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APPLICATION OF 2-DIMENSIONAL ELECTRICAL RESISTIVITY TOMOGRAPHY AND VERTICAL ELECTRICAL SOUNDING IN AQUIFER VULNERABILITY ASSESSMENT IN ABAK, SOUTHERN NIGERIA

By

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Abstract

2-Dimensional Electrical Resistivity Tomography (ERT) and Vertical Electrical Sounding (VES) were used to study the vulnerability of aquiferious zone in Abak, Southern Nigeria. A total of 10 ERT and 10 VES soundings were carried out. The Werner electrode configuration was employed for ERT data acquisition, while the Schlumberger electrode configuration was used for VES data acquisition. The data were collected using a SSP-ATS-MRP model resistivity meter. The ERT data was analysed using RES2DINV software, while the VES data was modelled using WINRESIST software. Three to four geoelectric units (laterite topsoil, medium-grained sand, coarse-grained sand, and sandy clay sand) were identified in the area. The aquifer thickness in the area ranged from 24.2 m to 43.7 m, with an average value of 33.45 m. The area has very small overburden layer above the aquiferious zone (0.6 to 13.9 m), hence it may not provide sufficient protection against infiltration of contaminants from the overlying layers. Longitudinal conductance varied from 0.0053 Ω^{-1} to 0.1025 Ω^{-1}, with an average value of 0.020 Ω^{-1}. This value is less than 0.1 Ω^{-1}, indicating the aquifer in the study area is situated within zones of poor protective capacity and therefore vulnerable to surface contaminations.

***KeyWords**: Aquifer, electrical resistivity, longitudinal conductance, electrical resistivity tomography, aquifer vulnerability.*

INTRODUCTION

Recently, rural expansion has increased demand for safe water. This has led to increasing need for social amenities especially water, which is mostly gotten from surface sources such as streams and ponds. However, the surface sources are not hygienic for direct consumption due to their exposure to waste materials from human activities and surface runoffs. In Nigeria, groundwater has gained popularity as a source of drinkable water due to its reliability and superior quality when compared to other water sources (Alabi *et al*., 2020). The degree of weathering and the extent of fracturing of the bedrocks, controls the formation and movement of groundwater in the subsurface. Similarly, topography, permeability, lithology, geological structures, lineament density, aperture and connectivity, as well as secondary permeability, command the amount of groundwater sources in the hydrogeologic layers (Omeje *et al*., 2021).

According to Sunkari *et al*. (2021), before the industrial revolutions, quality water was sourced from ponds, rainfall, rivers, streams and dews which are seasonal and highly prone to contamination especially from anthropogenic influences and extremely degraded. Groundwater is usually free from odour, colour and has a very low dissolved solid content, generally, proven to be a better source of sustainable and clean water supply (Akpan *et al*., 2024; Akankpo *et al.*, 2009; Ibout *et al*., 2013; Joel *et al*., 2020; Uwa *et al*., 2018). However, any undetected contamination of this resource poses a threat to the well-being, health and continuous existence of man in the environment (Adelusi *et al*., 2013). There is proper need for quality assessment of groundwater stored in aquifers found in the subsurface layers of the earth. The information on groundwater vulnerability is required for groundwater protection and management. Vulnerability of aquifer reflects whether the subsurface characteristics can prevent or favour the transport of contaminants into the aquifer repositories (Obiora and Ibout, 2020)

Electrical Resistivity Tomography (ERT) is one of the most current geophysical techniques that has proven very effective in delineating subsurface imaging and aquifer identification. The method gives a wide range of resistivity values; shows high correlation between electrical resistivity and lithology of the subsurface layers; provides the required depth of investigation, and evaluates the subsurface via 2D and 3D imaging (Hung *et al*., 2020). ERT data provides an image with the distribution of subsurface resistivity when modelled using an appropriate software. An integrative combination of electrical resistivity tomography (ERT) and vertical electrical sounding (VES) in investigating aquifer vulnerability is a proven method for identifying how prune an aquifer is to

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contaminant and its present state of contamination. VES and ERT display the conductivity/resistivity of the distributed geological formations vertically and horizontally. The basic principle of ERT is based on the varying electrical conductivity of the subsurface materials, which depends on many factors, such as rock type, porosity, permeability, connectivity of pores, temperature, salinity, cation exchange capacity, clay content, nature of the fluid/water, weathering degree, fractures/faults, rock association, rock deformation, water-rock interaction and alteration, etc (Hasan *et al*., 2021; Ibout *et al.*, 2021).

