e-ISSN 3050-9653
p-ISSN 2805-4364

Check for updates

10.5281/zenodo.16743299 | Vol. 8 Issue 06 June - 2025 | Manuscript ID: #02038

MAPPING OF SUBSURFACE CONTAMINATION ZONE USING 2-D ELECTRICAL RESISTIVITY IMAGING AND VES TECHNIQUE IN ORON, NIGER DELTA, NIGERIA

F. D. Eyenaka, [1] E. A. Idiong, [2] S. O. Uwak, [3] A. A. Udo[4]

[1, 2 & 3] Department of Physics, College of Education, AfahaNsit, AkwaIbom State, Nigeria.
[4]Department of Physics, Federal University of Kashere, Gombe State, Nigeria.
Correspondence: francisayenaka@gmail.com
+2348027038870

ABSTRACT:

The integrated geophysical survey measurements carried out in the coastal part of AkwaIbom State specifically Oron Local Government Area located with latitude $4^0$42‘0‘‘ and $4^0$51‘0‘‘N of the equator and longitudes $8^0$12‘0‘‘ and $8^0$18‘0‘‘E of the Greenwich Meridian reveals the extent of aquifer intrusion by saltwater. The geophysical methods employed were 2-D electrical resistivity tomography (ERT) and vertical electrical sounding (VES) techniques using state of the art resistivity meter (IGIS-SSP-ATS-MRT model). The 2-D (ERT) and VES used Wenner and schlumberge electrode configurations respectively with maximum current electrode spacing ranging from 5 to 200m for the field measurement. A total of 8 ERT and 8 VES traverses were covered and the interpretation of resistivity thickness and depth to bottom layer showed that the lithologies are predominantly saline clay/saline clayey sand, medium to coarse sand, fine medium sand, and lateritic/gravelly sand with upper limit resistivity of about 29.15 Ωm for saline clay/saline clayey sand, 362 Ωm for fine medium sand and 68,380 Ωm for lateritic/gravelly sands. The DC resistivity surveys also reveals significant variations within the subsurface coastal sediments with AK curve type having the highest occurrence showing dominant trend of decreasing resistivity with depth. The apparent resistivity of the field data delineate the subsurface formation with evidence of fresh water aquifer at VES 3, 6,7 and 8. The low resistivity values of about 2.4 Ωm, 6.0 Ωm and 6.2 Ωm with thickness of about 1.3m, 2.1m and 0.7m and depth to bottom values of about 1.3m, 2.1m and 0.7m respectively. High resistivity recorded in VESs 7 and 8 were interpreted as lateritic/gravelly sand. Interpreted 2D geoelectrical models showed surface and subsurface aquifer intrusions with lowest electrical resistivity value of about 6.60 Ωm ERT results also showed both surface and subsurface intrusion within the aquifer system at some locations. Hence, the interface mapped showed saline intrusion which is as a result of both anthropogenic and natural factors within the study area.

Keywords:

Contaminated Zones, 2-D electrical resistivity tomography (ERT), vertical electrical sounding (VES), saltwater intrusion and coastal aquifer

How to cite: Eyenaka, F. D., Idiong, E. A., Uwak, S. O., & Udo, A. A. (2025). MAPPING OF SUBSURFACE CONTAMINATION ZONE USING 2-D ELECTRICAL RESISTIVITY IMAGING AND VES TECHNIQUE IN ORON, NIGER DELTA, NIGERIA. *GPH-International Journal of Applied Science*, 8(6), 42-62. https://doi.org/10.5281/zenodo.16743299

Introduction

One of the major challenges faced by the communities within the coastal regions of any nation is the encroachment of seawaterinto the coastal aquifers due partly to excessive abstraction of groundwater in the coastal area George, N. J. Akpan, A. O. and Obot, I. B. (2010). Nigeria has a coastline that is 1, 000km long boarding some statein the South with the Atlantic Ocean. These are Lagos, Ogun, Ondo, Delta, Bayelsa, Rivers, Cross Rivers and AkwaIbom State specifically Oron Local Government Area Oyeyemi, K. D., Aizebeokhai, A. P. and Oladunjoye, M. A. (2015). The induced gradients usually cause migration of saltwater from the sea toward a borehole where groundwater is being pumped from aquifers that are in hydraulic connection with the sea (Abdaua, Ali, Ali-Higgi, Al-Zidi, El-Hussan and Al-Hinai, 2010). This will definitely make the freshwater in the well unusable and thus hamper the development of potable water from municipal use. Almost two thirds of the world's population are said to be living within 400km of the ocean shoreline and just over half live within 200km, an area only taking up 10% of the earth's surface (Hinrichsen, 2007).

These coastal dwellers depends largely on groundwater as main source of freshwater for daily survival, industrial and agricultural purposes; a development that could lead to excessive groundwater extraction. Basically, freshwater is less dense that saltwater and so it floats on top. Therefore, saline water is found below fresh water discharge from higher attitude on coastal areas. Also, the boundary between saltwater and freshwater is not distinct; the zone of dispersion, transition zone. Thus, saltwater interface is brackish with saltwater and freshwater mixing. It then means that salinity will increase with depth where both freshwater and saline water occur. As such, the increase in salinity will produce consequent decrease in electrical resistivity of water and thus resistivity varies with depth within groundwater well in coastal aquifer (Igboekwe*et al.*, 2019). These variations could then by mapped by method capable of detecting differences in salinity.

The use of geophysical techniques for groundwater exploration and water quality evaluations has increased over the past few years due to the rapid advances in computer software and associated numerical modeling solutions (Chinwuko, *et al.*, 2016). Some of these geophysical method includes: vertical electrical sounding (VES), electrical resitivity tomography (ERT), self-potential method, etc.

The work therefore, intends to give interpretation of data using the efficiency of the 2-D electrical resistivity tomography (ERT) as well as vertical electrical sounding (VES) methods for the mapping of subsurface salinity in the coastal region of Oron in AkwaIbom State (Niger Delta), Nigeria and recommend measures for its proper management.

Location and Geology of the Study Area

Oron Local Government Area lies on coordinated 4.8217^{0}N, 8.2350^{0}E around the Gulf of Guinea with a total land area of 126.5km^2. According to Mbipom*et al.* (1996), the survey area falls within the Niger Delta coastal region of AkwaIbom State of Nigeria, dominated by the Benin Formation which is also known as the Coastal Plan Sands (CPS) and Quaternary alluvial deposits typical of the Southern Niger Delta Region.

The sediments of the Benin formation consist of interbedded beach sands, alluvial silts/clays, gravel, and organic layers (including lignite streaks) formed in lagoonal, tidal and fluvial settings (Reynoids, 1997; Nyananyo*et al*., 2007). Both confined and unconfined aquifers are encountered at varying depths and sometimes contain varying saline and clay groundwater (Esu and Adekon, 2011). The Benin formation consists predominantly of massive highly poros sands and gravels with locally thin shales and clay interbeds to form a multiaquifer system in the Delta (Akpabio and Eyenaka, 2008). Many quality water yielding boreholes have been drilled to tap water from the Benin Formation. However, many of these borehole have been abandoned due to salinity problem (Oteri, 1998). In the study area, saltwater intrusion into the recent sedimentary aquifer occurs below the freshwater lens stretching a few kilometers inland, freshwater is available from deeper aquifers (often 20-40m depth).

The coastal plan sands (CPS) forms the major hydrogeologic units in the area which are dominantly overlain by fine to coarse sands, with occasional clay or mud layers in swampsand flood plain zones (Udosen*et al.*, 2014).

In the upper aquifer: clayey sand to sand (with some gravel), up to approximately 30m thick are fully saturated. Thus, recharge are mainly from rainfall and river infiltration while middle and lower aquifer may exist at greater depths, but are beyond, the scope of this coastal shallow system (Udosen*et al*., 2014). The general groundwater flow direction is from upland topographic highs towards the Atlantic Ocean while it recharge rates is approximately 36% of annual rainfall (Approx. 3,000 mm year) becoming groundwater input.

The study area has sand mining in some areas which altered the aquifer parameters while the in-stream mining sites are characterized by high resistivity layers and impaired shallow well productivity, requiring deeper groundwater withdrawal (Udosen*et al.*, 2014).In view of this, measured and calculated formations contamination induces are not absolute but relative and therefore only relative deduction about saltwater-freshwater indices can be made (Akpan*et al.*, 2015).

