

REVIEW ARTICLE

INVESTIGATION OF SALINE WATER INTRUSION IN SELECTED COASTAL AREA OF RIVERS STATE, SOUTH-SOUTH NIGERIA

Adaora G. Atuchukwu, B.U. Amechi, O.I Horsfall, Benjamin S Udota*

Department of Physics, Rivers State University of Science and Technology Ringgold ID 108005, Nigeria
*Corresponding Author Email: benudota@yahoo.com

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ABSTRACT

The study was aimed to investigate the intrusion of saline water in some selected areas of Rivers State Nigeria. The objectives of the present study were summarized by the use of electrical resistivity signatures of the area's subsurface to study the occurrence of Saltwater-freshwater interface, determining the depth and thickness of different subsurface layers for groundwater exploitation and delineate saline-water intruded sands in the study area using the borehole geophysical logging tool. The study scoped at producing geologic maps of the study area to gather information concerning the geomorphologic features, application of the electrical resistivity method (VES) to obtain necessary data to investigate the occurrence of seawater intrusion by determining the resistivity, depth and thickness of the various lithologic layers and delineating saline-water intruded sands in the study area by exploring the potential of borehole geophysical logging tool. A total of 11 geoelectric (VES) surveys and four (4) downhole logging was carried out in selected locations within the River State Metropolis to investigate the saline water intrusion in the area. The obtained results reveal that from the Electrical resistivity sounding, the predominant lithologies in the area includes clay, clayey sand, coarse sand, consolidated sand, gravelly sand, consolidated gravel sand, gravelly sand, silty sand, freshwater bearing sand and saltwater bearing sand. Geoelectric layers identified across the area ranged from 3 to 6 layers. Resistivity ranged from 29.60 to 364058.00 Ohm.m for lithologic units, 113 to 181 Ohm.m for freshwater sands and 0.11 to 28.50 Ohm.m for saline water sands. Resistivity field type curves recognized included; H, QQ, AA, KHA, QH, HKH, QQHK, A, HK, KHK and KQH depicting the heterogenous nature of soils in the area. Six of eleven VES points encountered salt water at varying depths and include; Ogonokom, Eagle Island, Okirika, Assarama, Ikuru and Opobo sounding points. Thickness of the saline sandy layers ranged 3.10 m to 71.48 m. Downhole logging (SP and Resistivity) conducted in four coastal communities of the study area revealed four lithologic units which includes clay, clayey sand, coarse sand and saline water bearing sand. Saline zones were identified as having negative SP values and low resistivities. Clay were mapped as areas having positive SP values and low resistivities. The thickness of the saline zones ranged from 16 to 74 m. The largest saline layer thickness was obtained at Bonny. This study has shown that boreholes in Bille and Bonny communities exceeding depths of 15 m are likely to encounter salt water. The saltwater intrusion is predominantly concentrated around the southern part of the study area around Bonny and Opobo communities. The presence of Opobo River, Bonny River and a suite of creeks which are open to the Atlantic Ocean area responsible for the salt intrusion into these coastal boreholes. The outcome of the study yielded the importance that boreholes in Bonny, Opobo and Bille communities that has encountered saline water should be prevented from further use until treatment for salt water intrusions are conducted and water exploitation plan should be developed by the government and enforced to be utilized by residents in Buguma, Degema, Abonnema and NLNG to prevent saline intrusion because these communities are the most vulnerable to saline intrusion from over-exploitation of freshwater in the area.

KEYWORDS

Geomorphologic Features, VES, Saltwater Intrusion, Atlantic Ocean, Salt Water

1. INTRODUCTION

The availability of freshwater aquifers in coastal regions act as a vital source of portable water around the world, particularly in most arid and semi-arid zones (UN-WWAP, 2006). Most coastal communities in Rivers State and other parts of Nigeria are gradually becoming urban hubs due to developmental and economic growth propelled by oil and gas activities in the region. This has caused the demand for freshwater even more critical amongst the inhabitants with much dependence on groundwater

resources for their domestic, commercial and agricultural uses. Coastal aquifers are highly susceptible to variations in quality due to natural and man-made disturbances. Inappropriate management of a coastal aquifer may lead to its destruction as a source for freshwater much earlier than other aquifers which are not connected to the sea. The reason is the threat of seawater intrusion. Improper administration of coastal freshwater seaside spring may prompt its obliteration as a hotspot for freshwater significantly sooner than different springs which are not associated with the ocean. The explanation is the danger of seawater interruption (Bear

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et al., 1999; Ayolabi et al., 2013).

Saline water intrusion is the progressive migration of saltwater into fresh water zones which leads to the pollution of potable fresh water sources (Werner and Simmons, 2009; Bayowa et al., 2020). This is usually common in coastal aquifers where freshwater has direct contact with saline sea water. Several researchers have identified certain factors as being the propellants of this problem (Bear et al., 1999; Al-Sayed and El-Qady, 2007; Kayode et al., 2017). Due to excessive abstraction (pumping) of underground water from these coastal aquifers, the water level drops below the natural water table altering the hydraulic gradient in the coastal aquifer. Also due to variation in density between saltwater and fresh groundwater in these coastal aquifers, over-abstracted wells tend to encounter more salinity when the top freshwater is depleted; causing leading to saline intrusion into the well, thereby making the freshwater well unusable for drinking and other uses (Stringfield, 1966; Lanbo, 2016; Kayode et al., 2017; Robinson et al., 2006; Kayode et al., 2017). As groundwater abstraction continues, seawater intrusion progresses into existing pumping wells, especially those close to the coast and become contaminated, unhealthy and are abandoned. Understanding the complex interaction that occurs between fresh and saline water bodies in these aquifers requires the deployment of geophysical monitoring tools (Jimoh et al., 2018). Such tools/ methods would also serve to guides in the management of coastal aquifers and ensure the sustainability of fresh underground water for the coastal communities. In more recent times, the use of electrical resistivity, geochemical analysis and electromagnetic methods to monitor the unique balance of saltwater-freshwater interface has become one sure way of properly managing this problem (Domenico and Schwartz, 1998; Hwang et al., 2004).

2. LITERATURE REVIEWS

Groundwater studies in relation to seawater intrusion in freshwater aquifers have been a recurrent issue in the study of groundwater resources in the Niger Delta and the world at large. Most of these studies have been carried out using various geophysical techniques which provide a near vivid interpretation of the subsurface formations in the region. Such studies by were carried out along coastal communities aimed at understanding the occurrence of saltwater intrusion (Goldman et al., 1991; Fitterman and Deszcz-Pan, 2001); Khalil, 2006; Al-sayed and E.A, 2007); Oyedele and Momoh, 2009). These studies show that this occurrence causes groundwater to be considerably conductive, causing the resistivity of the aquifer to reduce; as resistivity contrast become evident, the electrical resistivity method proves to be quite useful in delineating these variations (Oyedele and Momoh, 2009; Ayolabi et al., 2013).

There a Employed the Vertical Electrical Sounding method in mapping boundary conditions in an aquifer system in Yemen; the works of all demonstrate the effectiveness of electrical techniques in the planning, detection and management of wells and boreholes in crystalline basement aquifers throughout sub-Saharan Africa (Van Overmeeren, 1989; Barker et al., 1992; Carruthers and Smith, 1992).

According to study the salt water intrusion problem on the coastal area of South Korea and observed that salinity of the fresh ground water is highly associated with ground water withdrawal. A geochemical study was used to determine the possibility of seawater intrusion. However, for enhanced results, a combination of geophysical and geochemical analysis was proved useful by (Hwang *et al.*, 2004, Oyedele and Momoh, 2009; Lee and Song, 2007).

To whom successfully applied the resistivity method to model perched water tables containing saltwater and fresh water lenses in parts of southern Australia (Amos-Uhegbu et al., 2013; Barret et al., 2002).

The combined geophysical and physicochemical analyses to monitor saltwater intrusion in parts of Victoria Island and Iwaya in Lagos state, south-western Nigeria. His findings showed that the freshwater/saltwater interface occurs at relatively shallow depths and identifies excessive groundwater abstraction to be a major cause of seawater intrusion into these aquifers (Oyedele and Momoh, 2009).