Ozegin *et al.* (2018) carried out an integrated geophysical investigation using Vertical Electrical Sounding (VES) and 2-D Electrical Resistivity Tomography (ERT) to characterise the subsurface geology and evaluate groundwater potential in Okpella, Edo State, Nigeria. The study revealed a heterogeneous subsurface sequence consisting of four distinct geoelectric layers. Chukwudi *et al*. (2022) explored the groundwater potential in specific areas of Enugu metropolis, employing a combination of Vertical Electrical Sounding (VES) and 2D Electrical Resistivity Tomography (ERT) techniques. By integrating the results from both VES and ERT techniques, the researchers sought to improve the reliability of the findings, reduce uncertainties, and gain a more comprehensive understanding of the area's groundwater potential, ultimately contributing to the development of sustainable groundwater resources in the region. VES and ERT interpretation using curve matching and inversion have been successfully applied across Nigeria. In Abeokuta for foundation studies (Amadi *et al*., 2012); In Akure and Ife for groundwater development (Olorunfemi & Fasuyi, 1993); In Benin and surrounding deltaic areas for aquifer delineation (Aizebeokhai, 2010).

According to Obiora and Ibout (2020), aquifer vulnerability assessment is essential for protecting groundwater from potential contamination and ensuring its sustainable use. Areas with highly permeable soils, shallow water tables, and fractured rocks are generally more vulnerable to pollutants (Artimes *et al.*, 2021). Therefore, understanding the degree of vulnerability of different aquifers is essential for guiding land use planning and pollution prevention strategies (Benkalil, 2016). In this work, we seek to establish an empirical correlation between ERT and VES data to ascertain the vulnerability of the aquiferious zone in Abak, Southern Nigeria.

LOCATION AND GEOLOGICAL SETTING OF THE STUDY AREA

The survey area is located between Longitudes 7˚40'E and 7˚50'E and Latitude 4˚50'N and 4˚10'N with the total area of about 50 km^2 (Figure 1). Abak, with a varying elevation between 36 - 91 m, is located within the Niger Delta basin, one of Nigeria's major sedimentary basins. This basin is known for its thick sequences of sedimentary rocks, including sandstones, shales, and conglomerates. The sedimentary rocks in the Niger Delta basin are often grouped into several formations. These include the Benin Formation, Agbada Formation, Akata Formation, and others. These formations consist of various layers of sediments, which may include sand, silt, clay and organic matter. Abak belongs to the area designated as shoreline plain-sands referred to as the Benin Formation (Figure 1).

The Benin Formation, which is found at shallower layers, is a sedimentary deposit of gravel and sand, significant for groundwater investigation. This formation is made up of gravel and sand from the continent that were accumulated in the highest deltaic plain (Abam and Nwankwoala, 2020). The texture of the grain sizes ranges from coarse to fine grained sand, and they are poorly-sorted. Along with being thick and friable, they have some modest sandstone, silt, and clay intercalations. The different order creates systems of several aquifers of varying thicknesses (George *et al.*, 2009). It has been discovered that the aquifer systems are a mixture of the various sand grain sizes. The aquifers of Abak are sedimentary rock layers which have the capacity to store and transmit groundwater. The area is situated within a climatic zone with two distinct seasons: the rainy season which begins from March to October and the dry season which begins from November to February of every year (Uwa *et al*., 2018).

