SAS 1000 Terrameter were used. One pair of electrode (AB) was used for current injections to the ground, while the other pair (MN) was used for potential difference measurements (Figure 4). From the current (I) and voltage (V) values, an apparent resistivity ρ_a value is calculated for all VES locations using equation 1. The apparent resistivity obtained together with the electrode spacing were used to generate sounding curves and the obtained results used as input data for computer iteration using the winResist software. The true aquifer layer resistivity and thicknesses were obtained after iteration.

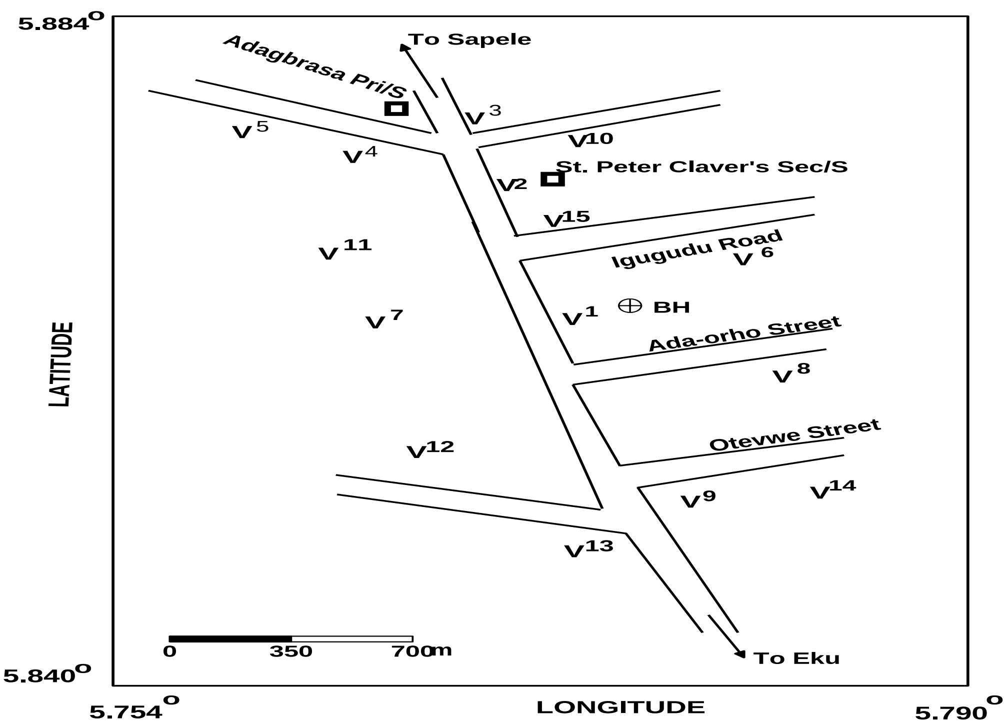

Figure 3: Location and data acquisition strategy map

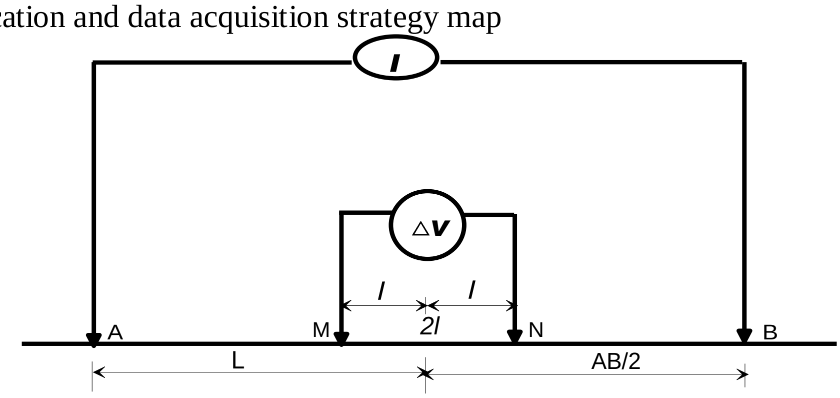

Figure 4: Schlumberger electrode arrangement

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Theory of the Vertical Electrical Sounding

There is a direct proportionality between the measured potential difference and the resistivity of the earth medium. In practice, the variation in electrical conductivity being sought for in a medium, is a function of the change in apparent resistivity and also connected with hydraulic parameters (Anomohanran and Orhiunu, 2018). The layer apparent resistivity (ρ) were calculated following the equation,

$$\rho = \pi R L^2 / 2l \quad (1)$$

where $R = \Delta V / I$ is the resistance and ΔV and I are change in voltage and current respectively.

A geoelectric unit is characterized by two parameters called the first order geoelectric parameters derived from the iterated resistivity field curves, and they are the layer resistivity (ρ_i) and the layer thickness (h_i) for the ith layer (i = 1 for the surface layer). These first order geoelectric parameters were used to generate the second order geoelectric indices or the Dar-Zarrouk parameters, namely; longitudinal unit conductance (S_i) and transverse unit resistance (Reynolds, 1997). For n layers,

The total longitudinal unit conductance $$S_i = \sum_{i=1}^{n} \frac{h_i}{\rho_i} \quad (2)$$

The total Transverse unit resistance $$T_i = \sum_{i=1}^{n} \rho_i h_i \quad (3)$$

The longitudinal layer conductance *Si* can also be represented by

$$S_i = \sigma_i h_i \quad (4)$$

where σ_i is the layer conductivity. Conductivity in this case is analogous to the layer transmissivity Ti used in groundwater hydrology and it is given by

$$T_i = K_i h_i \quad (5)$$

where K_i is the hydraulic conductivity of the *i* layer of thickness h_i.

