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Studies of Salt Water intrusion in Opobo/Nkoro Rivers State Using Geophysical and Hydrochemical Methods

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ABSTRACT

Salt water intrusions into fresh water aquifers in Opobo town in Nkoro L.G.A, Rivers state is becoming an issue of concern to the community, and as such requires detailed analysis through an integration of qualitative (geo-electric) and quantitative (hydrochemical) methods. Twenty vertical electrical soundings (VES) labelled as O/MSC/01 to O/MSC/20 and three 2D electrical resistivity tomography (ERT) data were acquired in the area. Results from interpretation of the twenty VES profiles showed 4 geo-electric layers, which are topsoil, sand, sandy clay and clay. In VES geo-electric sections, it was observed that salt intrusions occur at depths of 43.135m, 55.20m, 43.528m, 51.63m, and 28.357m along O/MSC/02, O/MSC/05, O/MSC/07, O/MSC/11 and O/MSC/15 profiles respectively. No salt intrusion was observed in O/MSC/01, O/MSC/04, O/MSC/09, O/MSC/10, O/MSC/12 and O/MSC/14 within the depth investigated. Results of 2D imaging along VES profiles 10, 11 and 12, show salt intrusions observed along the three profiles at different depths within the subsurface. Along profile O/MSC/10, saltwater intrusions (with resistivity range of 59.2Ωm-60.1Ωm) was observed at depth of 7.59-9.59m at lateral distance of 34.0-36.0m and depth of 5.59-7.59m at lateral distance of 94-96m. Along profile O/MSC/11 salt intrusions (with resistivity range of 58.8Ωm-59.2Ωm) was observed at depth of 2.59-5.59m at lateral distance of 28-40m, and 110-128m, while along profile O/MSC/12 salt intrusions (with resistivity range of 14.5-20Ωm) was observed at depth of 3.59-5.59m at lateral distance of 112-118m. These findings were not observed in VES surveys along similar profiles where 2D ERT was carried out. 3D map computed to connect aquifers within the third geo-electric layers for VES points 1-20, showed that within the third geo-electric layers for O/MSC/02, 05, 07, 11, 16, 17, and 20 lies saline water. The reliability of these results was validated by results from quantitative assessment of physiochemical parameters (P^H, electrical conductivity (EC), and total hardness) and hydrochemical contents (HCO_3^-, Na^+, K^+, CL^-, and $SO4^{2-}$) used to evaluate the ionic abundance of water samples taken from seven wells/boreholes in the area. P^H values of 6.40-6.90 were predominant in the samples which indicates slight acidity and unsuitable for human consumption, EC values in the order of 1705μS/cm, & 1853.74μS/cm were obtained and total dissolved Solids (TDS) was in the order of 700.30mg/l & 750.02mg/l. Elevated EC values in water is indicative of high ionic abundance, and is diagnostic to salinity of the water as reflected in the 1D and 2D geo-electric surveys. However, the study area also contains fresh water aquifers lying within the third geo-electric layers for VES profiles O/MSC/01, 03, 06, 08, 09, 10, 12, and 18, hence a water supply tube well can be drilled in these areas for groundwater production but the water should be subjected to hydrochemical test to ascertain its level of contamination and prior treatments before human consumption.

Keywords: Saltwater Intrusion, Groundwater, Vertical electrical sounding (VES), Electrical resistivity tomography (ERT), Geo-electric section.

1. Introduction

Saltwater intrusion is the movement of saline water into freshwater aquifers, which leads to contamination of drinking water sources and other consequences. Saltwater intrusion occurs naturally to some degree in most coastal aquifers, owing to the hydraulic connection between groundwater and seawater (Paul 2006). Groundwater is the main source of drinking water in many coastal areas of the world, and its extraction which has increased over time is the primary cause of saltwater intrusion. Land and Lautier (2004), opined that most aquifers contain salt because they receive recharge from nearby marine bodies. The source of the recharge is transmitted through the sediments that are in contact with them, hence acting as conduit for the passage of salty sea water into the aquifer. These has become a major concern (Blattaeharya and Patra, 1968), because it constitutes the most common pollutants to fresh water aquifers. In coastal areas, fresh groundwater flowing from land towards the sea comes in contact with salt and sea water. A transition zone is developed between the fresh and salty groundwater due to mixing. The position of this transition zone depends on local circumstances such as distribution of hydraulic properties, climate and human interference in the form of land reclamation. This situation has been described by authors such as (Paul 2003, Bairds 1995, and Oteri 1988).

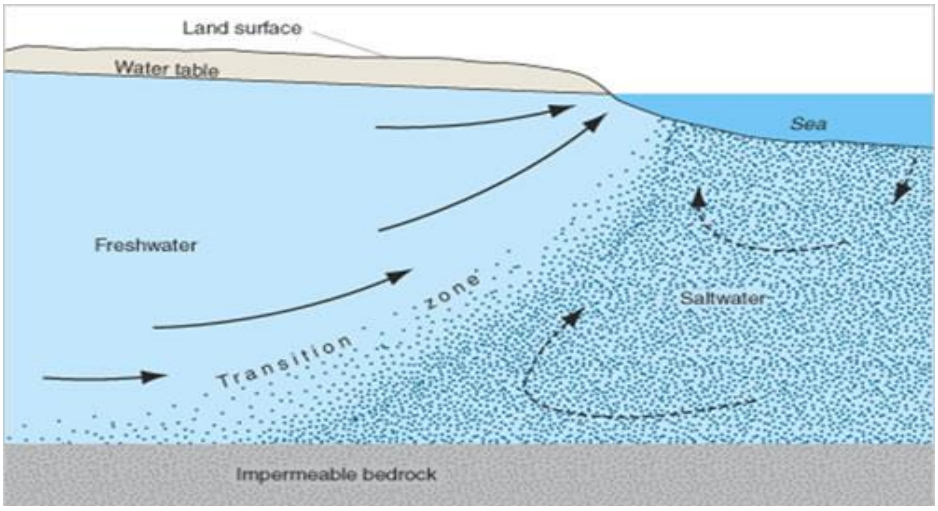


Figure 1: Showing fresh and salt water transition zone. Modified from Cooper (2006).

The ionic abundance of the aquifer is raised by intrusion of salt water into it, and this increases the concentration of metal ions in the water. High level concentration of chloride ions (Cl^-), sodium ion (Na^+), and other heavy metal ions such as Ca^{2+}, Mg^{2+}, Pb^{2+} in fresh water, can make the water unfit for human consumption and for many industrial uses. High concentrations of sodium and lead ions in water can contribute to certain heart disease or high blood pressure, particularly in susceptible individuals (World health organization, 2001).