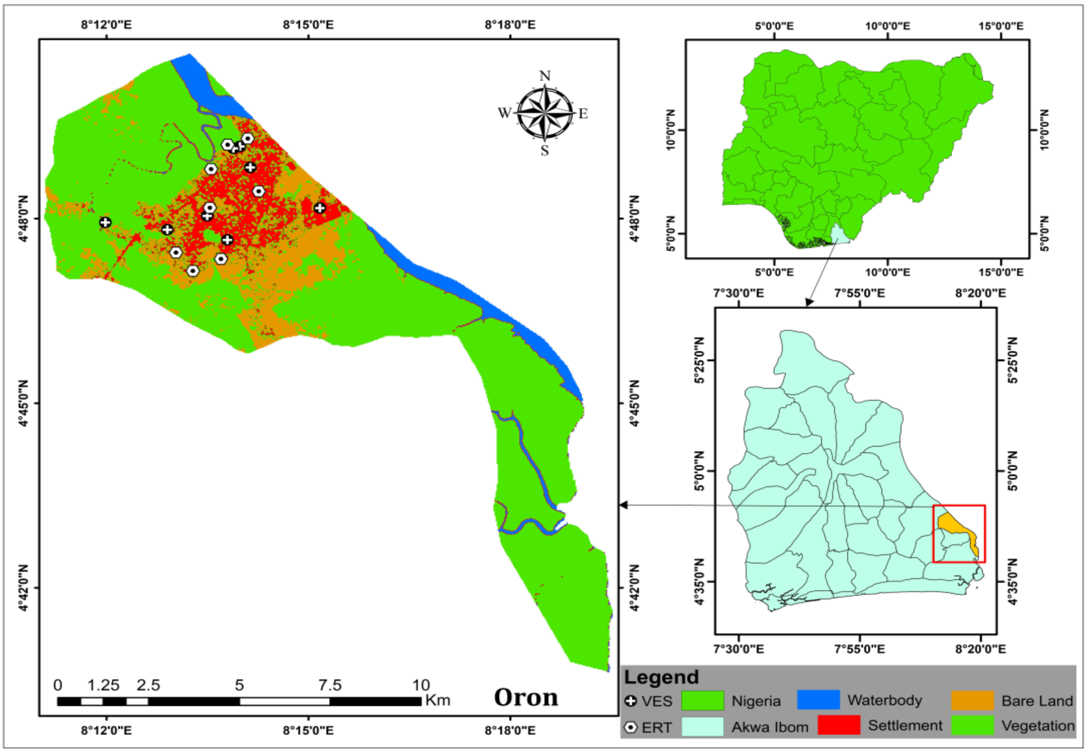

Figure 1: Map showing the location of the survey area and field measurement point

Materials and Methods

Techniques adopted in assessing the extent of saline water encroachment into freshwater aquifers in the coastal region of AkwaIbom State specifically, Oron Local Government Area consists of integrated electrical resistivity techniques (electrical resistivity tomography, ERT and vertical electrical sounding, VES). They are popular members of the conventional geophysical investigating tools. Several researchers have successfully applied the electrical method in solving a wide range of hydrological and hydrogeophysical problems including mapping of saturated aquifer horizons from the adjoining formations, groundwater potential investigations aquifer characterization, assessment of infiltration rate of the Vadose Zone and groundwater contamination studies (Minsley*et al.*, 2011; Akpan*et al.*, 2013; Ebong*et al.*, 2014; Igboekwe*et al.*, 2019). Hence, both the 2-D ERT and VES were carried out during the field survey.

Four parallel 2-D electrical resistivity tomography (ERT) surveys were performed at the proposed sites using the SSP-ATS-MRP model of an IGIS (Integrated Geo-instruments and services) resistivity meter and multicore cable to which electrodes were connected at take-outs moulded in predetermined equal interval. A computer controlled system then used to select the active electrodes for each electrode set-up automatically. By using Wenner configuration, current was injected into C_1 electrode to the ground and received from the ground through C_2 electrode. The potential difference was measured between two inner electrode P_1 and P_2. The configuration was kept constant and more along the profile until all possible measurements have been made with the electrode spacing (Figure 2).

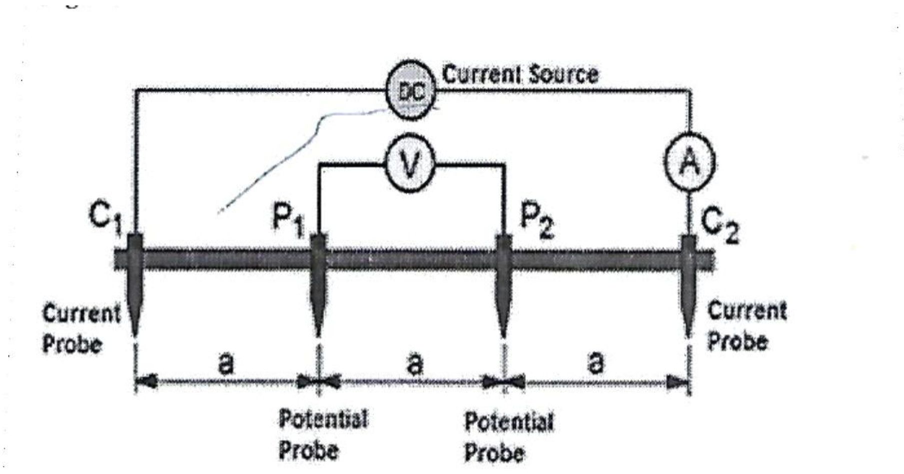

Figure 2: Wenner Array

There were variations in the profile length, 200 m with electrode spacing of 5m for ERT profile point ERT 1, and 150 m for the ERT profile point ERT 2, 4, 5, 6 and while the ERT points (3 and 7), the profile were 100m long; owing to constraint in space. Notwithstanding a fairly deeper depth was probed in the transverse having used expansion factor n-38.

The Wenner array configuration was used among the common arrays for the ERT survey. The Wenner has the strongest signal strength. This can be an important factor, if the survey is carried out in areas with high background noise as attributed to the coastal regions of the research work. The choice of the array for the survey was based on a desire to have good sensitivity to vertical and horizontal changes in the subsurface resistivity at both shallow and deeper depths, and at the same time probe into the deeper depth to have good vertical and horizontal data coverage under the ERT profile. The Wenner array system (Figure 2) is of added advantage because of its sensitivity to detect geologic noise and other abundant interpretational material (Loke, 2004).

The spacing in Wenner array is usually referred to as "a". The resistance measured from the meter was recorded for both point; this resistance was converted to apparent resistivity using the geometric factor which is constant for Wenner array ($2\pi aR$), where R is the resistance measured from the field which can also be known as the ground resistance and "a" is the spacing between the electrodes

Mathematically,

Mathematically,

$$\ell\left(\frac{2\pi}{G}\right)R \qquad \text{i}$$

$$\text{Where } G = \frac{1}{C_1P_1} - \frac{1}{C_2P_1} - \frac{1}{C_1P_2} + \frac{1}{C_2P_2} \qquad \text{ii}$$

$$= \quad G = \frac{1}{a} - \frac{1}{2a} - \frac{1}{2a} + \frac{1}{a} \qquad \text{iii}$$

$$G = \frac{1}{a} \qquad \text{v}$$

Apparent resistivity for Wenner array

$\ell = \left(\frac{2\pi}{1/a}\right)R$ - - - - - - - - - - vi

$\ell = 2\pi \times a \times R$ - - - - - - - - - - vii

$\ell = 2\pi \times aR$ - - - - - - - - - - viii

$\therefore \ell = 2\pi \times aR$

In all, eight (8) 2-D ERT profile (Figure 4-11) were measured covering the whole coastal area. One of the latest software for the inversion of 2-D data RES2DINV, was used to invert the apparent resistivity profiles to obtain a 2-D images of the subsurface resistivity distributions. In this section, horizontal axis is the electrodes spacing and vertical axis is the depth. The ERT profiles were inverted using an iteration smoothness constrained least-squares inversion algorithm otherwise known as "OCEAM" inversion after (DeGroot-Hedlin and Constable, 1990; Loke and Barker, 1996). These inversion routines involve a cell based inversion techniques: it subdivides the subsurface into a number of rectangular cell in which resistivities are varied to obtain the best fit with the observed data (Loke, 2004). The differences between the observed and calculated data are minimized to obtain an acceptable agreement (Loke and Barker, 1996). A measured of this difference is given by the root-mean square-error (RMS%). However, smoothness constrained models do not allow for large and unreasonable variations in the output model as its name suggests.

In addition to the above 2-D ERT survey carried out, eight (8) vertical electrical sounding (VES) were also carried out with the SSP – ATS-MRP model of an IGIS (Integrated Geo-Instruments and Services) resistivity meter using the Schlumberger electrode configuration.

The instruments measures the resistance of the subsurface earth structure sampled by the survey. Resistance of the earth subsurface measured by the instruments was used to calculate the apparent resistivity (ℓa)in Ohm-meter (R) by the geometric factor (K). A log-log graph plot of apparent resistivity (ℓa)against current electrode distance (AB/2) was plotted for each VES station to generate a sounding curve using the conventional partial curve matching technique, in-conjunction with auxiliary point diagrams (Keller and Frischknecht, 1966), layer resistivity's and thickness with depths were obtained. Table 1 showed the summary of the VES interpretations

Table 1: SUMMARY OF VERTICAL ELECTRICAL SOUNDING RESULTS
GPS reading to show location, elevation and coordinate of each VES sounding point

Location	Elevation (m)	No. of layer(s)	Northing	Easting	Curve Type(s)	Resistivities of layers(m)					Thickness of layers(m)					Depth of layers (m)				
						ρ_1	ρ_2	ρ_3	ρ_4	ρ_5	t_1	t_2	t_3	t_4	t_5	d_1	d_2	d_3	d_4	d_5
VES 1	12	5	4.7989	8.1996	HQ	301.0	13.3	20.1	15.3	2.4	1.3	17.1	25.4	34.0	-	1.3	18.4	43.8	77.8	-
VES 2	15	5	4.7942	8.2299	QK	183.7	98.8	21.1	23.0	6.0	2.1	10.2	21.7	38.0	-	2.1	12.3	34.0	72.0	-
VES 3	20	4	4.8139	8.2356	QQ	700.1	625.9	396.0	309.4	-	1.9	27.4	67.8	-	-	1.9	29.3	97.1	-	-
VES 4	28	4	4.7969	8.2151	AK	47.3	50.9	79.1	56.5	-	1.8	19.2	66.9	-	-	1.8	21.0	87.9	-	-
VES 5	43	4	4.8195	8.2330	HA	126.8	6.2	224.6	48.1	-	0.7	1.9	41.3	-	-	0.7	2.6	43.8	-	-
VES 6	11	5	4.8029	8.2581	HQ	638.9	132.0	150.3	102.8	14.4	4.9	10.7	26.4	32.4	-	4.9	15.6	42.0	74.4	-
VES 7	35	4	4.8007	8.2249	AK	566.4	1,166.5	3,741.2	669.5	-	3.6	27.4	272.1	-	-	3.6	31.0	303.1	-	-
VES 8	7	4	4.8190	8.2314	AK	141.4	610.0	1,848.8	350.2	-	1.8	13.6	130.5	-	-	1.8	15.4	145.9	-	-

Results and Discussion

The 2-D resistivity images obtained from the study areas are shown in Figures 4 to 11 and are presented in a colour format consisting of the inverted 2-D resistivity tomography while the coordinate/elevation of profile (ERT 1-8) are presented in table 2.

