APPLICATION OF ELECTRICAL RESISTIVITY TOMOGRAPHY AND MODELING TO MAP SALTWATER INTRUSION IN OGHEYE AREA OF WESTERN NIGER DELTA, NIGERIA.

Ugbome Onyeka Daniel, Ohwoghere-Asuma Oghenero

ABSTRACT

Saltwater intrusion into coastal aquifer of Western Niger Delta has been a major challenge due to strategic position to Atlantic. This study investigates the depth and distance of intrusion from the ocean using Vertical Electrical Sounding (VES), 2D Electrical Resistivity Tomography (ERT) and intrusion modelling. Three zones of intrusion were delineated; saltwater at 3.6-36.6m (1.1-4.7Ωm), saltwater-freshwater zone at 36.6-55m (18.7-29.2 Ωm) and freshwater zone >55m (56.3-115 Ωm). Longitudinal conductance, transverse resistance and longitudinal resistance delineated saline water to range from 33-15S 200-2400Ωm^2, 1–5.6Ωm respectively. The Dar-zarrouk parameters described the intrusion as a gradual lateral encroachment. 2D ERT delineated saltwater intrusion at various distance from the ocean within a depth of 10m, saltwater zone (2.23-3.20Ωm) and interface (3.83-5.94Ωm). The model result revealed that groundwater tends to flow towards the ocean and river with hydraulic head ranging from 0-1.5m. The model revealed that intrusion was caused by lateral intrusion which increases with time, depth and distance. The model divides the intrusion into three zones; saltwater zone (13.0-35Mg/L), transition zone (2.0-13.0mg/l)and freshwater zone (<2.0mg/l). The model also revealed that the lateral intrusion is greater at deeper layers >150m than at top layers. Relict saltwater and lateral intrusions are two forms of salt water occurrence delineated within the study area.

Key words: Saltwater intrusion, relict saltwater, lateral intrusion.

INTRODUCTION

The exploitation of groundwater aquifers located within the coastal regions of the Niger Delta have been a major problem for freshwater resources due to their vulnerability to contamination by saltwater from the adjoining sea.

Intrusion occurs when saline water from the sea is drawn into a freshwater aquifer. Freshwater stored within coastal aquifers is particularly vulnerable to degradation due to its proximity to saltwater intrusion (Werner *et al.*, 2013). It can occur as a result of natural processes or human activity. Intrusion into coastal aquifers is driven by a variety of processes; the common one is the lateral intrusion from the coast caused by extreme water pumping from the aquifer. Rarely common is the vertical intrusion caused by lowering of the freshwater hydraulic head. Surface infiltration from saltwater pits, ponds, or lagoons is common is some regions of the world. The last is relict saltwater caused by changes in seawater level over geologic time (Shaw and Zamorano, 2020).

Several available studies have been carried out on saltwater intrusion and the movement of the interface between freshwater and saltwater, these studies have employed geophysical, geochemical, and groundwater modeling approaches.

However, this research has integrated electrical resistivity tomography with modeling in the delineation of saltwater zone and its interface, and factors influencing the intrusion. The electrical resistivity contrast plays a vital role in delineating saltwater from freshwater aquifer zone in the subsurface as saltwater tends to have lower resistivity values. The use of groundwater models in groundwater management is becoming more common in the 21st century, groundwater models can be used to analyze flow direction, interaction of groundwater in the subsurface with water bodies such as rivers, oceans etc. Contaminant transport and prediction of possible contaminant site in an area, the impact of rainfall and over-pumping on the aquifer system, saltwater intrusion into aquifers and future groundwater investigation in any area by using various modules such as Modflow, Modpath, and Seawat. Few models exist which have been used in the Niger Delta basin which include; Okocha and Atakpo (2013), who simulated groundwater flow around Umuaja, Ophori (2007) in the simulation of large-scale groundwater flow in the Niger Delta, Ohwoghere-Asuma *et al.* (2021) modeled saltwater intrusion in Delta State using seawat. This study therefore, tends to delineate intrusion, interface between freshwater and saltwater zones, freshwater zones, and causes of intrusion.

MATERIALS AND METHODS

Location and Geology

The study area Ogheye is located within Latitude N 5º46'12.0" and N 5º47'24.0" and longitude E 5º03'00" and E 5º04'30" in the coastal region of Warri North Local Government Area in Delta State, Nigeria as shown in figure 1. The study area is only accessible through the Benin River as it is surrounded by both the Benin River and the Atlantic Ocean. The study area is located in the Niger Delta basin and falls within the recent deposits of the Basin. It has been established from studies by various authors (Corredor 2005, Short and Stauble 1967, Aweto 2019) that the Niger Delta sedimentary basin has a distinct three major formations namely from the base to the top; Akata formation which is of marine environment, mainly of uniform dark grey over-pressured marine shales with sandy turbidites and channel, Agbada formation which overlies the Akata formation was deposited under a transitional environment with alternation of sandstone and shale, Benin formation consist of localized clay/shale interbeds, mainly continental sandstone/gravel and the most prolific aquifer in the region which is tapped by both hand dug traditional wells and boreholes. The Benin Formation is masked by the youngest Sombreiro-Warri Deltaic deposit, mangrove swamp and freshwater swamp wetlands as a continuation of the Benin formation (Aweto, 2019).

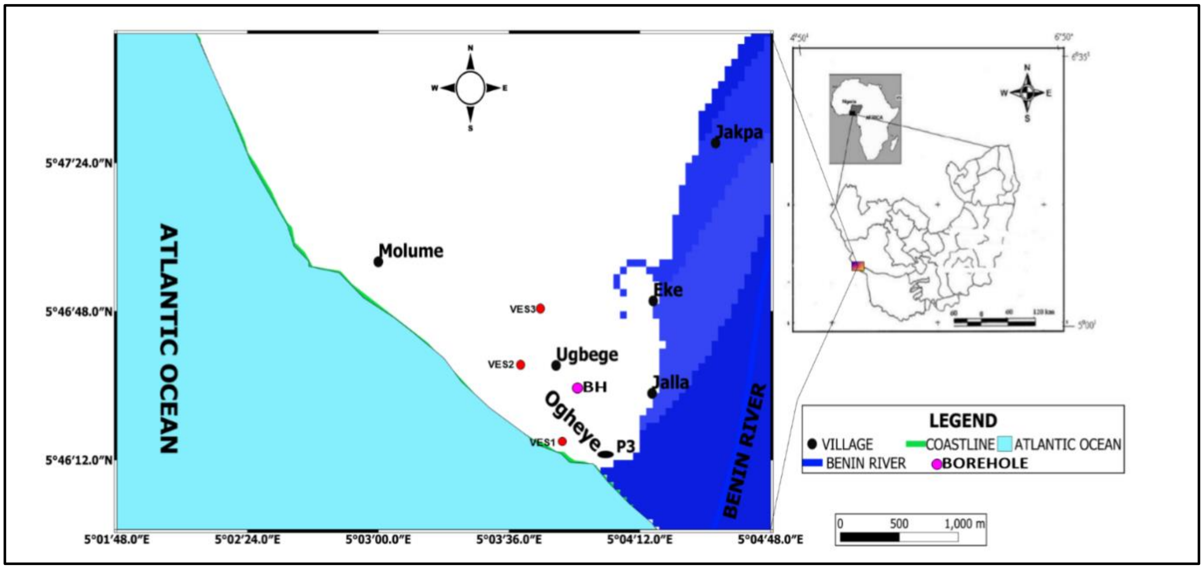

Figure 1: Map showing location of research terrain.