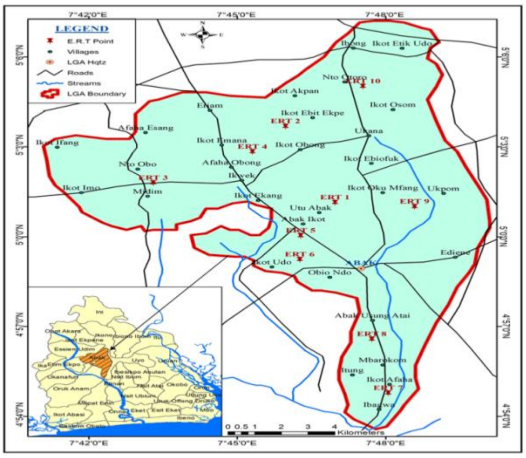

Figure 1: Map of Abak indicating ERT profile points

MATERIALS AND METHOD

The vertical electrical sounding and electrical resistivity tomography methods were used for this survey using an SSP-ATS-MRP model of an IGIS (Integrated Geo-instruments and Services) resistivity meter. A flow diagram which summarizes the methods applied is presented in Figure 2.

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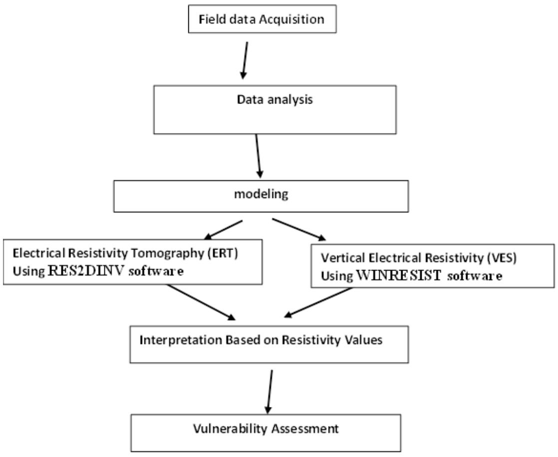

Figure 2: Summary of Methodology

For vertical electrical sounding (VES), a total of ten VES stations were surveyed using Schlumberger electrode configuration. Direct current was sent into the ground through a pair of current electrodes (A and B), and another pair of potential electrodes (M and N) measured the potential difference created (Figure 3). The four electrodes were placed on a straight line with AB ≥ 5MN, with a maximum current electrode spread of 400 m. The current electrodes placed on a straight profile were deployed with a pair of potential electrodes having a common midpoint "O". The reference point "O" was located midway between the potential electrodes and was kept constant throughout the VES sounding. The potential electrodes (M and N), with half electrode spacing, varied from 0.25 to 10 m from the centre point "O". The current electrodes (A and B), with half electrode spacing, were varied from 1 to 200 m from midpoint 'O' along a profile line. The apparent resistivity values obtained with the geometric factor were plotted against half the current electrode spacing on a bi-logarithmic graph to determine the apparent resistivities and thicknesses of various layers penetrated during the survey. The result of the field measurements was used to compute the apparent resistivity considering its geometric factor and resistance value as collected on the field using Equation (1). The calculated apparent resistivity is measured in Ωm, and $\frac{\nabla V}{I}$ represents the resistance as measured on the field. The geometric factor was calculated with $\left[\frac{\left(\frac{AB}{2}\right)^2-\left(\frac{MN^2}{2}\right)}{MN}\right]$ using schlumberger array, as shown in Figure 3.

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

(1)

where;

ρ_a = Apparent Resistivity of formation

AB = Current Electrode Spacing and,

MN = Potential Electrode Spacing (Ibuot *et al.*, 2021).

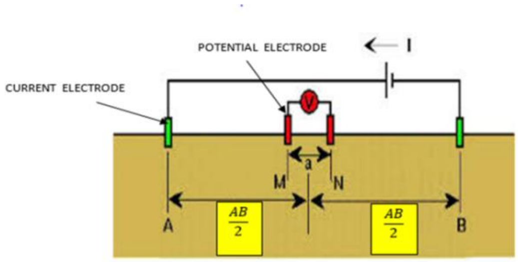

Figure 3: Schlumberger Array

The coordinates and elevations of each location were obtained using the Global Positioning System (GPS). The WINRESIST software was used to generate inversion models for the earth's primary parameters such as resistivities, thicknesses and depths for different geologic subsurface layers. Secondary parameters such as water resistivity, porosity, hydraulic conductivity, transverse resistance, and formation factor were computed using respective formulae.

