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Investigation of Groundwater Aquifers in Otuoke and its Environs Using Vertical Electrical Sounding (VES) Technique

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Abstract

The investigative surveys for groundwater aquifers thickness and depths in parts of Otuoke community in Bayelsa state Nigeria for the sinking of boreholes were carried out using the geoelectric method in this work. These surveys involving vertical electrical sounding (VES), was carried in seventeen locations in the area by utilizing Schlumberger electrode configuration with a maximum current electrode spacing of 350 m and minimum current electrode distance of 100 m (min. AB/2 = 50 m) to determine the apparent electrical resistivity of the subsurface layers. The field electrical resistivity sounding surveys were carried out in these locations with adaptive boundary element method (ABEM) Terrameter (Signal Averaging System) SAS (1000). The field data obtained were interpreted using Win Resist and IpI2win Computer software. The interpreted results showed that water-saturated sandstone forms the major aquifers in the study area and geoelectric survey/analysis indicates that three to four geoelectric layers are present down to the depth of investigation. The electrical resistivity arrangement of these layers in the area is an A-type curve for two VES stations, a K-type curve for five VES stations, two KH-type curves, and seven HK-type curves. The depth of aquifers in the study area is in the range of 20 m to 90 m. The results of our investigation revealed that the majority of the VES stations intercepted good aquifer zones for portable groundwater development in the area with just a few stations showing a decline to good aquifers for groundwater exploration

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Introduction

The use of surface water for domestic purposes in Niger-Delta area today is almost considered an illusion. This is because, although most of the people in the area spend most of their daily lives on top of the water, the access to good drinking water and for other domestic uses has been a great challenge to the people of the area and even beyond. The Niger-Delta area has been highly rural and the people in the area relied on flowing water for drinking and other domestic purposes. However, the crude oil discoveries in this region and other activities have rendered this source of water deplorable. This problem has been greatly linked to various human activities such as the exploration of the crude oil discovered in the area, fish-farming by the people of the area, water transportation etc. that have been the order of the day in the region. The crude oil exploration has been tipped to be the most contributing factor as any available land and spaces are highly polluted due to oil spillage and gas flaring thereby making it impossible for people to use even rainwater for domestic purposes, (Atakpo and Ayolabi2009). To remedy this situation, the only alternative approach for people in the area to have access to water that is a bit quality for drinking and domestic use is groundwater. The susceptibility/vulnerability of the groundwater aquifer to contamination/pollution through seawater intrusion is one of the challenges to groundwater sources for portable water development in the area. The use of geoelectrical methods for groundwater aquifer delineation can serve as a good strategy to counter this challenge of the groundwater in the area.

Niger Delta is known to date back to the early Paleocene which resulted mainly from the build-up of fine-grained sediments eroded and transported by the River Niger and its tributaries. The subsurface geology of which is made up of three lithostratigraphic units (Benin, Agbada, and Akata Formations) and are in turn overlain by quaternary sediments. The Benin Formation which consists of loose and unconsolidated sands has a thickness of about 1800 m and is equally known to be the water-bearing formation of the area, (Okiongbo and Akpofure 2012). The underlying Agbada Formation consists of sandstone and shales. It is up to 3000 m thick and is underlain by the Akata Formation which consists of shales, (Uko-Etim, 2015). This quaternary deposit has a thickness of about 40-150 m and generally consists of rapidly alternating sequences of sand and silt/clay with the latter becoming increasingly more prominent seawards.

The use of the vertical electrical sounding technique as one of the preliminary steps to the investigation of groundwater in most of the Niger Delta regions has been carried out by some researchers in the past. However, our literature survey showed that very scanty works for groundwater exploration have been done in Otuoke axis of the Niger Delta region. To that effect, Amadi *et al.* (2012) used the vertical electrical sounding method to investigate the aquifer quality in Bonny Island eastern Niger Delta of Nigeria. The result of the computer modeled curve generated from the VES data showed that the study area is saline (30–90 m) and ferruginous (90–180 m) subsurface. Freshwater that is less in salt and iron content was found in the area at depths between (180–300 m). The study also reveals that the problem of saltwater intrusion in the area is caused by the increased abstraction of groundwater which disturbs the natural freshwater/saline water equilibrium.

A combined 2-D resistivity imaging and vertical electrical sounding have been used by Ehirim *et al.,* (2009) to conduct geophysical investigation of the solid waste landfill in Port Harcourt Municipality for a hydro-geophysical assessment of the contamination of soil and groundwater in the area. They found out based on their results that the surrounding soil and groundwater in Port Harcourt Municipality around the landfill have been contaminated to a depth exceeding 31 m which is well within the aquifer region in the area. Mgbolu *et al.* (2019) reported work on the investigation of groundwater potentials, aquifer characteristics, and vulnerability in parts of Ndokwa area, Niger Delta, Nigeria using the resistivity method. The results of the interpreted data obtained revealed five to six geo-electric layers/units were found across the study area. They also reported that the subsurface lithology is predominantly sandstone intercalated with clay, sandy clay, and clayey sand and average depth to aquifer as 71.91 m average aquifer thickness as 42.52 m, average aquifer resistivity value is 1289 Ωm. Nwankwoala and Omunguye (2013) used vertical electrical soundings to study the occurrence of groundwater in the Harold Wilson (Borokiri) and the Eastern Bye-Pass in Port Harcourt Metropolis, Eastern Niger Delta Nigeria. They reported that freshwater/saltwater interface is encountered in Harold Wilson (Borokiri) at about 30 m while at Eastern Bye-Pass area it is at about 120 m and the interface could fluctuate as the result of tidal influence on the hydrology of the area. Saline water was found to decrease to 94 m at Harold Wilson (Borokiri) but increased to about 120 m at Eastern Bye-Pass. Geophysical investigation involving the vertical electrical sounding technique using the Schlumberger configuration and the horizontal profiling method has been carried out in Ahoada, South-South Nigeria to evaluate the subsoil conditions and groundwater quality of the area three years after the post-spill clean-up exercise, (Nwankwo and Emujakporue 2012). The result of VES interpretation showed that the subsurface layers up to a depth of 49 m in the area have moderate to high resistivity values of 200 Ωm that may affect crops and groundwater development. They however projected that a good aquifer can still be obtained from the depth of 30 m and above in the area. Bello *et al.,* (2017) conducted VES at a solid waste landfill in Aluu community, Obio/Akpor local government area of Port Harcourt Metropolis in Rivers state, Nigeria to determine the hydrogeophysical assessment of the contamination of soil and groundwater in the area.