Vertical Electrical Sounding and 2D Resistivity Tomography

The resistivity methods were carried out using the SAS 4000 terameter. For the VES, three (3) VES stations were investigated with electrode spacing ranging from 1 to 200m using a schlumberger array, and VES points were placed perpendicular to the seashore. Schlumberger array was applied in this investigation due to the fact that the readings are obtained in a vertical direction displaying the resistivity of the layers and the presence of fluids. The acquired data were plotted on a bi-log graph and the curve matched with the master curve and auxiliary point chart curve. Geo-electric layers, thickness and depth interpreted were then modeled using inversion software. Dar Zarrouk measured from resistivity and thickness of the layers using the following equations (Maillet 1947):

Longitudinal unit conductance (S)= $\frac{h_1}{\rho_1} + \frac{h_2}{\rho_2} + \frac{h_3}{\rho_3} + \ldots\ldots\ldots + \frac{h_n}{\rho_n} = \sum_{i=1}^{N} \frac{h_i}{\rho_i}$

Transverse Unit Resistance (T)= $\rho_1 h_1 + \rho_2 h_2 + \rho_3 h_3 + \ldots\ldots\ldots + \rho_n h_n = \sum_{i=1}^{N} \rho_i h_i$

Longitudinal Resistivity (R_S)= $\frac{H}{S}$

Where;

S =Longitudinal Conductance, s =Transverse Resistance, R_S =Longitudinal Resistivity, h =Thickness, ρ =Resistivity, and H = Depth.

The 2D ERT was carried out using the dipole-dipole array. Three (3) profiles were occupied for the profiling, the electrode positions were marked at a=1m with four electrodes deployed at intervals of 1m, the two current electrodes (C_1 and C_2) were placed first and the potential electrodes (P_1 and P_2) were later put in place. The distance of a was increased n=1, n=2, and n=3. The resistivity data recorded were interpreted using DIPROWin software to create a 2D image of the acquired data.

Modeling

The simulation of the saltwater intrusion at Ogheye was done with and the Modflow, MT3DMS and SEAWAT module. The model was simulated for a stress period of 50 years to visualize the pattern, extent and impact of intrusion for a long period of time. The MODFLOW package was used to simulate the groundwater flow direction. The grid approach was used and x and y-axes (25 × 16 cell) were computed from the Digital Elevation Model (DEM) of the study area while the z-axis was computed from the well log obtained of the drilled well in the area (the layers include; top muddy soil, silty clay, clayey sand, fine sand, sandy clay, clayey sand and fine sand). Since the study area is surrounded by the Benin River and the Atlantic Ocean, they were simulated as time-variant specified head ranging from 0-0.1 m. Hydraulic heads measured from the field was used as starting heads in the model. The top and bottom elevations of the study area were computed from the DEM of the study area and the well log of the study area. In the Layer Property Function (LPF), the hydraulic conductivity values were assigned with values as suggested by Guideal (2011) for Formation materials (for this model due to the Formations, a value range of 0.2-5.0 m^3/day was used for the hydraulic conductivity). The annual rainfall of Koko was used in estimating the recharge rate in the study, this was done by subtracting evapotranspiration of 1000mm as suggested by Akpokodje *et al.*, (1996), 37% of remaining effective rainfall is known to recharge the subsurface aquifers while the remaining flows directly into the streams (201.3984mm/yr.= 0.000552m/day). In the well function, a discharge rate of 0.078m^3/min (112.32m^3/day) was used which was estimated from pump test of borehole in the study area. The model was then calibrated with hydraulic heads measured from the field to determine the correspondence of the model with the groundwater condition of the study area. The MTEDMS and SEAWAT packages were used to run the saltwater intrusion into the aquifer of the study area. For this model, the initial concentration of salt used is 35 kg/m^3 since the average salinity of the Ocean is about 35 parts per thousand. This concentration was computed at two cells in the area covered by the Atlantic Ocean at the 1st, 2nd, and 3rd layer respectively, this was done considering the depth of the ocean.

RESULTS AND DISCUSSION

Vertical Electrical Sounding

VES results were interpreted with respect to apparent resistivity value and the regional geology of the research domain with the following inferred; lithology, thickness and depth, saltwater, and freshwater zones. Table 1 below gives detailed information about the geo-electric layers.

Table 1: Summary of resistivity Interpretation

VES	Layer No	Resistivity(Ωm)	Thickness(m)	Depth(m)	Curve Type	Geology Inferred
1	1	3.5	4.0	4.0		Top Moist Soil
	2	4.7	130.4	134.4	AA	Sandy Clay (S)
	3	29.2	103.2	237.5		Clayey Sand (I)
	4	115	--	--		Fine Sand (F)
2	1	40.6	2.4	2.4		Top Moist Soil
	2	7.3	15.7	18.1	QH	Sandy Clay
	3	2.2	18.5	36.6		Clayey Sand(S)
	4	56.3	--	--		Fine Sand (F)
3	1	15.2	0.6	0.6		Top Moist Soil
	2	1.8	3.3	3.9	HKH	Sandy Clay (S)
	3	24.0	7.3	11.2		Clayey Sand (I)
	4	1.1	14.1	25.3		Sandy Clay (S)
	5	18.7	--	--		Clayey Sand (I)

Where S= Saline water, I= Saltwater-Freshwater Interface, F= Freshwater.

