

Evaluation of Aquifer Characteristics and Groundwater Protective Capacity in Abavo, Nigeria

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Abstract

Aquifer characteristics evaluation enables the determination of aquifer's ability to recharge as well as discharge. However, knowledge of aquifer characteristics has been scarce in Abavo area. Thus, geophysical and hydrogeological investigations, involving vertical electrical sounding (VES), pumping test and well logging were conducted in Abavo area, Nigeria, to evaluate the aquifer hydraulic properties as well as the groundwater protective capacity of the area. Seventeen (17) VES, using the Schlumberger configuration, were carried out. The field data were curve-matched, iterated, using Win Resist software. The VES result revealed subsurface lithology that comprised lateritic top soil/sand, sandy clay/clayey sand, fine sand, medium sand and coarse to gravelly sand. The VES result equally revealed an aquifer depth range from 28.8 - 76.6 m, with resistivity range from 1175 - 27,272 $\Omega\cdot\text{m}$. Two boreholes were drilled, the cuttings were collected and were used to model the subsurface lithology. Well logging result showed that the electrical conductivity (EC) as well as total dissolved solid (TDS) are 15 $\mu\text{s}/\text{cm}$ and 112 mg/l respectively, indicative of the fact that the values were within the standard organization of Nigeria (SON) permissible limit for drinking water. Pumping test analysis, using the Cooper Jacob's method, revealed that the transmissivity, specific capacity, storativity and hydraulic conductivity are 5.9 m^2/day , 33.13 m/day, 0.0069 and 0.1722 m/day respectively. The study revealed longitudinal conductance and transverse resistance range of 0.001048 - 0.027828 Ω^{-1} and 105470.4 - 1255775.3 $\Omega\cdot\text{m}^2$ respectively. These results have established that the aquifer is semi-confined, has poor protective capacity and high rechargibility and will provide adequate, potable groundwater for local water supply to communities for domestic and other purposes.

Keywords

Groundwater, Transmissivity, Abavo, Pumping Test, Vertical Electrical

1. Introduction

Exploitation of groundwater resources is of global concern and this has resulted in an increased awareness of groundwater resources management [1] [2]. Groundwater resources management needs a pragmatic and urgent scientific approach. One of the techniques used in evaluating aquifer hydraulic characteristics effectively, is through the determination of its parameters. Aquifer hydraulic properties (AHP) are those properties that enable the aquifer to recharge as well as discharge groundwater. AHP help to quantitatively predict the aquifer hydraulic response, and they are significant in efficient development and management of groundwater resources. Additionally, knowledge of AHP immensely contributes significantly to proper understanding of groundwater occurrence, as well as pumping effect on the aquifer in any environment. According to [3], “these properties include transmissivity, hydraulic conductivity, storativity, specific yield, transverse resistance, longitudinal conductance, aquifer thickness and depth”. Determination of aquifer hydraulic characteristics (transmissivity, storativity, specific capacity, hydraulic conductivity, transverse resistance, longitudinal conductance, aquifer thickness and depth) gives a first-hand knowledge about the aquifer and subsurface hydrology [2]. Pumping test provides an effective method of evaluating aquifer hydraulic parameters such as transmissivity, storativity, specific capacity and hydraulic conductivity. Moreso, pumping test analysis remains the conventional field method used in evaluation of aquifer hydraulic parameters.

However, in Nigeria lack of funds has adversely affected systematic pumping test analysis and this has resulted in paucity of data for successful development and management of groundwater resources. [4] asserted that “geophysical method remains an effective tool used for aquifer evaluation that can minimize the number of expensive pumping tests”. However, studies have revealed that the combination of resistivity parameters obtained from surface resistivity measurements and aquifer parameters computed from drilled boreholes can be highly effective in evaluation of aquifer characteristics [5]-[10].

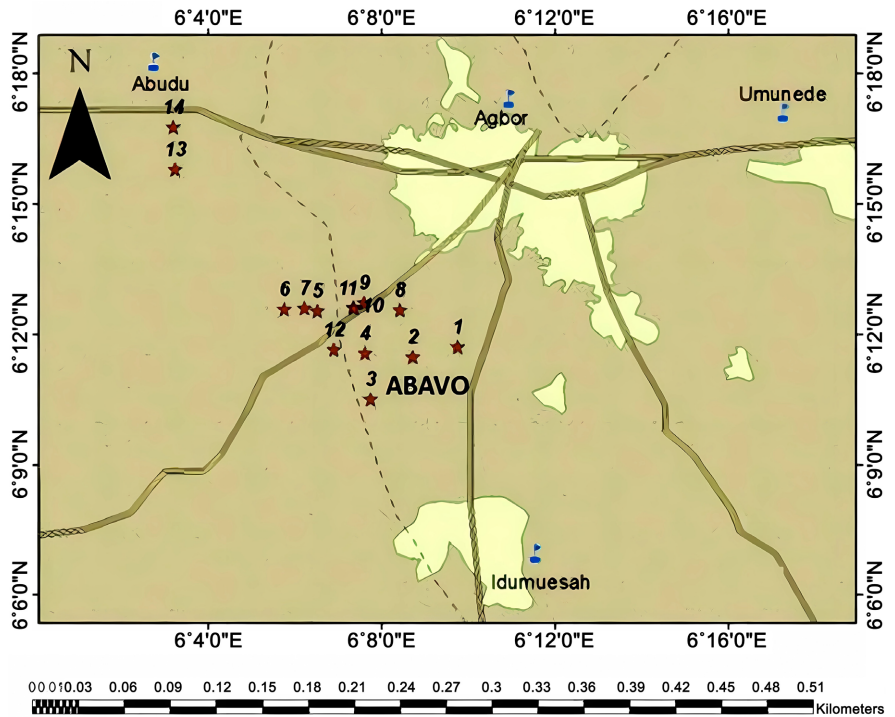
Several researchers such as [4] [11]-[17], have provided alternative ways of determination of some of the aquifer properties through the use of surface geophysical measurements (electrical resistivity techniques). [17] noted that the two useful parameters used in the computation of aquifer protective capacity are the longitudinal conductance (S) and transverse resistance (R). He noted that “when the thickness as well as the resistivity of the aquifer is known, its longitudinal conductance (S) and transverse resistance R (referred to as Dar Zarrouk Parameters) could be computed”. These parameters give a measure of the aquifer protective capacity. [18] studies focused on “using vertical electrical sounding to determine the groundwater potentials of the area as well as the lithologic distribution of the

aquifer” with no attempt to evaluate the aquifer hydraulic characteristics (such as transmissivity, storativity, specific capacity and hydraulic conductivity) as well as the aquifer protective capacity. [19] only applied “a geoelectric survey to compare the aquifer transmissivities of Abavo and Okwagbe without investigating other aquifer parameters with pumping test”. Thus, this study becomes crucial in order to bridge that gap.