For electrical resistivity tomography, the Wenner electrode array was adopted for data collection. This array was deployed for the survey because it is capable of producing a good 2D image of the subsurface. A survey profile line of 240 m, was marked at each profile point. A total of 10 profiles were taken across the study area. The profiling carried out involved moving the whole array with constant spacing of 10 m (first 'a' distance apart for the electrodes) along the line of survey till the 240 m was exhausted. After completing the sequence of measurements with 1a spacing (10 m apart for each electrode), next measurements with electrode spacing 2a (20m electrodes apart) was carried out along the same profile line. The same process was repeated for electrode spacing of 3a, 4a, 5a, 6a, 7a, and 8a; corresponding to 30, 40, 50, 60, 70, and 80m apart for the electrodes pinned along the profile line. The measured resistances R were converted to apparent resistivity values (ρ_a) by considering the geometrical factor of Wenner electrode array using Equation 2:

$$\rho_a = 2\pi a\left(\frac{\Delta V}{I}\right) \quad \text{or} \quad \rho_a = 2\pi aR \qquad (2)$$

Where;

"a" is the spacing between electrodes.

R = resistance as obtained in the field.

The RES2DINV software transformed the measured ERT data to an approximate picture of the true subsurface resistivity distribution and geometry of the subsurface features (Olayinka and Yaramanci, 2000).

Vulnerability of aquifer greatly depend on the thickness of the overlying layer (protective layer) before the sustainable water aquifer. The protective layers must have very high thickness and low hydraulic conductivity for effective groundwater protection (Obiora and Ibout, 2020). Aquifer vulnerability is analyzed using the calculated longitudinal conductance, considering the resistivities of the overlying layers before the aquifer. Longitudinal conductance can be classified into good, moderate, weak and poor protective capacity based on calculated values of S as shown in Table 1. The longitudinal unit conductance is used to predict the water's contamination

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susceptibility using geoelectrical characteristics (Akpan *et al.*, 2024).

The aquifer vulnerability of the area was estimated using Equation 3:

$$S = \sum_{i=1}^{n} \frac{h_i}{\rho_i} = \frac{h_1}{\rho_1} + \frac{h_2}{\rho_2} + \cdots \frac{h_n}{\rho_n} \qquad (3)$$

Where S is the longitudinal conductance, h_i is the layer thickness, ρ_i is layer resistivity while n is the number of layers from the surface to the top of aquifer, which varies from i = 1 to i = n (Ugwu *et al.*, 2016; Ibout *et al.*, 2021).

Table 1: Protective capacity rating of longitudinal conductance

Range	Strength
S > 10	Excellent
5 < S < 10	Very good
0.7 < S < 4.9	Good
0.2 < S < 0.69	Moderate
0.1 < S < 0.19	Weak
S < 0.1	Poor

Source: George *et al*. (2014).

RESULTS AND DISCUSSION

VES Results

The qualitative interpretation of results for the resistivity data using the WINRESIST software is given in Table 2. The variation in resistivity at different depths can be characterised by its geology, lithology, water quality and degree of layer saturation. The resistivity values for layer 1 ranges from 126.5 Ωm at AB_3 to 939.0 Ωm at AB_2, while its thickness and depth ranges from 0.6 m at AB_3 to 2.4 m at AB_9. The second layer resistivity values ranged from 46.3 Ωm at AB_7 to 2040.5 Ωm at AB_{10}, while its layer thickness ranged from 4.6 m at AB_7 to 13.9 at AB_4. The layer depth from the surface ranged from 5.3 m at AB_7 to 14.6 m at AB_4. The third layer has a resistivity value ranging from 1239.0 at AB_7 to 5719.8 at AB_9, while the layer thickness for the third layer ranged from 24.2 m at AB_8 to 43.7 m at AB_6, with layer depth ranging from 30.2 m to 54.8 m. The third layer which contains coarse-grained sand is said to be the aquiferous zone. The fourth layer has resistivity values ranging from 44.5 at AB_7 to 1924.8 at AB_3 with undefined layer thickness and layer depth.