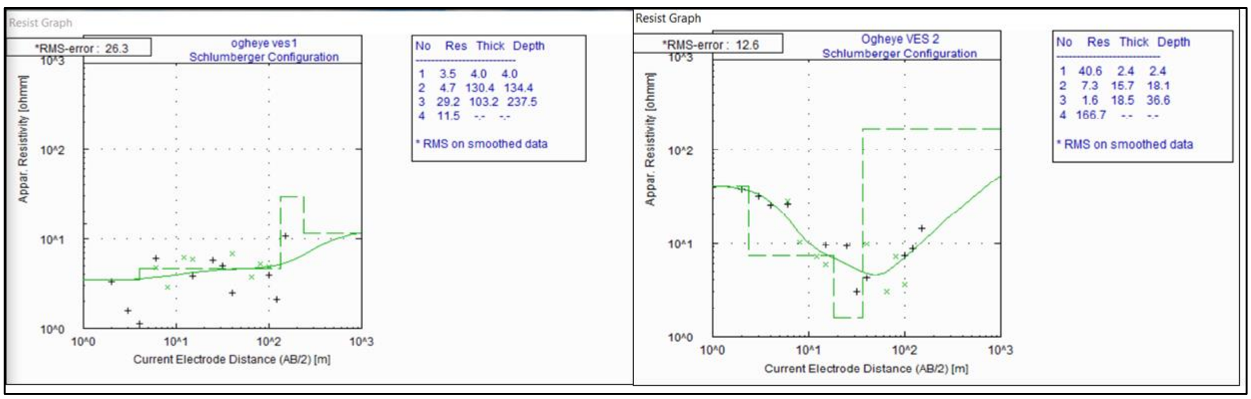

Figure 2: Geo-Electric Curve sounding for VES 1 and VES 2

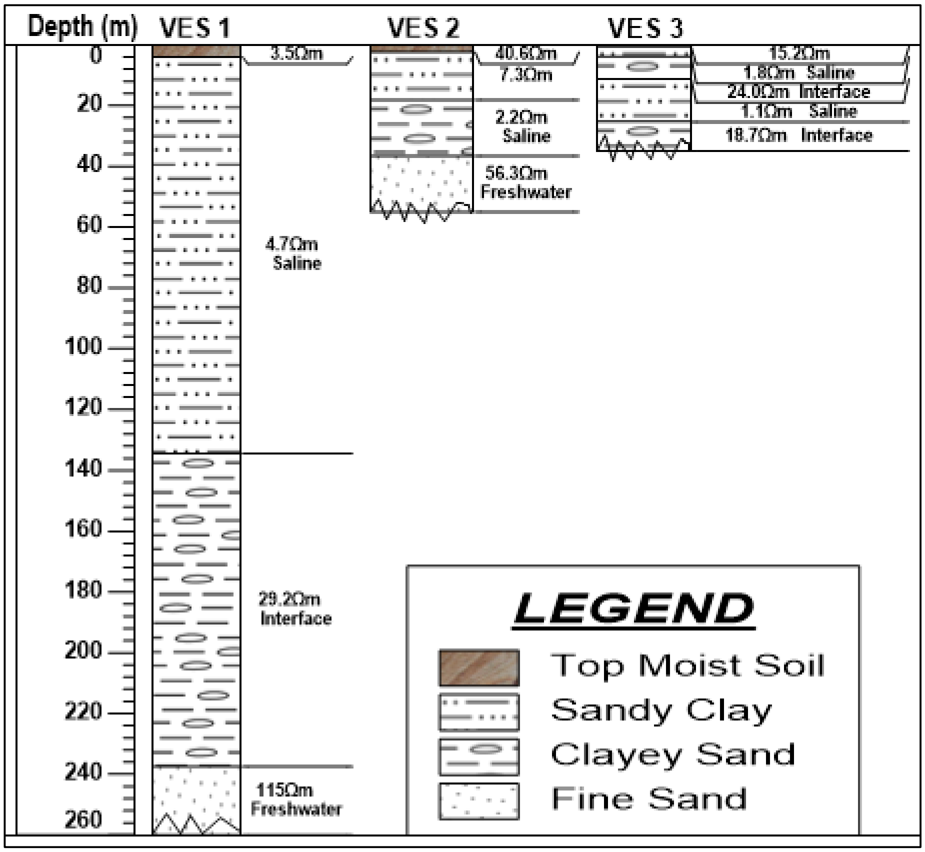

Figure 3: Geo-electrical section of VES1-3.

The VES data were interpreted for the geology and presence of saline water. The summary of the geo-electric layers is presented in Table 2, and Figure 3 shows the geoelectric sections. At VES 1, four geo-electric layers were interpreted (top moist soil, sandy clay, clayey sand, and fine sand). Sandy clay with a resistivity of 4.7Ωm was delineated as saline water, clayey sand with a resistivity of 29.2Ωm is the saltwater-freshwater interface, and fine sand with a resistivity of 115Ωm is the freshwater zone. The aquifer units are the clayey sand and fine sand layers.

In VES 2, four geo-electric layers were interpreted (top moist soil, sandy clay, clayey sand and fine sand). Clayey sand was delineated as saline water with resistivity of 2.2Ωm, freshwater was observed in the fine sand layer with a resistivity of 56.3Ωm. The aquifer units are the clayey sand and fine sand and (3rd and 4th layer).

In VES 3, five geo-electric layers were interpreted (top moist soil, sandy clay, clayey sand, sandy clay and clayey sand). The resistivity of 1.8Ωm and 24.0Ωm observed in 2nd and 3rd layer represents saline and saltwater-interface, the resistivity of 1.1Ωm and 18.7Ωm observed in 4th and 5th layer also represents saline and saltwater-interface. The aquifer unit in this VES point is the clayey sand in the 5th layer.

The three VES stations have delineated the geology and saltwater intrusion in the study area. Low resistivity values were attributed to saltwater intrusion (1.1-4.7 Ωm), medium resistivity was attributed to saltwater-freshwater interface (18.7-29.2 Ωm), and high resistivity values were attributed to freshwater (56.3-115 Ωm). The saltwater zones were delineated at the top layer, interface at the middle layer, and saltwater zone at the bottom layer. The result of the resistivity is similar to those obtained by Ohwoghere-Asuma and Essi, (2017). The intrusion, therefore, is more pronounced at the top layer from a depth of 3.6-36.6m while the freshwater is at the bottom layer from a depth of 55m.

Dar Zarrouk Parameters

Dar Zarrouk parameters were used to interpret saltwater intrusion and they include; longitudinal conductance, transverse resistance and longitudinal resistivity. Table 2 below gives a summary of the parameters estimated.

Table 2: Summary of Dar Zarouk parameters estimated

VES No	**Resistivity(Ωm)**	**Thickness(m)**	**Depth(m)**	**Longitudinal Conductance (Siemens)**	**Transverse Resistance (Ωm^2)**	**Longitudinal Resistivity (Ωm)**
1	3.5	4.0	4.0	32.42178	3640.32	7.325
	4.7	130.4	134.4			
	29.2	103.2	237.5			
2	40.6	2.4	2.4	10.61889	252.75	3.447
	7.3	15.7	18.1			
	2.2	18.5	36.6			
3	15.2	0.6	0.6	14.99516	205.77	1.687
	1.8	3.3	3.9			
	24.0	7.3	11.2			
	1.1	14.1	25.3			

Analysis of Longitudinal Conductance

A contour map of S values of the study area prepared by using the resistivity data of 3 soundings prepared with a contour interval of 5 Siemens is shown in Figure 4. It clearly demarcates the saline water region from the freshwater region. From the map, the saline water region encroaches the coastal aquifer with a high conductance value of 33-15 Siemens, areas of freshwater have values less than 20 Siemens. The saltwater decrease in concentration as it intrudes further into the terrestrial aquifer as shown by the decreasing conductance values.

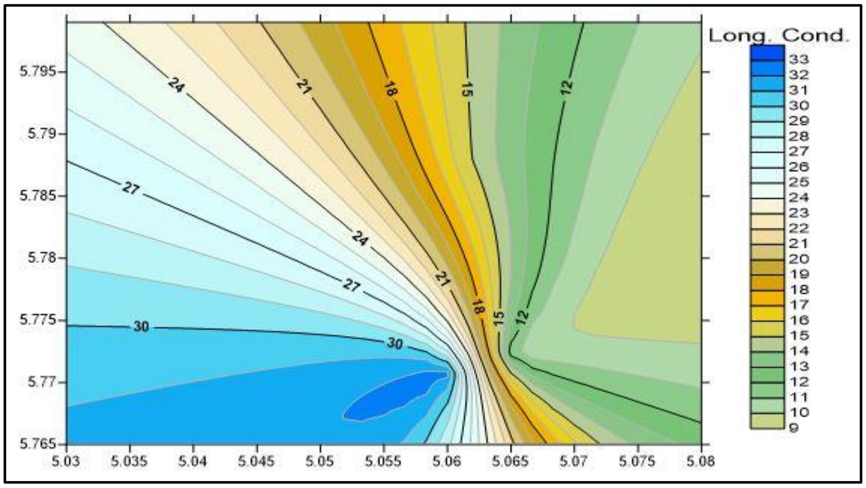

Figure 4: Longitudinal Conductivity Contour map of the study area.