The lack of portable water supply needed to serve the thousands of people living within the Opobo community, is becoming critical as the population of the community is increasing on a daily basis, and Salt water contamination is seriously affecting water quality, soil and vegetation in the area. To address this problem requires an integration of geophysical methods with widely employed hydrochemical analysis of water samples from borehole wells in the area. While the latter is a quantitative method, the former is rather qualitative and displays subsurface conditions of salt intrusions in the area. The geophysical method used involved both 1D and 2D electrical resistivity surveys. Various researchers have carried out geophysical survey to demonstrate the interface between fresh water and saline water. Oteri (1988) confirmed the depth to the freshwater/saline water sands interface in southeast Nigeria, to vary from 77m to 947m; Adepelumi *et al.*, (2008) delineated salt water intrusion into the fresh water aquifer of Lekki Peninsula, Lagos Nigeria; Nwankwoala (2011), opined that salt water intrusion occurs in both confined and unconfined aquifers resulting in abandonment of salt water borehole which hampers the development of potable water, Oteri (1988), opined that the salt contamination is due to the high rate of infiltration and coning of the saline water layer at the salt-fresh water interface also Aigbogun et al (2010) made use of primary sourced surface electrical resistivity data to attempt the delineation of salt water intrusion into the freshwater aquifer in the southwest region.

The method used by the above authors were strictly geo-electric surveys. 1D electrical method using Vertical Electrical Sounding (VES) has been employed over the years to characterize aquifers in different geologic environments and to map fractures in basement areas (Koefoed, 1979, McDowell, 1979, Ayolabi et al, 2003), however this result is limited to resistivity change in the vertical direction (1D), without taking into consideration the horizontal changes in subsurface resistivity; this is the greatest limitation of the resistivity sounding method (Dahlin 1996., Loke 2001). With advancement in technology, the resistivity method have shifted to a more accurate method of imaging the subsurface which is called Electrical resistivity tomography (ERT) (Loke and Barker, 1996 a, b). Early development of ERT in geophysics was confined to imaging rock core samples in the laboratory (Daily et al., 1987), but prototype data-collection hardware and research-grade inverse codes suitable for field scale applications soon followed (Ramirez et al., 1996). The method has been developed to detect leaks from large storage tanks (Ramirez et al., 1996), and mapping movement of contaminant plumes (Daily et al., 1987). More recently, ERT has been used for locating shallow cavities, fractures, fissures and mapping groundwater flow (Auken et al., 2006), identification of geological structures (Al-sayed and El-Qady 2007), engineering and environmental surveys (Olorunfemi et al., 2004, Ayolabi et al., 2009). The use of 2-D electrical resistivity imaging to address a wide variety of hydrological, environmental and geo-technical problems is increasingly becoming very popular (Loke 2001).

This paper aims to showcase the effectiveness of integrating non-invasive geophysical method involving 1D and 2D surveys with hydrochemical analysis of water samples to study the salt water intrusion occurrence in Opobo/Nkoro local government Rivers State.

2. Climate and Geology of the Study Area

The study area, Opobo and its environs is located in Rivers State, part of the Niger Delta between lat 4°30′41″N and long 7°32′24″E. It is located in the equatorial rain forest vegetation belt Southeast Nigeria. The mean annual temperature of the area is 25^0C and mean annual rainfall range of about 1800 to 2500mm (Meteorological Report of Portharcourt between 1999-2015).

Two climatic seasons are observed in the region namely,

- The Rainy season and
- The Dry season.

The dry season is a period of no rainfall, with temperature of about 8 to 30∘C. This season is accompanied by a laden air mass from the Sahara Desert known as Harmattan. The rainy season is influenced by another type of wind known as South-West air mass which blows cooled air from the Atlantic Ocean thereby causing rain to fall. The area has been severely affected by the current global climatic changes in such a way that there have been shifts in both the upper and lower boundaries of these climatic conditions (Illoeje, 1972). Geologically, the Opobo region, is part of the Niger Delta basin and consists of three litho-stratigraphic units, namely: The Akata Formation (Paleocene in age), which is overlain by the Agbada Formation (Eocene in age), and is overlain by the Benin Formation (Miocene to recent). These stratigraphic units are based on the works of Reyment (1965), Short and Stauble (1967); Murat (1970) and Merki et al., (1975). The study area (Opobo) lies on the coastal plain of the Niger Delta sedimentary basin and it is located in the Tertiary to Quaternary coastal plain sands (otherwise called the Benin Formation) and alluvial environments of the Niger Delta region of Southern Nigeria (George et al., 2014). The Benin formation is overlain by thin laterites overburden with varying thicknesses at some locations. The major aquiferous units in the area lies within the sands of the upper deltaic top lithofacies. The Benin formation comprises of poorly-sorted continental (fine, medium, and coarse) sands and gravels which alternate with streaks of lignite, thin clay lenses and horizons at some locations. These thin clay/shale horizons build up into multiples of aquifers in the area when they truncate and confine the vertical and lateral extents of the sandy aquifers. Thus both confined and partially confined aquifers are found in the area (George et al., 2014). The Opobo River and its adjoining tributaries flow towards the southwards direction and empty its water and loads directly into the Atlantic Ocean in the Bight of Bonny.

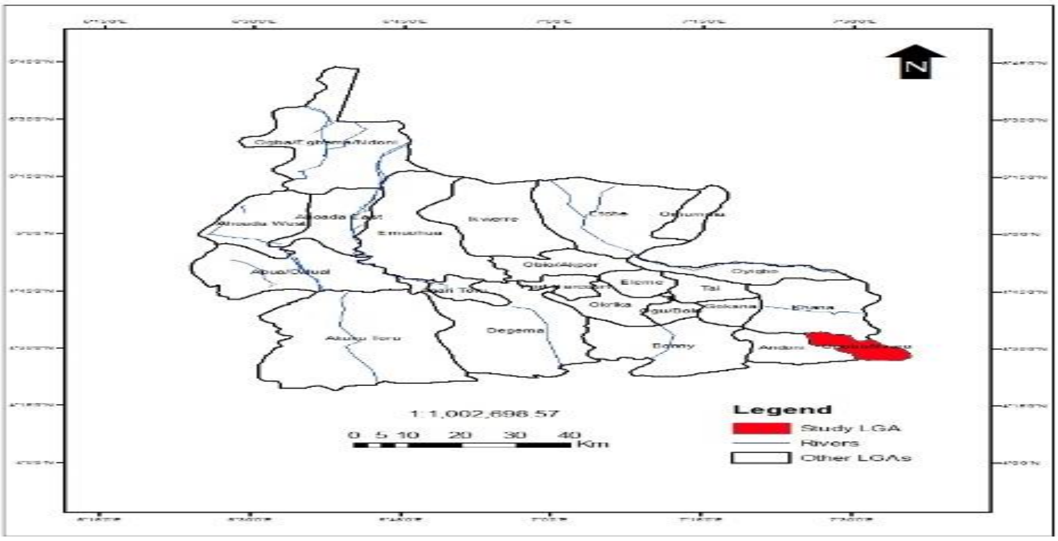


Figure 2: Map of Rivers State showing study location (in red).