Study Area Description

Otuoke is one of the communities in the Southern Niger Delta which lies between the latitudes 4o 46'N and 5o 51'N and Longitudes 6o 15E and 6o 23'E (Abadom and Nwankwoala 2018), There are two major climatic seasons in the area, the wet season from April to October and dry season from November to March. Average annual rainfall is about 3000mm and this serves as the major source of groundwater recharge. This ensures a large volume of water input into the environment and with poor drainage most parts of the area are flooded during the rainy season, April to October/November. The topography is invariably gentle. Otuoke is one of the coastal alluvium, mangrove, and fresh-water swamps hydrogeologic province that characterized the present-day Bayelsa state. The area is bounded on the North by Yenagoa, the capital of Bayelsa State, south by Brass and Nembe local government areas, to the West by southern Ijaw and Ahoada-west local government areas. Otuoke can be accessed from the north through Mbiama-Yenagoa road and on the south by the Nembe and Brass Rivers, (Abadom and Nwankwoala 2018).

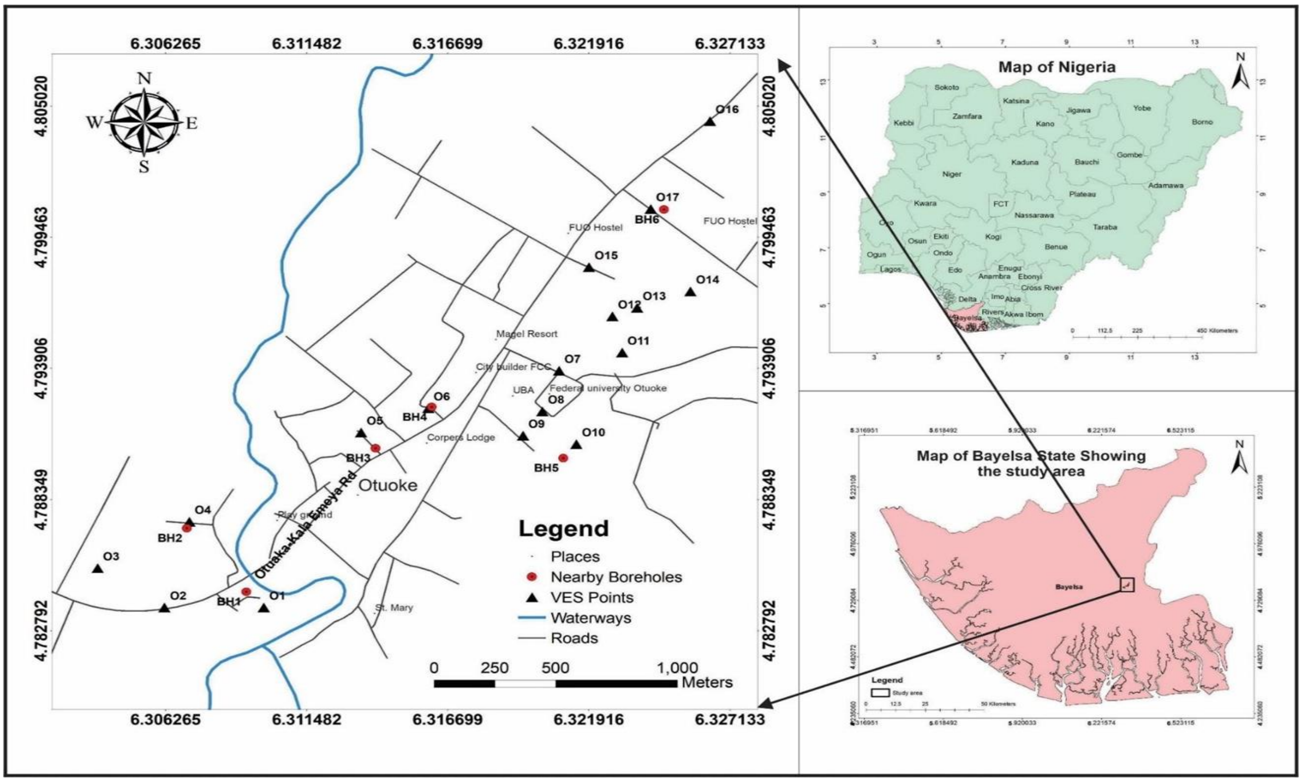

Figure 1. Geographical Map of Bayelsa State Showing the Location of Otuoke.