Analysis of Transverse Resistance

Transverse resistance estimated by interpolating T values of 3 soundings have been to a contour map with an interval of 200Ωm^2 is shown in Figure 5. Here, the regions of saltwater are represented by low values while high values represent freshwater. 0-1600Ωm^2 indicates saltwater intrusion, 1600-2000 Ωm^2 represent the interface, while a range of 2000-3800 Ωm^2 indicate freshwater. Therefore, saltwater intrusion in the study area decreases in concentration from the estuary.

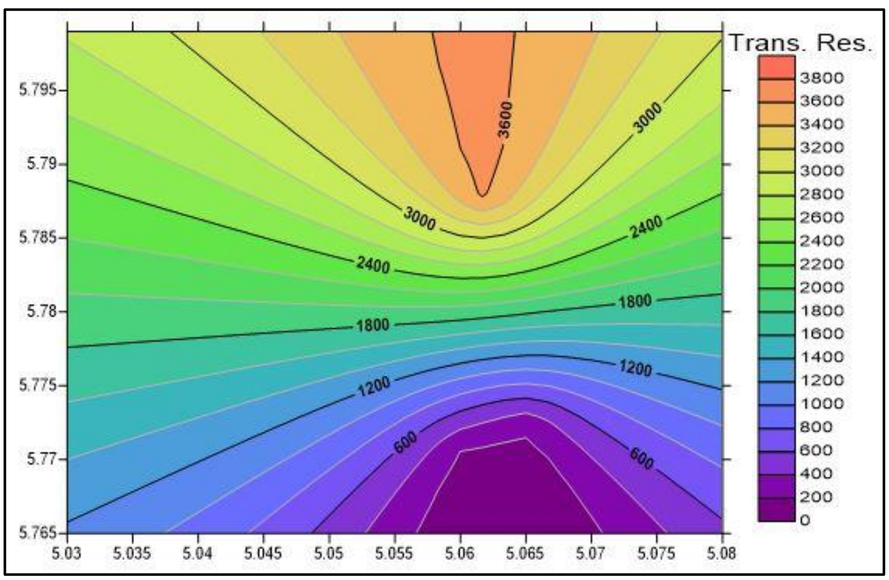

Figure 5: Transverse Resistance contour map of the study area.

Analysis of Longitudinal Resistivity

A contour map prepared using longitudinal resistivity values of the 3 soundings carried out in the study area as shown in Figure 6 demarcates the saline water aquifer region and freshwater region into two different entities based on their attained magnitudes. The contour interval in the maps is 0.2Ωm. The saline water aquifers possess the resistivity range of 1–5.6Ωm and those of freshwater aquifers possess value 4Ωm. The map has also shown gradational decrease in the concentration of saline water intrusion into coastal aquifer, the highest concentrations are closer to the ocean and river and decreases farther away from the water bodies.

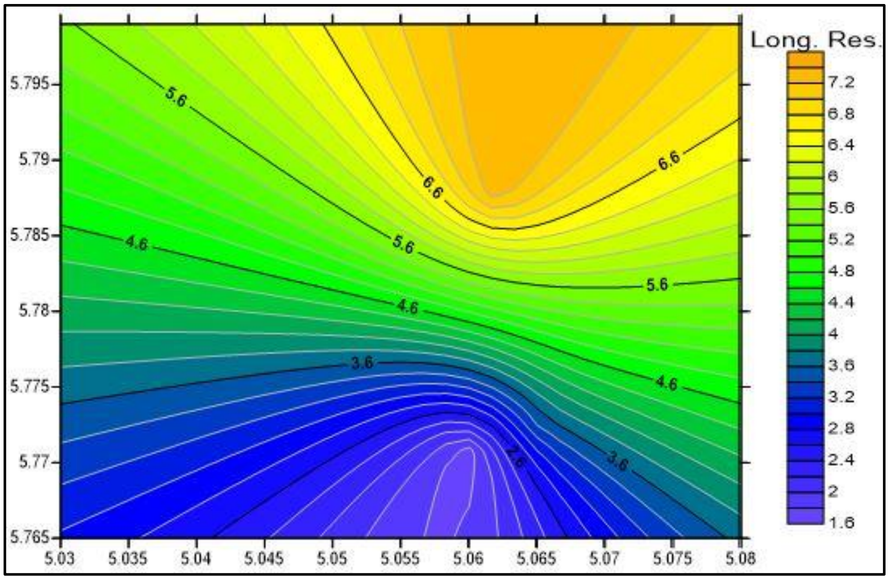

Figure 6: Longitudinal Resistivity contour map of the study area.

2D Electrical Resistivity Tomography

The three 2D profile images delineated in the study area are shown in Figures 7-9. The depth of penetration ranges from 0-10m with a maximum distance of 50m taken perpendicular to the ocean in each of the profile sections. The inverted resistivity model in Figure 7 shows variation in resistivity values ranging from 2Ωm–495Ωmdepicting freshwater and saline water zones at a depth of 0-10m. Resistivity range of 2-3.34 Ωm represents saline water, interface of saline/freshwater was indicated with value range of 3.34-4.53 Ωm, while 4.53-495 Ωm represents freshwater zone. The saltwater only occurs in parts of the profile from a depth of 3.0m

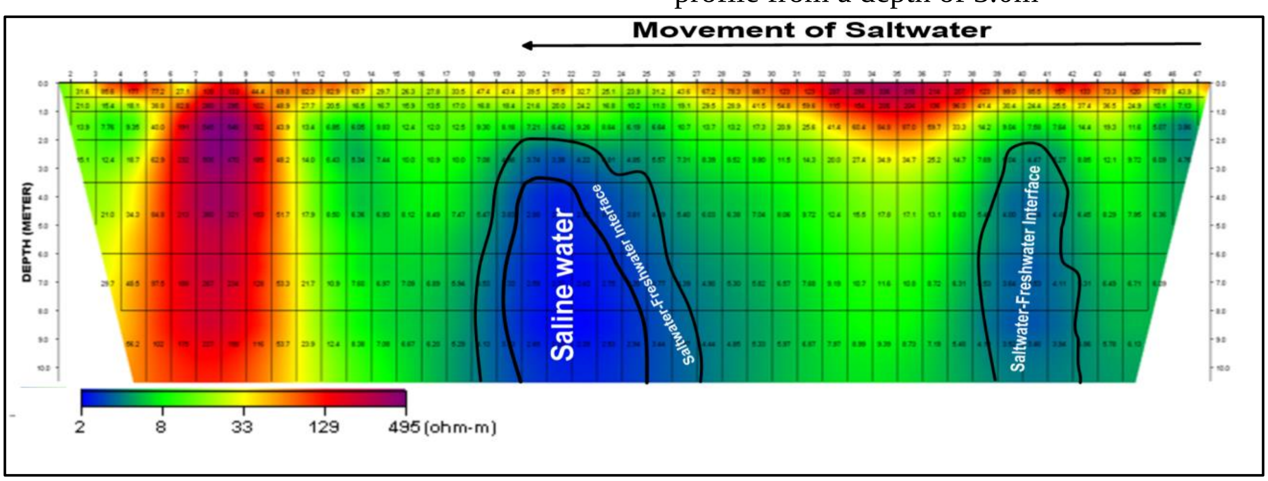

Figure 7: 2D ERT Profile 1 showing saltwater- freshwater interface

In Figure 8, the 2D profile image indicated saltwater, saline/freshwater interface, and freshwater with resistivity variation of 0-421 Ωm at a depth range of 0-10m. Resistivity range of 0-0.52 Ωm represents saline water, 0.52-1.18Ωm indicate saline/freshwater, while 1.18-421 Ωm indicate freshwater zone. Saltwater occurred from a depth of 3.0 m at a little portion of the profile.