According to a study carried out by where he cited the works of who stated that zones of saltwater contamination were delineated using VES results in the coastal area of Deghele in Warri South-West and the work of state that saltwater intrusion was caused by ancient seawater-flooding of beach was detected by 2D ERI in coastal aquifer of Selangor, Malaysia (Ohwohere-Asuma, and Oghenevovwero, 2017; Atakpo, 2013; Baharuddi et al., 2009).

The summarized that saltwater intrusion into coastal aquifers is generally caused by two mechanisms which are Lateral encroachment from the ocean due to excessive water withdrawals from coastal aquifers, or upward movement from deeper saline zones due to upcoming near coastal discharge or pumping wells (Krupavathi and Movva, 2016).

The who was able to map-out the saltwater/freshwater zones in the eastern shore of Virginia; while confirmed the depth to the freshwater/saline water sands interface in southeast Nigeria, to vary from 77m to 947m. carried out a study on saltwater intrusion and contamination of fresh water aquifer at Lekki Peninsula, Lagos Nigeria highlights the works of (Nowroozi A.A, 1999; Oteri, 1988; Adepelumi et al., 2008; Amos-Uhegbu et al., 2013; Amos-Uhegbu et al. 2013).

There also highlighted the findings of where electric resistivity method was used to estimate aquifer geoelectric properties, groundwater quality and likely contamination in parts of Rivers state (Amos-Uhegbu et al., 2013; Ehirim and Nwankwo 2010; Nwankwo and Emujakporue, 2012). The further cited a study carried out by where Vertical Electrical Sounding (VES) technique served as a useful tool in the investigation of groundwater resources (Amos-Uhegbu et al., 2013; Nwankwoala, and Omunguye, 2013).

There an also collaborates with eth findings of in which Saltwater bearing aquifers were found occurring at depth of 30-90m area of Bonny Island in the eastern Niger Delta region from VES and geochemistry studies (Ohwohere-Asuma and Oghenevovwero, 2017; Amadi et al., 2012). The utilization of electrical resistivity estimations has been a useful instrument of geophysicists due to the wide scope of resistivity values obtained when applied and has been used to address a wide range geophysical problem than most other normally utilized techniques (Aizebeokhai, 2010). Resistivity usually varies enormous from one material or medium to another; because of these variations in identifying a material, measuring the resistivity of an unknown material is very useful as it gives little further information.

These electrical methods have been utilized to tackle issues identified in relation to environmental and health problems, particularly those relating to subsurface contamination of aquifers in an area (Sorensen et al., 2005; Atakpo and Ayolabi, 2009; Vaudelet et al., 2011; Ayolabiet al., 2013). Vulnerability of groundwater aquifer is defined as the susceptibility of a given aquifer to pollution (Younger, 2007; Ayolabi et al., 2013). The study of electrical resistivity in geophysics is viewed in the context of current being flowed through a subsurface medium consisting of layers of materials with different resistivity individually, as all layers are assumed to be horizontal (Herman, 2001). The resistivity (ρ) of a material is the measure of how a material restrains the flow of electrical current through it.

Several authors have identified aquifer vulnerability as a result of anthropogenic influences on groundwater resources, particularly from the surface, and thus, without a plan of action for proper understanding of the subsurface materials (soil, minerals and water) issues of geogenic contamination will not be observed or managed (Ayolabi et al., 2013). These issues are quite peculiar when observed in coastal regions, especially when related to saline intrusion caused by over abstraction from adjoining inland groundwater aquifers (Ayolabi et al., 2013).

3. DESCRIPTION OF THE STUDY AREA

The locations that make up the area of study are all within River State, Nigeria. The state is located in the southernmost part of Nigeria with rich tropical rainforest and mangrove vegetation in its riverine areas. The study area is located within coordinates: 4°45'N to 6°50'E (Figure 1). It is bordered on the Southern part by the t, to the East by Akwa Ibom State, and to the West by Bayelsa and Delta states, and to the North by Imo, Abia and Anambra States. The most southern section of Rivers State is referred to as Riverine, due to the presence of several rivers and creeks. It is a state made up of many indigenous ethnic groups: such as Ogoni, Abua, Ekpeye, Ikwerre, Ibani, Opobo, Eleme, s, and Kalabari, Etche, Ogba, Engenni, Egbema, Obolo and others (Wikipedia, 2019). The selected study areas all lies within the Niger delta region along the coastal line with the regular features of the Deltaic formation which comprises of sand, gravel and the inter-fingering of clayey-shale which is dominant in Benin formation. The respective geographical locations were all within Rivers State, covering eleven different sounding areas which are Ogonokom, Ikuru, Abonnema, Okujagwu, Abalama, Idoh, Assarama, Oyebi Ando, Eagle Island Okirika and Opobo and four geophysical logging areas (Bille, Bonny, Onne, and Admin block of NLNG headquarter Port Harcourt).

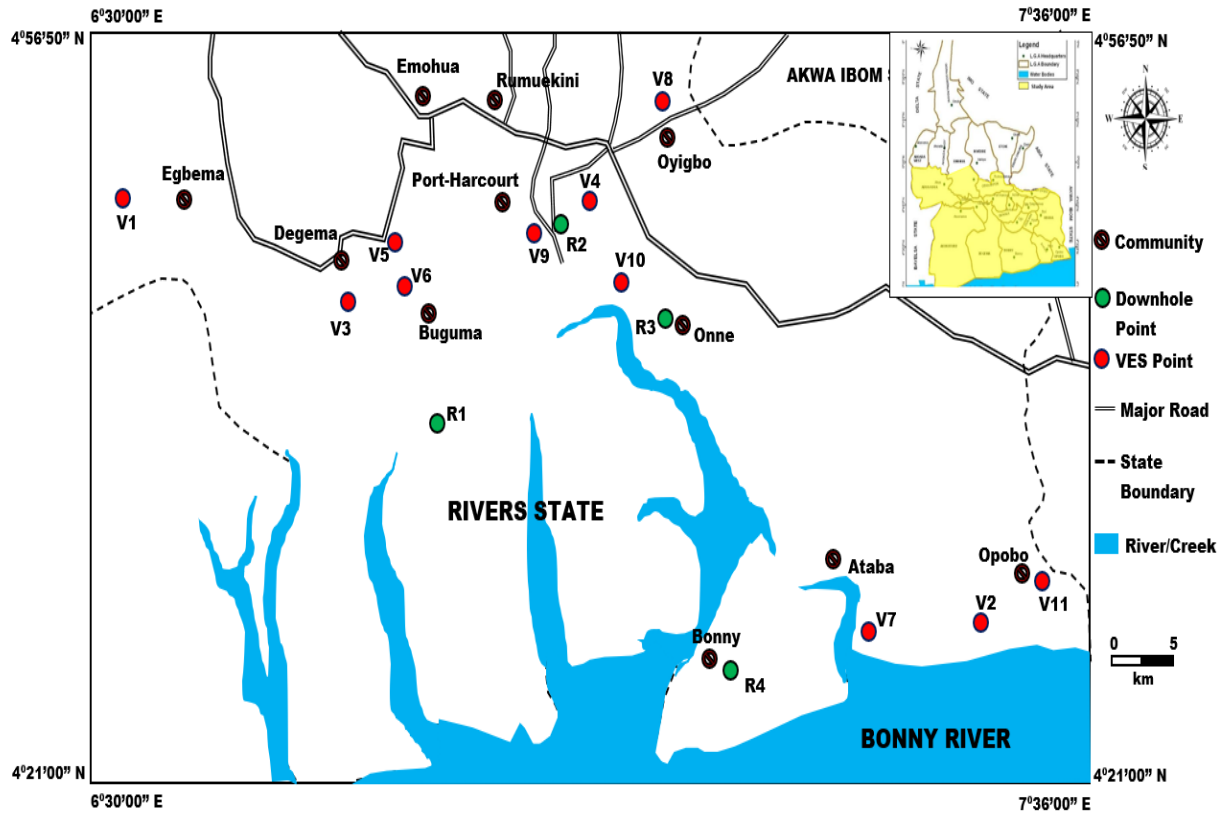


Figure 1: Map of study area showing VES sounding points along with downhole logging points