Abavo is a fast-growing community with a rapidly increasing population. This has resulted in water scarcity as the people in the area depend on rain harvesting, water hawkers and tankers for their water supplies. There is no functional public water supply from either government agencies or non-governmental organizations. The major surface water supplies which are the River Asimiri and River Orogodo are several kilometers from the community and are vulnerable to contaminations. This has led to the people drilling personal boreholes which are often aborted boreholes (shallow boreholes) because of the cost implications of drilling to the adequate aquifer depth. It is against this background that this study seeks to evaluate the aquifer hydraulic characteristics and protective capacity in Abavo, western Niger Delta, Nigeria, through the use of integrated geoelectric, geophysical well logging and pump testing methods, with a view to providing sufficient and potable water to the people, that will meet their domestic, industrial and agricultural needs.

Location and Geology of the Study Area

The study area, Abavo is located within latitude 6°00' and 6°11'N and Longitude 6°06' and 6°16'E (Figure 1). The area is accessible through Agbor-Abraka-Sapele major roads. It is situated in Ika South Local Government Area of Delta State, Nigeria, and is at a distance of some kilometers from Agbor, the Local Government Headquarters. Abavo area is a fast-growing urban town, an agglomeration of several communities that have grown in size, conjoined to form what is now referred to as Abavo Urban. These communities include; Ekuma-Abavo, Udomi, Abavo-Urban, Igbogidi, Idumu-Isogba, Azuwa, Oyoko, Ogba, Urhomehen and Obi-Ayima. It has an elevation of between 120 - 150 m above sea level. The area is a typical tropical rain forest characterized by two prevailing seasons rainy (April to September) and dry (October to March). The annual mean rainfall is 2000 m, while the annual mean temperature of the area is 28°C. The drainage pattern is basically dendritic controlled by bedrocks within the area. The area falls within Western Niger Delta oil rich sedimentary region of Nigeria (Figure 2). It is composed of three lithostratigraphic units [20]-[25]. These three geologic units; the Benin, Agbada and Akata formations constitute the main geologic units in the rich oil Niger region. The study area falls within the Benin Formation, which is composed of deposits of sands and clay—coastal plain sands. [22] noted that “the Benin Formation (Coastal Plain Sands—sands and clay units) is continuous with depth of approximately 2000 m, constitute the hydrogeologic unit in the Niger Delta”.



Legend

- ★ VES Points
- Express Road
- ▲ Locations
- State Boundary
- Built-Up Area
- Study Area

Figure 1. Location/accessibility map of the study area.

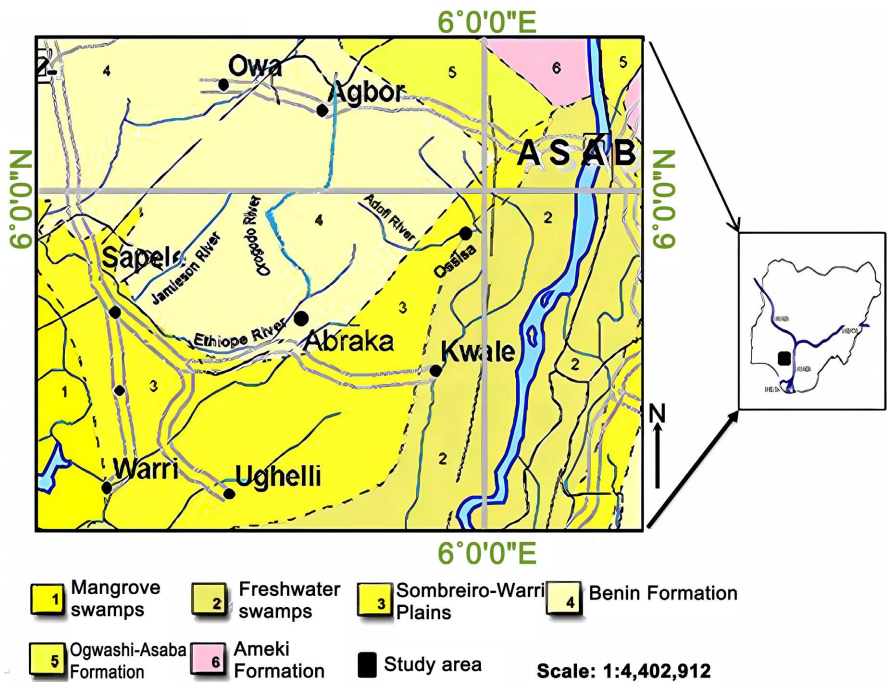


Figure 2. Geological map of Western Niger Delta, showing the study area (modified [24]).

2. Materials and Methods

2.1. Field Geophysical Survey

Seventeen (17) vertical electrical sounding (VES), employing the Schlumberger electrode array, were conducted using SAS 1000 Terrameter and other accessories (four rolls of connecting cables, two rolls of tapes, compass, hammer, a pair of crocodile clips, cutlass etc.) in the study area (**Figure 1**). The maximum current electrode separation ranged between 300 - 450 m. The choice of using the Schlumberger array was based on the fact that it is more efficient in differentiating subsurface lateral and vertical variations in resistivity as well as the fact that its field operation is simpler and faster when compared with other geophysical methods. The SAS 1000 Terrameter has an in built 12 V battery that ensured adequate energy to be supplied to the subsurface thereby giving a reliable signal as well as good quality data. It also has an in-built digital display unit. The geoelectric survey was carried out with all the four electrodes placed in a straight line in such a way that the distance between the two potential electrodes were kept at a metre (1 m) apart, while the other two current electrodes at two metres (2 m) apart. Consequently, an electrical field within the subsurface was established, generated and determined through the pair of current electrodes and the pair of potential electrodes, connected to the SAS 1000 Terrameter. The process was repeated by increasing the current electrode spacing symmetrically from the central position, while the resultant increase in potential difference of the subsurface was recorded. An increase was made on the potential electrode spacing when a decreasing potential difference was observed on the instrument and the survey continued. During the survey, precaution was taken in line with the works of [26] and [6] that “the distance between the potential electrodes never exceeds one fifth of the distance between the current electrodes”. All the VES data were curve matched, using standard master curves to enable the subsurface layer parameters (resistivity, thickness and depth) to be determined. This was done by plotting the apparent resistivity of the subsurface against half of the current electrode distance for each VES data. Thereafter, the data were subjected to iteration in Win Resist Software, as used by [27], [28]. Finally, the results from the iteration enabled the determination of the true subsurface layer parameters (resistivity, thickness, depth).