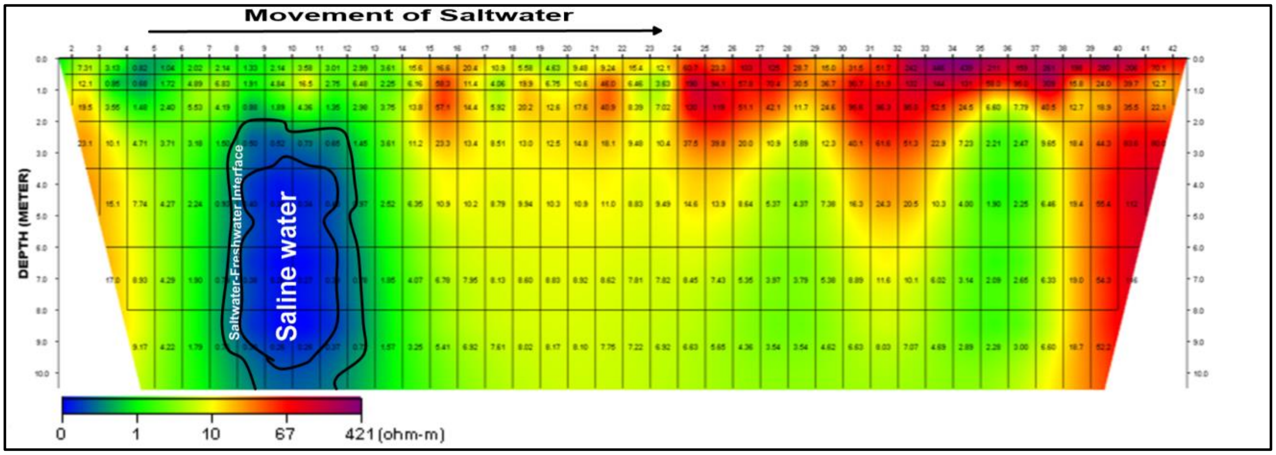

Figure 8: 2D ERT Profile 2 showing saltwater- freshwater interface

In profile 3, the resistivity of the 2D image range from 6-284 Ωm at a depth range of 0-10m. Saltwater was not detected in this profile; however, interface was delineated at a depth of 2.5-9.0 m with a resistivity range of 6-9.11 Ωm. Resistivity range of 9.11-284 Ωm represent freshwater zone.

The pattern of saltwater intrusion delineated by the 2D ERT is relict saltwater which was suggested by Shaw and Zamorano (2020). The occurrence of such saltwater is due to trapping of saline water by lower permeable layer (sandy clay, clayey sand).This occurs in rainy season when hydraulic head is high which is often accompanied by saltwater, when the head is lowered portions of the saltwater are trapped within the sediments leading to *"relict saltwater"* in the study area.

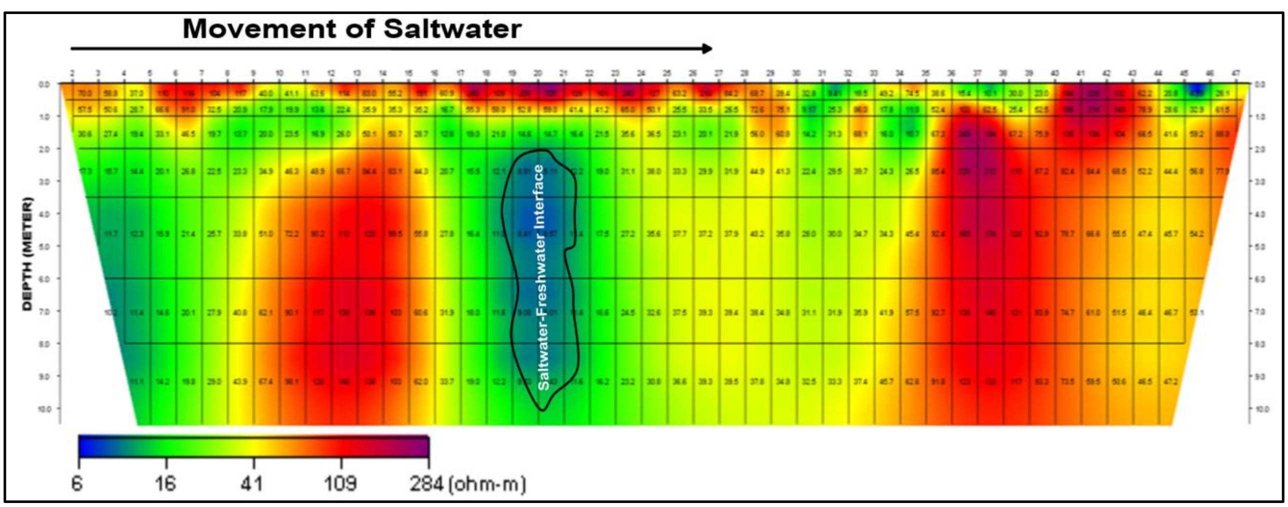

Figure 9: 2D ERT Profile 3 showing saltwater- freshwater interface

Groundwater Flow

The range of values for the hydraulic head for model output ranged from 0-1.5m. The groundwater flows from a hydraulic head of 1.5m to 0m which is around the ocean (Figure 10). Precipitation recharges the top layer of the model domain and infiltrates into subsequent layers. The magnitude of flow and the pattern of flow are slightly different from the first layer and subsequent layers. The hydraulic head decreases towards the estuary as shown in Figure 11, therefore groundwater flows towards that direction. Moreover, from the first layer, groundwater flows with a velocity magnitude of 0.0-0.00583 m/day, while at the sixth layer, it flows from 0.00662-0.09068 m/day. Hence, as seen in Figure 10. The velocity vectors are greater in the sixth layer (clayey sand) than the first layer (muddy soil), this may be due to porosity and permeability which are higher in the clayey sand than the muddy soil. The hydraulic heads are comparable with those obtained by Ohwoghere-Asuma *et al.*, (2021), Ophori (2007) and Akpoborie *et al.*, (2014).

The interaction between groundwater of the coastal aquifer, the Benin river and Ocean is shown in figure 11. The top layer is recharged by precipitation and subsequently the water infiltrates into deeper depths as indicated by the velocity vector pointing downward in Figure 11, while the velocity vectors pointing towards the ocean indicates the discharge of groundwater to the ocean. A combination of surface water loss from the river to the groundwater and seepage of groundwater to the river exists as shown by Figure 11.