Also, the relationship connecting the transmissivity T_i and transverse resistance R can be stated as follows:

$$T_i = K\sigma R = Kh \quad (6)$$

Transmissivity and Longitudinal conductance S can also be connected with a similar relationship,

$$T_i = \frac{KS}{\sigma} = Kh \quad (7)$$

Niwas and Singhal (1981) affirmed that the product Kσ remains literally constant where there are no considerable variation in the geologic setting and water quality. Thus, from the known value of K generated from pumping test, and σ from the vertical electrical sounding interpretation around the boreholes, the value of transmissivity and its variation from one place to another in the study area can be evaluated through the determination of R or S according to Equations (6) and (7).

Borehole Assessment

Two boreholes 26 m deep and 7 m away from each other representing the test and observation wells were drilled to determine the aquifer parameters. Prior to pumping, the well heads were opened and the static water level was measured and recorded using a calibrated Dipmeter. The submersible pump was then lowered to appreciable depth and connected to the power generating set. A known 20 litres volume of container was set in place to collect discharge and the stop watch set to zero start time. Pumping was then started, drawdown measured at a scheduled interval time of 5 mins. The time and water level discharge were also measured and record simultaneously. The pumping test techniques was carried out in three sequential stages; the discharge stage, constant rate test and the recovery stage A submersible pumping machine of 5.5 hp capacity was installed in the test well and used to power the pump. The well was pumped at a constant rate of 0.317 m^3/min. At some interval of time, the depth of the water level in the well was measured. This process was continued and the drawdown determined. The drawdown is obtained by subtracting the water level at a given time from the water level before pumping commenced. The difference in the elevation of the water level before and after pumping was plotted against time of pumping on a semi-logarithmic graph sheet for the different locations. The results of the pumping test were interpreted by employing Cooper-Jacob's straight line approach (Jiao and Rushton, 1995; Fetter, 2001; Anomohanran, 2014). The method estimates transmissivity by fitting a straight line to aquifer drawdown against the time since the pumping was started on a semi-logarithmic scale. Transmissivity in m^3/s, is given by:

$$T = \frac{2.3Q}{4\pi \Delta Ss} \quad (8)$$

Q is the rate of discharge, measured in m^3/s, Δs is the slope in m. Also, The hydraulic conductivity (K) was calculated from the relation;

$$T = Kb \quad (9)$$

where b is the saturated aquifer thickness (in metres) obtained from the VES result. The storativity, S is given as

$$S = \frac{2.3Tt}{r^2} \quad (10)$$

t is the time since pumping started and r, the radial distance from the test well.

RESULTS AND DISCUSSION

The data obtained from the electrical resistivity survey was plotted on a log-log graph paper with apparent resistivity values along the ordinate and half electrode separation along the abscissa. The resulting curves are referred to as depth sounding curves. The acquired data were processed qualitatively and quantitatively. A typical depth sounding curve description and summary of the aquifer parameters are shown in figure 5 and Table 1 respectively.

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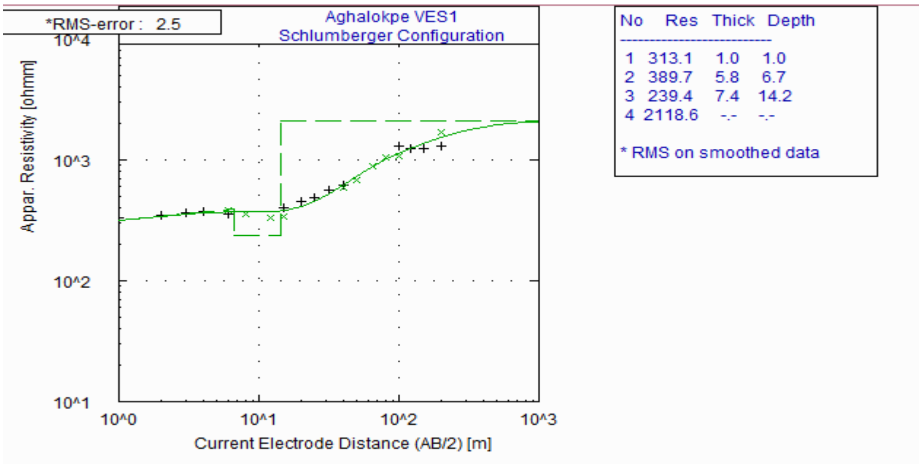

Figure 5: Plot of Apparent Resistivity against Electrode Separation (AB/2) for station 1

Table 1: Interpreted resistivity sounding results

VES Stn.	Resistivity (Ωm)	Thickness (m)	Depth (m)	Inferred Lithology	Curve Type	Longitudinal Conductance	Protective Capacity Rating
1	313	1.0	1.0	Lateritic topsoil	KH	0.0491	Weak
	389	5.8	6.7	Lateritic sand			
	239	7.4	14.2	Fine sand			
	2118			Coarse sand			
2	167	0.9	0.9	Lateritic topsoil	KH	0.0521	Weak
	2662	8.5	9.4	Coarse sand			
	503	21.9	31.3	Fine sand			
	2405			Coarse sand			
3	295	3.1	3.1	Lateritic topsoil	K	0.0322	Weak
	1510	32.7	35.8	Medium sand			
	644			Fine sand			
4	303	1.0	1.0	Lateritic topsoil	H	0.0934	Moderate
	172	15.5	16.5	Lateritic sand			
	5210			Coarse sand			
5	152	0.7	0.7	Lateritic topsoil	KH	0.1674	Good
	221	1.4	2.1	Lateritic sand			
	69	7.3	9.4	Clay			
	5914			Coarse sand			
6	220	0.9	0.9	Lateritic topsoil	KH	0.0260	Weak
	982	9.6	10.4	Lateritic sand			
	437	5.3	15.7	Fine sand			
	3012			Coarse sand			
7	1342	0.5	0.5	Lateritic topsoil	KHK	0.0141	Weak
	3891	1.6	2.1	Coarse sand			