Theory

Electrical Resistivity Method

The electrical resistivity method involves the measurement of the apparent resistivity of soils and rock as a function of depth or position. The most common electrical technique that is used for hydrogeological and environmental investigations is vertical electrical soundings (resistivity sounding). In resistivity surveys, current is injected into the Earth through a pair of current electrodes, and the potential difference is measured between a pair of potential electrodes. The current and potential electrodes are generally arranged in a linear array. Common arrays include Wenner array, Schlumberger array, dipole-dipole array and pole-pole array, (Alabi et al., 2010; Uhegbu and John 2017). The bulk average resistivity of all soils and rock influencing the current is calculated by dividing the measured potential difference by the input current and multiplying by a geometric factor specific to the array being used. Vertical electrical soundings are applied to a horizontally or completely horizontally layered earth. Thus in VES, the geological targets may include among other things; sedimentary rocks of different lithologies, layered aquifers of different properties, sedimentary rocks overlying igneous rocks, or the weathering zone of igneous rocks. But in most favorable cases, the number of layers, their thicknesses and resistivities are the major outcomes of a VES survey. The basic idea of resolving the vertical resistivity layering is to stepwise increase the current-injecting electrodes AB spacing, which leads to an increasing penetration of the current lines and in this way to an increasing influence of the deep-seated layers on the apparent resistivity (ρ_a). The step-wise measured apparent resistivities are plotted against the current electrode spacing in a log/log scale and interpolated to a continuous curve. A great success has been achieved in the search for groundwater potentials in many places including Nigeria through the use of electrical resistivity method, (Hassan *et al.*, 2017).

The generalized form of electrode configurations in VES technique is drawn schematically in Figure 2.

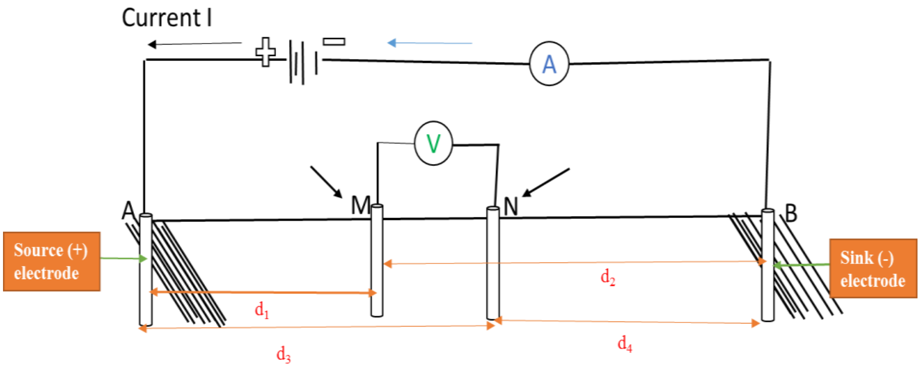

Figure 2: Generalized form of electrode configurations in VES technique

In the diagram, the voltage between the inner electrodes (*M* and *N*) with respect to electrode *A* and electrode *B* respectively, can be computed as given by Okolie *et al.* (2005); Adagunodo et al., (2013) & Bashir *et al.* (2014).

$$V_M = \frac{\rho I}{2\pi}\left[\frac{1}{d_1} - \frac{1}{d_2}\right] \quad (1)$$

$$V_N = \frac{\rho I}{2\pi}\left[\frac{1}{d_3} - \frac{1}{d_4}\right] \quad (2)$$

where $d_1 = AM$, $d_2 = BM$, $d_3 = AN$, and $d_4 = BN$ are electrodes spacing.

The voltage between the *M* and *N* electrodes can then be calculated as follows

$$V_M - V_N = \Delta V = \frac{\rho I}{2\pi}\left[\frac{1}{d_1} - \frac{1}{d_2} - \frac{1}{d_3} + \frac{1}{d_4}\right] \quad (3)$$

This is the potential difference that is measured by the voltmeter and if represented by V. then (Eqn. 3) can be rewritten for the resistivity ρ as follow

$$\rho = 2\pi\frac{V}{I}\left[\frac{1}{d_1} - \frac{1}{d_2} - \frac{1}{d_3} + \frac{1}{d_4}\right]^{-1} \quad (4)$$

$$\rho = G\frac{V}{I} \quad (5)$$

Where

$$\mathrm{G} = 2\pi\left[\frac{1}{\mathrm{d}_1} - \frac{1}{\mathrm{d}_2} - \frac{1}{\mathrm{d}_3} + \frac{1}{\mathrm{d}_4}\right]^{-1} \quad (6)$$

is the generalized form of geometric factor or configuration factor which depends on the electrode configurations. For inhomogeneous conditions, (Eqn. 5) gives the resistivity of an equivalent homogeneous half-space. For this situation the term apparent resistivity (ρ) is introduced and it will be a function of the form of the inhomogeneity. Apparent resistivity is defined as the resistivity of an equivalent electrically homogenous and isotropic half-space that would yield the potential measured on the heterogeneous earth using the same applied current.

Electrode configuration in Vertical electrical soundings (VES)

The common electrode configurations are the Wenner, and Schlumberger configuration.

Wenner Configuration

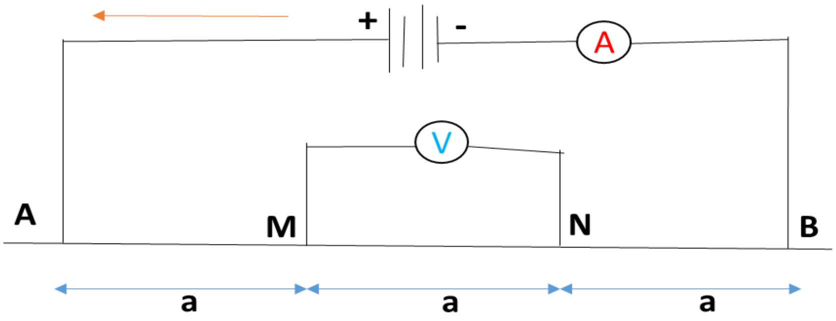

Figure 3: Schematics diagram of Wenner array in VES.

In Wenner configuration, the electrodes spreading is symmetrical with current electrode spacing being three times the potential electrode. The geometric factor in Wenner array as a consequence of the electrode configurations can be derived from the generalized geometric factor expression given in(Eqn. 6) Concerning the generalized electrode spacing as shown in Figure 2.