3. Materials and methods

3.1. Geophysical Method

The electrical resistivity method and hydrochemical analysis of water samples from seven boreholes in the area were used for the investigation of possible contamination of groundwater by salt intrusions. Twenty vertical electrical soundings (VES) were occupied using the Schlumberger technique and labelled as O/MSC/01 to O/MSC/20 and three electrical resistivity tomography (ERT) profiles were also taken in the area along VES profiles 10, 11, and 12 using the dipole-dipole technique. The VES profiles O/MSC/02, O/MSC/06, O/MSC/07, O/MSC/10, and O/MSC/12 are located at the precincts of the areas while others are within neighboring towns to enhance a vivid coverage of the entire land mass.

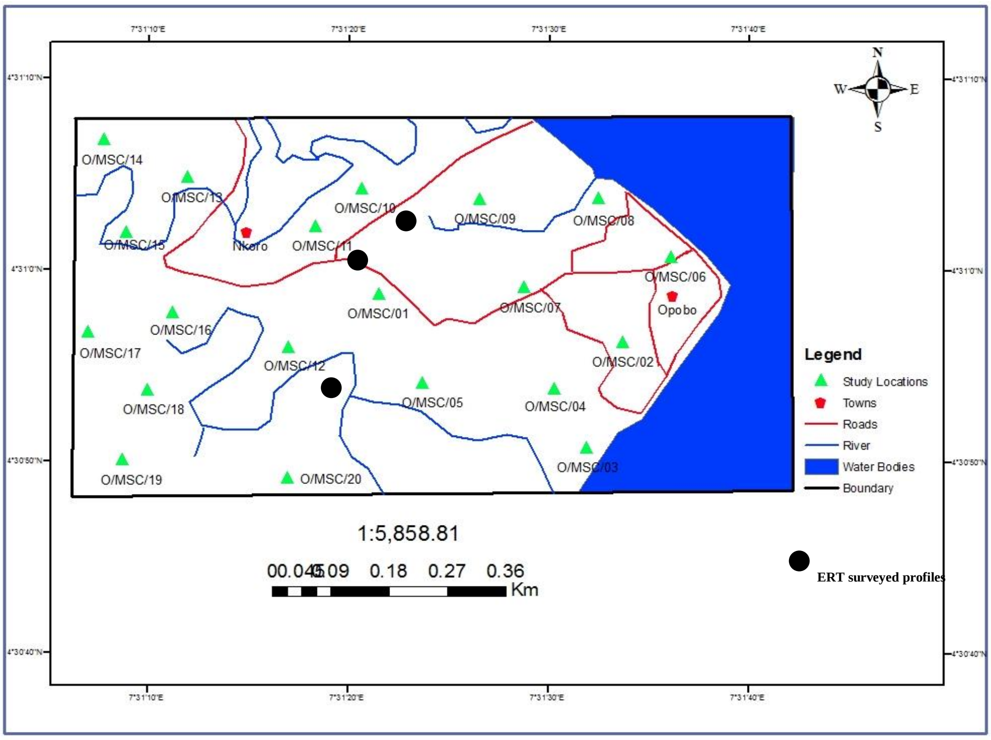


Figure 3: Base map of data acquisition of the Study area showing the surveyed locations for VES and ERT.

The VES data was acquired with a maximum electrode spacing (AB/2) of 250m while the apparent resistivity data from tomography (2D Imaging) was acquired with electrodes spaced at a=10m with n = 1, to n=5 to give a total profile length range of 140m. In each case ground resistivity data acquisition were made using an OMEGA Terrameter and the co-ordinates of each sampled location was taken using a GPS (global positioning satellite). 1D resistivity data was inverted using the Interpex 1-D sounding inversion program while 2D resistivity data was inverted using Res 2-D inversion program. The subsurface is divided into small rectangular blocks with position and size fixed by forward modelling. The resistivity of the block is then determined so that the calculated apparent resistivity values agree with the measured values from the field survey by adjusting the resistivity of the model blocks and consequently iterate to reduce the difference between the calculated and measured (field) apparent resistivity (Loke et al., 2003). These differences are expressed in form of RMS error. Moderate RMS errors were obtained from the survey as electrode coupling had to be improved by using water to aid conductivity. Beside resistivity inversion of 1D and 2D ERT data, cross-profile geoelectric sections for the resistivity surveys were produced using Strata-4 software application.

3.2. Hydrochemical and Hydrophysical analyses Methods

Water samples obtained from seven wells/boreholes in the study area were analyzed for hydrophysical and hydrochemical contents to reveal the ionic abundance, and anomalous distribution of the chemical elements and ions within the water samples. Physical properties such as Electrical conductivity (EC), total hardness, total dissolved solids (TDS), P^H and ionic abundance of Sodium (Na^+), potassium (K^+), Chloride (CL^-), and Carbonates (CO_3^{2-}) contents were determined locally in the Cross Rivers state water board quality control laboratory and results compared with threshold values using WHO standard.

4. Results, interpretation and discussion

4.1 Vertical electrical sounding (VES) results

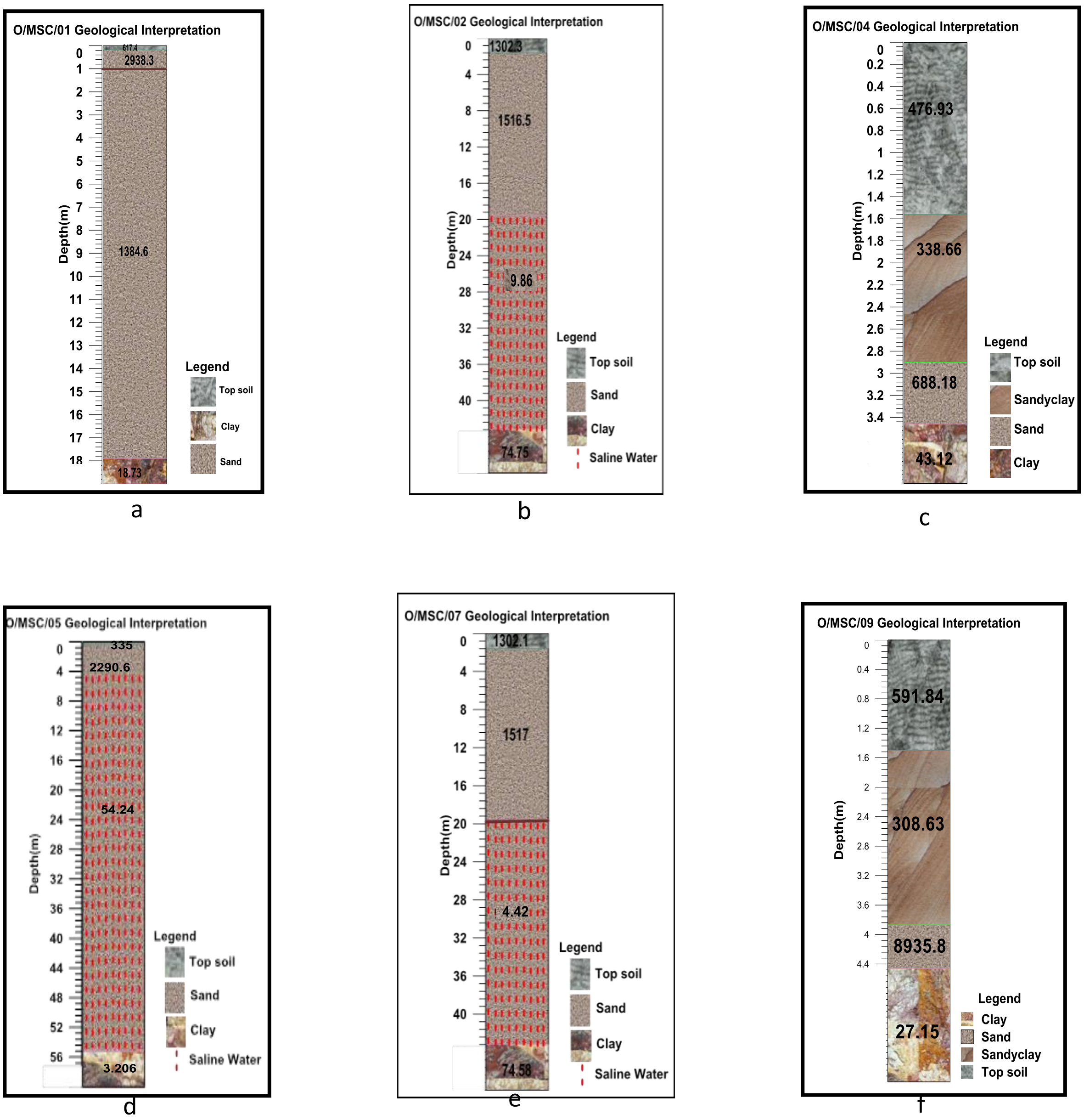
After interpretation of VES data to generate the layer parameters, the result showed 3 – 4 geo-electric layers which are: top soil made up of laterites, clay, sand, and sandy clay with sand acting as the aquifer unit. From the layer parameters, the sand layers intruded with salt water have a characteristic low resistivity which is diagnostic to presence of ions (contained in salt water) which have raised the conductivity of the water, and as such its resistivity is low, in the absence of clay minerals within the sediments. See table 1 below for the summary of the results.