3.1 Geology and Hydrogeology of The Area

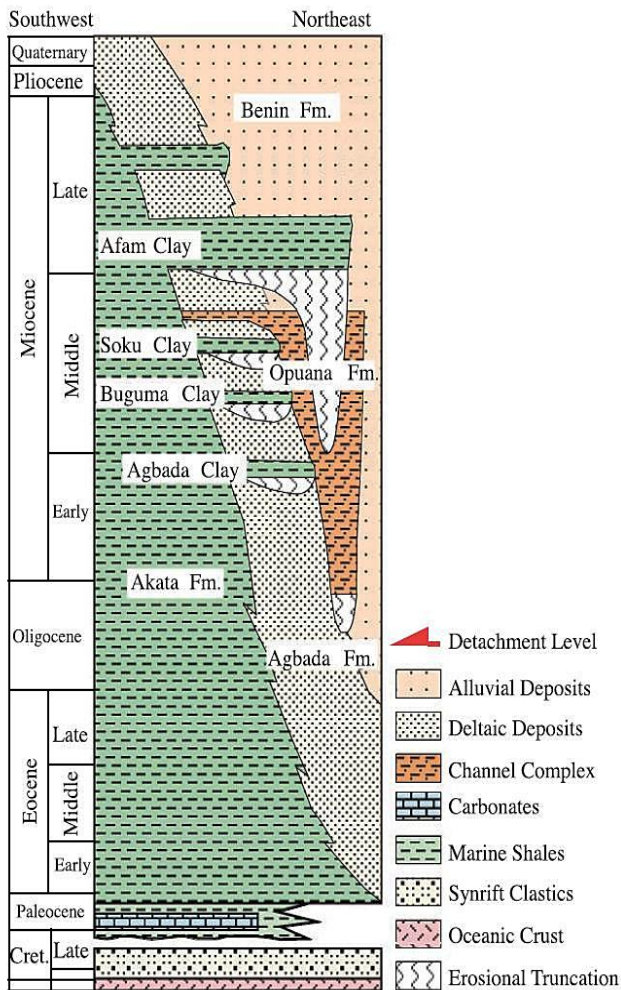


Figure 2: Regional Stratigraphy of the Niger Delta. (Odumodu et al., 2016)

Rivers State lies on the modern coastal plain of the eastern Niger Delta. The Niger Delta is the biggest basin in Africa and third in the whole world (Figure 2) covering about 70,000km² in geographical area. It composes of 12% of the whole surface area in Nigeria. The Niger delta basin is situated in the Gulf of Guinea which is located in the Central West Africa, at the crest of Benue Trough. The boundaries of the Niger Delta basin are defined as; The Anambra basin and Abakaliki in the north, the Gulf of Guinea to the south, the Cameroun volcanic line to the east and the Dahomey Embayment to the west. The evolution of the present-day Niger Delta consists of marshy landforms overlapped by countless creeks and waterways with their banks and inland mass composed of sediment accumulation involved with the tributaries of River Niger.

The Niger Delta is stratigraphically made up of three depositional units which are; The Benin formation, The Agbada formation and The Akata Formation (Figure 2). The basal Akata Formation and most part of the overlain Agbada formation serve as the main source rock for oil and gas exploration activities in the Niger Delta region. The Akata formation dates from Late Eocene to recent times and is made up of even dark grey well-pressured marine shales with sandy turbidities and channel pack (Short and Stauble, 1967). The thickness of the Akata formation ranges from 2000 m (6600 ft.) at the end part of the delta to 7000 m (23,000 ft.) below the continental shelf and about 5000m (16,400 ft.) for the deep fold and thrust belts in the offshore Niger Delta (Corredor et. al, 2005; Short and Stauble, 1967; Whiteman, 1982). The Akata formation is followed unevenly by the Agbada formation which consists of alternate Layers of Sand Stone and Shale. The Agbada formation is the major petroleum-bearing strata in the Niger Delta and is made up of variation of sand and shale layers.

The distribution of ground and surface water bodies in the study area is consistent of an aquatic environment with several freshwater aquifers and high presence of saltwater intrusion in coastal borders and occurrence of ferruginous sands caused by high oxidation rate in shallow aquifers which extremely affects the hydrogeochemical balance of the area (Amos-Uhegbu, et. al., 2013). The major aquifers in the area are formed by sand while the aquitards are formed by clay/shale. The water table is quite shallow and with season which ranges from 0.7m to 1.5m during the rainy and dry seasons (Amos-Uhegbu, et al., 2013). The Benin Formation composed mainly of sedimentary sands having clay and silt deposits and is the dominant source rock for fresh water in the area. Generally, according to the Niger Delta is characterized by intercalations of clay and sand deposits which makeup an elaborate system of viable aquifers (Etu-Efeotor and Odigi, 1983; Amajor 1989; Amos-Uhegbu et al., 2013).

4. DATA ACQUISITION

Two approaches were considered and utilized in the investigation of saline water intrusion in coastal areas of Rivers State. They include; Vertical Electrical Sounding (VES) resistivity survey and downhole geophysical survey which measured both Spontaneous Potential (SP) and Resistivity (Long Normal Resistivity and Short Normal Resistivity). The following equipment were utilized for a successful completion of the field exercise; Abem Tetrameter SAS 300B, Tetrameter SAS Log 200B, Probes, Metal Electrodes, Reels of Cables, Boosters, Measuring Tapes, Logging Cable, Multi-Function Cable, Garmin Global Positioning System, 12 volts Battery, Cutlass and Data recording sheets.

4.1 Vertical Electrical Sounding (VES) Resistivity Survey

The most commonly used geophysical method in groundwater exploration as well as for demarcation of saline water-fresh water areas is DC resistivity sounding. The method of Vertical Electrical Sounding (VES) (The Schlumberger field array configuration) is the direct current resistivity sounding method employed in the study of intrusion of saline water in the study area because it provides a means of determining the changes in subsurface electrical properties with depth. Saline water is highly conductive and will therefore show a remarkable decrease in apparent resistivity when compared with the less conductive fresh water bearing layers. The presence of salt in water (sodium and chloride) increases the ionic state of water, and since ions are the media by which electrical current travels, higher salt concentrations significantly increases the conductivity of water. In this study, electrical sounding was conducted along eleven (11) traverses within Rivers State. Communities where sounding stations were located include; Ogonokom, Ikuru, AbonnemaOkujagwu, Abalama, Ido, Assarama, Oyebe Ando, Eagle Island, Okirika and Opobo. Each sounding point was selected based on accessibility, space and proximity to Bonny River.

The current electrodes are A and B, while the potential electrodes are M and N. The four electrodes were symmetrically arranged in a straight line, *i.e.*, the external current electrodes (A and B) and the potential electrodes (M and N), which are also the internal electrodes positioned between the current electrodes. All four electrodes were pinned into the ground vertically to make firm contact. The Tetrameter was powered by a 12 volts battery, the number of averaging cycles was set at 4 cycles, and the current sent into the ground was set at 50mA. As measurements commenced and

proceeded, the spacing of the electrodes extends over the midpoint of the array while retaining an equal spacing between each electrode. Penetration depth increased with increased current electrode spacing. When the distance ratio between the current electrodes and the potential electrodes becomes too significant, the potential electrodes were shifted outward, otherwise the potential difference becomes too small to be calculated with sufficient precision. The resistance values obtained in the field were multiplied by their respective geometric factor (k) that gave the apparent resistivity results required (Hassan et al., 2017). The survey was carried out with total current electrode spread of 500 m ($AB/2 = 250m$) and total potential electrode spacing of 60m ($MN/2 = 30m$). The Garmin Global Positioning System was used in locating the longitudes, latitudes and elevations at each electrical sounding station (Table 1).