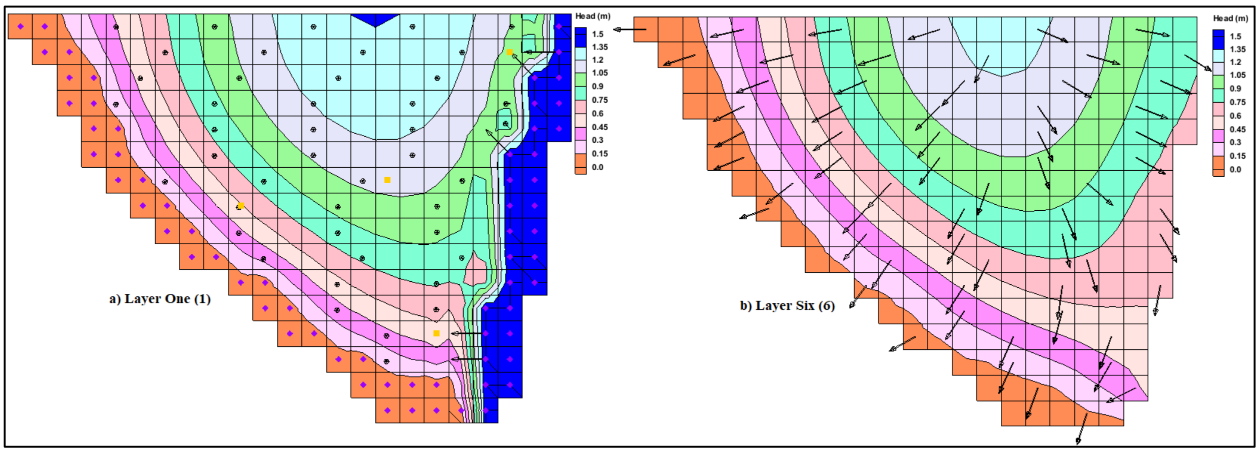

Figure 10: Groundwater flow in first and sixth layer.

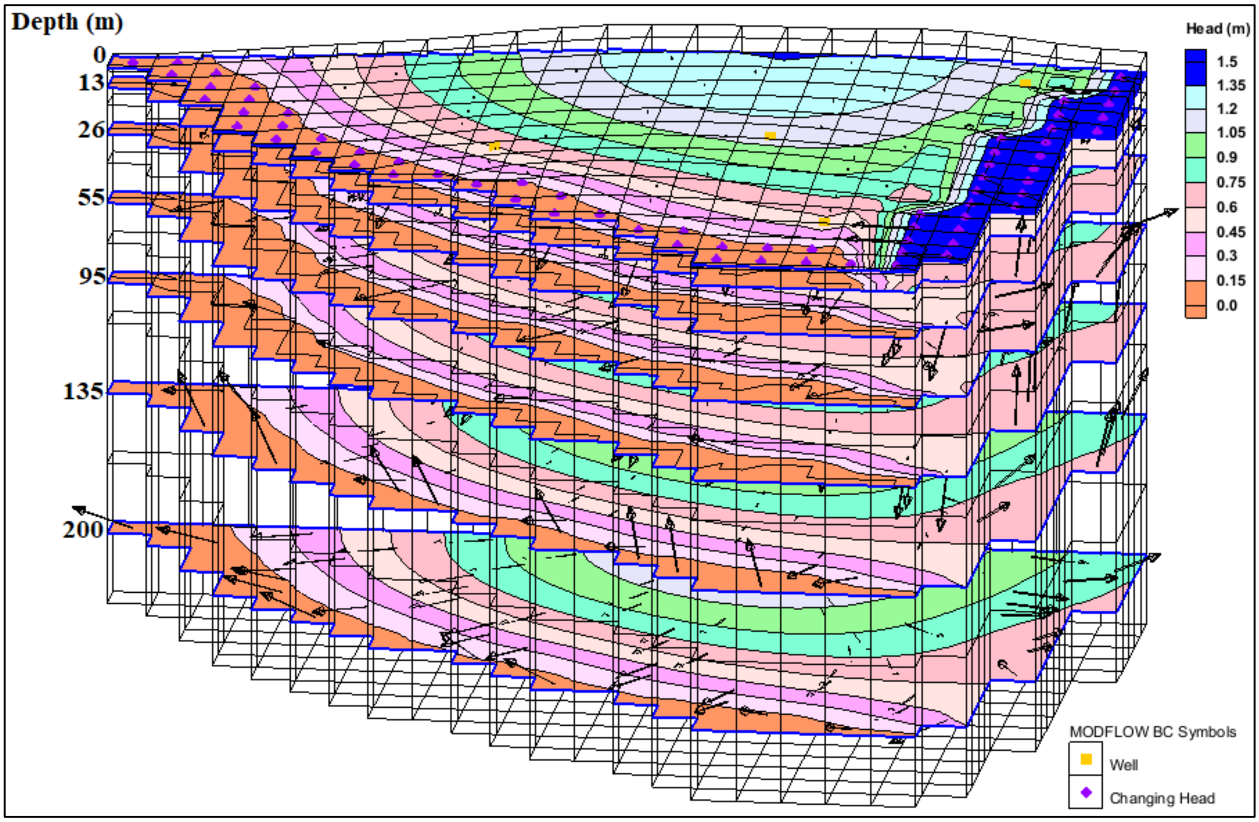

Figure 11: Oblique view of groundwater flow in the study area.

Calibration

The model was calibrated with hydraulic head measured in the field as shown in Figure 12,a correlation between the observed head in the field and the computed head by the model. The graph shows an almost perfect correlation between the observed and computed head along the 45° line, this shows that the model represents the groundwater condition of the study area, therefore the model can be used for groundwater management in the study area.

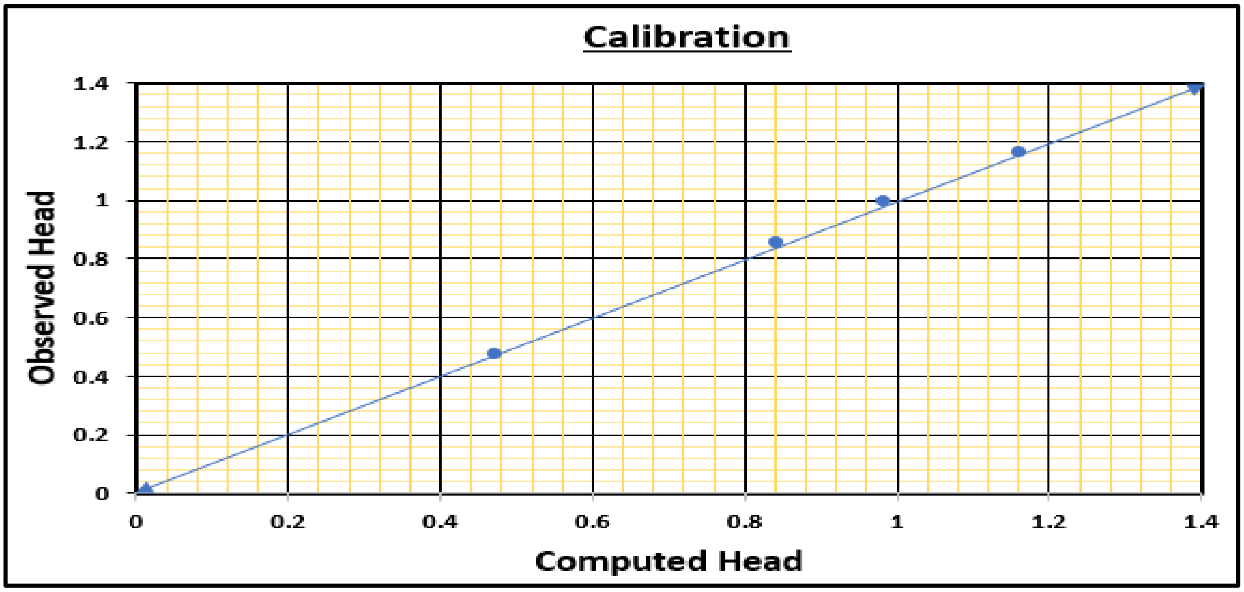

Figure 12: Calibration graph of the model.