Table 1: Summary of VES Results in the Study Area.

VES	Layer Apparent resistivity (Ωm)				Layer thickness(m)			
POINTS	**ρ1**	**P2**	**P3**	**P4**	h1	h2	h3	h4
O/MSC/01	617.44	29383.0	1384.6	18.730	0.77554	0.23120	16.894	-
O/MSC/02	1302.3	1516.	9.869 (Salt intruded sand)	74.753	1.5963	17.961	23.577	-
O/MSC/03	97.925	14065.	51229.0	27.969	0.53565	0.2706	0.97721	-
O/MSC/04	476.93	338.66	68818.0	43.120	1.5575	1.3402	0.56205	-
O/MSC/05	335.0	2290.6	54.235 (Salt intruded sand)	3.2059	0.28517	8.1978	46.71	-
O/MSC/06	637.67	7727.9	7125.7	30.200	1.3017	1.7984	7.9995	-
O/MSC/07	1302.1	1517.0	4.422 (Salt intruded sand)	74.583	1.5969	17.942	23.989	-
O/MSC/08	1400.1	10502	3438.6	59.281	2.7752	0.9313	10.944	-
O/MSC/09	591.84	308.63	89358	27.152	1.4945	2.1894	0.7723	-
O/MSC/10	676.90	520.29	24129	67.472	2.0358	1.7594	1.1397	-
O/MSC/11	388.58	1658.9	2.637 (Salt intrusion)	57.34	2.7880	11.062	37.78	-
O/MSC/12	473.48	1256.5	21473.0	56.684	3.0709	0.74197	0.9862	-
O/MSC/13	167.41	15309	1066.2	34.118	1.1494	0.30935	22.806	-
O/MSC/14	493.15	266.99	21951	44.572	2.0715	0.67035	1.6066	-
O/MSC/15	218.80	3032.7	36.388 (Salt intruded sand)	40.431	2.3361	8.2365	17.785	-
O/MSC/16	27.200	1854.5	1.3708 (Salt intruded sand)	255.97	0.2119	10.562	16.699	-
O/MSC/17	95.703	8571.3	379.29	124.66	0.26787	4.0470	19.011	-
O/MSC/18	81.039	96.169	47174	0.3587(Salt intruded sand)	0.678	0.960	4.994	-
O/MSC/19	21.769	46.944	1202.0	8.9638	0.3607	0.7810	11.961	-
O/MSC/20	74.408	11301.0	3.2338	344.98	0.20845	0.39336	14.126	-

4.1.1 Geo-electric sections for VES (1D) results

Geo-electric sections were computed using Strata-4 software to show the various lithologies and also indicate the salt intruded layers with respect to depth. The geologic sections and interpretations were computed for ten VES points which were further modelled using inversion to reveal the subsurface lithology and to aid geologic interpretation. See figures 4 (a-j) below.



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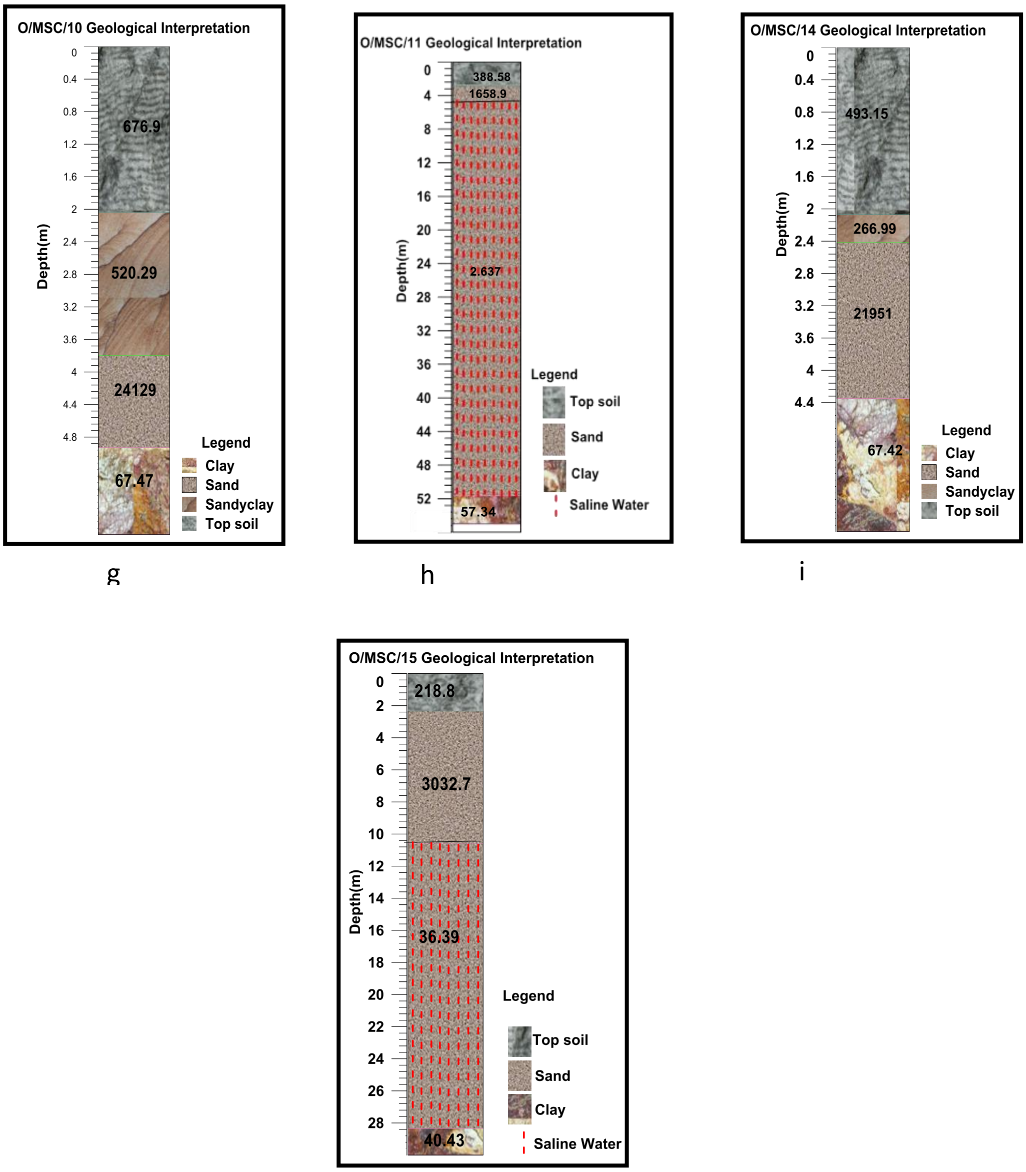