4.2 Downhole Geophysical Survey

Resistivity and SP logs were run in four (4) drilled and uncased boreholes within Rivers State (Table 1). The resistivity and SP logs were run in combination. The fundamental reason for these geophysical methods to be combined is that both saline water sand and clay layers will display the same resistivity order, but the SP effect for clays would be greater than saline water sands. Before commencing the logging procedure, all cables, current electrodes and reference potential electrode were connected properly to the Tetrameter SAS Log 200B which was also connected to the Abem Tetrameter using a multi-function cable. The return current electrode was placed >75 m away from the well to be logged while the reference potential electrode was placed > 50 m away from the well to be logged on the other end in a straight line. Both return current electrode and the reference potential electrode were all connected to the appropriate terminals on the Backpacking frame. The Backpacking frame and the upper end of the logging cable were all connected to the Tetrameter SAS Log 200B. The Tetrameter SAS Log 200B was subsequently connected to the Abem Tetrameter where all measurements were recorded. The Garmin Global Positioning System was used in locating the longitudes, latitudes and elevation of each logged station (Table 1). These steps were repeated across 4 sampling stations. The SP anomaly will be negative for saline water sand, while the SP anomaly will be positive for fresh water sand. This is referred to as the reversal of SP, *i.e.*, Changes in SP anomaly indication signs by (Roy, 2014). One gets positive SP sustained by relatively greater fresh water sand resistivity and negative SP supported by low saline water sand resistivity in joint SP and resistivity logging as conducted in this research.

Table 1: Sampling Stations and Geographic References for Each Station in The Study Area

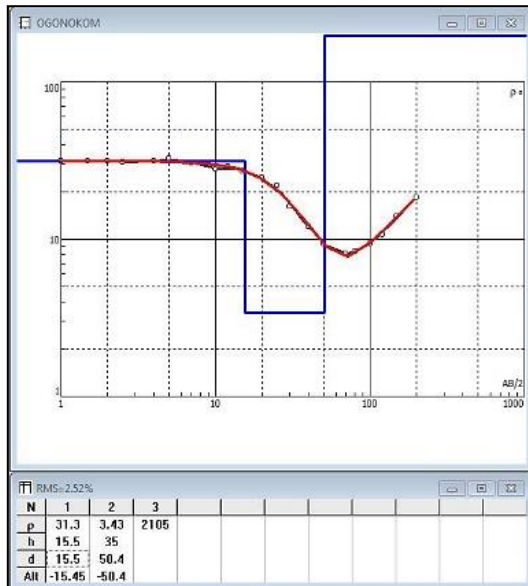
Location	ID	Survey Type	Northing	Easting	Elevation (Ft)
			(m)	(m)	(ft.)
Ogonokom	V1	VES	533336.15	226862.62	65.00
Ikuru	V2	VES	494061.51	330881.98	19.00
Abonnema	V3	VES	522051.80	253509.16	14.00
Okujagwu	V4	VES	532103.54	283701.95	3.00
Abalama	V5	VES	527655.30	259709.32	11.00
Ido	V6	VES	524448.94	261187.27	5.00
Assarama	V7	VES	492519.84	317057.28	19.00
Oyebe Ando	V8	VES	540313.34	292009.38	66.00
Eagle Island	V9	VES	528958.15	276246.85	10.00
Okirika	V10	VES	524867.15	287306.10	0.50
Opobo	V11	VES	499016.42	338144.51	0.50
Bille	R1	Downhole logging	508062.56	262056.89	23.00
NLNG	R2	Downhole logging	530107.96	280425.27	35.00
Onne	R3	Downhole logging	522475.23	294980.37	37.00
Bonny	R4	Downhole logging	488160.00	299130.65	33.00

5. RESULTS AND DISCUSSION

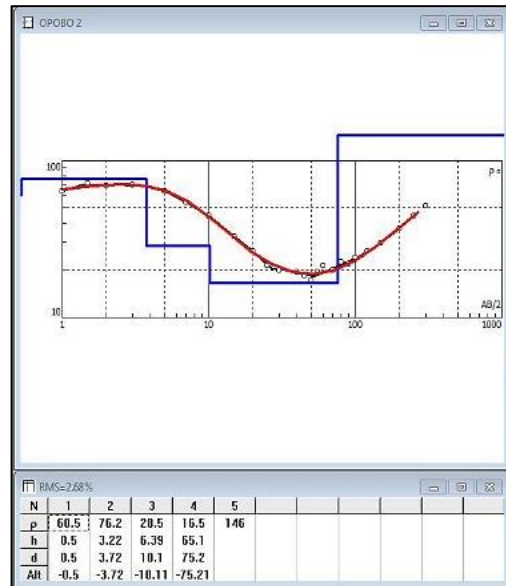
The field resistivity curves generated from processing the acquired resistivity sounding data are presented below and summarized in Table 2. Geoelectric layers identified ranged from 3 to 6 layers across the entire surveyed area. Resistivity values for the various geoelectric layers ranged from 0.11 to 364,058 ohm.m. Resistivity field curve types identified includes for the various geoelectric layers H, QQ, AA, KHA, QH, HKH, QQHK, A, HK, KHK and KQH for Ogonokom, Ikuru, Abonnema, Okujagwu, Abalama, Ido, Assarama, Oyebe Ando, Eagle Island, Okirika and Opobo community. The probed depth and thickness of all lithologic layers are presented in Table 2. The results show that the probed depth across the entire survey area ranged from 23.20m at Eagle Island to 272.00m at Ido

community. Similarly, thickness of the various layers ranged from 0.50m in Ido, Opobo and Abonnema community to 269.00m in Ido community.

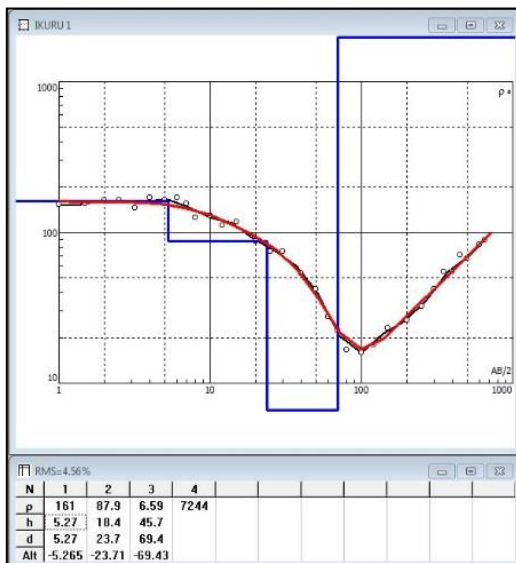
The geoelectric cross-section showing the composition of the various lithologic layers, their respective thicknesses along with fresh and saline water profiles are presented in (Figure 4). (Figure 5-9) are iso-resistivity maps showing variations in apparent resistivity measurements across Layer 1, Layer 2, Layer 3, Layer 4 and Layer 5 respectively. Similarly, (figure 10-13) are isopach maps developed for Layer 1, Layer 2, Layer 3 and Layer 4 respectively. (Figure 14) shows the cross-sectional profile of boreholes that encountered saline water along with their depth of occurrence in the surveyed area.



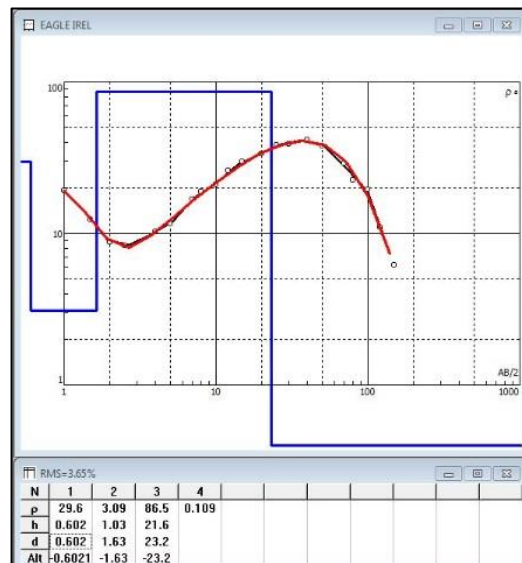
Vertical electrical sounding curve for Ogonokom.