Table 2: Coordinate /elevation of profiles (ERT 1-8) as taken by twelve channel global positioning system (GPS) Set the "GARMIN GPS 12"

Profile No	Elevation (m)	Northing	Easting
ERT 1	10	4.8134	8.2259
ERT 2	42	4.8029	8.2256
ERT 3	31	4.7907	8.2172
ERT 4	37	4.7858	8.2214
ERT 5	20	4.8217	8.2350
ERT 6	20	4.8200	8.2300
ERT 7	38	4.8074	8.2377
ERT 8	15	4.7891	8.2283

The horizontal scale on the image is the lateral distance while the vertical scale is the depth and both are in metres. A maximum speed of 200m with corresponding depth of 33.8m was investigated and modeled on the profile as shown in ERT 1- ERT 8.

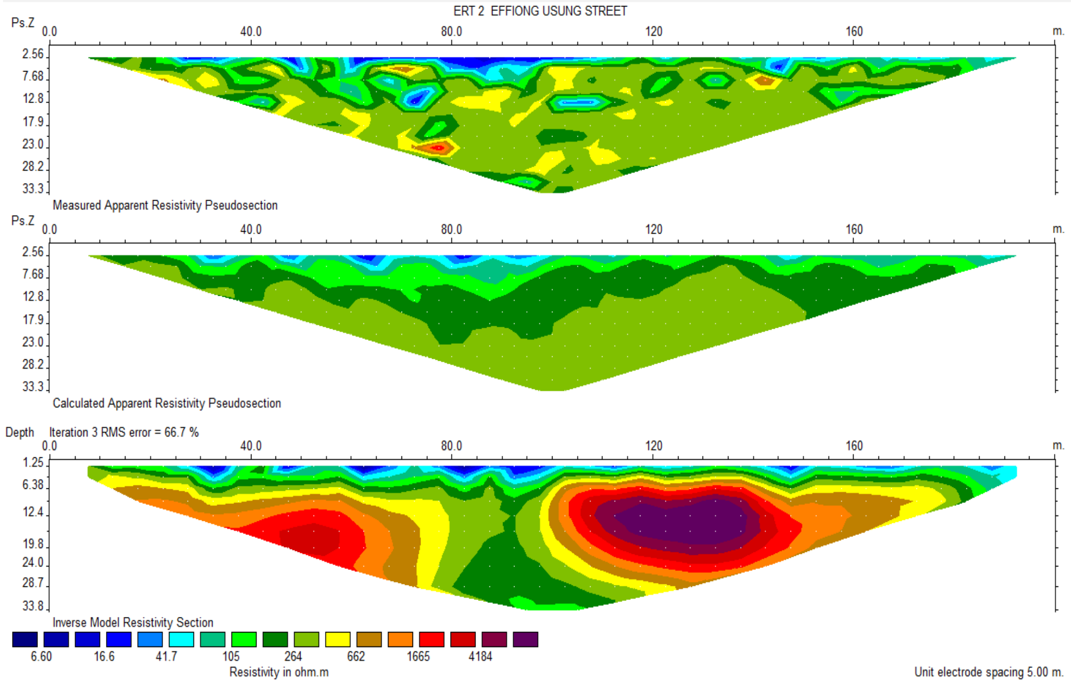

Figure 4: Subsurface image obtained along ERT 1 (EffiongUsung Street, Oron LGA)

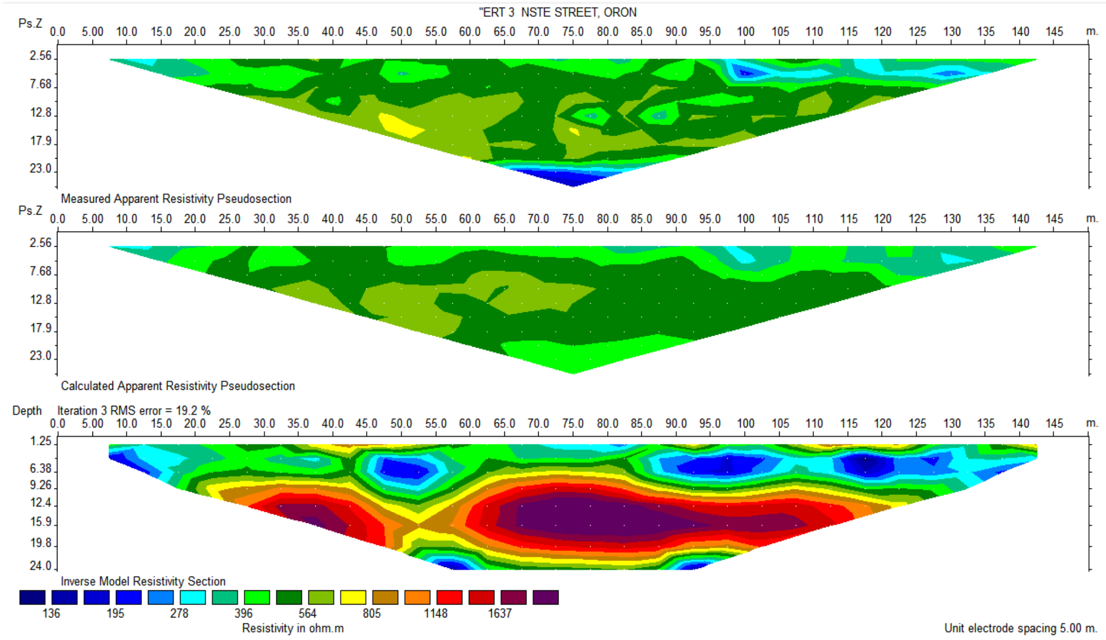

Figure 5: Subsurface image obtained along ERT 2 (Nsie Street, Oron LGA)

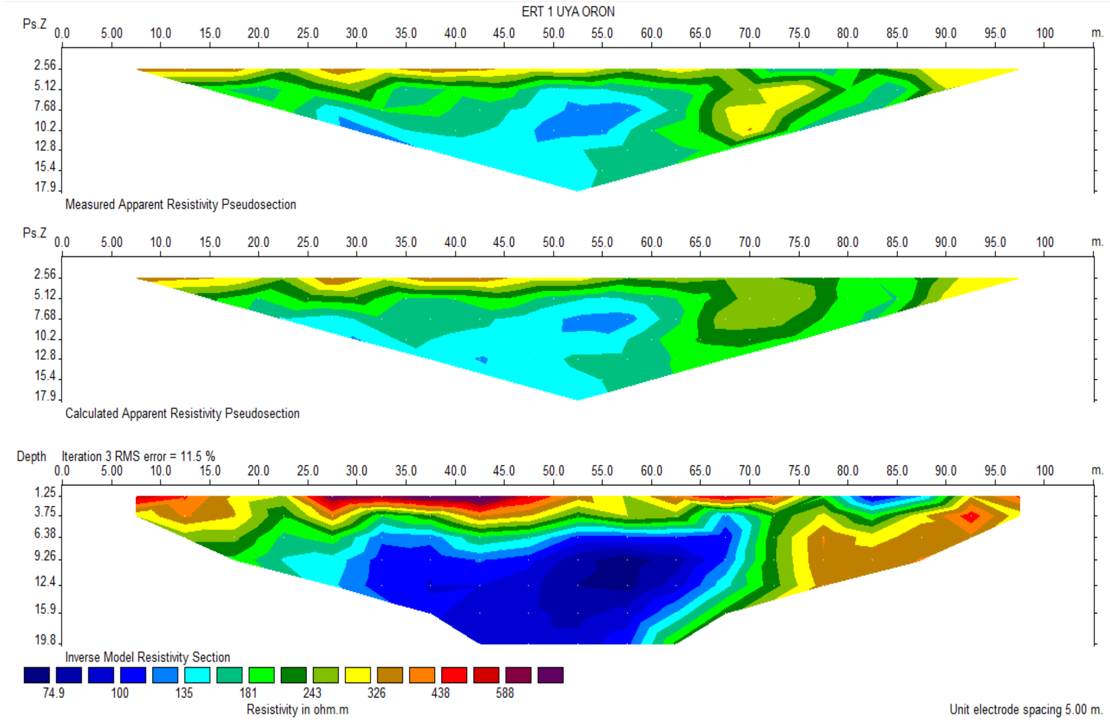

Figure 6: Subsurface image obtained along ERT 3 (Udesi Street, Oron LGA)