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Figure 4: VES (1D) geo-electric section for (a) VES 1 (b) VES 2 (c) VES 4 (d) VES 5 (e) VES 7 (f) VES 9 (g) VES 10 (h) VES 11 (i) VES 14 (j) VES 15. The figures show salt intrusions occurring within the third layers in VES 2, VES 5, VES 7, VES 11 and VES 15. The vertical thickness of saltwater intruded sand aquifers in the area were delineated from VES survey. However, the lateral extent of intrusions could not be delineated from VES survey.

4.2 Electrical resistivity tomography (ERT) results

To further delineate the salt intruded sand units in the area, 2D resistivity imaging (tomography) was carried out, which gives a better lateral view of the subsurface layers than geoelectric section from 1D models because of its ability to give a continuous record of subsurface image both vertically and horizontally. The program, Res2dinv was used in processing of the 2D data acquired in the area. The section of the subsurface that was imaged is about 2.5 -13.6m. When Correlated with the regional lithology shows that a surface sand layer is being captured. The low resistivity anomalies in the ERT (electrical resistivity tomography) images could be visualized as the saltwater intruded portion if clay is absence in the delineated sand layer. The data was filtered using Krigging algorithm, which is a geo-statistical tool that provides estimated values from some sampled points using variogram model (Clark and Harper, 2000; Loke, 2004). The inversion result and the constructed geologic sections (showing the background sand sediment and saltwater intruded zones) are presented in figures 5a, 5b and 5c below.

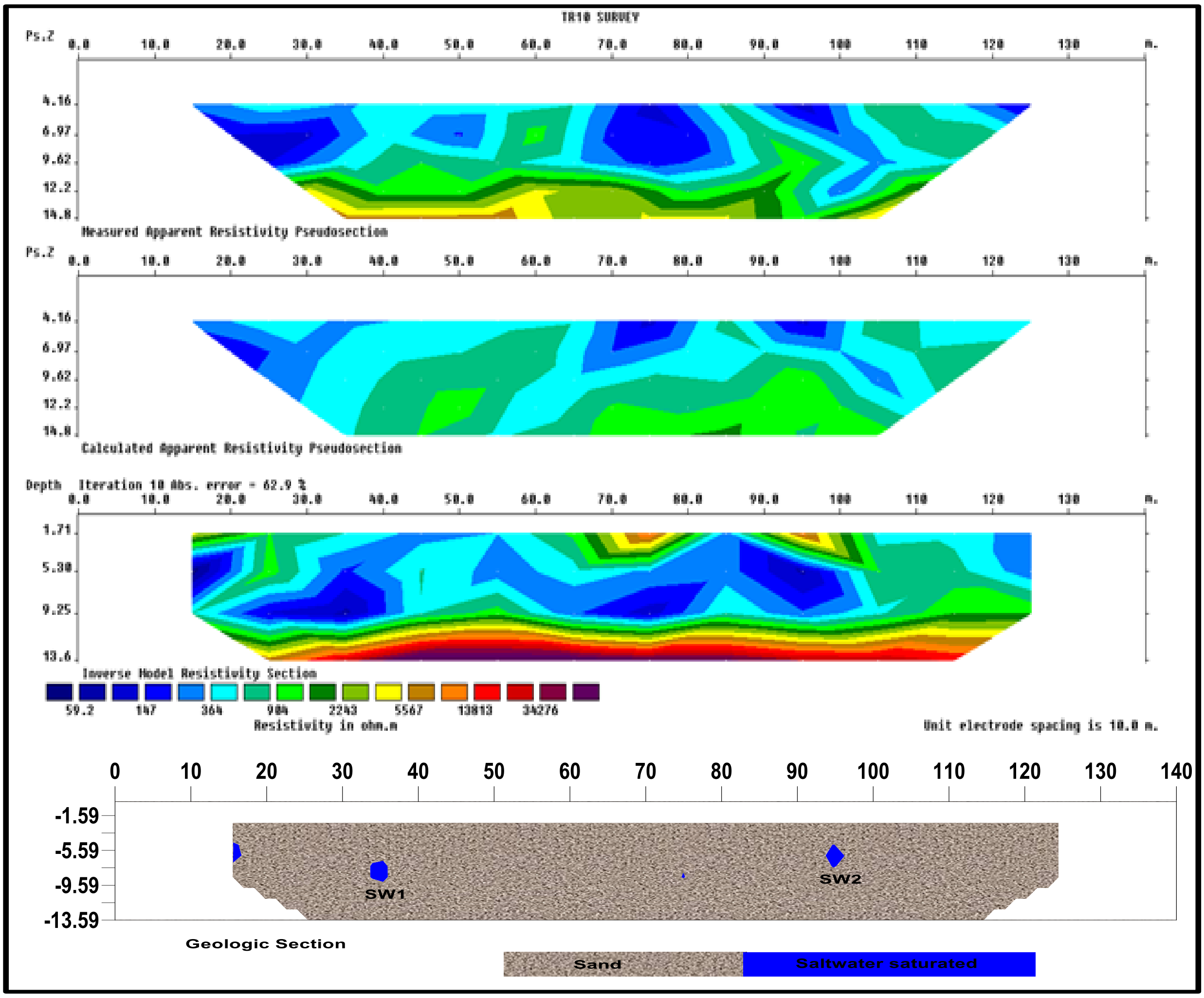

Figure 5 (a):2D model section for profiling along VES profile O/MSC/10, Opobo Rivers State Southern Nig. The anomalies, SW1 and SW2 (59.2- 93.2Ωm) most likely indicate portion of the sand layer intruded with saltwater in the absence of clay in the sediment. SW1 is located between 7.59m and 9.59m of the subsurface and laterally between 34.0 and 36.0m marks; SW2 anomaly (59.2- 93.2Ωm) is located between 5.59m and 7.59m of the subsurface and laterally between 94.0 and 96.0m marks.