$AM = d_1 = a; \quad MB = d_2 = 2a; \quad AN = d_3 = 2a; \quad NB = d_4 = a$

Thus the geometric factor is given by

$$\mathrm{G} = 2\pi\left[\frac{1}{\mathrm{d}_1} - \frac{1}{\mathrm{d}_2} - \frac{1}{\mathrm{d}_3} + \frac{1}{\mathrm{d}_4}\right]^{-1} = 2\pi\left[\frac{1}{a} - \frac{1}{2a} - \frac{1}{2a} + \frac{1}{a}\right]^{-1} = 2\pi\left[\frac{2}{a} - \frac{1}{a}\right]^{-1} = 2\pi a \qquad (7)$$

Hence using equation 5 the apparent resistivity (ρ_a) in Wenner array is given by

$$\rho_a = 2\pi a \frac{\mathrm{V}}{\mathrm{I}} \qquad (8)$$

Schlumberger Configuration

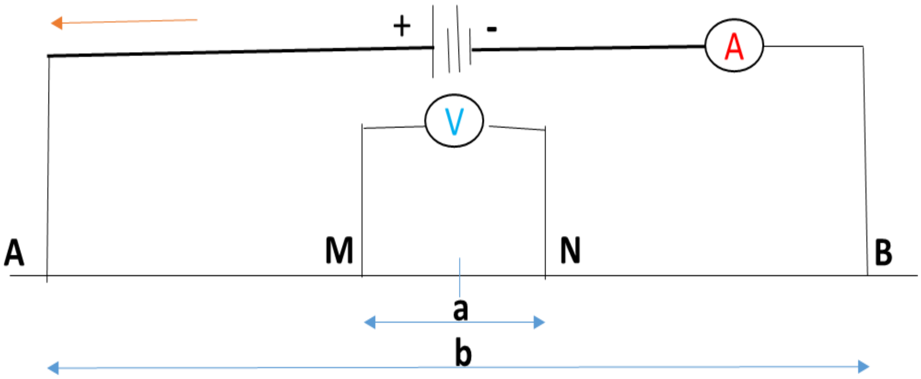

Figure 4: Schematics of Schlumberger array in VES.

In the Schlumberger configuration, the current electrode is normally placed in such a way that they are at least five times the potential electrode spacing. The geometric factor is a consequence of these arrangements and concerning generalized VES electrode spacing given in Figure 2 can be calculated. From Figure 3, the arrangements are viewed in comparison to Figure 2 as follows

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$AM = d_1 = {}^{b}/_{2} - {}^{a}/_{2}; \quad MB = d_2 = {}^{a}/_{2} + {}^{b}/_{2}; \quad AN = d_3 = {}^{a}/_{2} + {}^{b}/_{2}; \quad NB = d_4 = {}^{b}/_{2} - {}^{a}/_{2}$

Thus the geometric factor in Schlumberger configuration is given by;

$$\mathrm{G} = 2\pi\left[\frac{1}{\mathrm{d}_1} - \frac{1}{\mathrm{d}_2} - \frac{1}{\mathrm{d}_3} + \frac{1}{\mathrm{d}_4}\right]^{-1} = 2\pi\left[\frac{2}{(b-a)} - \frac{2}{(b+a)} - \frac{2}{(b+a)} + \frac{2}{(b-a)}\right]^{-1} = \pi\left[\frac{2}{(b-a)} - \frac{2}{(a+b)}\right]^{-1} = \frac{\pi}{2}\left[\frac{2a}{(b-a)(b+a)}\right]^{-1} \qquad (9)$$

Or

$$G = \frac{\pi}{4}\left[\frac{(b-a)(b+a)}{a}\right] = \frac{\pi}{4}\left[\frac{b^2-a^2}{a}\right] \qquad (10)$$

This can also be written as follows

$$G = \frac{\pi}{4}\left[\frac{AB^2-MN^2}{MN}\right] = \pi\left[\frac{(AB/2)^2-(MN/2)^2}{MN}\right] \qquad (11)$$

The apparent resistivity (ρ_a) in this configuration is thus written as in (Eqn. 12), (George *et al.*, 2013 and Kumar *et al.*, 2014).

$$\rho_a = \pi\frac{V}{I}\left[\frac{(AB/2)^2-(MN/2)^2}{MN}\right] \qquad (12)$$

Materials and Methods

The equipment used for this study is the ABEM Terrameter Signal Averaging System (SAS 1000), four metal electrodes, cable for current and potential electrodes, three hammers, measuring tapes, and a cell phone for long-distance communication. The ABEM Terrameter was used to display the apparent resistivity (ρ_a) of subsurface soil and is powered by a 12 volts DC Power Source (battery).

Vertical electrical sounding (VES) of electrical resistivity method was employed in this work for the groundwater aquifer investigation in the study area. The VES survey was carried out at seventeen locations in the study area as shown in Table 1 using Schlumberger electrode configuration. The total maximum current electrode spacing used is 350 m (max. AB/2 = 175 m) while the total minimum current electrode distance is 100 m (min. AB/2 = 50 m). On the other hand, the total maximum potential electrode spacing used is 40 m (max. MN/2 = 20 m) while the total minimum potential electrode spacing is 7.0 m (min. MN/2 = 3.5 m). The criteria for Schlumberger electrode configuration is that current penetration is proportional to current electrodes spacing. The field data obtained was interpreted using Win Resist and IpI2win Computer software.