2.2. Geophysical Well Logging

A well was drilled to a depth of 130 m and well cuttings were collected at 3 m intervals and analyzed in the study area with the aim of evaluating the subsurface lithology with respect to depth. Subsequently, geophysical well logging comprising spontaneous logging [SP] (**Figure 3(a)**) and resistivity logging (**Figure 3(b)**) were conducted using SAS 1000 and its accessories (SAS 200 logging tool, a logging probe and a calibrated cable) by lowering the probe into the well (**Figure 3(c)**) at 3 m intervals. The result obtained from the logging exercise was used to evaluate the electrical conductivity as well as the total dissolved solid of the groundwater.

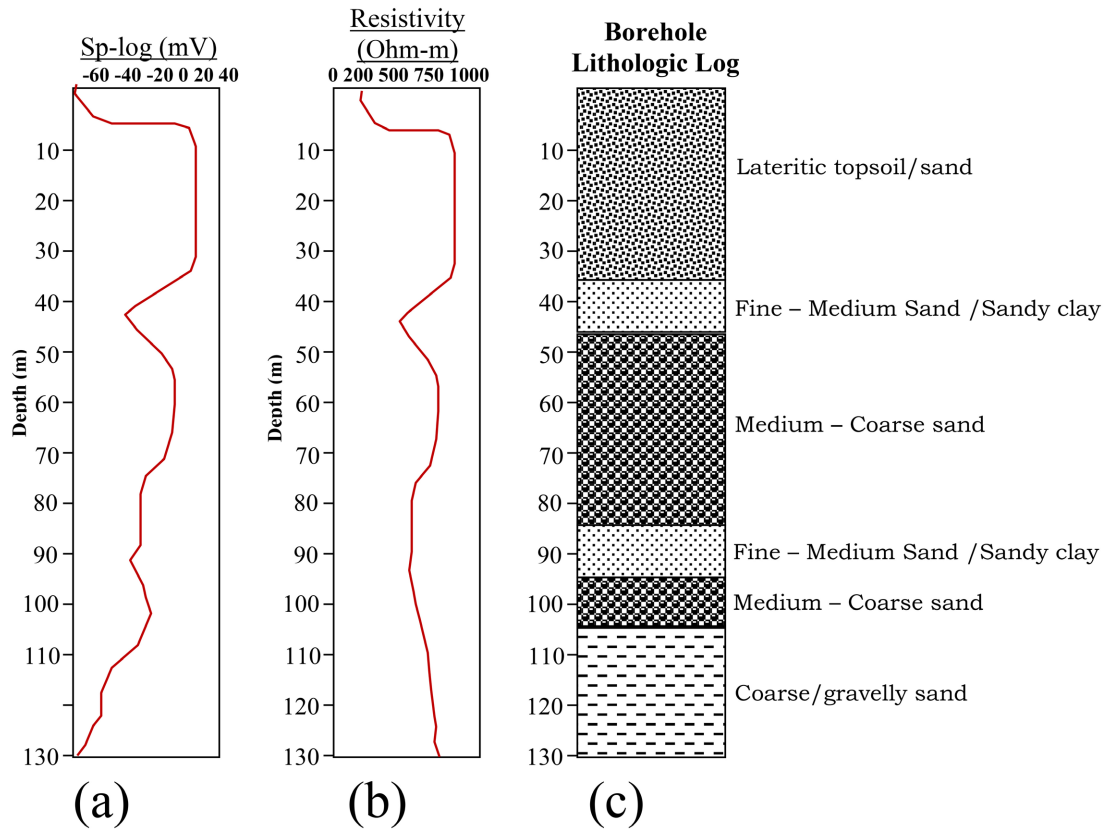


Figure 3. Borehole geophysical log (a) SP log (b) Resistivity log plotted against (c) lithologic log in the area.

2.3. Pumping Test

Conventionally, pumping test was conducted in two separate wells drilled to evaluate the aquifer parameters in the study area. The two wells (one referred to as test well while the other designated as observation well) were located 2 m apart. A 1 KW submersible pump was installed into the test well and connected to a 2.5 KW generator. Water was pumped from the well at a constant rate of 0.018 m³/min and after some interval, the depth of water in the observation well was determined through the use of a sensible probe which was attached to a cable fixed to a water detector. The data obtained from the drawdown (difference in the water level at a given time from the water level before the commencement of pumping) of the well was plotted against time of pumping on a semi-logarithm graph. The graph sheet was then used to determine the drawdown per log cycle of time (Δs) and the horizontal intercept (t_0) and the data obtained were then substituted into the [29] straight line equations to evaluate aquifer hydraulic parameters (transmissivity T , Storativity S , Specific Capacity S_c , and Hydraulic Conductivity K). Applying the [29] formula, as used by [6]-[8] as follows:

$$\text{Transmissivity } (T) = \frac{2.25Q}{4\pi\Delta s} \tag{1}$$

$$\text{Storativity } (S) = \frac{2.25Tt_0}{r^2} \tag{2}$$

$$\text{Specific Capacity (Sc)} = \frac{Q}{\Delta s} \quad (3)$$

$$\text{Hydraulic Conductivity } K = \frac{T}{b} \quad (4)$$

where Q is the rate of discharge (m^3/s),

Δs is the slope (m),

t_0 is the time pumping started (m),

r is the radial distance from test well (m),

b is aquifer thickness (m).

3. Results and Discussion

3.1. Lithological Evaluation

The result of the lithologic log from the drilled well and the well logging is presented in **Figure 3**. **Figure 3** shows a thick lateritic soil material as the first layer. This thick lateritic crust/layer is composed essentially of reddish lateritic top soil, clayey sand, sandy clay and fine sand. The thickness of this lateritic layer is about 36 m. This first layer is underlain by the second layer composed of reddish brown fine to medium sand of 8 m thick (36 - 44 m). The second layer is underlain by the third layer which is composed of grayish, medium grain sand, stretching from a depth of 44 - 75 m. This represents the first aquifer in the area. The third layer is underlain by another sandy clayey unit from a depth of 75 m to 88 m. Underling the fourth layer is the fifth layer, which consists of medium to coarse sand, extending from 88 m to 108 m depth. This formation is greyish in colour and represents the second aquiferous region. The fifth layer is underlain by the sixth layer which is made up of greyish to whitish coarse sand/gravels, extending to 108 m to 128 m depth where the drilling terminated.

Analysis of the well log (resistivity log) indicates that the resistivity of the subsurface increases downwards from 10 m to 36 m depth, representing the lateritic sand layer. At 36 m depth the value of the resistivity log decreases slightly from the formation above it, indicative of a fine to medium sandy formation. At a depth of 44 m, a steady increase in the resistivity log was observed. This observation supports the fact that the subsurface material is sandy in nature. This increase in resistivity value of the log is suggestive of an increase in grain size of subsurface material as well as increase in hydraulic conductivity of the aquifer with depth. The spontaneous potential (SP) log on the other hand showed a low value of -60 mV to an increase of about 20 mV, within 10 m to 36 m depth. This was followed by a steady increase throughout the depth of the well. This stability in the resistivity values as well as increase in the SP value downwards shows that the underlying formation would be better source of groundwater for domestic and other purposes than the overlying layers.