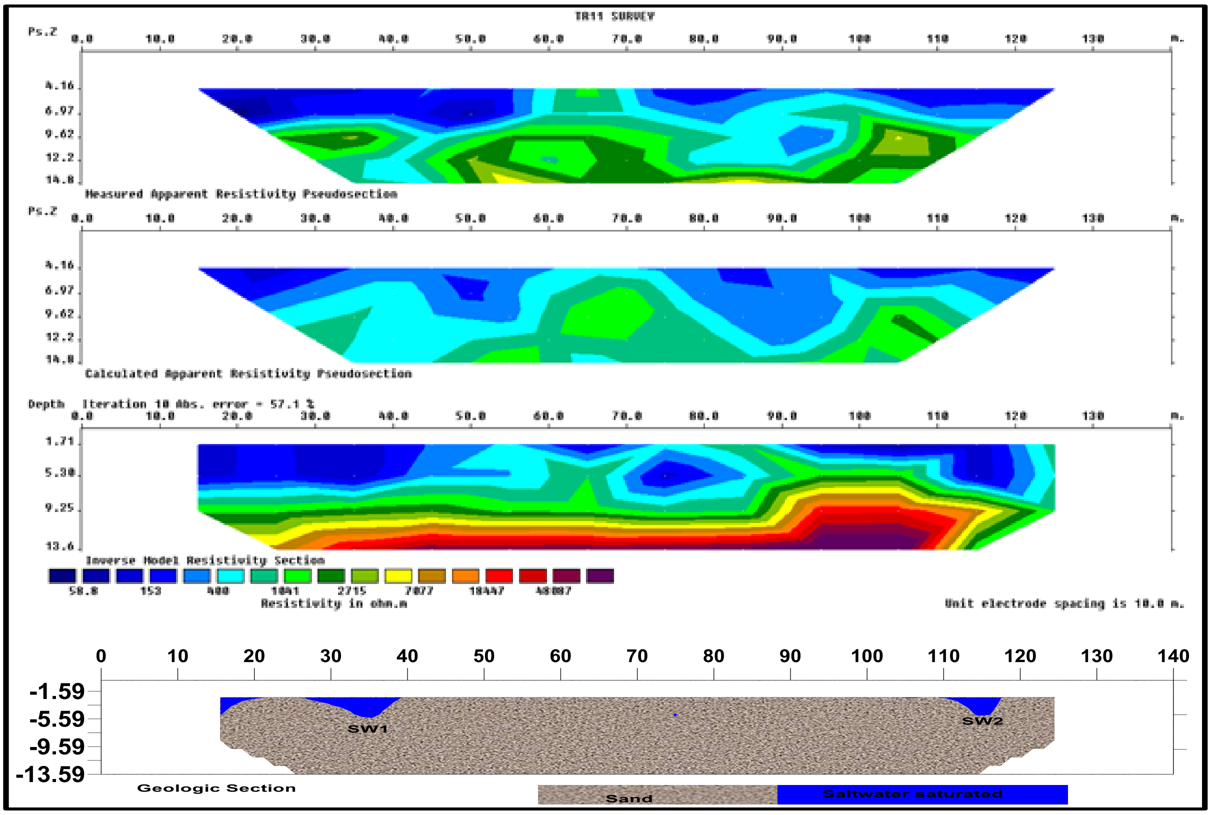

Figure 5(b): 2D model section for profiling along VES profile O/MSC/11, Opobo Rivers State Southern Nig. The low resistivity anomalies, SW1 and SW2 (59.2- 93.2Ωm) is indicative of sand layer intruded with saltwater in the absence of clay in the sediment. SW1 (58.9-94.9Ohm-m) extended from a depth smaller than the data collection start depth (2.59m) to a depth of 5.59m and laterally between 28 and 40m marks; anomaly, SW2 (58.9-94.8Ohm-m) extended from a depth smaller than the data collection start depth (2.59m) to a depth of 5.59m and laterally between 110.0m and 128.0m marks.

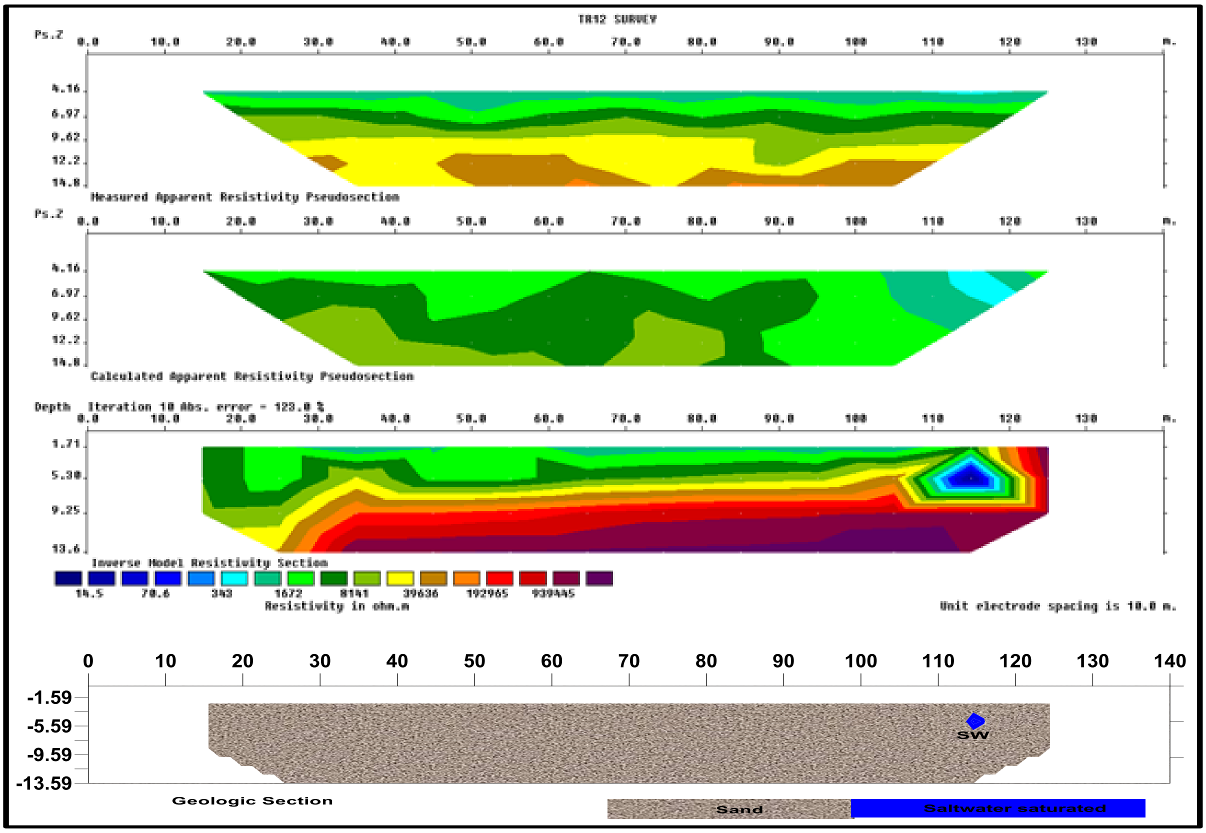

Figure 5 (C): 2D model section for VES profile O/MSC/12, Opobo Rivers State Southern Nigeria. The low resistivity anomaly, SW (14.5-70.6 Ohm-m) is located between the depths of 3.59m and 5.59m of the sand layer and laterally between 112.0 and 118.0 marks. This resistivity anomaly is indicative of saltwater intrusion in to the sand layer in the absence of clay in the sediment.