	715	9.5	11.7	Fine sand			
	4633	26.3	38.0	Coarse sand			
	422			Fine sand			
8	1251	1.0	1.0	Lateritic topsoil	KHK	0.0298	Weak
	2569	2.8	3.8	Coarse sand			
	451	12.6	16.4	Fine sand			
	3156	26.5	42.9	Coarse sand			
	561			Fine sand			
9	138	0.5	0.5	Lateritic topsoil	HK	0.0271	Weak
	715	16.8	17.3	Lateritic sand			
	2883	45.3	62.7	Coarse sand			
	262			Fine sand			
10	127	0.9	0.9	Lateritic topsoil	KH	0.0979	Moderate
	1662	11.6	12.5	Medium sand			
	303	25.4	37.9	Fine sand			
	2216			Coarse sand			
11	203	1.0	1.0	Lateritic topsoil	HA	0.1612	Good
	102	12.6	13.6	Lateritic sand			
	859	28.1	41.7	Fine sand			
	1542			Coarse sand			
12	1516	0.5	0.5	Lateritic topsoil	KHK	0.0254	Weak
	3647	2.9	3.4	Coarse sand			
	519	12.6	16.0	Fine sand			
	2589	28.2	44.2	Coarse sand			
	510			Fine sand			
13	220	0.5	0.5	Lateritic topsoil	KH	0.0508	Weak
	853	12.4	12.9	Lateritic sand			
	262	8.9	21.8	Fine sand			
	2516			Coarse sand			
14	1336	1.0	1.0	Lateritic topsoil	KH	0.0279	Weak
	2895	2.8	3.8	Coarse sand			
	662	15.4	19.2	Fine sand			
	3156	28.1	47.3	Coarse sand			
	489			Fine sand			
15	285	0.9	0.9	Lateritic topsoil	KH	0.0722	Moderate
	1662	10.6	11.5	Coarse sand			
	503	31.5	43.0	Fine sand			
	3365			Coarse sand			

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The VES results as shown in Table 1 revealed four geoelectric layers which are composed of lateritic topsoil, lateritic sand, fine to medium sand, medium grain sand and coarse grain sand. The geoelectric sections in the northwest to southeast (NW-SE) and northeast to southwest (NE-SW) and across the study area are shown in Figure 6 and 7.