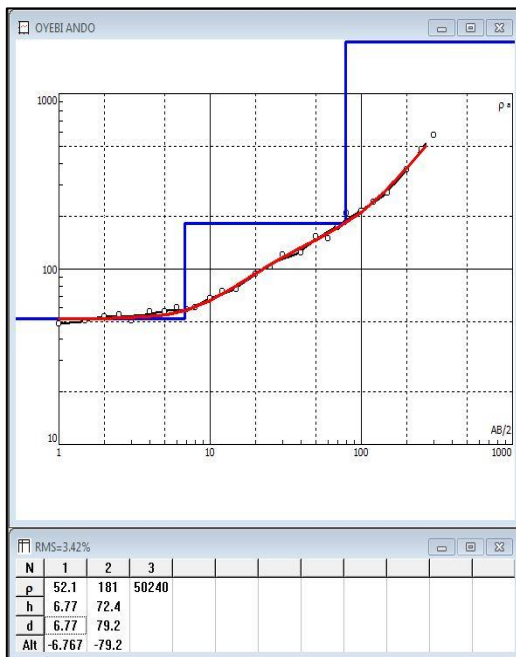
Vertical electrical sounding curve for Opobo



Vertical electrical sounding curve for Ikuru.



Vertical electrical sounding curve for Eagle Island



Vertical electrical sounding curve for Oyebi Ando.



Vertical electrical sounding curve for Okirika

Figure 3: Computer Modelled of Vertical Electrical Sounding Curves

Table 2: True Resistivity and Type Curve for The Various Layers Identified in The Study Area

VES ID	Location	Northing (m)	Easting (m)	Elevation (Ft) (ft.)	L ₁	L ₂	L ₃	L ₄	L ₅	L ₆	Error (%)	Type Curve	L1	L2	L3	L4	L1	L2	L3	L4	L5	
V1	Ogonokom	533336.15	226862.62	65.00	31.30	3.43	2105.00				2.52	H	15.50	50.40			15.50	35.00				
V2	Ikuru	494061.51	330881.98	19.00	161.00	87.90	6.59	7244.00			4.56	QH	5.27	23.70	69.40		5.27	18.40	45.70			
V3	Abonnema	522051.80	253509.16	14.00	4255.00	19215.00	364058.00	1505.00			4.47	AK	0.50	2.45	6.92		0.50	1.95	4.47			
V4	Okujagwu	532103.54	283701.95	3.00	54.20	113.00	48.10	128.00	25158.00		4.89	KHA	0.67	11.60	19.80	161.00	0.67	10.90	8.28	141.00		
V5	Abalama	527655.30	259709.32	11.00	463.00	151.00	39.40	38320.00			8.8	QH	3.85	29.40	59.30		3.85	25.60	29.90			
V6	Ido	524448.94	261187.27	5.00	21459.00	133.00	293.00	142.00	2871.00		4.94	HAH	0.50	1.23	3.02	272.00	0.50	0.73	1.79	269.00		
V7	Assarama	492519.84	317057.28	19.00	1184.00	393.00	94.50	3.29	57.50	7.52	5.91	QHK	0.65	2.33	11.20	26.80	0.65	1.68	8.89	15.60	28.10	
V8	Oyebi Ando	540313.34	292009.38	66.00	52.10	181.00	50240.00				3.42	A	6.77	79.20			6.77	72.40				
V9	Eagle Island	528958.15	276246.85	10.00	29.60	3.09	86.50	0.11			3.65	HK	0.60	1.63	23.20		0.60	1.03	21.60			
V10	Okirika	524867.15	287306.10	0.50	55.30	263.00	10.90	66.50	0.21		5.75	KHK	0.51	3.93	32.20	84.70	0.51	3.43	28.20	52.50		
V11	Opobo	499016.42	338144.51	0.50	60.50	76.20	28.50	16.50	146.00		2.58	KQH	0.50	3.72	10.10	75.20	0.50	3.22	6.39	65.10		

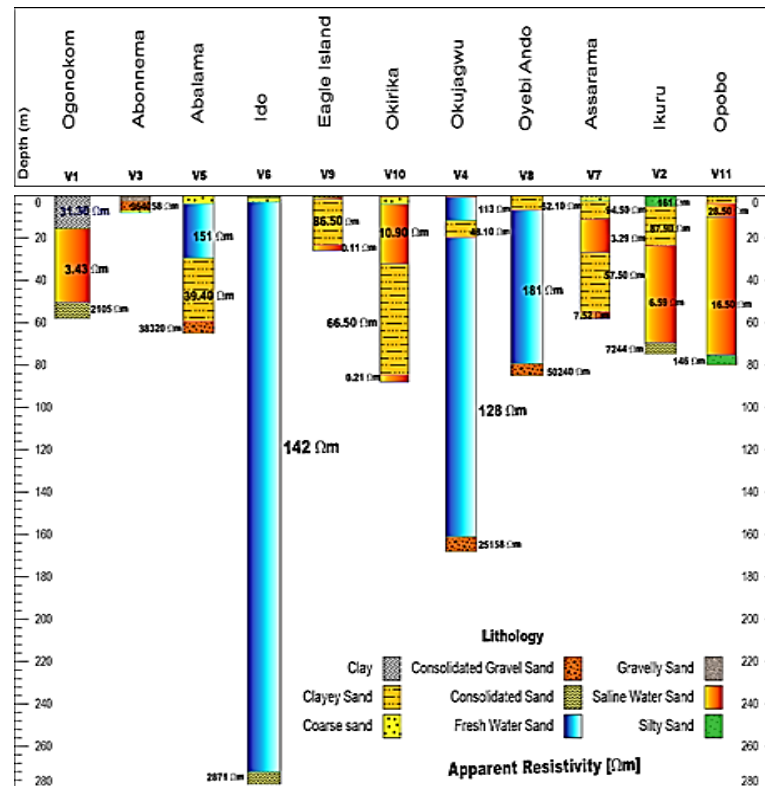


Figure 4: Geoelectric section showing apparent resistivity, depth, thickness and geology of the various layer

Iso-resistivity maps generated for five geoelectric layers revealed significant variations in resistivity across the area. Generally, resistivity values ranged from 29.60 to 21459 Ohm.m, 3.09 to 19215 Ohm.m, 6.59 to 364058 Ohm.m, 0.11 to 38320 Ohm.m and 0.21 to 25158 Ohm.m respectively across the first, second, third, fourth and fifth geoelectric layers. These results show that the soil layers in Rivers state are generally heterogeneous in nature. The iso-resistivity maps show higher resistivities around Ido community (V6) for layer 1 which is situated towards the west-central part of the area (Figure 5). Similarly, for layer 2 and layer 3, the highest resistivity is found around Abonema community (V3), which is also situated towards the west-central part of the area

(Figure 6 and 7). The fourth layer revealed a somewhat different resistivity distribution pattern, having the highest resistivity values around Abalama community (V5) situated towards the north-western part of the area (Figure 8). Meanwhile, the largest lithologic thicknesses are obtained in Ogonokom (V1) in the northwest, Oyebi Ando (V8) in the north-central, Ikuru (V2) in the southeast and Ido (V6) in the west-central for layer 1 (Figure 5), layer 2 (Figure 6), layer 3 (Figure 7) and layer 4 (Figure 8) respectively. This result shows that no relationship exists between layer thicknesses and apparent resistivity values of the lithologic units.