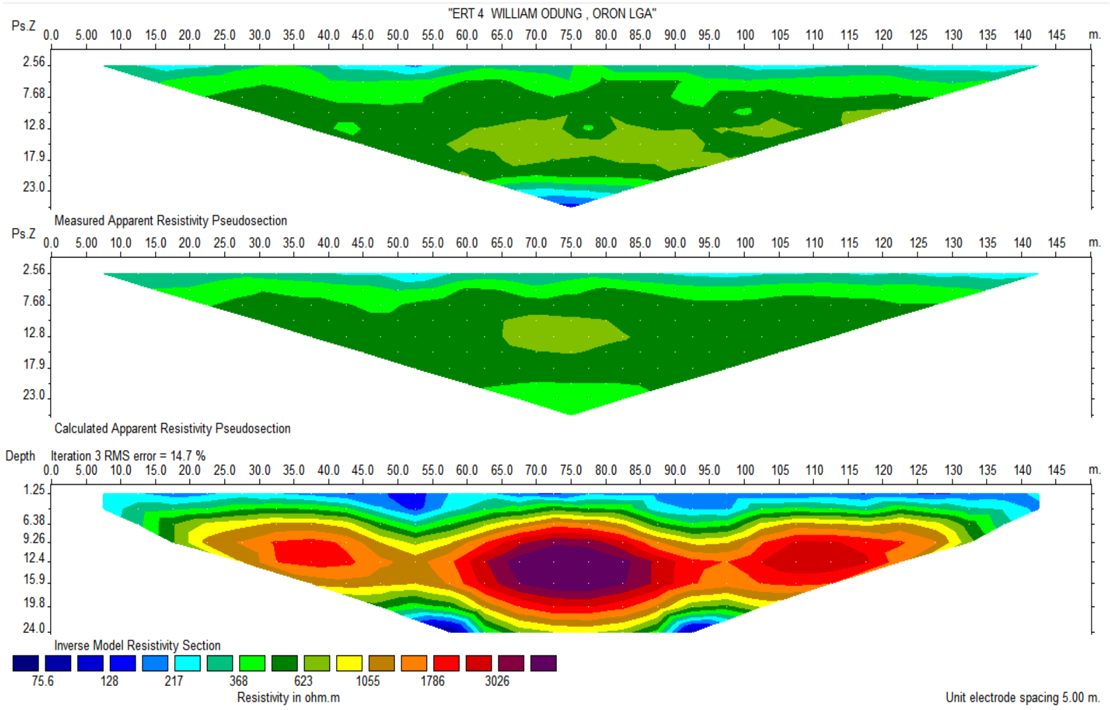

Figure 7: Subsurface image obtained along ERT 4 (Eyotong, Oron LGA)

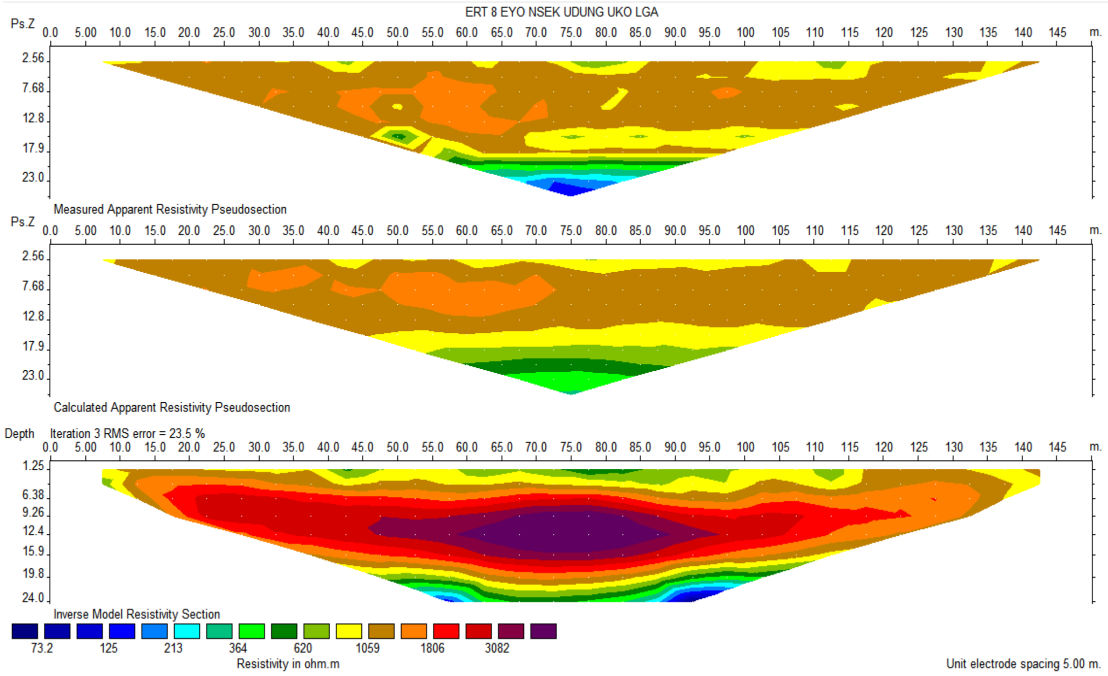

Figure 8: Subsurface image obtained along ERT 5 (Marina Coastal, Oron LGA)

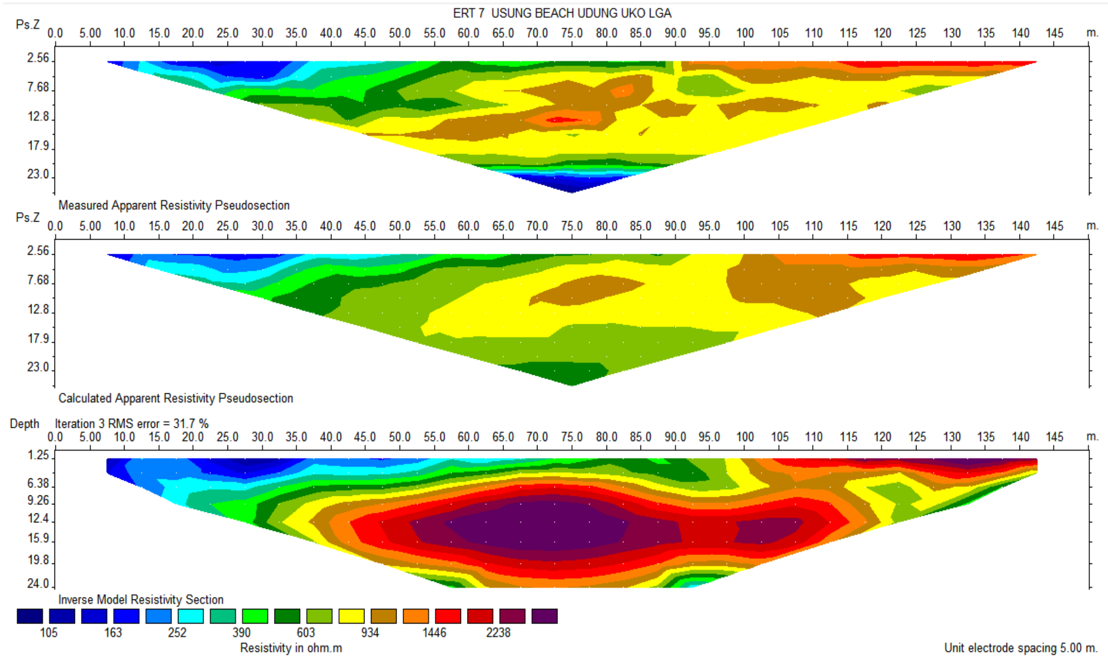

Figure 9: Subsurface image obtained along ERT 6 (EffiongEssang, Oron LGA)

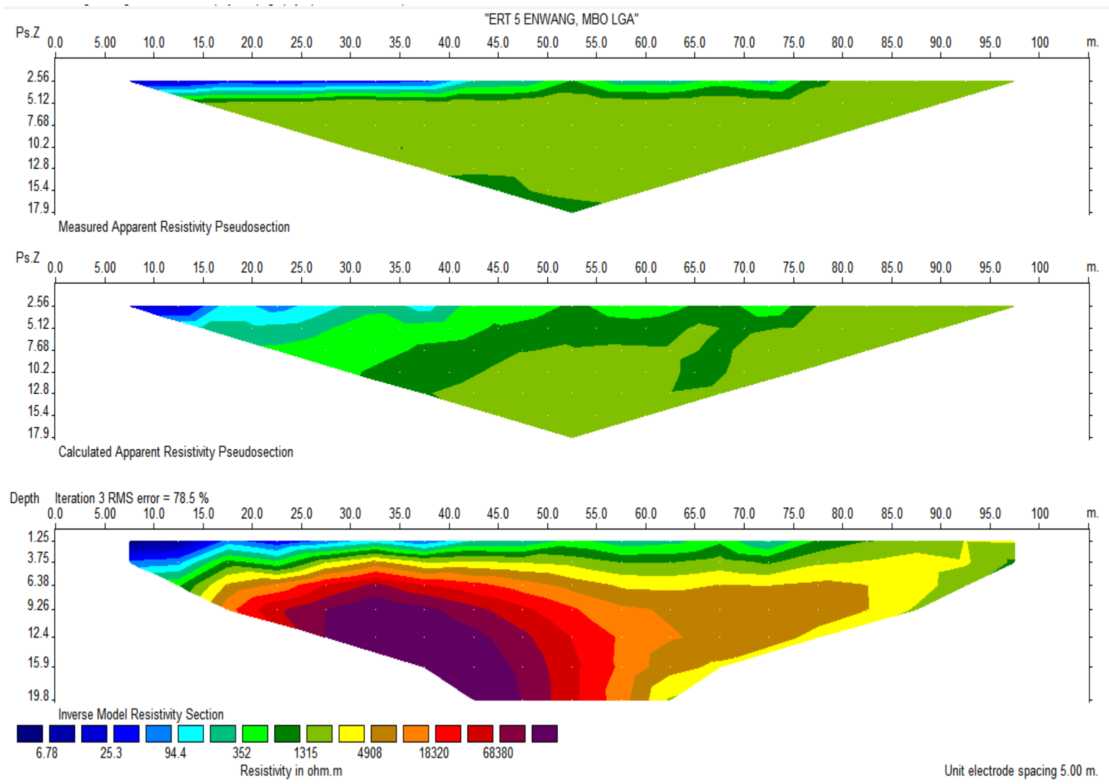

Figure 10: Subsurface image obtained along ERT 7 (AwanaMba, Oron LGA)