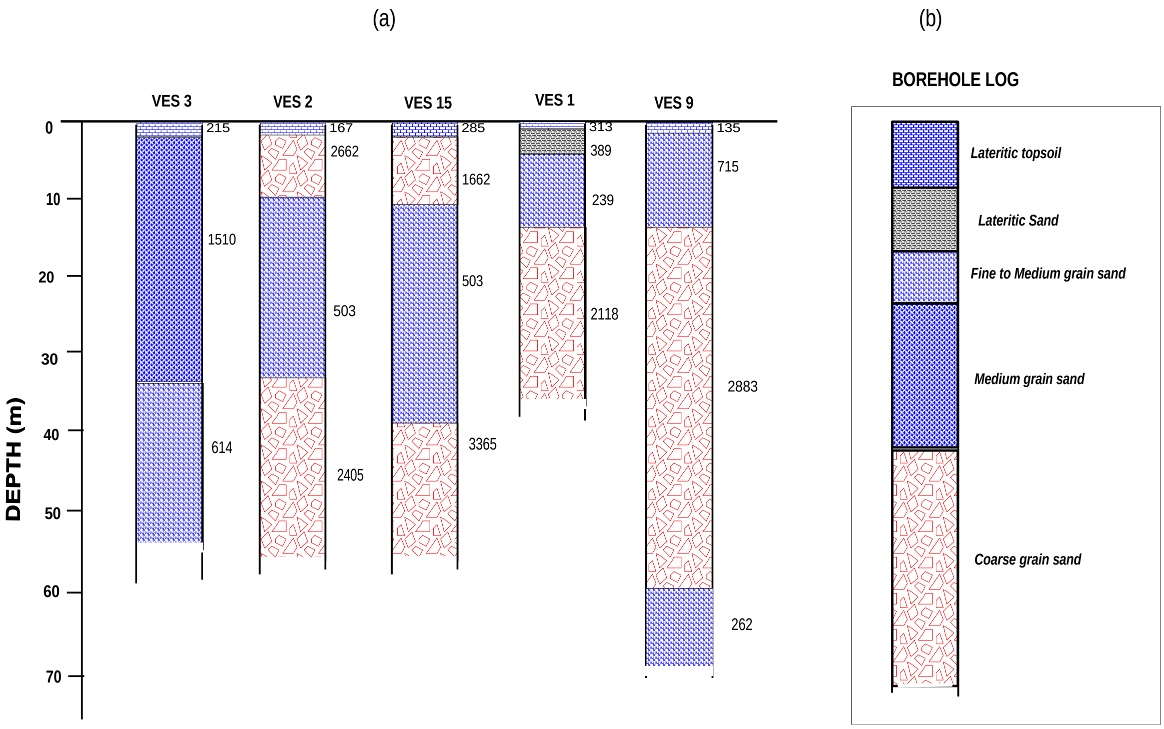

Figure 6: Geoelectric Section across the study in the NW-SE direction

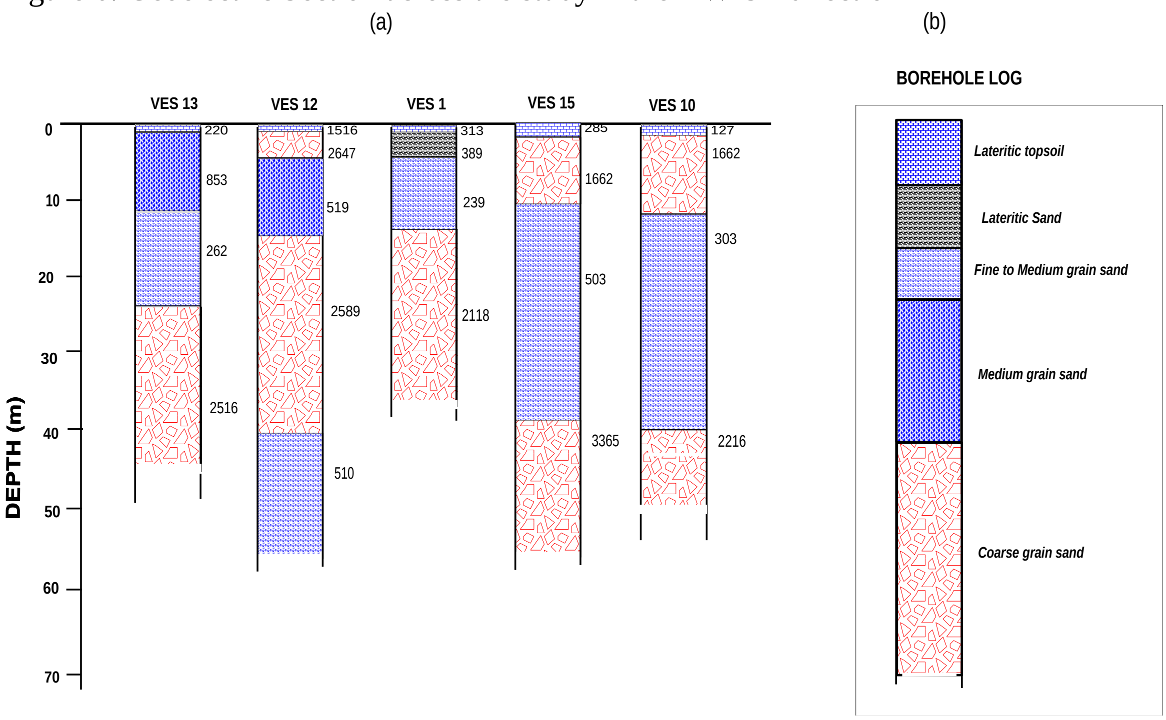

Figure 7: Geoelectric Section across the study in the NE-SW direction

Four geoelectric layers were delineated. Figure 6 shows the geoelectric section in the NW-SE direction, having VES 3, 2, 15, 1 and 9. When compared with the borehole log in the area, the first layer is the lateritic topsoil with resistivity values ranging from 138 to 295 Ωm and thickness varying from 0.5 to 3.1 m. The second layer consists of coarse sand in VES 2, and 15, and fine to medium grain sand in VES 1, 3 and 9. The resistivity ranges from 172 to 2662 Ωm and thickness varying from 5.8 to 32.7 m. The third layer composed of fine to medium to coarse grain sand with resistivity values ranging from 239 to 10210 Ωm and thickness varying from 7.4 to 45.3 m. The fourth layer is made up of fine to medium to coarse grain sand with resistivity values ranging from 262 to 3365 Ωm.

Figures 7 shows geoelectric sections in the NE - SW direction. The sections have VES 13, 12, 1, 15 and 10. It is also consists of four geoelectric layers. Comparing with the borehole log in the area and from the resistivity values, the first layer is the lateritic topsoil with resistivity values ranging from 127 to 1556 Ωm and thickness varying from 0.5 to 1.0 m. The second layer consists of fine to medium to coarse grain sand with resistivity values ranging from 389 to 3647 Ωm and thickness varying from 2.9 to 12.4 m. The third layer is composed of fine to medium to coarse grain sand with resistivity ranging from 239 to 859 Ωm and thickness varying from 7.4 to 31.5 m. The fourth layer is also composed of coarse grain sand with resistivity ranging from 2118 to 3365 Ωm.

Aquifer isoresistivity and depth map

The aquifer isoresistivity map is shown in Figure 8, with the resistivity values ranging from 400–6000 Ωm. The higher resistivity values were observed in the western and eastern flank with resistivity values greater than 4000 Ωm which is an indication that the area would be more prolific in groundwater production. The central part occupying 80 % of the study area has resistivity values ranging from 400 - 2800 Ωm. Figure 9 shows the aquifer depth/ isopach overburden map generated for the area. The depth to aquifer ranges from of 3.1–22.0 m. Also, the central part of the area has depth values ranging from 11 - 22 m. Therefore the mean depth to the aquifer for adequate water production is given as 13.87 m and a maximum of 22 m. Figure 9 will assist drillers with adequate information on borehole citing depth in the area.