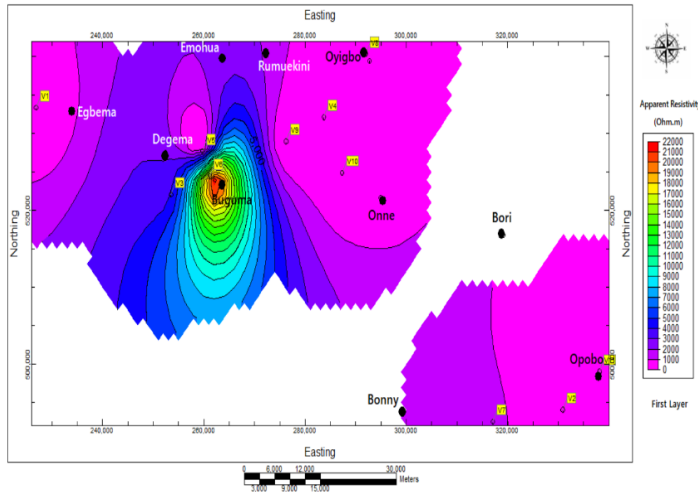


Figure 5: Iso-resistivity map showing variation in resistivity across Layer 1

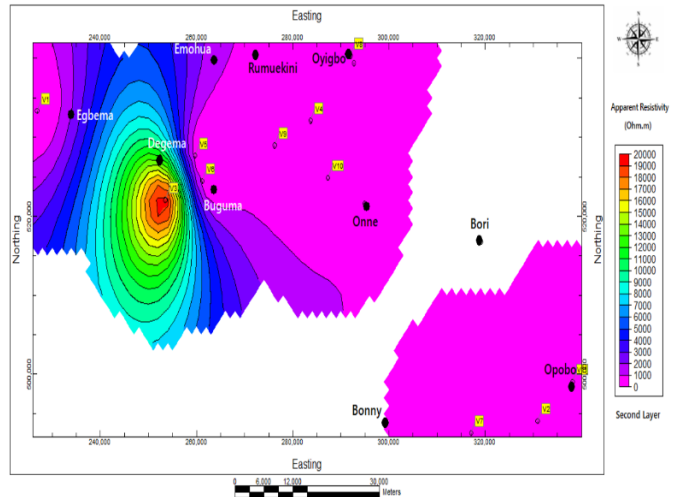


Figure 6: Iso-resistivity map showing variation in resistivity across Layer 2

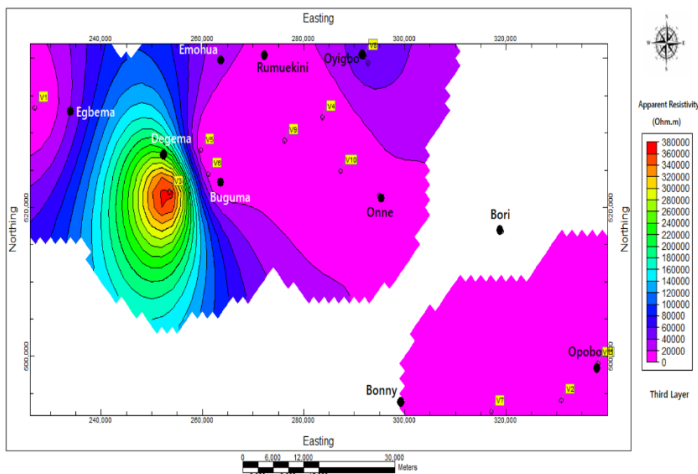


Figure 7: Iso-resistivity map showing variation in resistivity across Layer 3

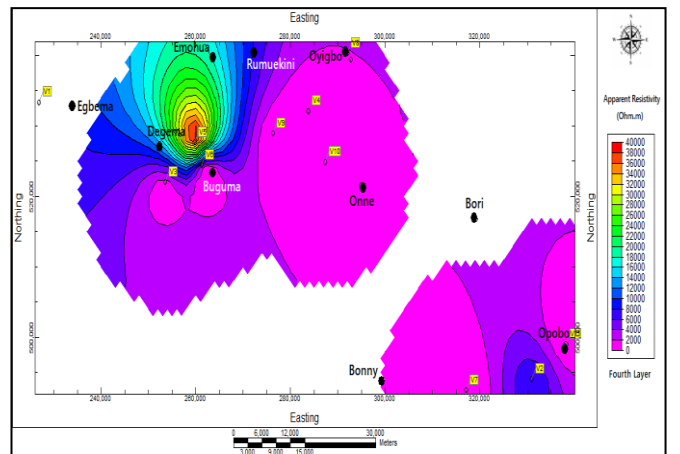


Figure 8: Iso-resistivity map showing variation in resistivity across Layer 4

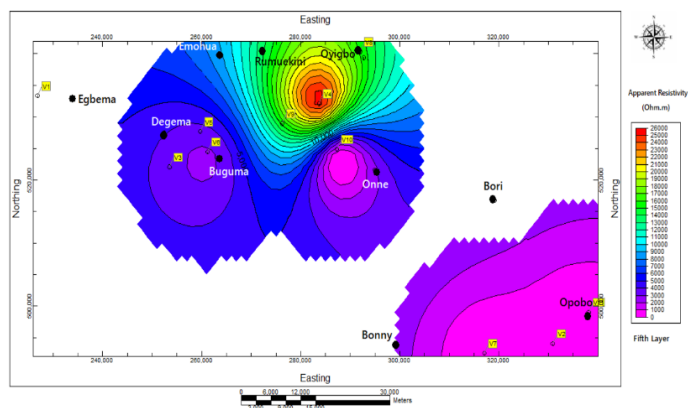


Figure 9: Iso-resistivity map showing variation in resistivity across Layer 5

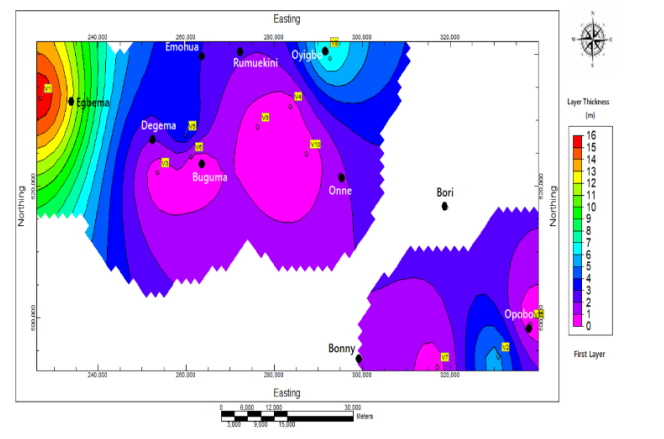


Figure 10: Isopach map showing thickness variation across Layer 1 in the study area

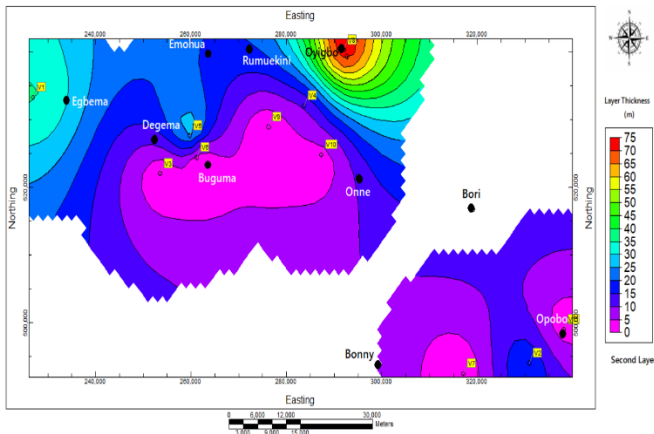


Figure 11: Isopach map showing thickness variation across Layer 2 in the study area

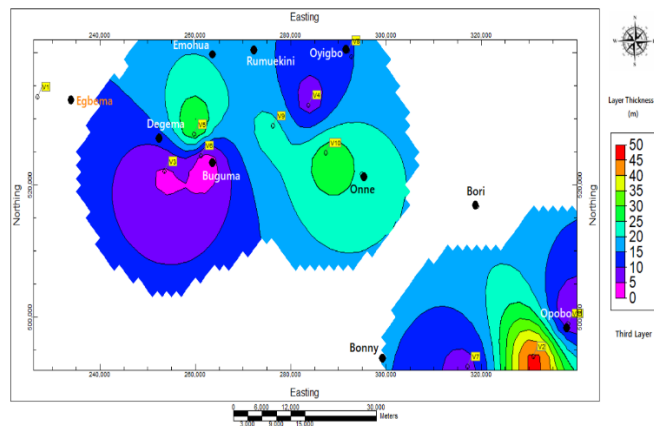


Figure 12: Isopach map showing thickness variation across Layer 3 in the study area

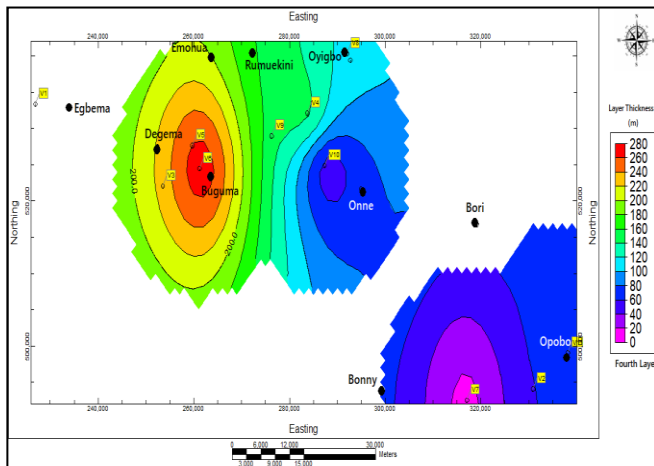


Figure 13: Isopach map showing thickness variation across Layer 4 in the study area.