Saltwater Intrusion

The saltwater concentration as observed in figure 14 ranges from -20mg/l to 35mg/l. The concentration of intrusion increases with distance, depth and time. At 365 days, salt concentration is noticed at the 6th layer, depth of 115m distance of 170m from the ocean with a concentration of 2.5mg/l (figure 13a). At 18250 days (50 years), the salt concentration and extent of intrusion has increased, the salt exceeds the 200m depth with a concentration of 35mg/l, the distance of intrusion from the coastline has increased to 1914m with a concentration of 2.0mg/l (figure 13b). The intrusion of saltwater into the is influenced by the recharge, constant presence of river and ocean and time. The model demonstrates the effect of time on the intrusion, with time the spread increases with depth and covers a larger distance into the surrounding coastal aquifer which is also influenced by sea level rise and storm surge, this explains why the ocean at the study area continues to move inward into the land, the inhabitants in the area have relocated inner into the land because of the ocean. This model has shown that the ocean will continue to claim more land as the intrusion of saltwater into the coastal aquifer continues to increase. The pattern of saltwater intrusion as seen in figure 154 is continuous but more pronounced in the bottom layers, the saltwater infiltrates from the ocean into deeper depth and start spreading faster in the bottom layer than in the top layer, this can be attributed to the presence of groundwater in the bottom layer and its absence in the top layer. Variable-density flow controls the intrusion of saltwater and it is a natural process, optimum pumping of groundwater in the study area with the current pumping rate of 112.32m^3/day does not influence or accelerates the intrusion; therefore, the intrusion is a lateral intrusion from the coast as suggested by Shaw and Zamorano, (2020). The model can be divided into three (3) zones; saltwater zone, transition zone (interface) and freshwater zone. Saltwater zone ranges from 13.0-35mg/l and within 1 year, the zone is at 40m from the ocean (figure 13a) and within 50 years it's at 1660m from the ocean (figure 13b). The transition zone (saltwater-freshwater interface) ranges from 2.0-13.0mg/l, within 1 year it extends from 40m-170m and within 50 years, it extends from 1660m-1914m. The freshwater zone is <2.0mg/l, within 1 year, the zone starts from 170m from the ocean and within 50 years, it starts 1914m from the ocean. The aquifer unit under exploration is the 4th layer (fine sand) and the impact of intrusion is felt closer to the ocean.

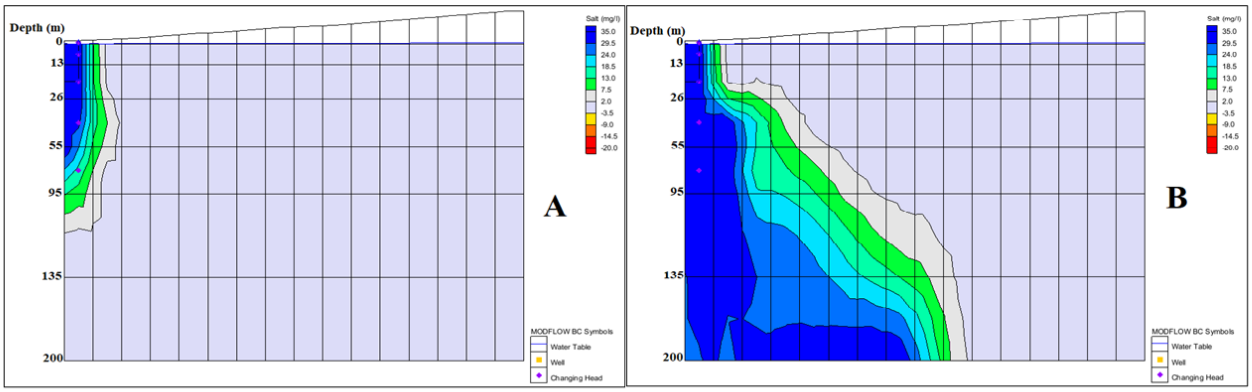

Figure 13: Saltwater intrusion within (A) 365 days. (B) 18250 days.

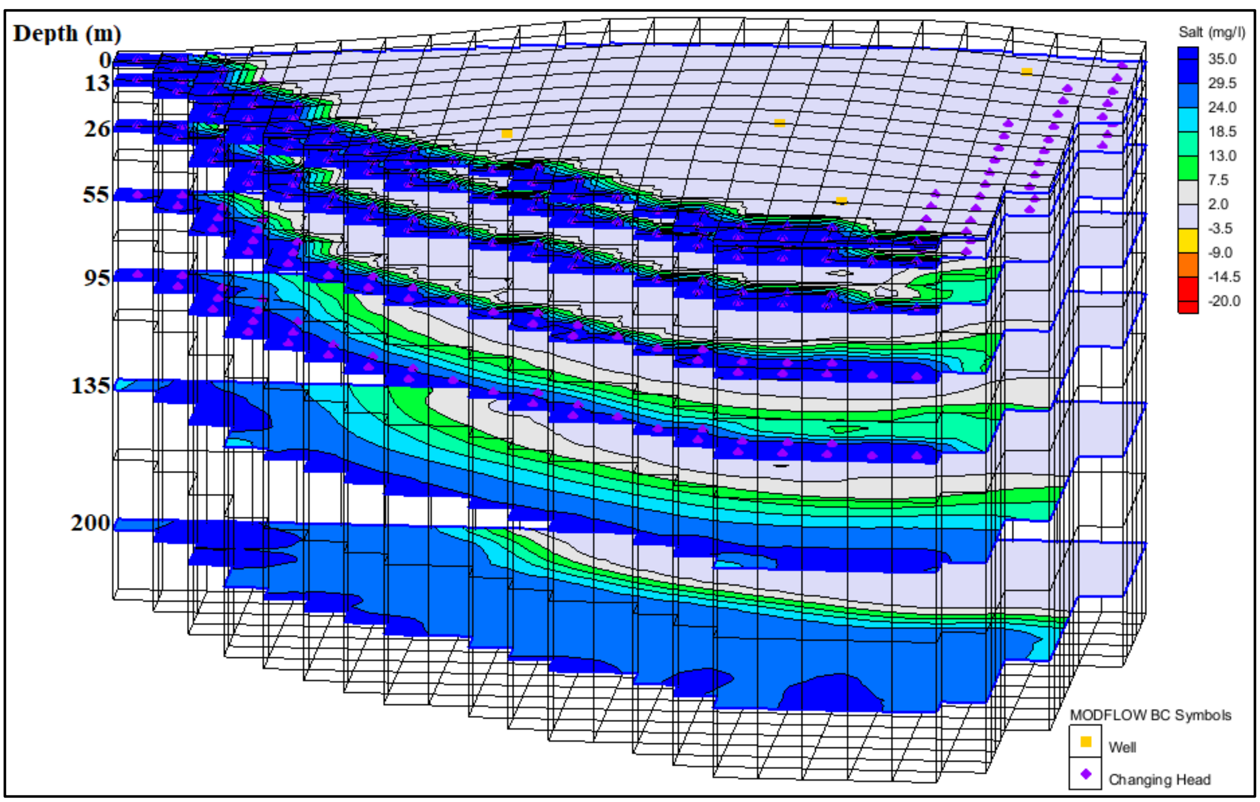

Figure 14: Oblique view of saltwater intrusion within 18250 days (50 years).