The longitudinal conductance which is one of the Dar Zarrouk parameters was estimated using Equation 3. The results of the findings show that, the longitudinal conductance as shown in Table 3 varied from 0.0053 Ω^{-1} to 0.1025 Ω^{-1}, with an average value of 0.01985 Ω^{-1}. This value is less than 1 Ω^{-1}. According to Ugwu *et al.* (2016), values of longitudinal conductance less than 0.1 Ω^{-1} indicate zones of poor aquifer protective capacity. This means that the aquifers in our study area are vulnerable to surface contaminations. More so, the earth medium acts as a natural filter of percolating fluid, thus, its ability to retard fluid flow is a measure of its protective capacity (Ibout *et al*., 2019). The thickness of the over burden layer (confining layer) above the aquifer is thin (0.6 m to 13.9 m thick), suggesting, it may have been eroded or weathered and hence may not provide sufficient protection against the infiltration of contaminants from the overlying layers. Our findings agree with the findings of Uwa *et al*. (2018), whose values for longitudinal conductance range less than 1 Ω^{-1}.

The result shows that VES AB_7 has weak protective capacity while the other surveyed locations in the study area have poor aquifer protective capacity and hence, highly susceptive to aquifer contamination. From the contour map (Figures 4), low longitudinal conductance with a range of 0.0031Ω^{-1} to 0.0086 Ω^{-1} was observed at the eastern and north-eastern part of the contour, notably, Ukpom, Ikot Etuk Udo and Atai Otoro Abak. Also, low longitudinal conductance was also observed in the north-western part of the contour at Midim and Edem Anwa. Areas with moderate longitudinal conductance within the range: 0.0086 Ω^{-1} to 0.0141 Ω^{-1} were recorded at the central, south western and south eastern parts notably, Ikot Ndue, Utu Abak, Ikot ebit Ekpe and Ikot Ndue. Only areas within Ikot Afaha at the south-eastern part of the contour recorded a high longitudinal conductance of the range: 0.0141 Ω^{-1} to 0.0196 Ω^{-1}.

According to Ugwu *et al*. (2016), values of longitudinal conductance less than 0.1Ω^{-1} indicate zones of poor aquifer protective capacity. This indicates that the aquifers in our study area are vulnerable to surface contaminants. More so, the thickness of the over burden layer (confining layer) above the aquifer is thin (0.6 m to 13.9 m thick). This indicates that the over burden layer may not provide sufficient protection against the infiltration of contaminants to the aquifer, even though the earth acts as a natural filter of percolating fluid and can retard fluid flow as a measure of its protective capacity (Ibout *et al*., 2019). The thin layer of the overburden suggests that it may have been recently eroded or weathered, effectively compromising its protective capacity. Our result agrees with the findings of Uwa *et al*. (2018) on values of longitudinal conductance less than 1 Ω^{-1}.

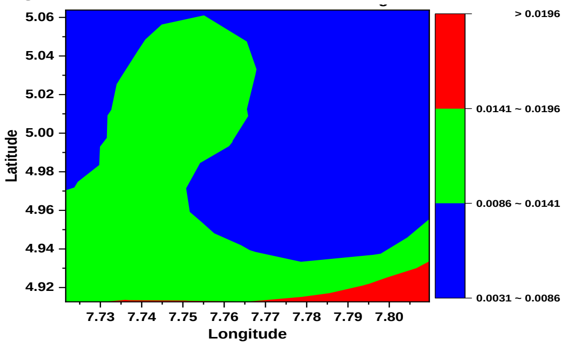

Figure 4: Contour map showing the variation of longitudinal conductance

Table 2: Summary of aquifer hydraulic properties at VES Results

VES	Location	Longit	Latit	Elevat	Layer Resistivity (Ωm)	Layer thickness	Layer depth (m)	Curves