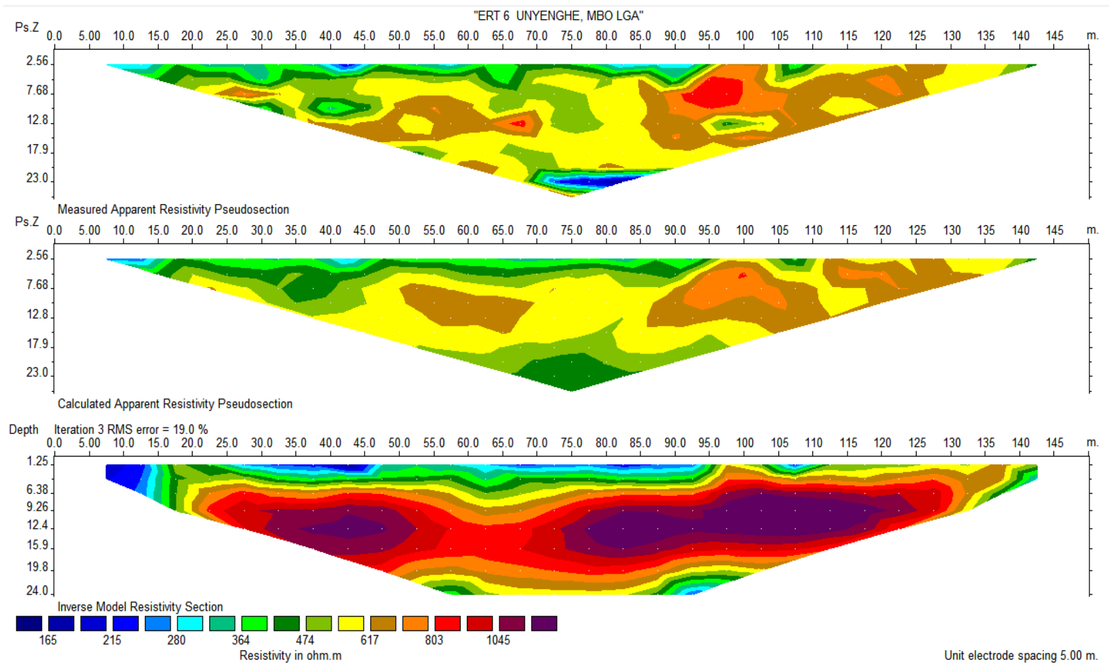

Figure 11: Subsurface image obtained along ERT 8 (John Taylor, Oron LGA)

The inversion of traverse 1 is a display in figure 4. The image shows four geologic zones beneath the profile. These include the top soil (saline clay/saline clayey sand) with resistivity ranging from 6.00m to 41.7mm. It extends margin from the top to a depth of about 12.4m, these zone shows a typical salinity zone because of the low resistivity value recorded this, water is highly conductive. The second subsurface geoelectric layer has resistivity ranging from 73.85 Ωm to 199.00 Ωm (The third geoelectric layer extends from a depth of about 12.4 m to beyond 28.7 m with resitivity ranging from 2.64 Ωm to 66.2 Ωm (Lateritic sand). The last layer extends from a depth of about 29.7m to beyond 33-8m, with resistivity ranging from 758Ωm to 4300Ωm (Gravelly sand). This layer could serve as aquifer where groundwater could be tapped. The 2-D resistivity image in location two presented in the figure 5. Three distinct relatively layer indicating medium to coarse sand, fine /medium grained sands and lateritic/gravelly sand are revealed. The medium to coarse sand is fairly continuous with the thickness varying from 0 to 12.4m and beyond bottom at about 16.9 to 19.8m and resistivity values ranging from 136mm to 278mm. The fine/medium grained sand thickness varies from 16.9 to 19.8m and resistivity values vary from 430mm to 805mm while the laterite/gravelly sand thickness values vary from 975.5mm to beyond 1637.0mm, which serve as a fresh groundwater zone. The 2-D resistivity imaging for location 3 is shown in the figure 6. It present a two-layer lithology amongst are the top soil which ranges from 74.9mm to 284.5mm with the maximum depth of 19.8m. The second layer ranges from 326mm to beyond 588 mm in resistivity and 1.26 - 12.4m in depth and is more permeable than others, as such contain the aquifer.

In ERT 4, three distinct layer was presented as shown in figure 7. The first layer which is the top soil has resistivity value ranging from 75,6 – 292.5 Ωm and depth of 6.0m and also beyond 24.0m, it is medium to coarse sand. The second layer ranges from 368 Ωm to 844.5 Ωm in resistivity value while the depth ranges from 9.26 to 15.9m. The third layer has the highest resistivity values. The resistivity ranges from 1,066 Ωm to beyond 3,026 Ωm and the depth ranges from 19.6 – 24.0m. The ERT imaging for point 5 is shown in Figure 8. This image shows a three-layer lithology composition. This include, the top soil which is medium to coarse sand with resistivity range of 73.2 Ωm to 288.5 Ωm and depth of 24.0m at the bottom. The second layer is sandy clay with resistivity range of 364 Ωm to 839.5 Ωm and depth of 19.8m and the third layer having resistivity values ranging from 1069 Ωm to 3062 Ωm, and the depth range of 24.0m. The 2-D resistivity image obtained from location 6 is displayed in Figure 9. It comprises of three geoelectric zones beneath the profiles. These include the topsoil (medium to coarse sand) with resistivity values ranging from 106 Ωm to 262 Ωm. It extends from the top to a depth of about 15.9m. The second subsurface geoelectric layer has resistivity values ranging from about 360 Ωm to 1,190 Ωm and it extends from a depth of about 19.6m. This subsoil encloses the third geoelectric material whose resistivity ranges from 1,446 Ωm to 2,236 Ωm and it extends from a depth of about 19.6m to beyond 24.0m.

The ERT imaging for point 7 is shown in the figure 10. This image shows a three-layer lithology composition. This include, the top which is clayey sand with resistivity range of 6.76Ωm to 94.4Ωm depth of 1.25 to 9.26m, this resistivity values showed salinity zone because salinity increases with depth and the groundwater at this zone is highly conducive. The second layer is medium to coarse sand with resistivity range of 223.2Ωm to 838.5 Ωm and depth of 12.4m and the third layer is the aquifer layer because of the high resistivity values ranging from 1315-68380 Ωm and the depth range of 15.9 – 19.8m. It is a saturated medium and lateritic/gravelly sand. The 2-D resistivity image in location 8 is presented in Figure 11. Three distinct resistivity layers indicating medium to coarse sand, fine medium sand and lateritic/gravelly sand are revealed. The medium to coarse sand topsoil is fairly continuous with the thickness varying from 1.25-9.26m and resistivity value ranging from 165-260 Ωm. The fine medium sand thickness varies from 12.4 -19.0m and resistivity values ranging from 364-924 Ωm. The third layer is the aquifer layer because of the high resistivity values ranging from 1,000 -1,045 Ωm and the depth range of 24.0m. It is a saturated medium and lateritic/gravelly sand.

Additionally, the vertical electrical sounding method (VES) is a depth sounding method and has proved useful in groundwater and other environmental related studies due to its simplicity and reliability of results. A total of 8 randomly distributed vertical electrical sounding were conducted in the study area, their locations and results of analyses and interpretations are presented in the form of modelled curve (VES 1-8) in Figure 12-19.

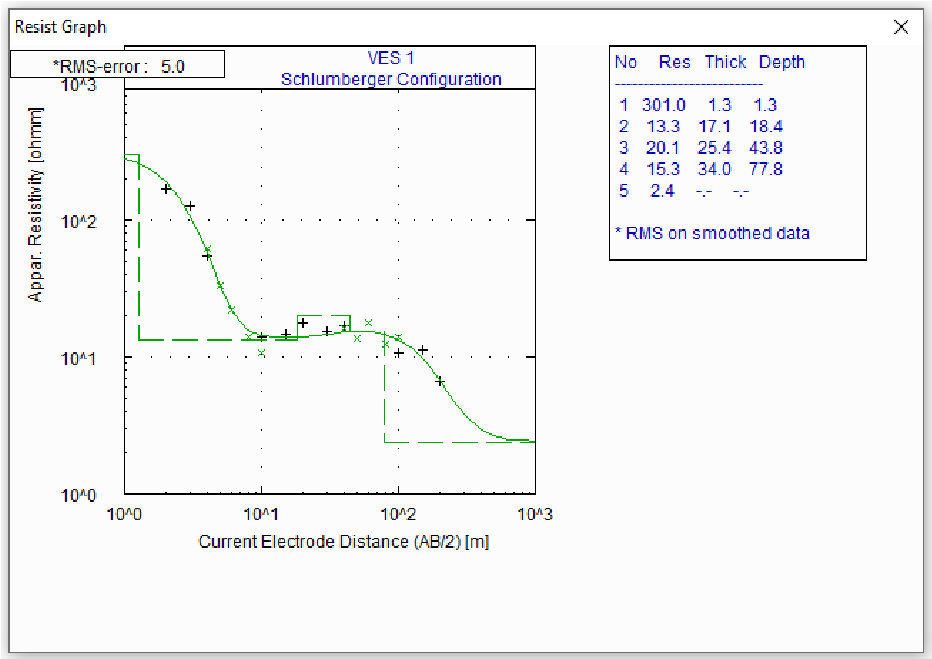

Figure 12: Modelled geoelectric curve for UyaOron (VES 1)