Table 1: Location of VES Stations

VES NO	VES Stations/locations	Latitude	Longitude	Elevation (m)
01	Engoye hotel road	N 04^{0} 47^{l} 01.6^{ll}	E 006^{0} 18^{l} 35.6^{ll}	2
02	Ekeki road	N 04^{0} 47^{l} 01.6^{ll}	E 006^{0} 18^{l} 22.4^{ll}	8
03	Beside Otuoke Market	N 04^{0} 47^{l} 07.6^{ll}	E 006^{0} 18^{l} 13.5^{ll}	1
04	Beside Beeh Hostel	N 04^{0} 47^{l} 14.7^{ll}	E 006^{0} 18^{l} 25.7^{ll}	1
05	Beside Patience Square	N 04^{0} 47^{l} 28.3^{ll}	E 006^{0} 18^{l} 485.7^{ll}	6
06	Beside RCCG King Favour	N 04^{0} 47^{l} 32.0^{ll}	E 006^{0} 18^{l} 57.5^{ll}	11
07	Beside FUO NASU Secretariat building	N 04^{0} 47^{l} 37.7^{ll}	E 006^{0} 19^{l} 14.9^{ll}	6
08	Beside Faculty building II humanity	N 04^{0} 47^{l} 31.5^{ll}	E 006^{0} 19^{l} 12.7^{ll}	6
09	Beside Faculty of education	N 04^{0} 47^{l} 27.8^{ll}	E 006^{0} 19^{l} 10.1^{ll}	3
10	Behind Faculty of science	N 04^{0} 47^{l} 26.5^{ll}	E 006^{0} 19^{l} 17.2^{ll}	9
11	Behind FUO female hostel	N 04^{0} 47^{l} 40.5^{ll}	E 006^{0} 19^{l} 23.3^{ll}	8
12	FUO new PG building	N 04^{0} $47^{l}46.0^{ll}$	E 006^{0} 19^{l} 22.0^{ll}	6
13	FUO Engineering site	N 04^{0} $47^{l}47.3^{ll}$	E 006^{0} 19^{l} 25.3^{ll}	7
14	FUO new site back gate	N 04^{0} 47^{l} 49.8^{ll}	E 006^{0} 19^{l} 32.4^{ll}	1
15	Beside FUO admin office	N 04^{0} $47^{l}53.5^{ll}$	E 006^{0} 19^{l} 18.9^{ll}	4
16	Beside major road to Otuoke	N 04^{0} $48^{l}15.8^{ll}$	E 006^{0} 19^{l} 35.0^{ll}	1
17	Kakata road	N 04^{0} $48^{l}02.4^{ll}$	E 006^{0} 19^{l} 27.1^{ll}	7

Results

Figures 5 (a & b), Figures 6 (a & b), Figures 7 (a & b), Figures 8 (a & b) and Figures 9 (a & b), are the representative field curve, the interpreted model, results and the geoelectric sections out of the 17 VES stations in the study area. The summary of the interpreted results of the VES data for all the 17 VES stations in the study area is presented in Table 2

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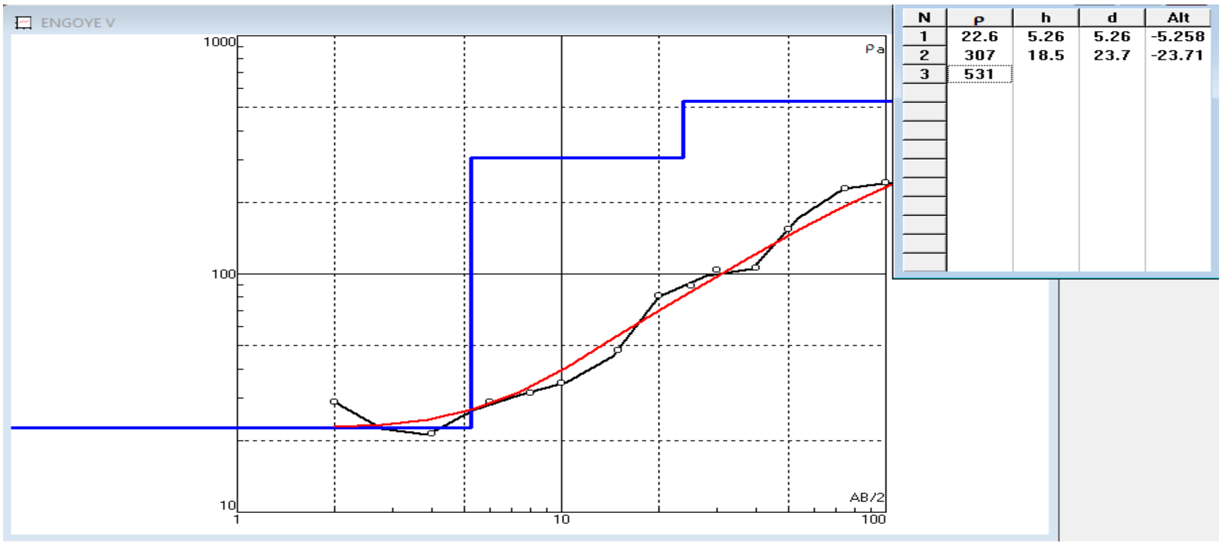
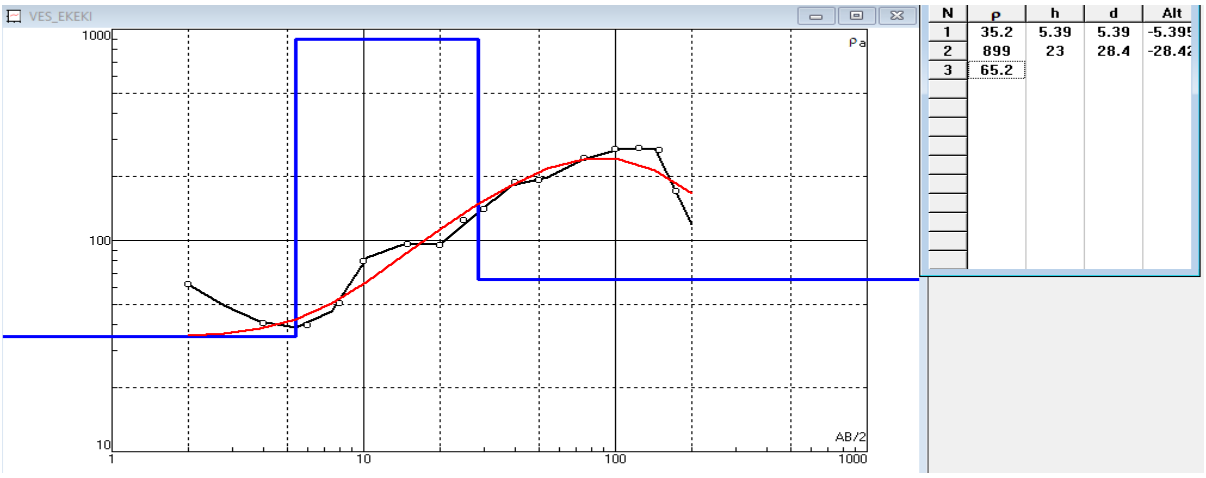