The groundwater parameters (electrical conductivity and total dissolved solids) were evaluated in the field from the result of the electrical and SP logs. The result presented (**Table 1** and **Figure 3**) revealed an average value of 15 $\mu\text{s}/\text{cm}$ for

electrical conductivity (EC) while an average of 112 mg/l was obtained for the total dissolved solid (TDS). These values, when compared with the Standard Organization of Nigeria [30] permissible limit for drinking water are lower than the 1000 $\mu\text{s}/\text{cm}$ value set for EC 500 mg/l set for TDS. These low values (EC and TDS) indicate that the groundwater is free from pollutants, as well as a fresh to moderately mineralized subsurface which is suggestive of a groundwater that is suitable and adequate for domestic and other purposes (Figure 4).

Table 1. Result of water quality parameters.

Depth (m)	Electrical conductivity ($\mu\text{s}/\text{cm}$)	Total dissolved solid (mg/l)
5	100	80
10	110	80
15	350	250
20	500	350
25	300	200
30	250	180
35	200	160
40	150	130
45	120	100
50	100	80
55	90	70
60	80	60
65	80	50
70	70	50
75	60	50
80	50	40
85	50	40
90	50	40

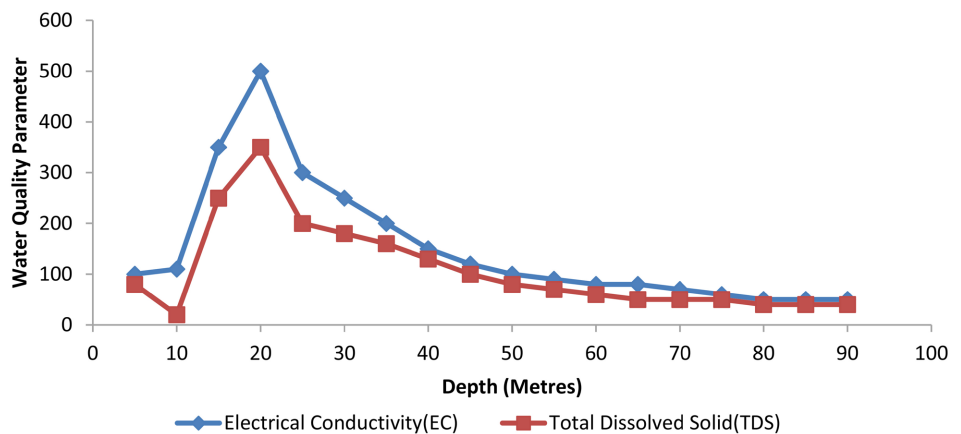


Figure 4. The water quality parameters (EC and TDS) plotted against depth of borehole.

3.2. Geophysical Data Evaluation

Seventeen (17) VES data obtained from the area was curve matched and later subjected to computer iteration, interpretation using Win Resist software. The representative model field curves obtained from the iteration of the VES are presented in **Figures 5(a)-(c)**. **Table 2** shows the geoelectric parameters obtained from the geophysical interpretation. The result revealed a four to six geoelectric layers that consist of lateritic top soil, fine grained sand, sandy clay/clayey sand, medium grained sand, sandy gravel and coarse/gravelly sand. The table indicates a four layered subsurface in VES 1, 2, 3, 4, 5, 11, 13, 14, 15, 16, 17; a five layered subsurface in VES 6 and 7, while it is six layered subsurface in VES 8, 9, 10 and 12. **Figure 6** shows the borehole log in comparison with the geoelectric section of some selected VES stations in the area. A close examination shows a good correlation between the borehole log and the geoelectric data. The parameters used in generating the geoelectric sections include the layer's thicknesses and the resistivity values. The geoelectric section gives a two-dimensional insight into the structural disposition and subsurface geologic sequence of the area.

Table 2. Summary of geophysical data interpretation.

VES Station	Layer No	Resistivity ($\Omega \cdot m$)	Thickness (m)	Depth (m)	Inferred Lithology
VES 1	1	1834.8	1.6	1.6	Lateritic clay/top soil
	2	2557.5	27.3	28.9	Medium grain sand
	3	19896.2	31.7	60.6	Coarse/gravelly sand
	4	6104.3	--	--	Medium-coarse grain sand
VES 2	1	388.7	0.8	0.8	Lateritic clay/top soil
	2	903.3	31.8	32.6	Medium grain sand
	3	12384.5	37.3	69.9	Coarse/gravelly sand
	4	1591.3	--	--	Medium-coarse grain sand
VES 3	1	448.2	0.9	0.9	Lateritic clay/top soil
	2	1159.5	22.0	22.9	Medium grain sand
	3	12799.0	28.2	51.1	Coarse/gravelly sand
	4	5400.8	--	--	Coarse grain sand
VES 4	1	609.4	0.8	0.8	Lateritic clay/top soil
	2	1726.0	13.4	14.2	Fine-medium grain sand
	3	7224.4	14.6	28.8	Medium grain sand
	4	6331.7	--	--	Medium-coarse grain sand
VES 5	1	233.2	1.2	1.2	Lateritic clay/top soil
	2	822.3	19.2	20.4	Fine-course grain sand
	3	11463.0	37.6	58.0	Medium/coarse sand
	4	2503.9	--	--	Medium-coarse grain sand