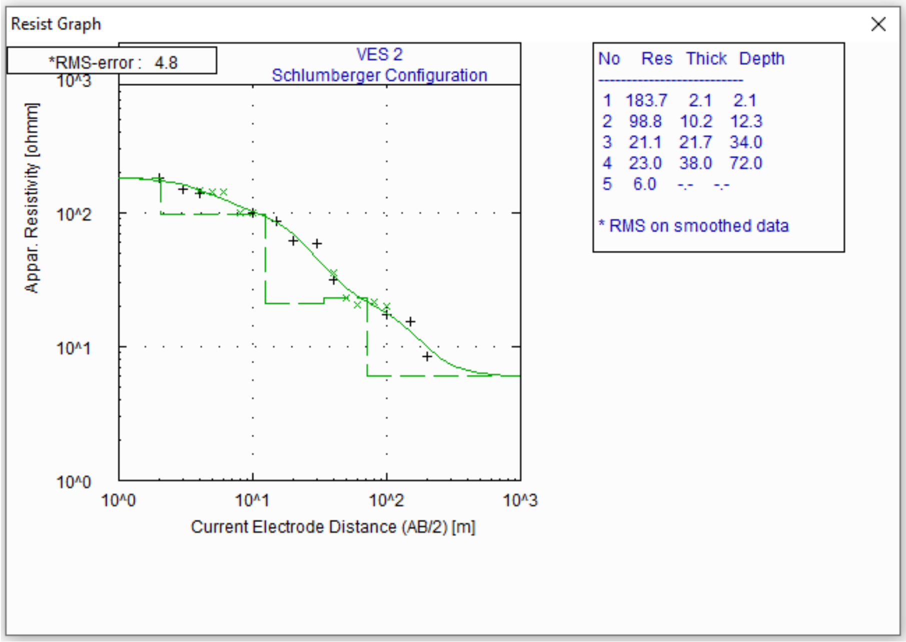

Figure 13: Modelled geoelectric curve for OronMusuem(VES 2)

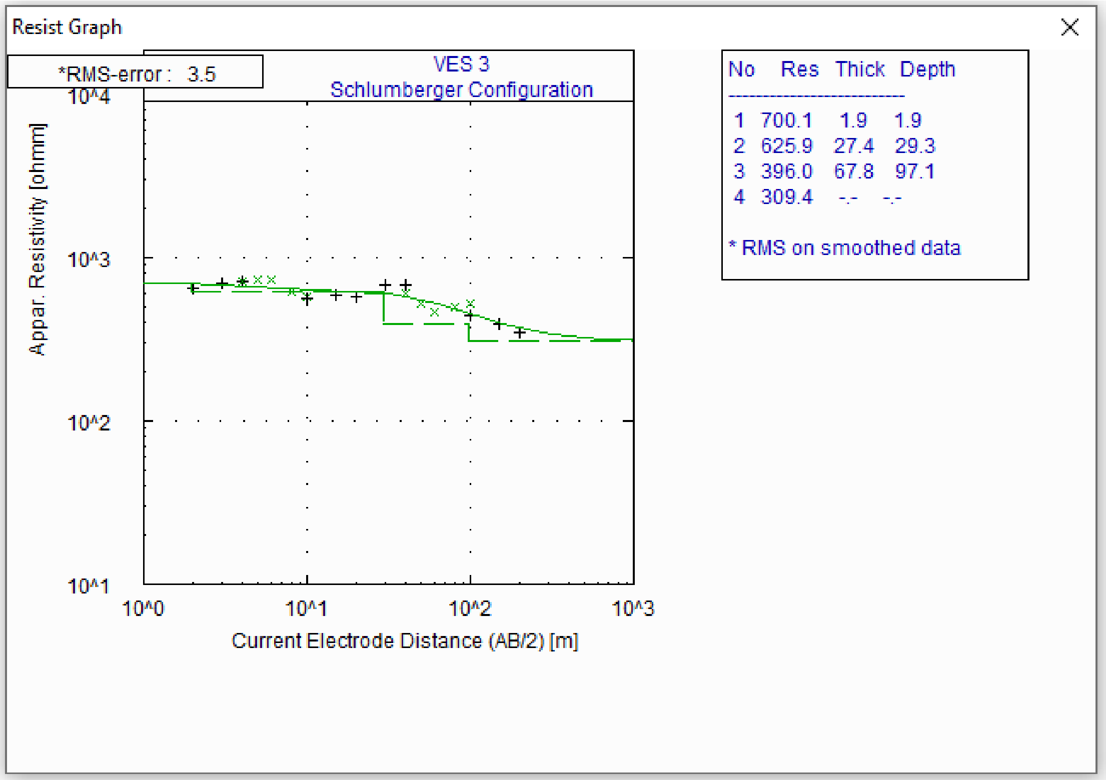

Figure 14: Modelled geoelectric curve for Holy Child Convent, Eyo-Abasi (VES 3)

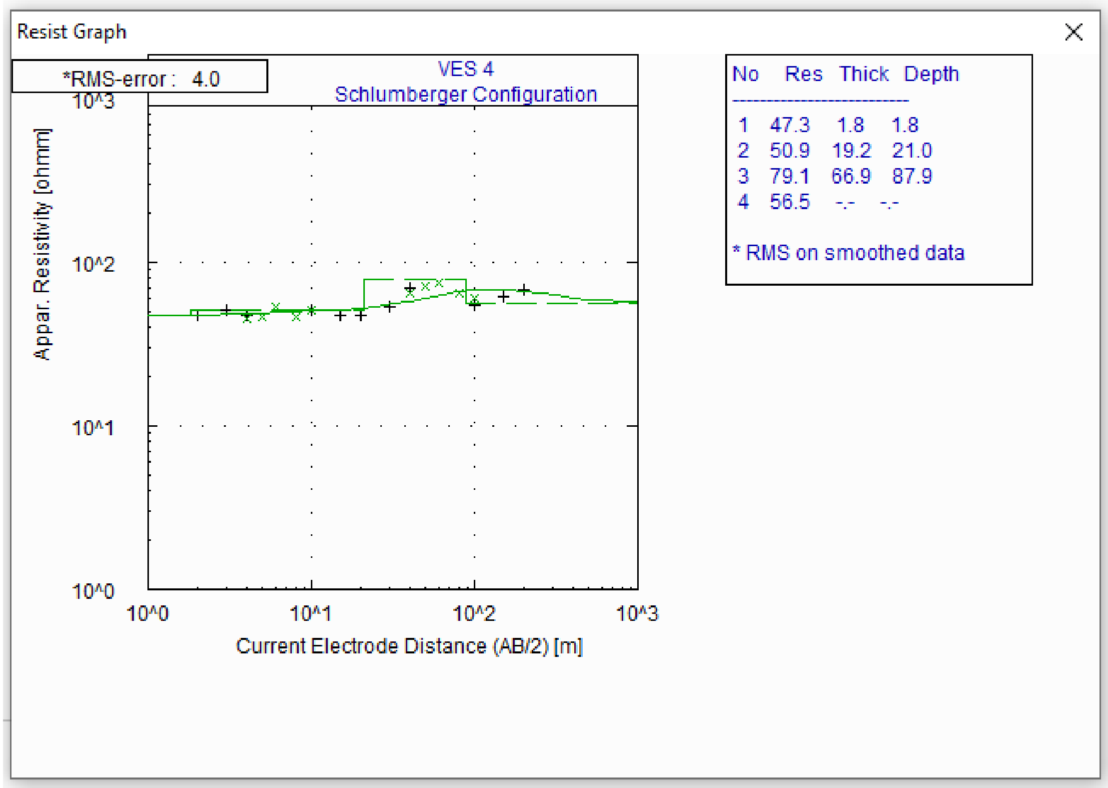

Figure 15: Modelled geoelectric curve for AfahaOkpo (VES 4)

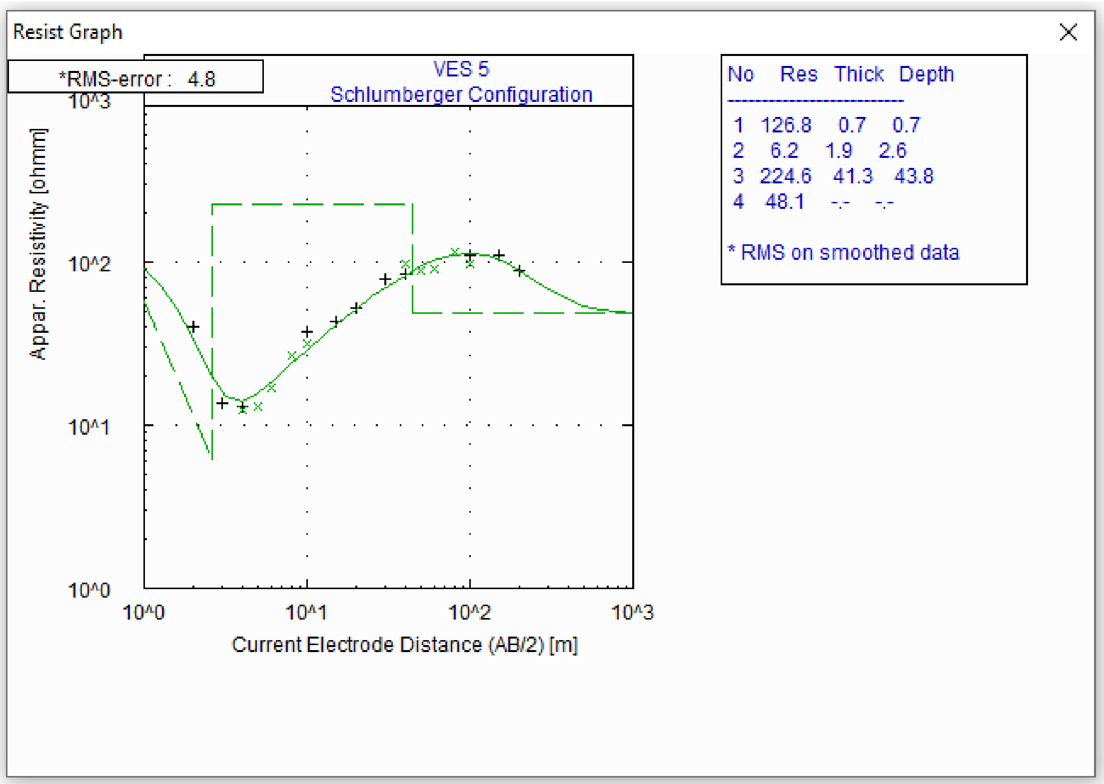

Figure 16: Modelled geoelectric curve for IquitaOron (VES 5)