Saline intrusions were identified on six (6) VES points at varying depths across the entire survey area (Figure 14). The VES points in which saline intrusions were encountered include; Ogonokom, Eagle Island, Okirika, Assarama, Ikuru and Opobo sounding points. Two saline zones were each encountered in VES points at Eagle Island, Okirika and Assarama. The saline water sands were all separated by clayey sands of varying thicknesses which ranged from 21.57 m at Eagle Island to 52.50 m at Okirika (Figure 14). Generally, apparent resistivity of the saline zones ranged from 0.11 in Eagle Island to 28.50 Ohm.m in Opobo, and the thickness of the saline zone ranged from 3.10 m in Assarama to 71.48 m in Opobo. Similar salinity results have been reported by in a study conducted in Opobo community using tomography of electrical resistivity (Eze et al., 2018). The presence of Opobo River and the close proximity of Opobo community to Bonny River (<2 km) accounts for the high saline intrusion in the area. Hence, any borehole drilled in Opobo at depths exceeding 5.0 m could likely be invaded by saline intrusion.

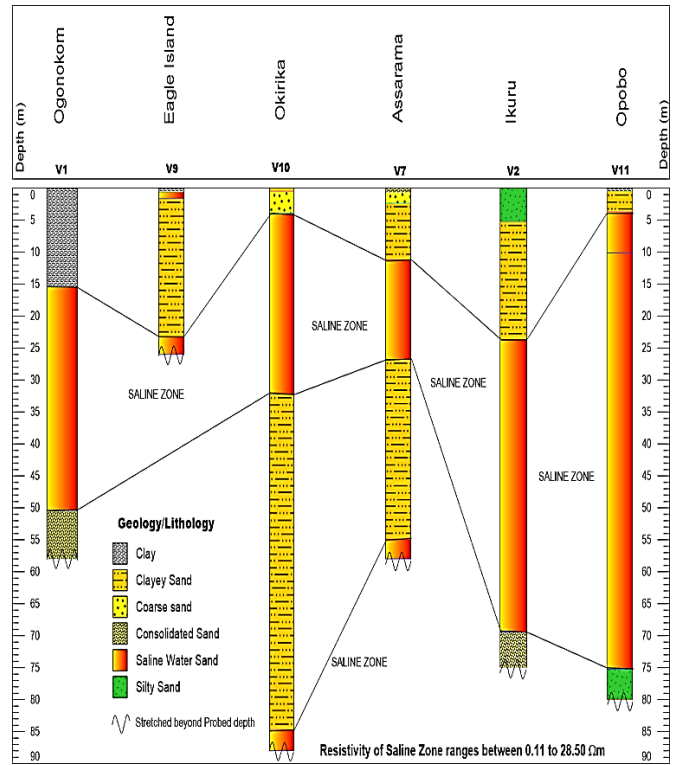


Figure 14: A cross sectional profile showing boreholes that encountered saline water along with their depth of occurrence.

The results obtained from self-potential (SP) and resistivity (short normal and long normal) logging from boreholes are presented in Appendix B and interpreted in (Figures 15-18) respectively. The logs revealed SP values ranging from -155 mV in Bille community (at depth of 9.5m) to 184 mV in Onne community (at depth of 35m). Generally, areas on the logs that revealed negative SP values which corresponded with very low resistivity values were indicative of brine, whereas, logged sections having very low resistivity values with positive SP values were identified as clay. This is because brine and clay are known to exhibit low resistivity values, but brine will also show negative SP values as opposed to positive values exhibited by clays. The results of short normal resistivity ranged from 0.01 ohm.m in Bille, Bonny, Onne and NLNG to 630 ohms.m in NLNG at a depth of 14.0m depth. Similarly, long normal resistivity ranged from 0.01 ohm.m in Bille, Bonny, Onne and NLNG to 640 ohms.m in NLNG at a depth of 14.0m depth. Generally, lithology identified from the combined use of resistivity logs and self-potential log included clay, clayey sand, coarse sand and saline water sand.

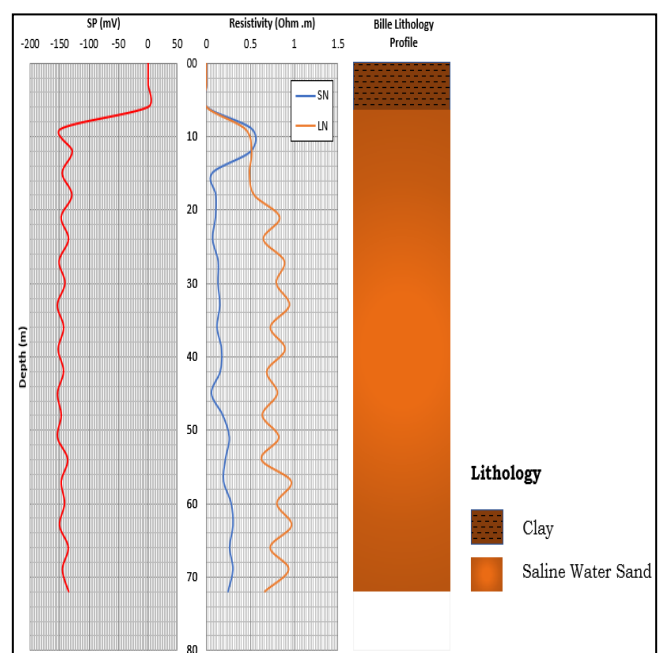


Figure 15: Lithologic profile generated using combined SP and resistivity logs for Bille

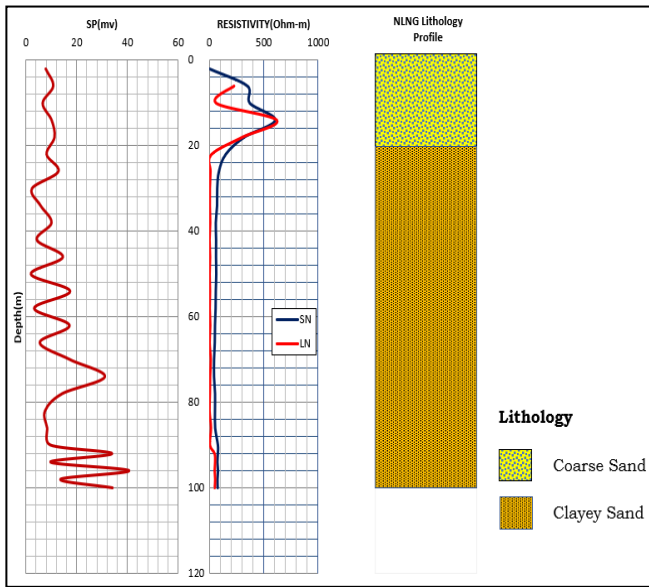


Figure 16: Lithologic profile generated using combined SP and resistivity logs for NLNG