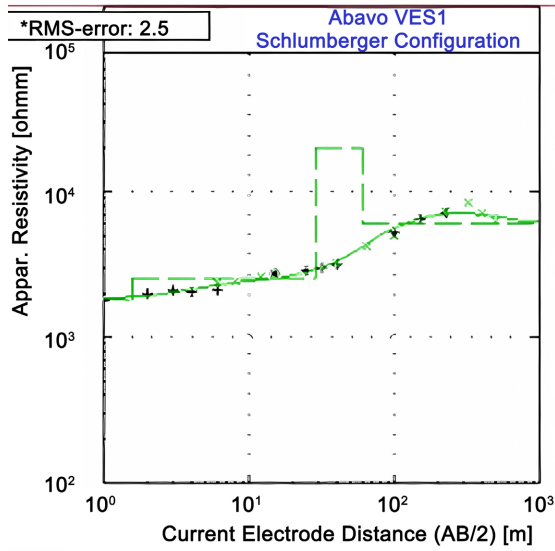
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VES 6	1	485.1	0.5	0.5	Lateritic clay/top soil
	2	2193.8	2.9	3.4	Fine-medium sand
	3	416.5	8.9	12.3	Sandy clay
	4	8811.4	34.9	47.2	Medium-coarse grain sand
	5	4127.4	--	--	Medium-coarse grain sand
VES 7	1	111.7	0.6	0.6	Lateritic clay/top soil
	2	446.2	7.7	7.7	Sandy clay
	3	592.6	11.7	11.7	Fine-coarse grain sand
	4	15166.1	51.1	51.1	Medium grain sand
	5	1215.2	--	--	Medium-coarse grain sand
VES 8	1	2237	0.8	0.8	Lateritic clay/top soil
	2	444.6	4.3	5.1	Fine-medium sand
	3	126.2	6.8	11.8	Sandy clay
	4	976.1	12.5	24.3	Medium grained sand
	5	20535.7	34.3	58.7	Medium/coarse sand
	6	492.0	--	--	Medium-coarse sand
VES 9	1	224.4	0.9	0.9	Lateritic clay/top soil
	2	1125.5	5.5	6.4	Fine-medium grain sand
	3	269.8	7.2	13.6	Sandy clay
	4	1331.5	11.3	24.9	Medium grain sand
	5	16144.0	38.9	63.7	Coarse/gravelly sand
	6	8022.2	--	--	Medium-coarse grain sand
VES 10	1	490.1	1.0	1.0	Lateritic top soil
	2	1202.2	3.1	4.2	Medium coarse grained sand
	3	370.5	4.9	9.1	Fine-medium grain sand
	4	1876.6	9.3	18.4	Fine grained sand
	5	23542.8	36.4	54.8	Coarse grain sand
	6	1130.4	--	--	Medium-coarse grain sand
VES 11	1	135.7	1.1	1.1	Lateritic clay/top soil
	2	883.0	12.9	14.0	Fine-medium grain sand
	3	1175.4	32.7	46.7	Medium grain sand
	4	5563.4	--	--	Medium-coarse grain sand
VES 12	1	668.9	0.5	0.5	Lateritic clay/top soil
	2	1908.1	2.4	2.9	Fine-medium grain sand
	3	571.6	5.7	8.6	Sandy clay/clayey sand
	4	2671.9	17.9	26.6	Fine-Medium grain sand
	5	18943.3	50.1	76.6	Coarse/gravelly sand
	6	3544.7	--	--	Medium-coarse sand

Continued

VES 13	1	232.0	1.7	1.7	Lateritic clay/top soil
	2	636.0	9.7	11.4	Fine-Medium grain sand
	3	24010.8	52.3	63.8	Medium grain sand
	4	1528.9	--	--	Medium-coarse grain sand
VES 14	1	150.9	0.9	0.9	Lateritic clay/top soil
	2	358.3	18.7	19.6	Fine-medium grain sand
	3	27742.0	29.1	48.7	Coarse/gravelly sand
	4	199.3	--	--	Sandy clay
VES 15	1	252.1	1.0	1.0	Lateritic clay/top soil
	2	594.7	15.6	16.6	Fine-medium sand
	3	10336.5	26.4	43.0	Medium grain sand
	4	5481.6	--	--	Medium-coarse grain sand
VES 16	1	181.9	1.9	1.9	Lateritic clay/top soil
	2	962.9	24.7	26.6	Medium grained sand
	3	21991.4	38.0	64.8	Coarse grained sand
	4	1302	--	--	Medium-coarse grain sand
VES 17	1	64.2	0.6	0.6	Lateritic clay/top soil
	2	266.4	20.9	21.5	Fine-medium grained sand
	3	1306.6	15.7	37.2	Medium grain sand
	4	11215.7	--	--	Medium-coarse grain sand

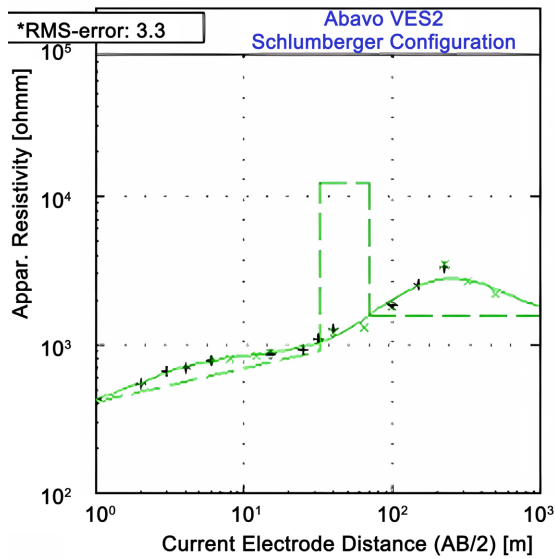
The first layer consists of lateritic topsoil/sand with resistivity range from 64 - 1835 Ω .m and thickness range from 0.5 - 1.9 m. The second layer consists of lateritic sand/fine grained sand with resistivity range from 266 - 2558 Ω .m and thickness range from 2.4 - 31.8 m. The third layer comprises fine to coarse gravelly sand with resistivity range from 126 - 27,742 Ω .m and thickness range from 4.9 - 52.3 m. The fourth layer comprises of medium to gravelly sand with resistivity range from 976 - 15,166 Ω .m and thickness range from 9.3 - 50.4 m. The fifth layer consists of coarse to gravelly sand with resistivity range from 1215 - 23,543 Ω .m and thickness range of 34.4 - 50.0 m. The sixth layer is coarse to gravelly sand with resistivity range of 1130 - 3540 Ω .m. The current electrode separation terminated in this layer; thus, the exact thickness could not be ascertained. This phenomenon was also observed in the fourth layer of VES 1, 2, 3, 4, 5, 11, 13, 14, 15, 16, 17 and the fifth layers of VES 6 and 7. The VES data analysis revealed that groundwater can be sourced from 18.4 - 76.6 m depths from the fourth, fifth and sixth layers respectively but the fifth and sixth layers would provide more prolific aquifers than that of the fourth layer. This assertion is correlated with the borehole log, which gives a good correlation between the two results.



No	Res	Thick	Depth
1	1834.8	1.6	1.6
2	2557.5	27.3	28.9
3	19896.2	31.8	60.6
4	6104.3	--	--

*RMS on smoothed data

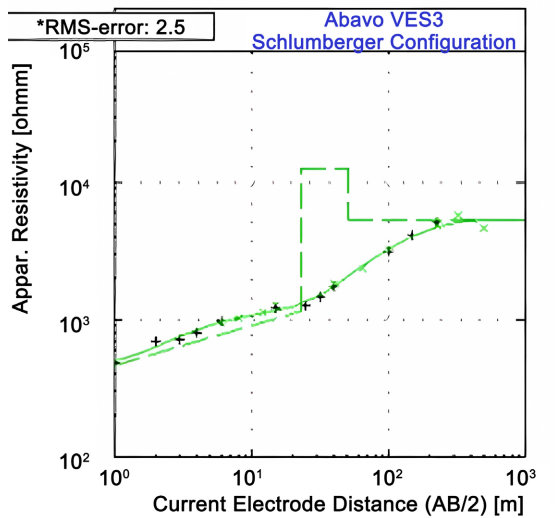
(a)



No	Res	Thick	Depth
1	388.7	0.8	0.8
2	903.3	31.8	32.6
3	12384.5	37.3	69.9
4	1591.3	--	--

*RMS on smoothed data

(b)



No	Res	Thick	Depth
1	448.2	0.9	0.9
2	1159.5	22.0	22.9
3	12799.0	28.2	51.1
4	5400.8	--	--

*RMS on smoothed data

(c)

Figure 5. Typical model field curves for: (a) VES 1, (b) VES 2, (c) VES 3.