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No.	Name	ude (°E)	ude (°N)	ion (m)	ρ_1	ρ_2	ρ_3	ρ_4	(m) h_1	h_2	h_3	d_1	d_2	d_3	types
AB 1	Utu Abak	7.7713	5.0033	60	325.5	872.9	1554.5	641.1	0.8	7.9	27.7	0.8	8.5	36.4	AK
AB 2	Ikot Ebit Ekpe	7.7662	5.0612	91	939.0	1181.9	2078.7	602.8	1.2	12.5	39.2	1.2	13.8	52.9	AKQ
AB 3	Midim	7.7216	5.0298	71	126.5	1437.8	4028.7	1924.9	0.6	7.3	35.5	0.6	7.9	43.5	AK
AB 4	Ikot Ndue	7.7550	5.0470	83	377.6	890.1	2000.1	380.9	0.7	13.9	37.0	0.7	14.6	51.6	AK
AB5	Edem Anwa	7.7348	5.0638	80	595.6	1826.3	2271.7	485.8	1.3	10.1	33.9	1.3	11.5	45.4	AK
AB6	Ikot Etuk Udo	7.7710	4.9870	69	365.7	1582.0	1704.2	636.3	1.2	9.9	43.7	1.2	11.2	54.8	AK
AB 7	Ikot Afaha	7.8008	4.9126	36	224.8	46.3	1239.0	44.5	0.7	4.6	24.9	0.7	5.3	30.2	HK
AB 8	Abak Usung Atai	7.7953	4.9427	65	664.8	1338.7	3283.5	79.4	1.1	11.1	24.2	1.1	12.1	36.3	KQ
AB 9	Ukpom	7.8097	5.0165	78	890..5	899.5	5719.8	153.2	2.4	9.2	27.3	2.4	11.6	38.9	HKQ
AB 10	Atai Otoro Abak	7.7829	5.0188	69	796.2	2040.5	2616.6	1211.0	1.3	7.4	41.1	1.3	8.8	49.9	AK

Table 3: Summary of estimated aquifer hydraulic properties at VES points

VES No.	Location Name	Long. (°E)	Lat. (°N)	Elevation (m)	Aquifer resistivity (Ωm)	Aquifer thickness (m)	Long. Conductance (Ω^{-1})	Protective capacity rate
AB 1	Utu Abak	7.7713	5.0033	60	1554.5	27.7	0.0115	Poor
AB 2	Ikot Ebit Ekpe	7.7662	5.0612	91	2078.7	39.2	0.0119	Poor
AB 3	Midim	7.7216	5.0298	71	4028.7	35.5	0.0098	Poor
AB 4	Ikot Ndue	7.7550	5.0470	83	2000.1	37.0	0.0175	Poor
AB 5	Edem Anwa	7.7348	5.0638	80	2271.7	33.9	0.0077	Poor
AB 6	Ikot Etuk Udo	7.7710	4.9870	69	1704.2	43.7	0.0095	Poor
AB 7	Ikot Afaha	7.8008	4.9126	36	1239.0	24.9	0.1025	Weak
AB 8	AbakUsung Atai	7.7953	4.9427	65	3283.5	24.2	0.0099	Poor
AB 9	Ukpom	7.8097	5.0165	78	5719.8	27.3	0.0129	Poor
AB 10	AtaiOtoro Abak	7.7829	5.0188	69	2616.6	41.1	0.0053	Poor

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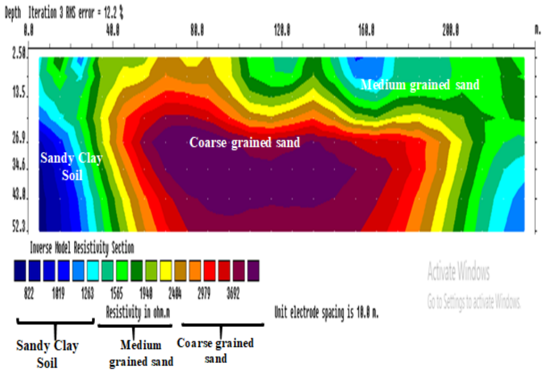