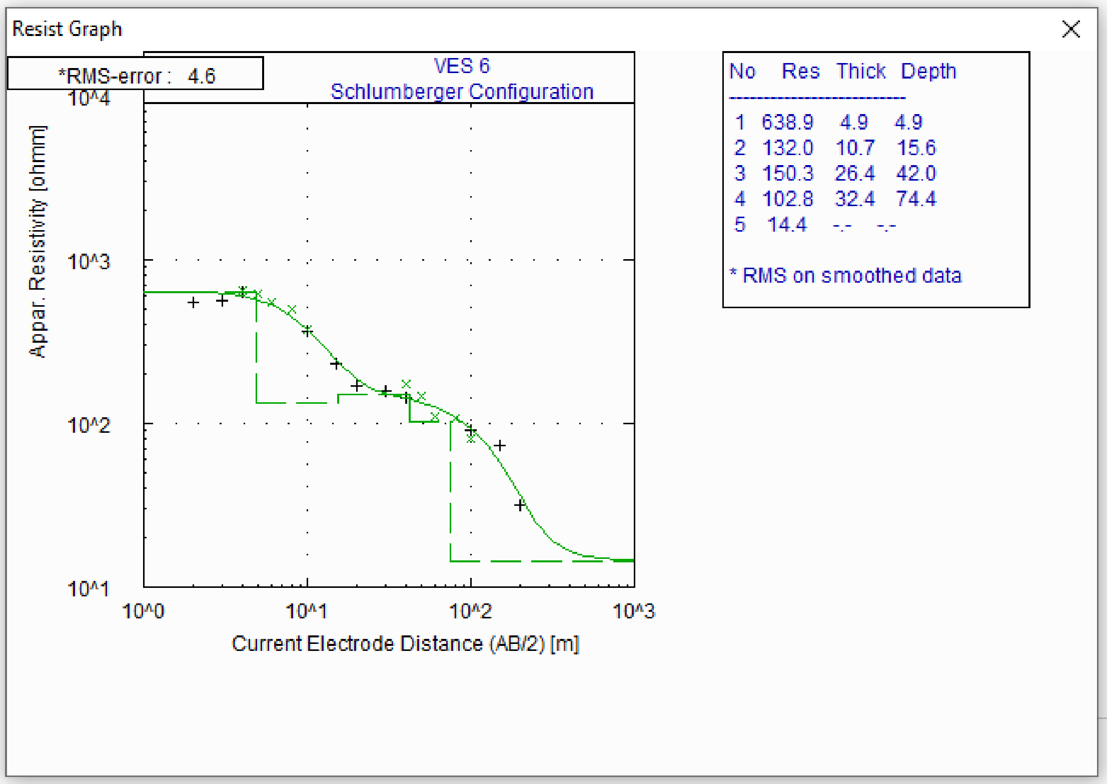

Figure 17: Modelled geoelectric curve for EsukOrok (VES 6)

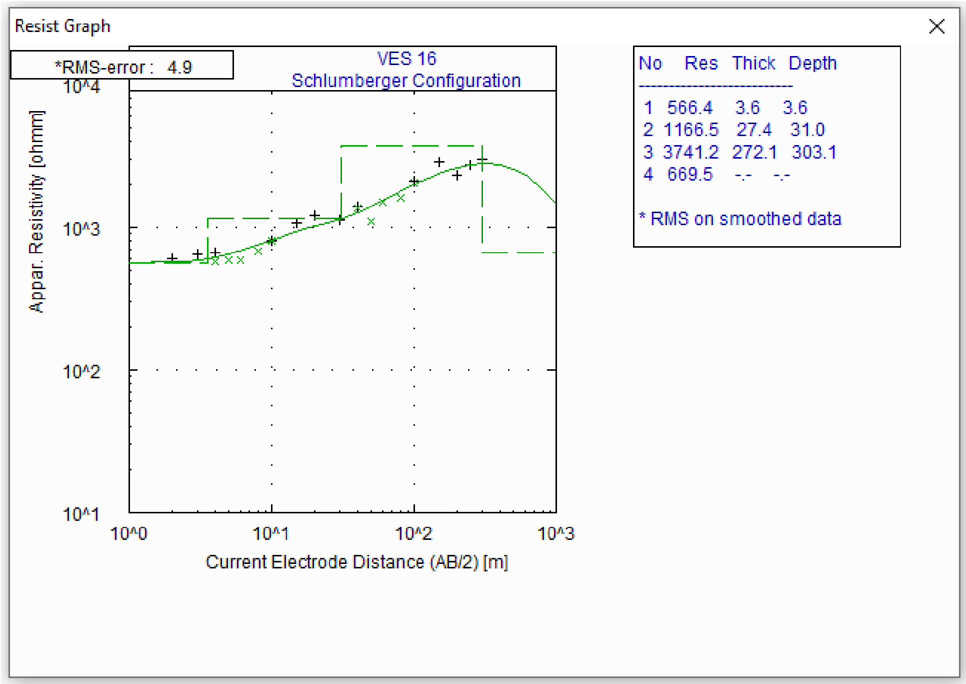

Figure 18: Modelled geoelectric curve for William Odung (VES 7)

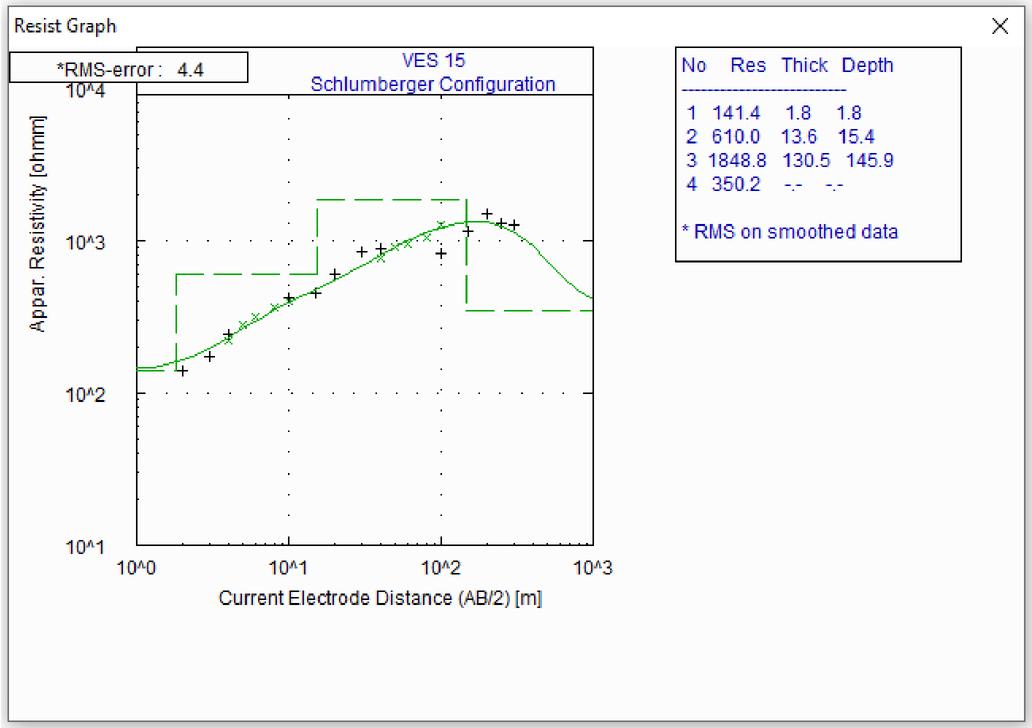

Figure 19: Modelled geoelectric curve for Usung Close (VES 8)