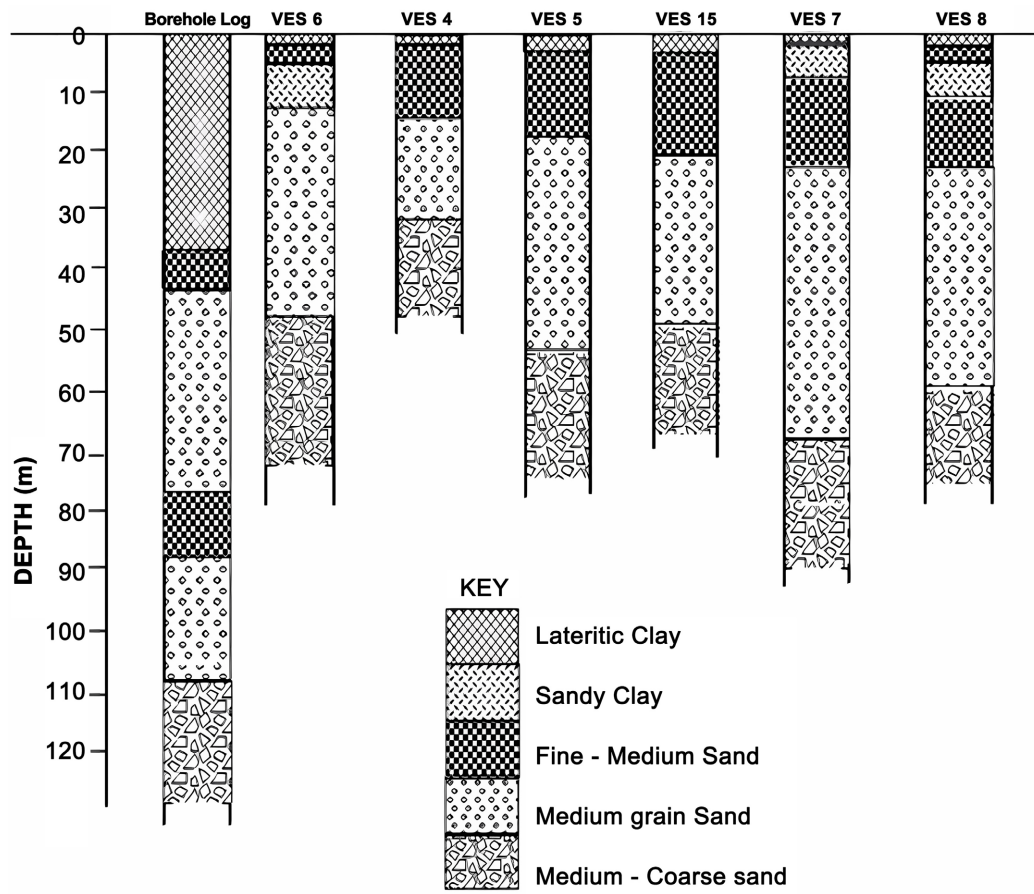


Figure 6. Typical geoelectric sections from Abavo correlated with borehole log.

3.3. Evaluation of Second Order Geoelectric Parameters from VES Data

Table 3 shows the summary of the geophysical data interpretation in terms of the aquifer parameters obtained from the VES stations. The aquifer resistivity ranged from 1175 $\Omega\cdot\text{m}$ (VES 11) to 27,272 $\Omega\cdot\text{m}$ (VES 14), while the thickness ranged from 9.7 m (VES 14) to 52.3 m (VES 13) with an average of 34.28 m. The transmissivity ranged from 0.81 m^2/day (VES 14) to 17.30 m^2/day (VES 11) with an average of 2.82 m^2/day . Also, the longitudinal conductance ranged from 0.001048 Ω^{-1} (VES 14) to 0.027828 Ω^{-1} (VES 11). The transverse resistance estimated ranged from 105470.4 $\Omega\cdot\text{m}^2$ (VES 4) to 947150 $\Omega\cdot\text{m}^2$ (VES12). The values for hydraulic conductivity estimated ranged from 0.028 m/day (VES 14) to 0.529 m/day (VES 11), with an average value of 0.1042 m/day. The aquifer depth ranged from 28.8 m (VES 14) to 76.6 m (VES 12). These values agreed with similar VES survey results at Agbor by [6], where the aquifer depth range of 29 - 82 m was revealed. Abavo is about 13 kilometers from Agbor and belongs to the same geological formation. Figure 7 shows the depth to the aquifer map. It reveals that the northeast, southeast and northwestern parts have the highest aquifer depth while a moderate aquifer depth was revealed in majority of the VES stations in the central part of the study area.