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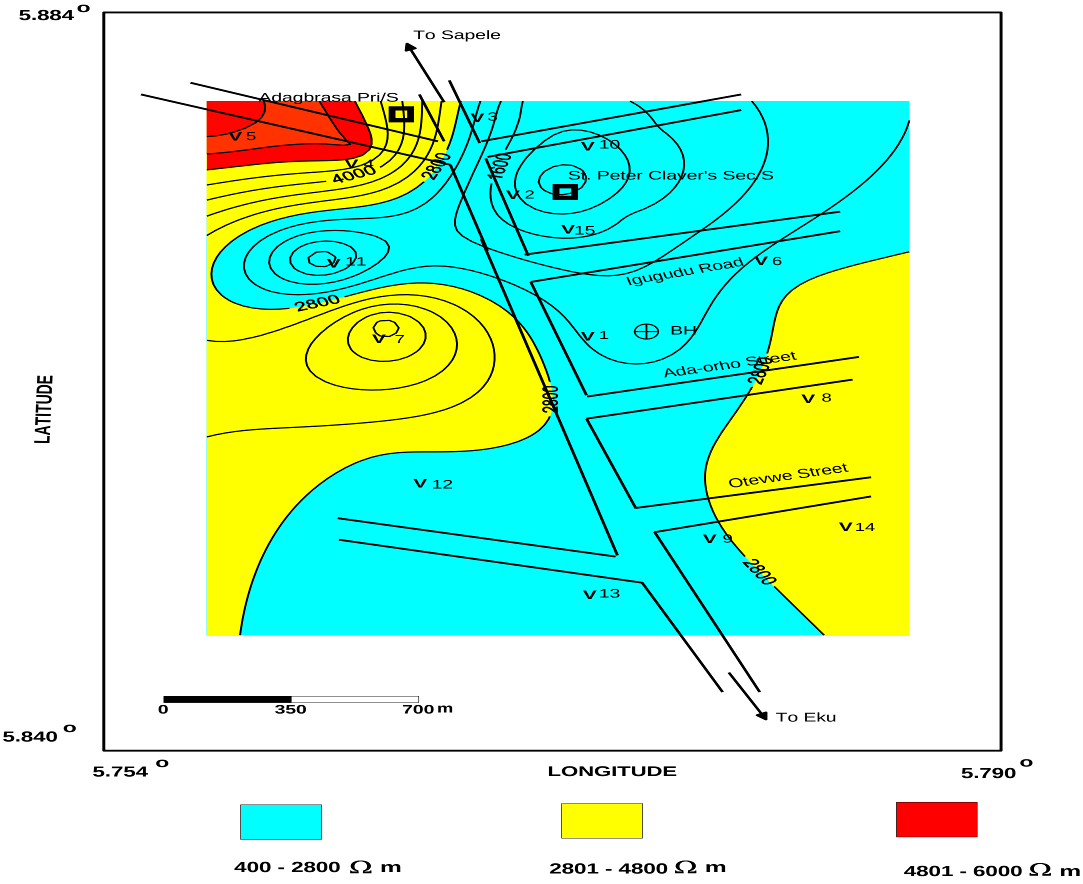