N	ρ	h	d	Alt
1	22.6	5.26	5.26	-5.258
2	307	18.5	23.7	-23.71
3	531			

Figure. 5 (a) Interpreted model for VES 1 along Engoye road

Figure 5 (b) Geoelectric and inferred geologic sections for VES 1 along Engoye road



N	ρ	h	d	Alt
1	35.2	5.39	5.39	-5.39
2	899	23	28.4	-28.4
3	65.2			

Figure 6 (a) Interpreted model for VES 2 along Ekeki road

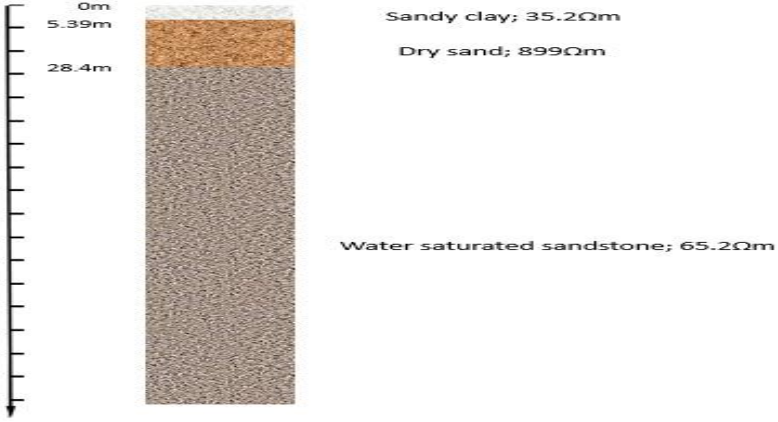
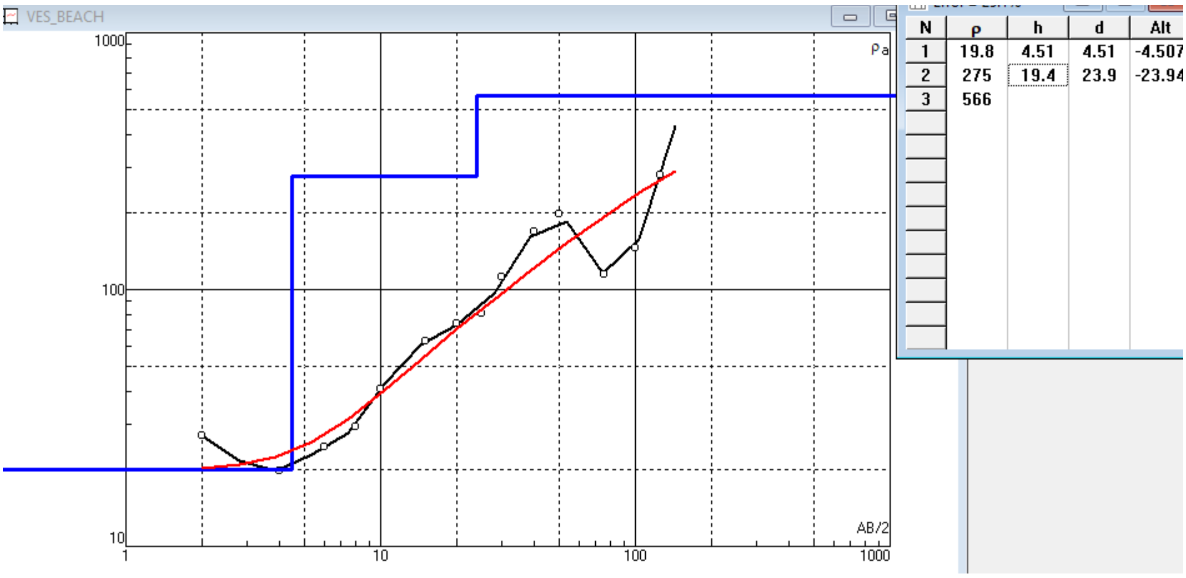