Figure 5: Subsurface imaging obtained along ERT point 3

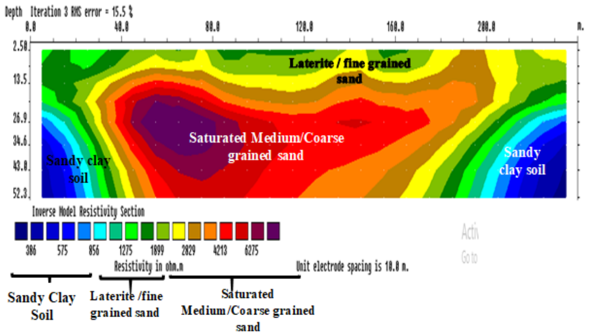

Figure 6: Subsurface imaging obtained along ERT point 1

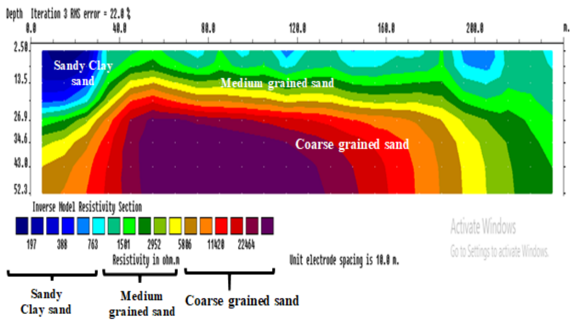

Figure 7: Subsurface image obtained along ERT 7

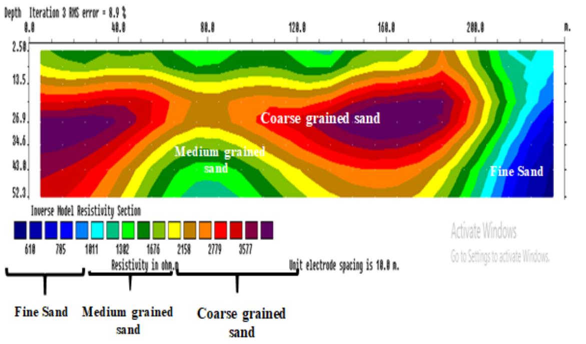

Figure 8: Subsurface image obtained along ERT 10

ERT Results

The 2-D ERT data acquired were processed using RES2DINV software. The modeled results show the subsurface imaging, delineate the aquiferous zone between 5.0 m to 14.0 m from the subsurface (Figures 5 to 8). The ERT imaging gives a total image depth of 52.3 m, with warmer colours such as brown, orange, red and deep brown indicating the aquiferous zone.

Based on the VES data analysis, the warmer colours correlate to zones of medium to coarse-grained sand. The lighter colours such as blue, yellow and green indicate zones of clayey fine- / medium-grained sand. From the ERT modeled resistivity values, the subsurface consists of 3-4 geoelectric sections, which include clay/fine-grained sand, medium-grained sand, and coarse-grained sand. From the ERT imaging, the aquiferous zone is seen to be close to the surface, with a thin overburden layer. This corroborates the result obtained from the VES result indicating that the aquifer is highly susceptive to contamination. According to Ibout *et al.* (2019), a low longitudinal conductance less than 0.5 Ω^{-1}, indicates the susceptibility and vulnerability of the hydrogeological units.

CONCLUSION AND RECOMMENDATIONS

The ERT results correlates to the VES results, and support that the subsurface within the study area is made of 3 - 4 geoelectric layers. The aquiferous zone is found mostly within the third layer, which is made of medium / coarse-grained sand. This zone also carries the greatest layer thickness and hence is capable to host sufficient amount of water which can be profitably exploited. The identified aquifer is unconfined, with little overburden layers, mostly made of medium grained sand. With values of longitudinal conductance less than $0.1\Omega^{-1}$, the area has a poor protective capacity and hence the aquifer can easily be contaminated if exposed to unhealthy waste disposal. From the findings of this research, it is recommended that due to the shallow nature of the overburden layer, locations such as Utu Abak, Midim, Ikot Afaha and Atai Otoro Abak, should be investigated for possible sources and eradication of overburden erosion and weathering. Proper waste collection and disposal should be carried out to avoid infiltration of pollutants into the unconfined aquifer. Furthermore, Physico-chemical analysis of water samples should be carried in the area to know the current groundwater quality status.

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