Figure 8: Aquifer resistivity map

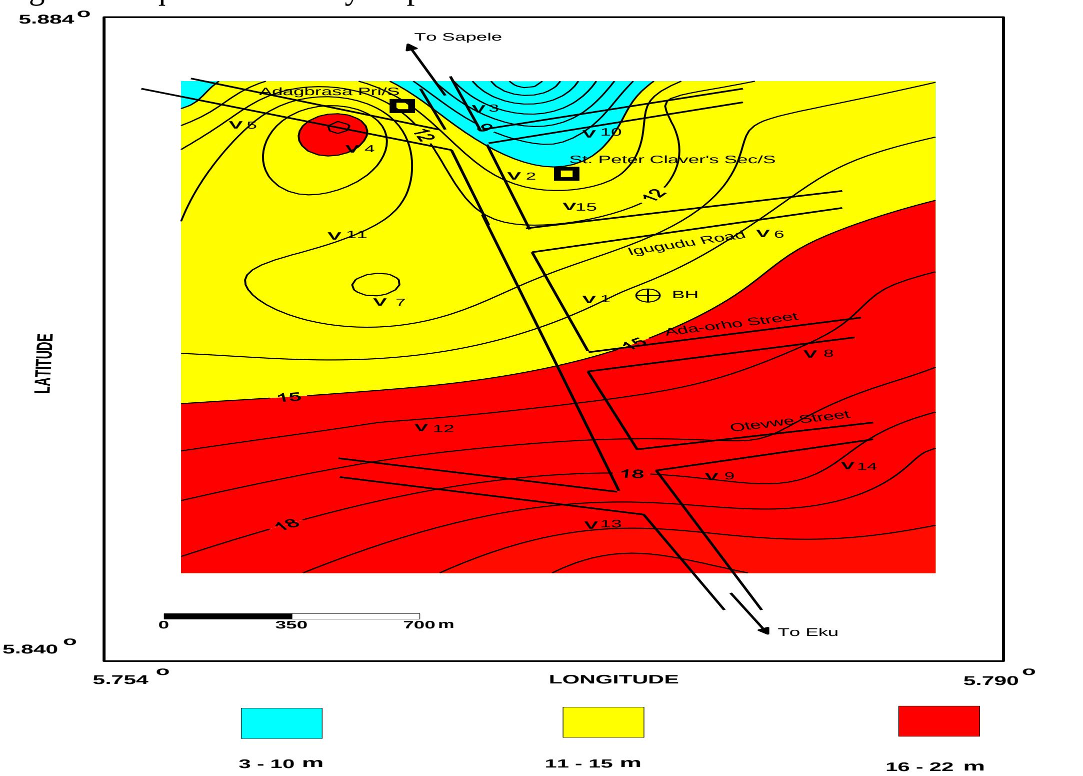

Figure 9: Depth to Aquifer map

Aquifer Protective Capacity

The classification of the aquifer protective indices was done from the computed longitudinal conductance values (Table 1) by using the first order geoelectric parameters of inferred layer thicknesses and resistivity of the overburden (Adeniji et al., 2014; Obiora et al., 2015; Mosuro et al., 2017). Consequently, high longitudinal conductance is an indication of high protective capacity. From the VES points, the protective capacity map was generated and this provides visual information for aquifer vulnerability and protection for groundwater resources and quality management. The evaluation of protective capacity of the aquifer was done based on the ranking by Oladapo et al., (2004), and modified by Ofomola (2014) for sedimentary terrain in the Niger Delta. This ranking is given as >1 (Excellent), 0.5 – 1 (Very Good), 0.1 – 0.49 (Good), 0.06 – 0.09 (Moderate), 0.01 – 0.05 (Weak) and <0.01 (Poor). The calculated longitudinal conductance and inferred protective capacity shown in Table 1 ranges from 0.0141 - 0.167 mho, and weak to moderate respectively. Figure 10 shows the map of the longitudinal conductance, displaying the aquifer protective capacity.

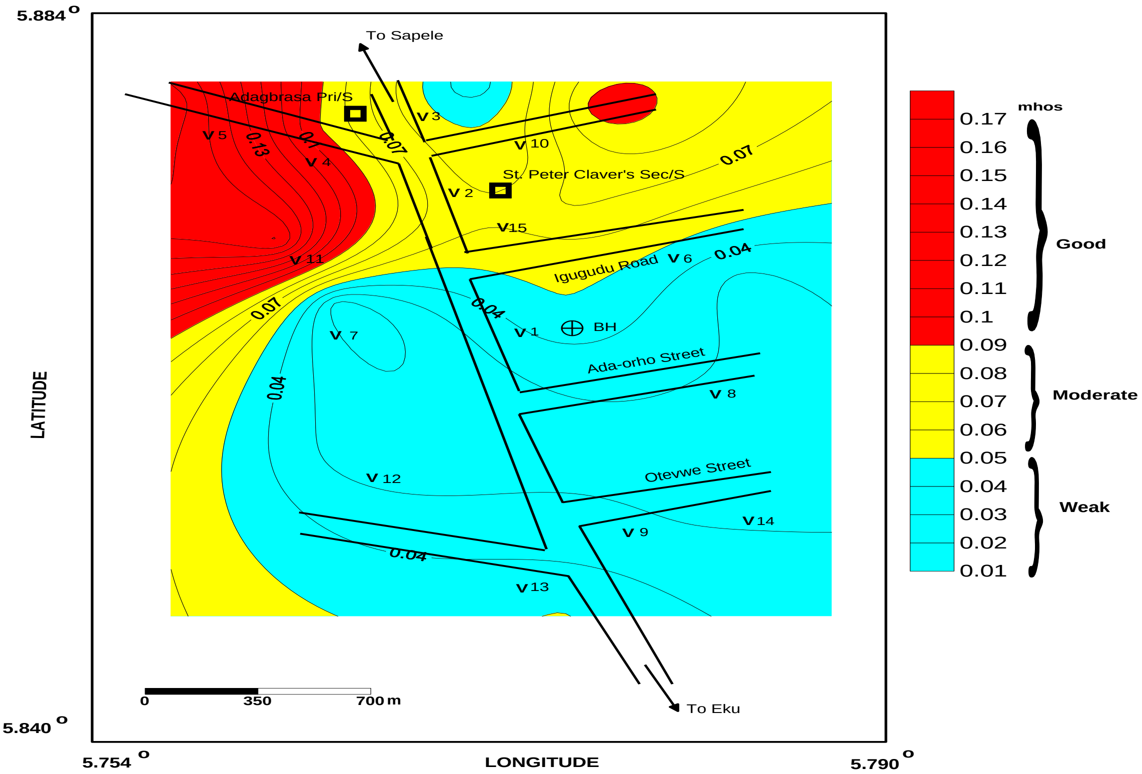

Figure 10: Longitudinal conductance map showing protective capacity

The map shows that the area is predominantly of moderate to weak protection. The implication is that the clay content in the overburden layers is minimal or generally thin at all the VES points, thereby providing little or no shield to the aquifer beneath them. Consequently, this will enhance the percolation of contaminants into the aquifer in the event of the release of contaminated surface runoff water in the area (Aweto, 2011). However, in the western part the protection is fairly

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good with values ranging from 0.1 - 0.17 mhos.

Borehole Pumping Test

The borehole pumping test data from the study area were analysed using the Cooper-Jacob method in determining the aquifer parameters of hydraulic conductivity (K), transmissivity (T), storativity (S) and specific yield. The estimated aquifer parameters are shown in Table 2.