4.3 Comparison between VES (1D) and ERT (2D) results

Results from interpretation of the twenty VES points showed 4 geo-electric layers, which are topsoil, sand, sandy clay and clay. 1D geo-sections computed for ten VES profiles were compared with geo-sections from 2D imaging to delineate the vertical and lateral extents of the salt intruded aquifers in the area. VES geo-electric section shows salt intrusions occurring at depths of 43.135m, 55.20m, 43.528m, 51.63m, and 28.357m along O/MSC/02, O/MSC/05, O/MSC/07, O/MSC/11, and O/MSC/15 profiles respectively (**figures 4 b, d, e h and j**). No salt intrusion was observed in O/MSC/01, O/MSC/04, O/MSC/09, O/MSC/10, O/MSC/12 and O/MSC/14 within the depth investigated. However, results of 2D imaging along VES profiles 10, 11 and 12, show salt intrusions along the three profiles at different depths within the subsurface. Along profile O/MSC/10, saltwater intrusions (with resistivity range of 59.2Ωm-60.1Ωm) were observed at depths between 7.59-9.59m of the subsurface at lateral distance of 34.0-36.0m and between 5.59 – 7.59m of the subsurface at lateral distance of 94-96m (**figure 5a**), along profile 11 salt intrusions (with resistivity range of 58.8Ωm – 59.2Ωm) were observed at depth of 2.59-5.59m below the subsurface at lateral distance of 28-40m, and 110-128m (**figure 5b**) while along profile 12 salt intrusions (with resistivity range of 14.5-20Ωm) were observed at depth of 3.59-5.59m at lateral distance of 112-118m (figure 5c). These observations were however not delineated in the geo-electric sections computed for VES interpretation along similar profiles were ERT (imaging) was carried out. In VES 10 geo-section (figure 4g), no salt intrusion was observed within the depth investigated (4.93m), however ERT imaging along this profile, showed salt intrusion occurring between 5.59-9.59m (**figure 5a)** at different lateral distances, also along VES 11 (**figure 4h**), salt intrusion was observed within the sand layer from depth of 4.10-51.63m, but 2D imaging along this profile shows that there was salt intrusion at the top of the sand layer occurring between 2.59-5.59m at lateral distance of 28-40m, and 110-128m respectively (**figure 5b**) which was not evident in VES result along profile 11 **(figure 4h).** Also 2D ERT along profile 12 showed salt intrusion occurring between 3.59-5.59m of the sand layer at lateral distance of 112.0-118.0m, which was not observed in VES survey along profile 12 within the depth investigated (4.78m). These observations show the advantages of ERT technique over VES (1D) surveys in environmental studies related to saltwater intrusion and contamination plume as noted by (Ayolabi et al., 2003, 2009) in their works on resistivity studies.

Table 2: Comparism of results from VES and 2D ERT interpretations.

VES PROFILES INTERPRETED.	INFERENCE	ERT INTERPRETATION	COMPARISM / DISCUSSION OF BOTH RESULTS.
O/MSC/01	No salt water intrusion		
O/MSC/02	Saline intrusion at 43.135m		
O/MSC/05	Saline intrusion at 55.20m		
O/MSC/07	Saline intrusion at 43.528m		
O/MSC/09	No saline intrusion		
O/MSC/10	No saline intrusion is observed from its geologic section between 0 - 4.93m	ERT along profile 10	Saline intrusion is observed at depth between 7.59-9.59m lateral extents of 34.0-36.0m; and depth 5.59-7.59m at lateral extents of 94.0-96.0m. This was not seen in VES10 geo-section along this profile. This show the advantages of ERT over 1D sounding.
O/MSC/11	Saline intrusion was observed at 51.63m	ERT along profile 11	Saline intrusion is observed at depth between 2.59-5.59m at lateral extents of 28.0-40.0m; and 110.0-128.0m respectively. These were not seen in VES11 Geo section were intrusion is seen at 51.63m. This explains the need for correlation of VES (1D) with ERT (2D) results for intrusion studies.
O/MSC/12	There are signs of saline intrusion from the resistivity values interpreted along this profile, but the depth to which it occurred was not delineated.	ERT along profile 12	Saline intrusion is observed at depth between 3.59-5.59m at lateral extents of 112.0-118.0m. This again shows one of the advantages of ERT over ID sounding. No one would expect to see saline intrusion at this depth from the VES result, if not for the 2D result (ERT) that produces continuous vertical and lateral imaging along the profile. Thus geoelectric section from VES does not depict the subsurface layers as often imagined, only ERT with continuous imaging along a traverse is reliable.
O/MSC/14	No saline intrusion Observed		
O/MSC/15	Saline intrusion is observed at 28.357m, although 2D tomography was not carried out along this profile, for correlation, with the VES results.		