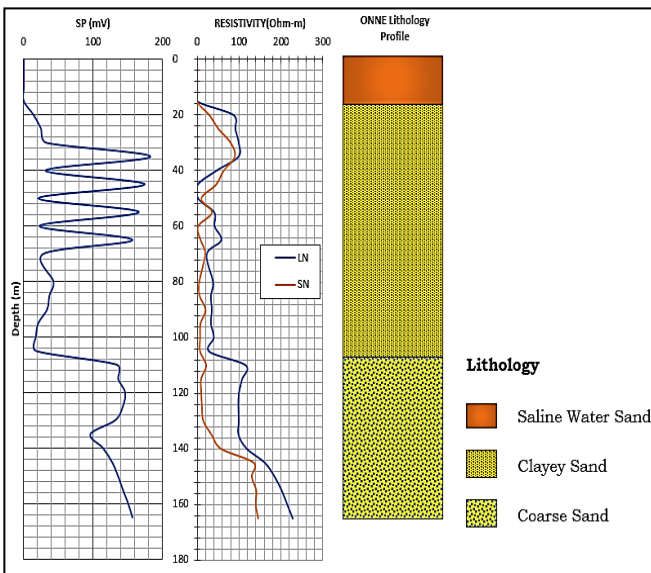


Figure 17: Lithologic profile generated using combined SP and resistivity logs for Onne

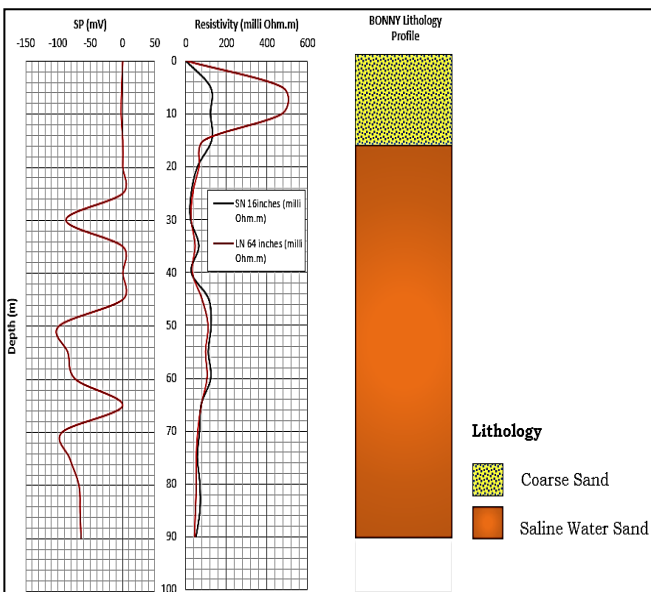


Figure 18: Lithologic profile generated using combined SP and resistivity logs for Bonny

The results of salt water- fresh water interface mapping from the combined use of VES and downhole geophysical logging are presented in (Figure 19-21) for 60m, 40m and 20m depth respectively. The maps show the encroachment of the salt water interface inland. Generally, the salt-water movement is from Bonny River in the south towards Buguma and Degema situated in the North of Bonny River.

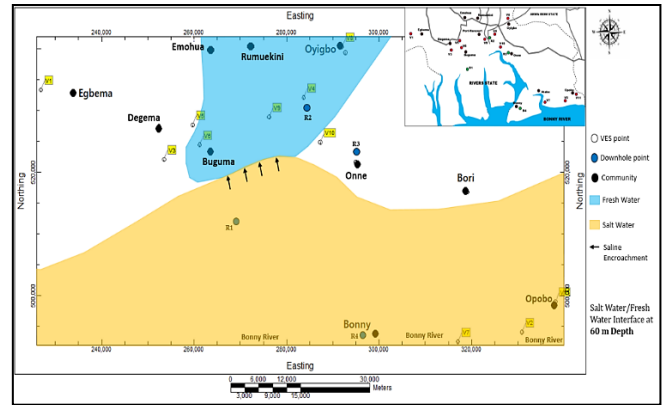


Figure 19: Salt water-fresh water interface inferred from combined VES and downhole geophysical investigation for the study area at 60m depth

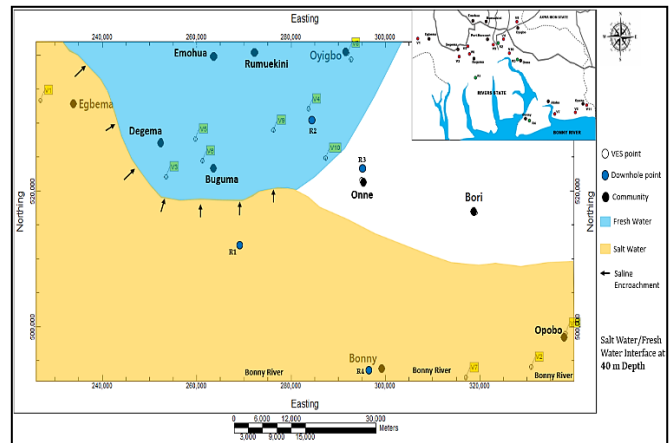


Figure 20: Salt water-fresh water interface inferred from combined VES and downhole geophysical investigation for the study area at 40m depth

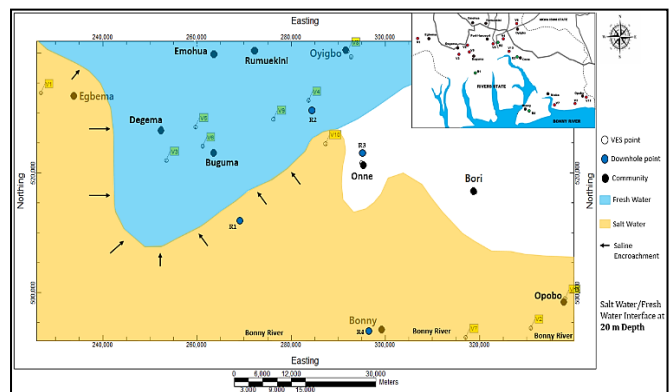


Figure 21: Salt water-fresh water interface inferred from combined VES and downhole geophysical investigation for the study area at 20m depth

The results of electrical sounding, downhole SP logs and downhole resistivity logs (short normal and long normal) were combined to develop a conceptual model for salt water encroachment in the area. The results presented on map views (Figure 19-21) revealed the migration of the saltwater-freshwater interface is towards the north. At 60.0m depth, saline water predominates in the southern part of the survey area around Bonny, Opobo and Bille communities. Freshwater is found around the north central part of the study area. The salt water/freshwater interface stretches just about 15 km and is centered around Buguma community (figure 19). At shallower depth (40.0m), the saline intrusion stretches further inland to include Ogonokom (V1) and Egbema communities situated at the north-western part of the study area (Figure 20). The saltwater/freshwater interface is more extensive at this depth, occupying

over 60 km. At 20 m depth (Figure 21), the saltwater/freshwater interface extends further northwards (70 km) to include Okirika community (V10). According to relationships, a 40-foot shift of the saltwater freshwater interface inland will occur from every foot of freshwater taken from an unconfined coastal aquifer above sea level (Gyben, 1889; Herzberg, 1901). Based on this relationship, boreholes centered around Buguma, Degema, Abonnema (V3) and NLNG (R2) are also susceptible to saline intrusion with continuous exploitation over time.

6. CONCLUSIONS AND RECOMMENDATIONS

Vertical Electrical sounding has been utilized to delineate saline water intrusion zone at varying depths ranging in thickness from 3.10 m to 71.48 m. Downhole SP and resistivity logs further identified saline layers ranging in thickness from 16 to 74 m. Combined downhole and VES conceptual model revealed a saltwater/freshwater stretch ranging from 15 km at 60m depth to >75 km at 20 m depth. The saltwater intrusion is predominantly concentrated around the southern part of the study area around Bonny and Opobo communities. The presence of Opobo River, Bonny River and a suite of creeks which are open to the Atlantic Ocean area responsible for the salt intrusion into these coastal boreholes.

The outcome of this study yielded the following recommendations;

- Boreholes in Bonny, Opobo and Bille communities that has encountered saline water should be prevented from further use until treatment for salt water intrusions are conducted.
- Water exploitation plan should be developed by the government and enforced to be utilized by residents in Buguma, Degema, Abonnema and NLNG to prevent saline intrusion because these communities are the most vulnerable to saline intrusion from over-exploitation of freshwater in the area.
- An alternative source of water supply can be provided by the state government (rain water harvesting, water-board, etc.) in order to reduce the dependence on groundwater from individually pumped boreholes in these coastal communities.
- Very deep industrial boreholes (>200m) are preferred in these coastal areas of Rivers State in order to gain access to confined aquifers where fresh water can be easily obtained, although this is may not always the case.

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