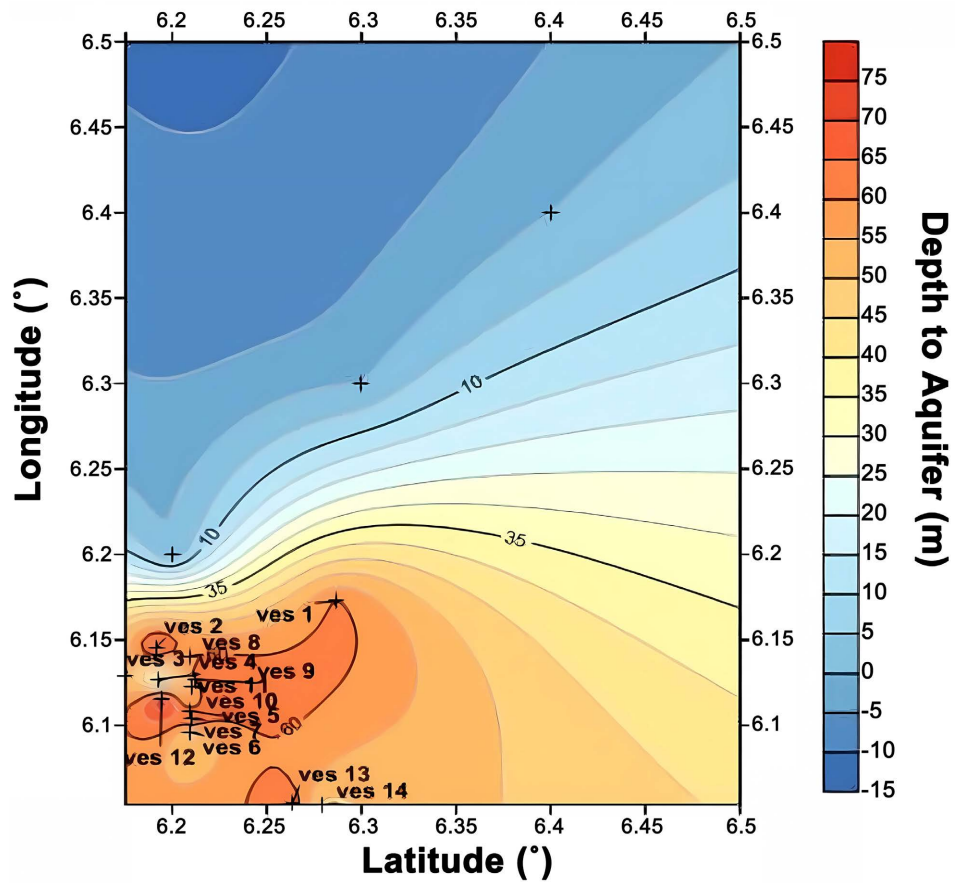


Figure 7. Depth to aquifer map.

Table 3. Aquifer parameters at Abavo.

VES Station	Aquifer resistivity ρ ($\Omega \cdot m$)	Aquifer thickness h (m)	Aquifer depth (m)	Aquifer conductivity $\delta = 1/\rho$ ($\Omega \cdot m^{-1}$)	Longitudinal conductance $S = \sigma h$ (Ω)	Transverse resistance $R = h\rho$ ($\Omega \cdot m^{-2}$)	Hydraulic conductivity from pump test (m/day)	$K\sigma$	Transmissivity $K\sigma R$ (m^2/day)	Hydraulic conductivity of VES Station (m/day)
1	19,897	31.7	60.6	0.000050	0.001585	630734.9	0.1721	0.0000086	5.42	0.1710
2	12,384	37.3	69.9	0.000081	0.003021	461923.2	0.1721	0.0000139	6.42	0.1721
3	12,799	28.2	51.1	0.000078	0.0022	360931.8	0.1721	0.0000134	4.84	0.1716
4	7224	14.6	28.8	0.000138	0.002015	105470.4	0.1721	0.0000237	2.50	0.1712
5	11,463	37.6	58.0	0.000087	0.003271	431008.8	0.1721	0.0000150	6.47	0.1721
6	8811	35.1	47.2	0.000113	0.003966	309266.1	0.1721	0.0000195	6.00	0.1709
7	15,166	51.1	71.1	0.000066	0.003373	774982.6	0.1721	0.0000114	8.71	0.1705
8	20,536	34.3	58.7	0.000049	0.001681	704384.8	0.1721	0.0000084	5.93	0.1729
9	16,144	38.8	63.7	0.000062	0.002406	626387.2	0.1721	0.0000107	6.70	0.1727
10	23,543	36.4	54.8	0.000042	0.001529	856965.2	0.1721	0.0000072	6.17	0.1695
11	1175	32.7	46.7	0.000851	0.027828	38422.5	0.1721	0.0001465	5.63	0.1722

Continued

12	18,943	50.1	76.6	0.000053	0.002650	949044.3	0.1721	0.0000091	8.62	0.1721
13	24,011	52.3	63.8	0.000042	0.002197	1255775.3	0.1721	0.0000072	9.04	0.1728
14	27,742	29.1	48.7	0.000036	0.001048	807292.2	0.1721	0.0000062	5.00	0.1718
15	10,337	26.4	43.0	0.000097	0.002561	272896.8	0.1721	0.0000167	4.56	0.1727
16	21,991	38.0	64.6	0.000045	0.00171	835658	0.1721	0.0000077	6.47	0.1703
17	1307	15.7	37.2	0.000765	0.012011	20519.9	0.1721	0.0001317	2.70	0.1720
Mean									5.95	0.1718

The implications of the result indicate that the average transmissivity value of 2.82 m²/day obtained when compared with the standard for transmissivity values by [31], implies “a low groundwater potential and smaller withdrawal for local water supply/private consumption”. The values of longitudinal conductance below 0.1 (poor) indicates that the aquifer is unprotected thus, prone to risk of contamination [31] [32]. Also, the high transverse resistance suggests high yield for private consumption/local water supply [33]. The hydraulic conductivity obtained indicates a heterogeneous aquifer material consisting of clay, silt and sand with average/moderate yield.

3.4. Pumping Test Analysis

The result obtained from the investigation (pumping test analysis) in the drilled well is presented in Table 4. Figure 8 shows the relationship between the water level and time of pumping, which enabled the evaluation of the drawdown. Applying the [29], with a constant pumping rate (discharge) Q , drawdown per log cycle Δs as 0.78 m (obtained from the plot), time pumping started t_0 (x -intercept) as 3 minutes, radius of the well r as 2 m and aquifer thickness b of 34.28 m, the aquifer parameters (transmissivity, specific capacity, storativity, hydraulic conductivity) were evaluated as follows:

$$\begin{aligned} \text{Transmissivity } (T) &= \frac{2.25Q}{4\pi\Delta s} = \frac{2.25 \times 0.018}{4 \times 3.14 \times 0.78} \\ &= 0.0041 \text{ m}^2/\text{min} \\ &= 5.9 \text{ m}^2/\text{min} \end{aligned}$$

$$\begin{aligned} \text{Specific Capacity } (Sc) &= \frac{Q}{\Delta s} = \frac{0.018}{0.78} \\ &= 0.023 \text{ m}^2/\text{min} \\ &= 33.12 \text{ m}^2/\text{day} \end{aligned}$$

$$\text{Storativity } (Sc) = \frac{2.25Tt_0}{r^2} = \frac{2.25 \times 0.004 \times 3}{2^2} = 0.0069$$

$$\begin{aligned} \text{Hydraulic Conductivity } K &= \frac{T}{b} = \frac{0.0041}{34.28} \\ &= 0.0001196 \text{ m}/\text{min} \\ &= 0.1722 \text{ m}/\text{day} \end{aligned}$$

Table 4. Result of pumping test analysis at Abavo.