Table 2: Aquifer parameters from borehole pumping test

Aquifer Parameters	Calculated Values
Transmissivity (m^2/day)	334
Hydraulic conductivity (m/day)	23.9
Storativity	0.0132

Note: t_o= 0.5, ΔS = 0.25, Q = 3170 m^2/day, h = 14m

The Transmissivity and hydraulic conductivity (Table 3) of the aquiferous layer across the study area were calculated from the borehole pumping test results and the second order geoelectric parameters. The Da-zarrouk parameters of aquifer longitudinal conductance and transverse resistance are shown in Table 3. The aquifer transmissivity and hydraulic conductivity were calculated from the results of the vertical electrical sounding first order geoelectric parameters and results from the pumping test analysis. Therefore, if the hydraulic conductivity from the pumping tests from the borehole, and *R* or *S* from the geoelectrical data interpretation are known, it becomes very easy to calculate the variation of transmissivity T across the VES stations in the area (Asfahani, 2007). The Kσ constant was determined by inserting the K value of 23.9 m/day obtained from the pumping test results and the σ from the electrical resistivity results at various VES stations. Therefore, the estimated aquifer transmissivity at all the VES locations were determined. The calculated transmissivity from Table 3 ranges from 198.8 m^2/day to 1473.6 m^2/day with an average of 459.8 m^2/day, which closely approximates the transmissivity of 334 m^2/day derived from the pumping test analysis. From the transmissivity determination from both the pumping test and vertical electrical sounding, the shallow aquifer underlying the study area can thus be considered to have moderate to high yield potential (Gheorghe, 1978). The calculated hydraulic conductivity also varies from 5.7 m/day to 66.7 m/day, with an average of 31.1 m/day. The averaged hydraulic conductivity value also approximates the 23.9 m/day obtained from the pumping test analysis. It is also significant that the calculated hydraulic conductivity from VES 1 close to the borehole has the same value of 23.9 m/day. From the hydraulic conductivity classification format of Vbrka et al., (1999), the values obtained range from Permeable to High. This signifies that the aquifer is prolific and of high yield. It is significant to note, that the average calculated hydraulic conductivity corresponds with the pumping test results of 21.6 m/day and 26.8 m/day of Gulraiz and Hasan (2016) and, Aweto and Akpoborie (2015) respectively. Spatial distribution maps of hydraulic conductivity and transmissivity (Figures 11 and 12) show that high hydraulic conductivity occurs in most parts of the study area, which correlates with areas of moderate to high transmissivity. Figure 11 revealed that the greater part of the study area has high hydraulic conductivity values, indicating that groundwater in the area has a greater ease of movement for recharge capacity.

The high transmissivity values is significant of high water bearing potential and the aquifer materials are highly permeable to the movement of fluid. This implies that a groundwater resource development can be established for the inhabitants in the area.

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Table 3. Aquifer Characteristics of VES Station in the Study Area

VES STN.	Aquifer Resistivity (? m)	Depth to Aquifer (m)	Aquifer Thickness (m)	Longitudinal Conductance (Ω^{-1})	Transverse Resistance (Ωm^2)	Conductivity, σ (Ω^{-1})	Hydraulic Conductivity from Pump Test (m/day)	Kσ	Hydraulic Conductivity At sounding locations (m/day)	Transmissivity, ($m^2 day^{-1}$)
1	2118	14.2	ND	0.0491	ND	0.0004721	23.9	0.011283	23.9	ND
2	503	9.4	21.9	0.0521	11016	0.0019881	23.9	0.011283	5.7	124.3
3	1510	3.1	32.7	0.0322	49377	0.0006623	23.9	0.011283	17.0	557.1
4	5210	16.5	ND	0.0934	ND	0.0000979	23.9	0.011283	58.8	ND
5	5914	9.4	ND	0.1674	ND	0.0000529	23.9	0.011283	66.7	ND
6	3012	15.7	ND	0.0260	ND	0.0003320	23.9	0.011283	34.0	ND
7	4633	11.7	26.3	0.0141	121848	0.0002158	23.9	0.011283	52.3	1374.8
8	3156	16.4	26.5	0.0298	83634	0.0003169	23.9	0.011283	35.6	943.6
9	2883	17.3	45.3	0.0271	130600	0.0003469	23.9	0.011283	32.5	1473.6
10	1662	12.5	11.6	0.0979	19280	0.0006017	23.9	0.011283	18.8	217.5
11	859	13.6	28.1	0.1612	24138	0.0011641	23.9	0.011283	9.7	272.4
12	2589	16	28.2	0.0254	73010	0.0003865	23.9	0.011283	29.2	823.8
13	2516	21.8	ND	0.0508	ND	0.0003975	23.9	0.011283	28.4	ND
14	3156	19.2	28.1	0.0279	88684	0.0003169	23.9	0.011283	35.6	1000.7
15	1662	11.5	10.6	0.0722	17617	0.0006017	23.9	0.011283	18.8	198.8