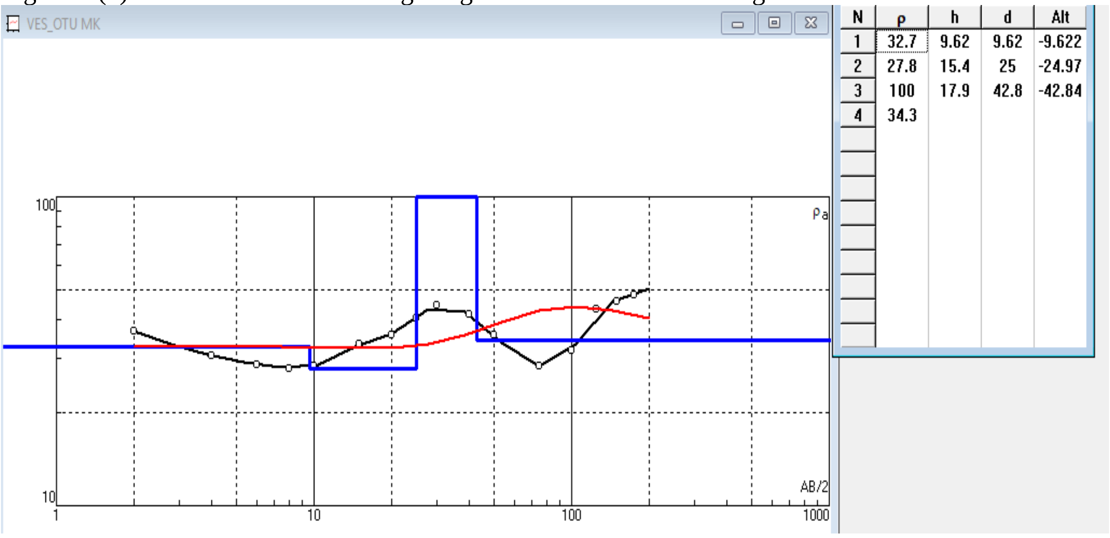
Figure 6 (b) Geoelectric and inferred geologic sections for VES 2 along Ekeki road



N	ρ	h	d	Alt
1	19.8	4.51	4.51	-4.507
2	275	19.4	23.9	-23.94
3	566			

Figure 7 (a) Interpreted model for VES 4 along Beeh Hostel road

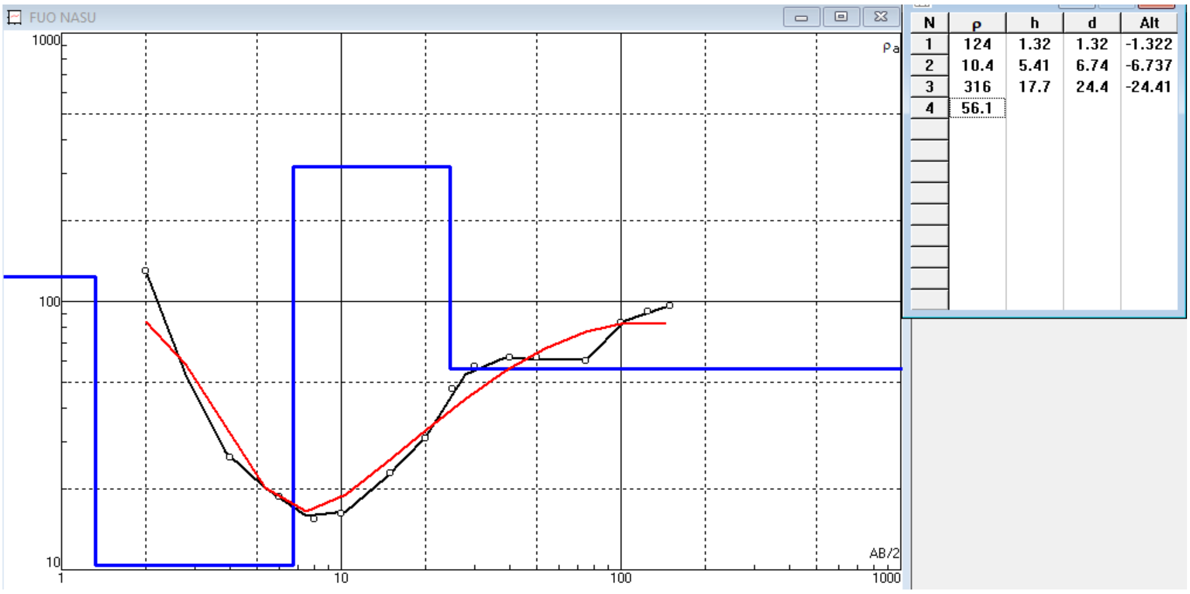
Figure 7 (b) Geoelectric and inferred geologic sections for VES 4 along Beeh Hostel road



N	ρ	h	d	Alt
1	32.7	9.62	9.62	-9.622
2	27.8	15.4	25	-24.97
3	100	17.9	42.8	-42.84
4	34.3			

Figure 8 (a) Interpreted model for VES 3 at Otuoke market.

Figure 8 (b) Geoelectric and inferred geologic sections for VES 3 at Otuoke market.



N	ρ	h	d	Alt
1	124	1.32	1.32	-1.322
2	10.4	5.41	6.74	-6.737
3	316	17.7	24.4	-24.41
4	56.1			

Figure 9 (a): An interpreted model for VES 8 along Faculty Humanity Building II road.

Figure 9 (b) Geoelectric and inferred geologic sections for VES 8 along Faculty Humanity Building II road

In summary of the interpreted results, eight VES stations displayed three-layered geoelectric sections while nine VES stations are four layered geoelectric sections.