Time of Pumping (Minutes)	Water level (m)	Drawdown (m)
0.00	0.00	0.00
1	42.50	0.065
2	42.65	0.085
3	42.74	0.090
4	42.85	0.10
5	42.92	0.20
6	43.20	0.30
7	43.35	0.38
8	43.48	0.40
9	43.54	0.48
10	43.62	0.50
12	43.70	0.68
15	43.75	0.70
20	43.82	0.78
25	43.86	0.90
30	43.90	1.00
40	43.93	1.20
60	43.98	1.50
120	43.98	1.50
150	43.98	1.50
180	43.90	1.50

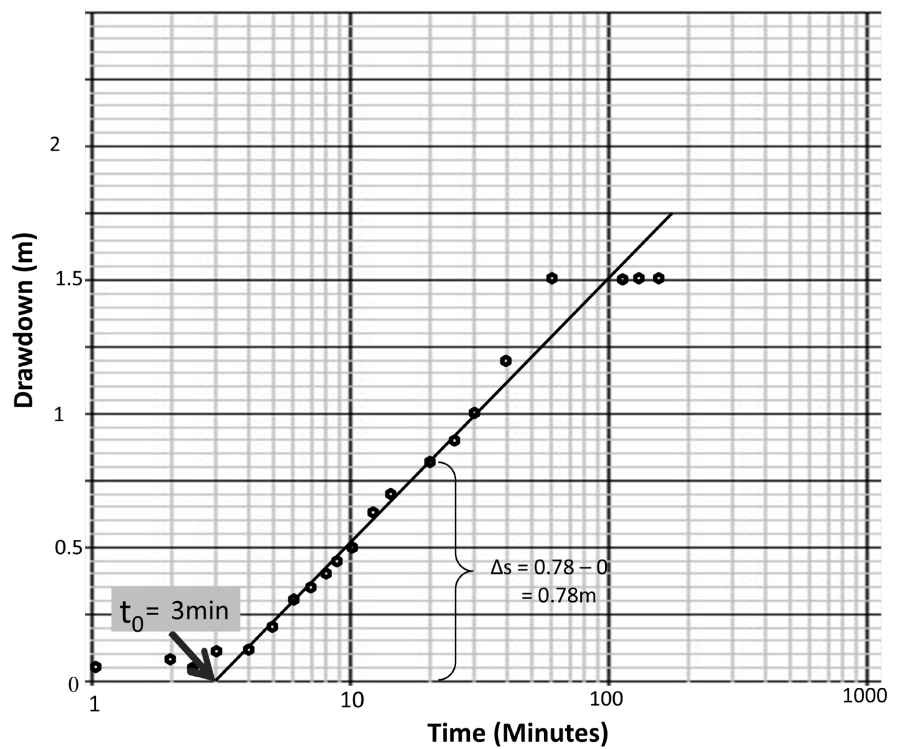


Figure 8. Graph of drawdown against time of pumping at Abavo.

Results of the analysis revealed that the transmissivity is $0.0041 \text{ m}^2/\text{min}$ ($5.9 \text{ m}^2/\text{day}$), specific capacity is $0.023 \text{ m}^2/\text{min}$ ($33.12 \text{ m}^2/\text{day}$), storativity is 0.0069 and hydraulic conductivity is $0.0001196 \text{ m}/\text{min}$ ($0.1722 \text{ m}/\text{day}$). The result obtained for transmissivity suggests a low/intermediate transmission rate of groundwater for local water supply to communities, plant etc. The specific capacity of $0.023 \text{ m}^2/\text{min}$ ($33.12 \text{ m}^2/\text{day}$) suggests that the aquifer can yield sufficient water for private consumption/local water supply to communities. The storativity (storage coefficient) of 0.0069 indicates that the aquifer is semi-confined and therefore implies that a substantial pressure exists within the aquifer which can withstand pumping for local water supply to communities. Also, this result is in agreement with $0.005 - 0.02$ standard set by [34] for semi-confined aquifer. The hydraulic conductivity value of $0.0001196 \text{ m}/\text{min}$ ($0.1722 \text{ m}/\text{day}$) obtained indicates a heterogeneous aquifer material consisting of clay, silt and sand with average/moderate yield. Thus, the results for transmissivity, specific capacity and storativity obtained are in agreement with the results obtained by [6] who carried out a similar investigation at Agbor (an area within the same geological formation) and obtained the values of $0.0036 \text{ m}^2/\text{min}$ ($5.184 \text{ m}^2/\text{day}$), $0.02 \text{ m}/\text{min}$ ($28.8 \text{ m}/\text{day}$) and 0.016 for transmissivity, specific capacity and storativity respectively. Thus, the values obtained for the aquifer parameters from this study indicate that the aquifer can yield sufficient water for local water supply to communities, though with low protective capacity.

4. Conclusion

Geophysical and hydrogeological investigations involving VES well logging and pumping test were carried out in Abavo, Nigeria to determine the aquifer hydraulic properties. The study revealed lithology that comprised lateritic top soil/sand, sandy clay/clayey sand, fine sand, medium sand and coarse to gravelly sand. The aquifer depth ranged from $28.8 - 76.6 \text{ m}$, while the resistivity and thickness (sub-surface) ranged from $1175 - 27,272 \Omega \cdot \text{m}$ and $9.7 - 53.3 \text{ m}$ respectively. The values of $15 \mu\text{s}/\text{cm}$ and $112 \text{ mg}/\text{L}$ obtained for EC and TDS respectively, indicate that the groundwater is within the [30] permissible limit for drinking water. Hence it is free of pollutants and suitable for domestic and other purposes. However, the values of $0.001048 - 0.027828 \Omega^{-1}$ (VES) for longitudinal conductance, revealed a low aquifer protective capacity, which suggests that the aquifer will be affected at any instances of release of contaminant in the area. The high transverse resistance of $105470.4 - 1255775.3 \Omega \cdot \text{m}^2$ indicates a good groundwater yielding material capable of promoting adequate recharge from precipitation. The estimated values of transmissivity from VES ranged from $0.81 - 17.3 \text{ m}^2/\text{day}$ with an average of $2.8 \text{ m}^2/\text{day}$, suggests a low to intermediate groundwater potential. Pumping test analysis revealed that the aquifer transmissivity, specific capacity, storativity and hydraulic conductivity are $5.9 \text{ m}^2/\text{day}$, $33.12 \text{ m}^2/\text{day}$, 0.0069 and $0.1722 \text{ m}/\text{day}$ respectively. These values suggest that the aquifer is semi-confined, high recharge with poor protective capacity and can supply adequate potable groundwater with

enough pressure for local supply to communities for domestic and other uses. The evaluated results of hydraulic properties from VES interpretation are in fair agreement with that obtained from pumping test and this will be useful for groundwater assessment in the area and beyond.

Availability of Data and Material

Applicable and available on demand from the corresponding author.

Code Availability (Software Used)

Surfer terrain software, Win Resist suite.

Ethical Approval and Consent to Participate

All ethical principles of research in field data acquisition, preparation, analysis and interpretation were implemented.

Conflicts of Interest

On behalf of the authors, the corresponding author states that there is no conflict of interest.

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