Discussion

The processes governing the intrusion of saltwater into coastal aquifers have been divided into four by Shaw and Zamorano (2020), they include; lateral intrusion, vertical intrusion, surface infiltration of saltwater from lagoons, ponds, and pits that are linked to aquifer, and relict saltwater. Three approaches were employed in delineating saltwater in the study area (VES, ERT, and Model).

The VES delineated saltwater from a depth of 0.6- 54.6 m, interface of saltwater/freshwater was delineated from 25.3-55 m, and freshwater from a depth >55 m. This occurrence suggests relict saltwater which is trapped by sediments of the top layers when sea level dropped. Aquifers in the study area have freshwater which may be altered when hydraulic head is reduced by pumping leading to relict saltwater intrusion into the aquifer. Longitudinal conductance, transverse resistance, and longitudinal resistivity suggested a lateral intrusion of saltwater into the coastal aquifer of the study area, this was inferred by the high values of longitudinal conductance around the estuary which deceases landward. Also, low values of transverse resistance and longitudinal resistivity around the estuary indicating saltwater areas which increases inward representing freshwater (Figure 4-6).

ERT delineated saltwater intrusion within a shallow depth of 0-10.0 m at distance of 50m perpendicular to the ocean. Saltwater lenses were observed at 3.0-10.0 m as low resistivity indicating relict saltwater trapped by the sediments.

The seawat model suggests a lateral intrusion which increases landward with time. The model explains that saltwater intrudes the area by displacing the less dense freshwater from the bottom, this continues over time leading to further intrusion. As shown by the model, by the end of the stress period, a lateral intrusion of 1914 m was measured at a depth of 200 m, while the distance of the lateral intrusion decreases with shallower depth, at 30m, the intrusion is at 100 m (Figure 14). The concentration of saltwater decreases as it intrudes from the estuary, the areas closer to the ocean have a higher concentration, therefore areas farther will have less impact of the intrusion, this is also illustrated in the Dar Zarrouk parameters. The Interface between the saltwater and freshwater is a gradual boundary with mixture of both as seen in Figure 13.

The Intrusion of saltwater in the study area is through two processes; lateral intrusion of saltwater and relict saltwater.

CONCLUSION

This study has delineated the intrusion of saltwater into the coastal aquifer of Ogheye. Lateral intrusion and relict saltwater were the patterns of intrusion delineated by the VES, 2D ERT, and Seawat model. Lateral intrusion in the area occurs owing to the displacement of freshwater by the saltwater and influence of tide. The lateral intrusion was delineated at 1914 m from the coastline at a depth of 200m with decrease in lateral extent at shallower depth. Relict saltwater was delineated at shallow depth of 3-10m, which occurs due to saltwater trapped within the sediments of the upper layer when sea level drops. The study area therefore has saltwater trapped within the sediments at the top layers and lateral saltwater intrusion at deeper depth of 150 m and above.

ACKNOWLEDGEMENT

We appreciate the effort of Prince Atiti, and final students of Geology Department (Ifeanyi and Princess) during the field data acquisition in the coastal region of Ogheye. Also, thanks to Mr. Anoemuah O. Rawson (FISLT) for his participation and activeness during data acquisition at the estuary.

REFERENCES

Akpoborie, A. I., Aweto, K. E., Ohwoghere-Asuma, O. (2014). Urbanization and major ion hydrogeochemistry of the shallow aquifer in the Effurun - Warri Area, Nigeria, 4(1); 37-46 450.

Akpokodje, E.G., Etu-Efeotor, J.O., and Mbeledogu,I.U (1996). A study of environmental effects of deep subsurface injection of drilling waste on water resources of the Niger Delta" CORDEC, University of Port Harcourt, Choba, Port Harcourt, Nigeria.

Allen, J.R.L. (1965). Late Quaternary Niger Delta and Adjacent Areas. *Sed. Environ. Litho.* Vol. 49(5):547-600

Atakpo E.A. (2013). Geoelectric Investigation of Deghele CommunityIn Warri South West L.G.A., Delta State Nigeria. IOSR Journal of Applied Physics, 3(1): 46-51.

Corredor F., Shaw J.H., Bilotti F. (2005). Structural styles in the deep-water fold and thrust belts of the Niger Delta: American Association of Petroleum Geologists Bulletin, 89: 753-780

Guideal R., Bala A.E. and Ikpokonte A.E. (2011). Preliminary Estimates of the Hydraulic Properties of the Quaternary Aquifer in N'Djaména Area, Chad Republic. Journal of Applied Sciences, 11: 542-548.

Maillet R. (1947). The Fundamental Equations of Electrical Prospecting. Geophysics, 12 (4): 529-556.

Ohweghero-Auma O., Oteng F.M, Ophori D., (2021). Simulation of saltwater intrusion into coastal aquifer of the Western Niger Delta. MedGu Mediterranean Geosciences Union, Annual Meeting, Instanbul, Turkey 25-28 November 2021.

Ohwoghere-Asuma O., Chinyem I.F., Essi O.E. (2017). Saltwater intrusion appraisal of shallow aquifer in Burutu Area of the Western Niger Delta with 2D Electrical Resistivity Tomography. Journal of Applied Science and Environmental Management, 21 (2) 372-377.

Ohwoghere-Asuma O., Essi O.E. (2017). Investigation of seawater intrusion into coastal groundwater aquifers of Escravos,Western Niger Delta, Nigeria. Journal of Applied Science and Environmental Management, 21 (2): 362-369

Okocha, F.O. and E. Atakpo. (2013). "Groundwater Flow Modeling at the Source of River Ethiope, Delta State, Nigeria". *Pacific Journal of Science and Technology*. Vol. 14(2): 594-600

Oomkens, E. (1974). Lithofacies relations in the Late Quaternary Niger Delta Complex. *Sed.* Vol. 21: 195-222.

Ophori, D.U. (2007). A simulation of large-scale groundwater flow in the Niger Delta Nigeria, Environmental Geosciences 14(4): 181-195.

Shaw J.E., Zamorano M. (2020). Saltwater Interface Monitoring and Mapping Program Technical Publication WS-58, December 2020.

Short, K. C., and A. J. Stauble (1967). Outline of Geology of Niger delta: American Association of Petroleum Geologists Bulletin, 51: 761-779

Werner D.A., Mark B., Vincent E.A., Alexander V., Chunhui L., Behzad A., Craig T.S., Barry D.A. (2013). Seawater intrusion processes, investigation and management: Recent advances and future challenges, Advances in Water Resources, 51: 3–26.