Discussion

The results of the VES curve and interpreted layers showed that eight VES stations; VES 1 – Engoye shown in Figure 5 a & b, VES 2 - Ekeki road displayed in Figure 6 a & 5b, VES 4 - Beeh Hostel road; Figure 7 a & b, VES 5, VES 6, VES 7, VES 10 and VES 13 have 3 layers while nine VES stations; VES 3 – Otuoke market, shown in Figure 8 a & b, VES 8 – (road beside Faculty Building II Humanity; FUO) displayed in figure 9 a & b, VES 9, VES 11, VES 12, VES 14, VES 15, VES 16 and VES 17 have four layers. These layers have different resistivity distributions and can be classified based on resistivity curve types, (Anudu *et al.*, 2014 & Nwachukwu *et al.*, 2019) [20, 21]. In addition, four geoelectric layers comprising loamy–sandy topsoil, clay, fine sand, and coarse sand with different resistivity arrangement similar to this work has been reported by Anomohanran, (2011) & Anomohanran, (2015) in the investigations of groundwater resources in Delta Central, Nigeria. VES 1 (Engoye) is characterized by homogeneous lithology with three geoelectric layers with an apparent resistivity values increasing with depth which represent a typical A-type curve arrangement ($\rho_1 < \rho_2 < \rho_3$). VES 2 (Ekeki road) has three layers with an apparent resistivity values 35.2 Ωm for the first layer, 899 Ωm for the second layer, and 65.2 Ωm for the third layer which signifies K- type ($\rho_1 < \rho_2 > \rho_3$) resistivity sounding curve arrangement. The first layer is composed of sandy clay with a thickness and depth of 5.39 m, the second layer is composed of dry sand with a thickness of 23 m and depth of 28.4 m while the third layer is made up of water-saturated sandstone with undefined thickness and depth. VES 3 (Otuoke market) is made up of four layers with an apparent resistivity values of 32.7 Ωm for the first layer, 27.8 Ωm for a second layer, 100 Ωm for and 34 Ωm for the fourth layer. The figure also indicates that the surveyed station is composed of sandy clay up to the depth of 9.62 m in the first layer, dry sand up to a depth of 25 m in the second layer, water-saturated sandstone up to a depth of 42.8 m in the third layer and clayey sand at infinite depth and thickness in the fourth layer. The typical curve type for this type of resistivity arrangement is HK curve type ($\rho_1 > \rho_2 < \rho_3 > \rho_4$). These results suggest that a good groundwater aquifer exists at the fourth layer and is confined since the thickness of the layer is appreciably in the order of 17.9 m. This type of four-layered resistivity arrangement has been reported by Okiongbo and Ogobiri (2011) in the work “geoelectric investigation of groundwater resources in some other parts of Bayelsa State, Nigeria”. VES 4 (Beech Hostel road) is characterized by three geoelectric layers of varying apparent resistivity values, thickness, and depth. The first geoelectric layer is composed of sandy clay with an apparent resistivity of 19.8 Ωm, thickness, and depth of 4.51 m. The second layer is made up of dry sand with an apparent resistivity value of 275 Ωm, a thickness of 19.4, and a depth of 23.9 m. The third layer is the water-saturated sandstone which has a high apparent resistivity value of 566 Ωm with infinite thickness and depth. The curve type for the station is A-type; that is ($\rho_1 < \rho_2 < \rho_3$) and these results indicate that groundwater aquifer can be intercepted at the third layer. VES 5 (Patience Square) composed of sandy clay at depth of 1.96 m for the first, dry sand at the depth of 23.7 m and thickness of 21.8 m for the second layer, and water-saturated sandstone at infinite depth and thickness for the third layer. Their apparent resistivity arrangement is a K - curve type ($\rho_1 < \rho_2 > \rho$) and their results showed that the water table in the area is unconfined and is susceptible to dry up in the second layer while the lower apparent resistivity of 56.2 Ωm in the third layer indicate that the water-bearing capacity of the layer is low and thus sinking bore-hole in the area for potable water will not be encouraged.

VES 6 (road beside RCCG King Favour) has three layers with the first layer having an apparent resistivity of 19 Ωm and depth of 1.11 m, the second layer has a resistivity of 737 Ωm, depth of 27.9 m, and thickness of 26.8 m while the third layer has a decreased apparent resistivity value of 526 Ωm and infinite depth and thickness. The geological section of the VES station reveals that the first layer is composed of sandy clay, the second layer is dry sand while the third layer is water-saturated sandstone. These results suggest that water-bearing zone (aquifer) in the area can be located in the third layer at depth of at least 27.9 m and the curve types of the resistivity arrangement in the station is K-type curve ($\rho_1 < \rho_2 > \rho$). Similar resistivity has been reported in the work of (Osele *et al.*, 2016) for groundwater exploration in Onitsha Anambra State and environs, one of the Niger Delta States of Nigeria. Figures 8a & 8b are the results of the interpreted model and geoelectric section for VES 8 (road beside Faculty Building II Humanity; FUO) respectively. In the VES station, the first layer has an apparent resistivity of 124 Ωm, the second layer has an apparent resistivity of 10.4 Ωm, third has an apparent resistivity of 316 Ωm while the fourth layer has an apparent resistivity of 56.10 Ωm. The soil profile of the station is composed of dry sand with a depth of 1.32 m for the first layer, clay soil with a depth of 6.74 m and thickness of 5.41 m for the second layer, dry sand with a thickness of 17.7 m at depth of 24.4 m for the third and water-saturated sandstone with infinite thickness and depth for the fourth layer. The apparent resistivity arrangement for the VES station showed an HK – curve type and the low value of apparent resistivity (56.10 Ωm) in the fourth layer which is saturated with sandstone (attribute of salinity of groundwater) thus making the station unreliable aquifer zone for sinking bore-hole for portable water development. This phenomenon can be attributed to the salinity of groundwater This argument is comparable to the one reported by Atakpo, (2013) and Oghenero and Emmanuel (2017).

Conclusion

In this work, the results of analysis of data acquisition done for groundwater investigation in seventeen VES stations in Otuoke and its environs using Schlumberger configuration have been interpreted. The results showed that generally, water-saturated sandstone forms the major promising groundwater aquifers in the study area. The geoelectric survey/analysis also generally indicates that three to four resistivity/geoelectric layers are present down to the depth of investigation. The resistivity arrangement of these layers in the area is A – type curve for two VES stations (VES 1 & VES 4), K – type curve for five VES stations (VES 2, VES 5, VES 6, VES 10 & VES 13), two KH – type curve (VES 14 & VES 15) and seven HK – type curve (VES 3, VES 8, VES 9, VES 11, VES 12, VES 16 & VES 17). The depth to groundwater aquifers in the study area according to our analysis is in the range of 20 m to 90 m. The results of our investigation reveal that the majority of the VES stations delineate good groundwater aquifer zones for portable water development in the area while very few in the case of VES 3 and 8 showed unreliable aquifers for the sinking of bore-hole for portable water development in the area.

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