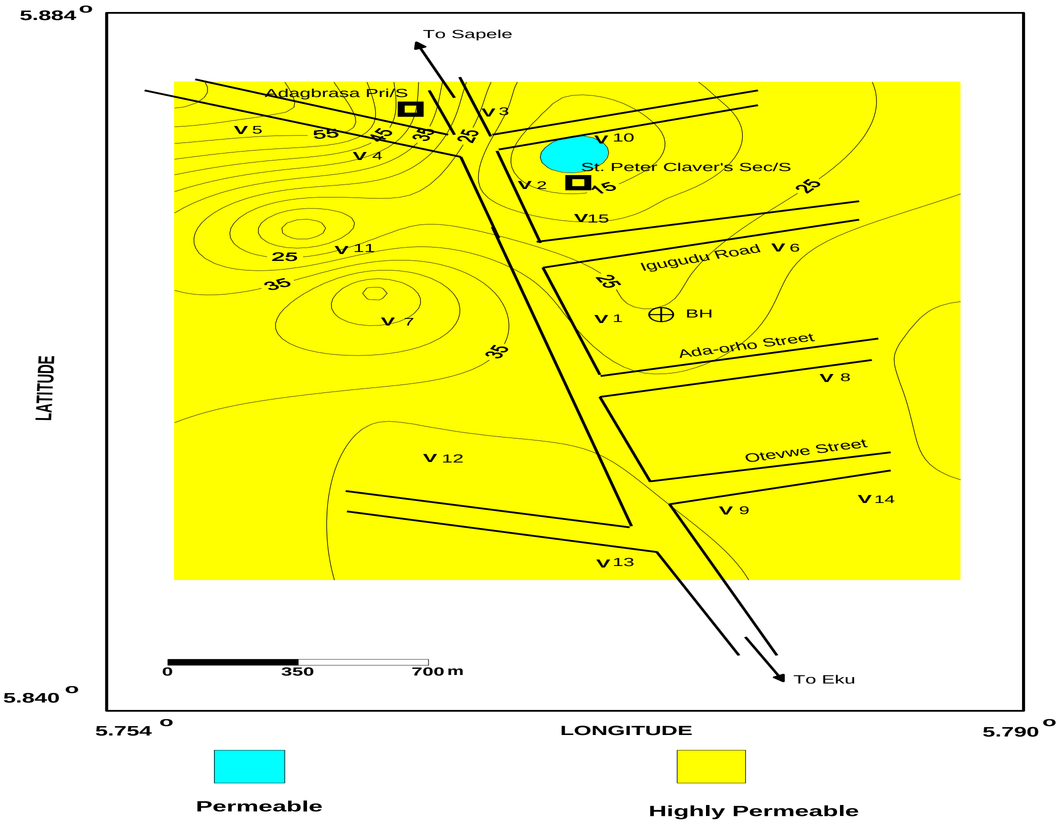

Figure 11: Map of Hydraulic Conductivity Variation

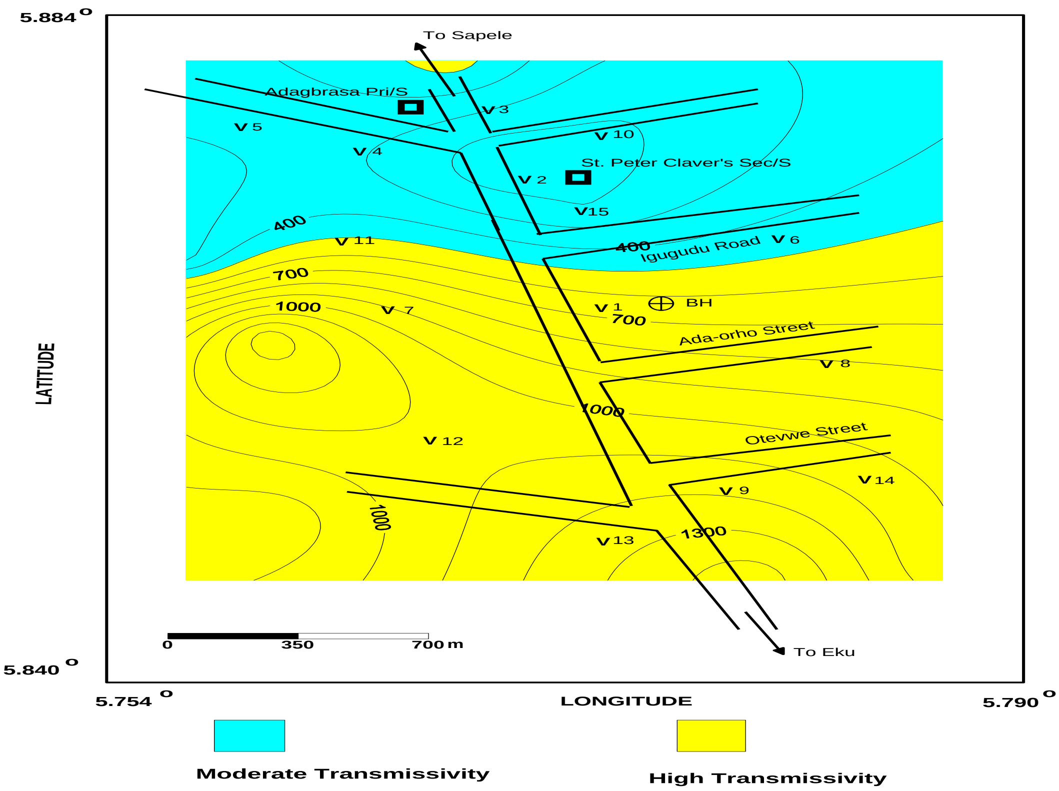

Figure 12: Map of Transmissivity Variation

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CONCLUSION

Evaluation of the protection and hydraulic characteristics of the aquifer formation in Aghalokpe, Nigeria has been studied using second order geoelectric indices and borehole pumping test analysis. Fifteen (15) vertical electrical sounding by utilizing the Schlumberger method were carried out at preferred points in the study area with the ABEM SAS 1000 Terrameter and maximum current electrode separation varied from 120 - 200 m. The second order geoelectric parameters generated showed that the area is generally of low protection and therefore prone to contamination. The hydraulic conductivity and transmissivity values obtained range from Permeable to High, and moderate to high yield potential, with greater ease of movement for recharge capacity. The results of this study signify that a combination of the analysis of borehole pumping test and second order geoelectric Dar-Zarrouk parameters provides more reliable estimation for aquifer hydraulic properties.

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