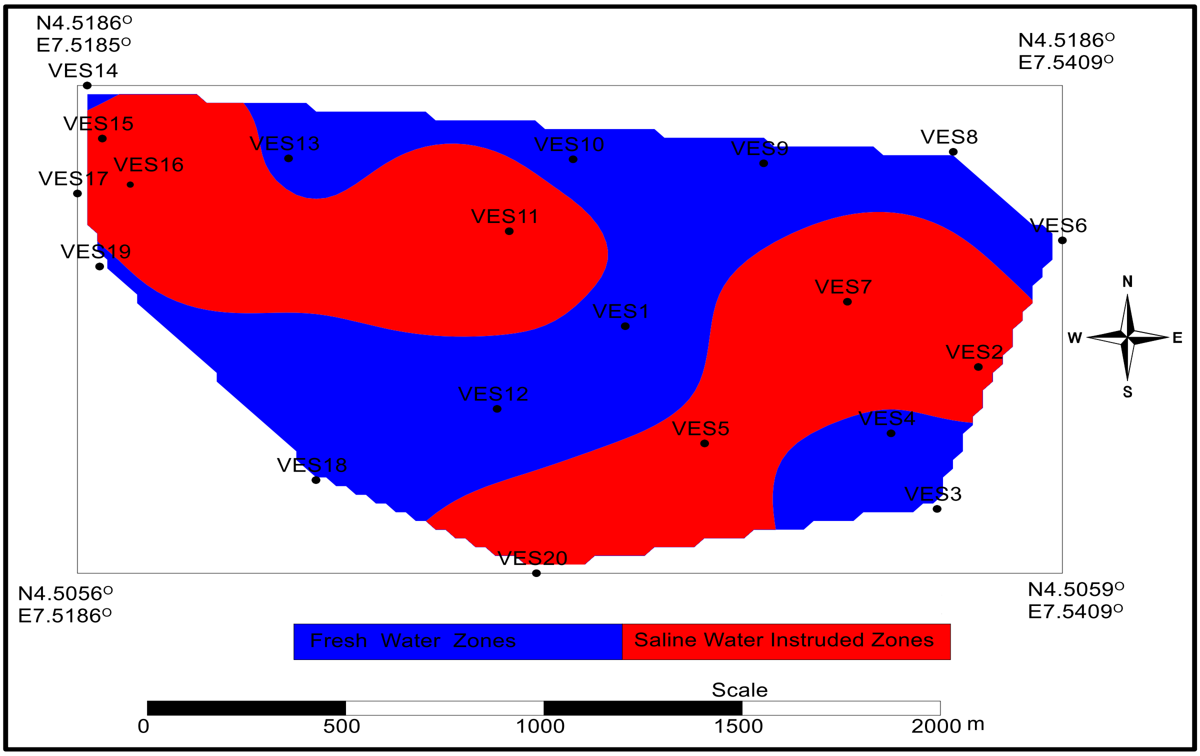

Figure 6: Third geo-electric layer map for VES profiles 1-20 used to image fresh and saltwater aquifers within the third layer. The map shows the fresh water locations, saline intrusion locations, and also contact locations between fresh and saline water within their third layers for VES profile 1-20, Opobo Rivers state Southern Nigeria. From the map it is observed that within the third geo-electric layers for O/MSC/02,05,07,11,16,17, and 20 lies saline waters, while contact locations between fresh water and saltwater is seen within the third geo-electric layers for O/MSC/04, 10, 13 and 19 at depths of 3.46m, 4.90m, 24.3m and 11.9m respectively.

4.4. Hydrochemical analysis

To ascertain the accuracy of the results from geophysical surveys which is qualitative, hydrochemical analysis was carried out to evaluate the ionic abundance of water samples from seven boreholes in the area. Results of hydrochemical and hydrophysical analyses is presented in table 3 below.

Table 3: Summary of hydrochemical analysis of water samples from seven wells (W1-W7) in Opobo/Nkoro Rivers State.

Wells/Boreholes	P^H	EC (us/cm)	Hardness mg/L	TDS mg/L	HCO_3^- mg/L	Na^+ mg/L	CL^- mg/L	K^+ mg/L	SO_4^{2-} mg/L
W1	7.10	15.00	7.30	60.91	15.0	3.00	5.00	4.81	4.67
W2	6.90	1203.1	19.50	700.30	42.91	62.00	176.00	33.57	12.32
W3	6.92	282	16.54	75.30	64.31	7.54	15.0	11.83	3.64
W4	6.55	50.00	13.80	52.84	30.06	4.50	70.17	3.72	9.02
W5	6.40	1705.00	21.60	717.93	99.6	148.91	285.10	38.45	11.04
W6	6.55	130.9	7.20	13.50	15.02	32.00	86.50	11.7	14.33
W7	6.42	1853.74	25.30	750.02	42.90	118.5	141.50	43.08	2.72

Where;

EC = Electrical Conductivity

TDS= Total Dissolved Solids

As a result of the presence of ions contained in salt water which persists in the sand aquifer and heterogeneous nature of the subsurface, pH value in the acidic domain is expected (pH of 6.40 - 6.92 are predominant in most samples). Physiochemical content of the water samples show electrical conductivity (EC) values of 1705µS/cm in W5 and 1853.74µS/cm in W7 which is high; total dissolved Solids (TDS) is high in W2 (700.30mg/l), in W5 (717.93mg/l) and in W7 (750.02mg/l); total hardness is high in W5 (21.60mg/l) and W7 (25.30mg/l). According to W.H.O standards, water sources which contain groundwater with chloride concentration greater than 150 mg/L, Electric conductivity greater than 1000us/cm and TDS greater than 700mg/L are considered to be affected by salt water intrusion. Elevated EC values in the water is indicative of high ionic abundance, and is diagnostic to salinity of the water. Most of the water showed elevated TDS values (by S.O.N 2007 standard), an indication of the presence of inorganic salts (principally potassium, sodium, bicarbonates, chlorides and sulphates) as reflected in the 1D and 2D geo-electric surveys. Hydrochemical analysis shows high content of bicarbonates (HCO_3^-) in W3 about 64.31mg/l and W5 about 99.6mg/l; Na^+ and K^+ show high values in W2, W5 and W7 but not necessarily at toxic level since the elements are essential in humans, though may cause some health effects in susceptible individuals while elevated concentration may give rise to unacceptable taste (W.H.O, 2011). Chloride (CL^-) and tetraoxosulphate (VI) (SO_4^{2-}) ions show high values in W2, W5, W6 and W7. The chemical parameters in the water samples show high values from the wells and boreholes in the area. However, the study area also contains fresh water aquifers lying within the third geoelectric layers for VES profiles O/MSC/01, 03, 04, 06, 08, 09, 10, 12, 13, 14, 18, and 19 as shown in (**figure 6**), with VES profiles 01, 04, 10, 12, 13 and 19 located at the fresh/saltwater boundaries and suggests that these profiles are economically not suitable for groundwater production in the area. Also VES profiles 03, 06, 08, 09, and 18 within the freshwater zones are located at the outermost locations in the area not prone to saltwater intrusion therefore a water supply tube well can be drilled along these profiles but the water should be subjected to quantitative assessment to ascertain its contamination level and prior treatments taken before domestic use.

5. Conclusion

The following conclusions can be made:

- The integration of qualitative method (electrical resistivity survey) with quantitative method (hydrochemical test analysis) is a robust technique for studying environmental problems involving intrusions and contamination plumes within the subsurface.
- The saltwater intrusion occurrence in Opobo in Nkoro local government area of Rivers State is a widespread incident, with salt water intruding into freshwater aquifers from shallow depths of 4.10m, 2.59-5.59m, and 5.59-9.59m to profound depths of 43.53m, 51.63m and 55.20m and is responsible for the lack of portable water supply encountered in the area.
- Electrical resistivity tomography (ERT) has proven to be a reliable tool in imaging the subsurface layers for contamination studies by providing a continuous record of subsurface resistivity both vertically and horizontally.

Recommendation

The following recommendations are being made for consideration:

- Groundwater production should be carried out in areas delineated to contain freshwater aquifers, but hydrochemical test analysis should be carried out on the water to ascertain its contamination level and prior treatments taken before domestic use.
- Detailed geological and geophysical mapping should be conducted in the area using high resolution ERT in a grid to have a vivid coverage of the subsurface.
- The socio-economic impact on the community caused by its dense population which affects groundwater usage should be evaluated.

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