From the results, 8 different curve types were identified from the modelling (Table 1) and the differences in curve types reflects the lithological compositions and variations in terms of resistivity, thickness and depths. Most of the curve generated are AK curve types (VES 4, 7 and 8). At VES 4 (AfahaOkpo) the resistivity values range between (47.3 to 56.3Ωm) with depth to bottom value of (1.8 to 87.9m) and thickness of (1.8 to 66.9m). Also at VES 7 (William Odung), the resistivity values varies between (566.4 – 669.5 Ωm) with depth to bottom value (3.6 – 303.1m) and thickness range of (3.6 – 272.1 m). The geophysical characteristics of the subsurface formation at VES 8 (Usung Close) shows that the resistivity values range between (141.4 – 350.2 Ωm) with depth to bottom value (1.8 to 145.9m) and thickness range of (1.8 – 130.5 m). The resistivity values and the lithologic composition of the study area derived from surface measurement shows the presence of sandy clay, gravelly sand and fine to medium sand which correlated well with the borehole lithologies of the area. This is a reflection of other VES locations with the characteristics AK curve type across the study area as indicated in Table 1. The HQ curve type was observed at two locations VIZ VES (1 and 6). At VES 1 (UyaOron) the resistivity values range between (301.0 – 2.4 Ωm) with thickness values of range between (1.3 – 34.0m) and depth of bottom values of range between (1.3 – 77.8m) was delineated. Also at VES 6 (EsukOron), the resistivity range showed range of between (638.9 – 14.4 Ωm), with thickness values of range between (4.9 – 32.4m) and depth to bottom values of (4.9 – 74.4m). Dry sand or sandstone, laterite, and fine sand with high moisture.salinity were clearly revealed. The QK, QQ and HK curve types displayed in Table 1 were also observed in the study area. At VES 2 (OronMuseum) with QK curve type shows resistivity values ranged from (183.7 to 6.0 Ωm), with thickness values range from (2.1 – 3800m) and depth to bottom values of (2.1 – 72.0m). VES 3 (Holy Child Convent, EyoAbasi), with QQ curve type shows resistivity values ranged from (700.1 – 309.4 Ωm), with thickness of range between (1.9 – 67.8m) and depth to bottom values of (1.9 – 97.1m), VES 5 with HA curve type shows resistivity values ranged from (126.8 – 48.1), with thickness of range between (0.7 – 41.3m) and depth to bottom values of (0.7 – 43.8m). In Summary, 4 to 5 subsurface geologic layers was delineated across the coastal part of AkwaIbom State, specifically Oron Local Government Area showing the presence of low to high resistivity values with good correlation with the borehole lithologic logs of the study area. The variations in the resistivity values delineated the saline clay/saline clayey sand, lateritic sand, fine and medium grain sand, gravelly and clay sands. The intrusion was noticed to occur both from the surface and the subsurface depending on the resistivity values of the formation.

Conclusion

Combined geophysical investigations (2-D and VES) techniques was properly used to study the subsurface geology and delineate the extents of the intrusion of saline water into the coastal fresh water aquifer units within the study area. The following conclusions are drawn from the study based on the results and interpretations:

i. Information generated from 2-D imaging technique showed that the intrusion can occur through the surface of the earth as shown in most of the 2-D surface image resistivity profiles
ii. Saline clay/saline clayey sand which constitute protective cap to the freshwater aquifer formations at different locations are characterized with low resistivity value (salinity zone, water is highly conductive), where salinity decreases with depth. At some locations the resistivity values are far less 5.0 Ωm while some location is greater than 100 Ωm (saturated medium, lateritic/gravelly sand).
iii. The inferred lithologies from the VES results include the top soil which is mainly sandy clay, gravelly sand and fine to medium sand units constitute the delineated layers within the subsurface of the area. The invasion of the fresh water aquifer units within the area by saline water is perhaps due to increase in groundwater extraction for industrial and domestic purposes, uncontrolled discharge of waste, oil spillage and hydraulic connection between freshwater and seawater thereby allowing saltwater to push further inland beneath the freshwater. Hence, the saline water intrusion mechanisms are both lateral and upcoming.
iv. The subsurface geology is characterized by a 4 to 5 layered structure and is being dominated with low, moderate and high resistivity valued materials while the majority of the curve types found were that of AK.
v. The fresh groundwater reservours in the coastal formation consists of fine to medium grained sands and lateritic/gravelly sands. They store water at commercial quantity for domestic and industrial purposes whereas low resistivities value for material like saline clay/saline clayey sand delineat salinity zone where the water is conductive.

Recommendation

The integrated geophysical techniques obtained from this research diligently carried out in the study area revealed that the coastal aquifer of AkwaIbom State specifically Oron Local Government Area, Niger Delta has been intruded gradually from the seacoast towards the inland. To avoid total depletion of fresh groundwater aquifers, the following recommendations are put forward:

i. Effective remediation measures including introduction of artificial recharge of fresh water and salt water extraction techniques should be adopted.
ii. Reduction of land use for waste disposal should be implemented through application of cleaner technology to reduce waste generation while prudent and environmentally friendly approach is recommended for use of chemical for agricultural purposes.
iii. Formulation of adequate policies by relevant government agencies towards regulation of groundwater pumping rate in coastal areas in order to mitigate intrusion of saline water into the aquifer systems are therefore recommended.

ACKNOWLEDGEMENT

The research team wishes to express their gratitude to the Tertiary Education Trust Fund (TETFUND), Nigeria for the sponsorship of this on-going work under the subheading: COE/PF/888/Vol.I/240.

CONFLICT OF INTEREST

There is no conflict of interest associated with this particular research work.

REFERENCES

Abdalla, O. A. E., Ali, M., Al-Higgi, K., Al-Zidi, H., El-Hussain, I. and Al-Hinai, S. (2010). Rate of seawater intrusion estimated by geophysical methods in an Arid Area. *Hydrogeology Journal*, 18: 1437-1445.

Akpabio, I. O. and Eyenaka, F. D. (2008). Aquifer transitivity determination using geoelectric sounding data in Uyo, Southern part of Nigeria. *An International Journal of the Pure and Applied Sciences, Scientia Africana*, 7(1): 81-90.

Akpan, A. E., Ebong, D. E. and Ekwot, S. E. (2015). Assessment of the state of soils, shallow sediments and groundwater salinity in Abi, Cross River State, Nigeria. *Journal of Environmental Earth Science.* Doi: 10.1007/S/2665-015-4014-6.

Akpan, A. E., Ugbaja, A. N. and George, N. J. (2013). Integrated geophysical, geochemical and Hydrogeological investigation of shallow groundwater resources in part of the IkommanmfeEmbayent and adjoining areas in Cross River State, Nigeria. *Journal of Environmental Earth Science,* 70(3): 1435-1456.

Chinwuko, A. I., Anakwuba, E. K., Okeke, H. C., Onyekwely, C. U. Usman, A. O., Osele, C. E. and Iheme, O. K. (2016). Assessment of hydrogeophysical and geotechnical properties in central part of Anambra State, Nigeria. *International Journal of Geophysics and geochemistry,* 3(2): 613.

DeGroot-Hedlin, C. and Constable, S. C. (1990). Occam's inversion to generate smooth dimensional models from megnetollelric data. Geophysics, 55:1613-1624

Ebong, F. D., Akpan, A. E. and Onwuegbuche, A. A. (2014). Estimation of geohydraulic parameter from fractured shale and sandstone aquifer of Abia (Nigeria) using electrical resistivity and hydrogeologic measurements. *Journal of African Earth Science*. 9(6): 99-109.

Esu, E. O. and Adekon, A. (2011). Report of the hydrogeophysical investigation of proposed borehole sites at Oruku in urue-Offong/Oruko Local Government Area.

George, N. J., Akpan, A. O. and Obot, I. B. (2010). Resistivity study of shallow aquifer in parts of Southern Ukanafun Local Government Area, AkwaIbom State. *Environmental Journal of Chemistry*, 7(3); 693-700.

Hinrichsen, Don (2007). Ocean planet in decline. http://www/peopleand planet.net/?/id-26/888 and topic = 44 and section = 35. Retrieved May 21, 2025.

Igboekwe, M. U., Eyenaka, F. D., Ubom, A. I., Kalu, E. U. and Udo, A. A. (2019). 2-D Electrical resistivity tomography (ERT) for delineating saltwater intrusion in the coastal region of AkwaIbom State, Nigeria. *Journal of Applied Geology and Geophysics (10SR-JAGG)*, 7(5): 35-45.

Loke, M. H. (2004). "Tutorial 2-D and 3-D electrical imaging surveys. Retrieved from www.gps.caltech.edu.classes/gelll/docs/DC Resistivity Notes.

Loke, M. H. and Barker, R. D. (1996). Rapid least squares inversion of apparent resistivity Pseudosection by Quasi-Newton method. *Geophys. Prospect*, 44:131-152

Mbipom, E. N., Okwueze, E. E. and Onwuegbuche, A. A. (1996). Estimation of transitivity using data from the Mbiase Area of Nigeria. *Journal of Physics*, 85: 28-32.

Minshey, B. I., Aso-franklin, J., Muikhopadhyay, A. and Morgan, F. D. (2011). Hydrogeophysical methods for analyzing aquifer storage and recovery systems. Groundwater, 49(2): 250-269.

Nyananyo, B. L., Gijo, A. H. and Ogamba, E. N. (2007). The physic-chemistry and distribution of water hyacinth (Eichloriniacressipes) in the river Nun in the Niger Delta. *Journal of Applied Science and Environmental Management*, 11(3): 133-137.

Oteri, A. U. (199). "Electric log interpretation for the evaluation of saltwater intrusion in the Eastern Niger Delta', *Hydrology Sciences Journal*, 33(12): 19-30.

Oyeyemi, K. D., Aizebeokhai, A. O. and Oladunjoye, M. A. (2015). Integrated geophysical and geochemical investigations of saline water intrusion in a coastal alluvial terrain, Southwestern Nigeria. *International Journal of Applied Environment Sciences*, 10(4): 1275-1288.

Reynoids, J. M. (1997). An introduction to applied environmental geophysics. *John and Sons*, New York, 796.

Udosen, C., Olabanjo, R. and Etok, A. S. (2014). Geospatial application in mapping gully development for effective remediation and control. *Journal of geography and geology*, 6(4): 153-163.