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Geophysical and Hydrochemical Studies to Map Saltwater Infiltration into Freshwater aquifers: A case study of Ikoyi, Lagos State, Nigeria

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Abstract

A total of three electrical imaging lines were measured using the Wenner configuration. And a total of fifteen VES was carried out within the area of investigation and six water samples was collected. The results were presented as profiles, model sections, inverted sections and tables. Interpretations of these results involve both qualitative and quantitative deductions from 1D and 2D geoelectric models and laboratory analysis for the water analysis. The VES data were processed by partial curve matching to generate the 1st order geoelectric parameters and inverted in 1D using the WinResist. The 2D resistivity data were processed by inversion using the DIPROFWIN to generate the 2D resistivity section across each traverse while the water samples were taken to the laboratory for comprehensive analysis. The 2D resistivity structures reveal the lateral and the vertical subsurface information with resistivity values ranging from 0.130 to 4741 Ωm. The resistivity values are representative of the clay, clay (saline), clayey sand (saline), clayey sand and sand. From the quantitative interpretation five to six distinct layers were identified. The layers are: topsoil, clayey sand, clay, saline clayey sand, saline clay and sand. The resistivity of the topsoil varies from

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38.2 Ωm to 155.3 Ohm-m. The resistivity of the sand varies from 100.8 Ωm to 115.8 Ωm. The resistivity of clayey sand varies from 56.6 Ωm to 90.1 Ωm. The resistivity of clay varies from 12.7 Ωm to 41.2 Ωm. The resistivity of the saline layer (saline clayey sand/clay) varies from 2.1 Ωm to 51.2 Ωm. The depth of saline clay interface varies from 25.7 m to 72.6 m. The depth to the saline clayey sand interface varies from 25.7 - 72.6 m. The chemical analysis of water samples showed that the pH varies from 7.05 to 8.42, total dissolved solids vary from 1786 to 2116 mg/L and electrical conductivity varies from 2106 to 2656 µS/cm. The anions and cation concentrations such as Ca2+, Mg2+, Na+, K+, Cl- and HCO3- ranges from 158 to 185 mg/L, 36 to 48 mg/L, 222 to 287 mg/L, 3.2 to 3.8 mg/L, 10.86 to 20.87 mg/L and 2.33 to 3.88 mg/L respectively. The ratio of Cl/HCO3- ion ranges from 4.05 to 7.67. The interpreted results show saline water intrusion where they occur in different part of the area investigated. The results showed the effectiveness and usefulness of electrical resistivity method in mapping saline water intrusion problem in coastal areas. However, it is necessary to carry out integrated geophysical surveys involving electrical resistivity and induced polarization methods prior to drilling in the study area.

Keywords: Geophysical investigation, saline water, induced polarization, inversion, topsoil.

1. Introduction

Fresh water of acceptable quality is a troublesome trend for human life around the world. Due to the great need for drinking water and for industrial purposes, water resources are more affected by anthropogenic pollutants. Saltwater intrusion is defined as the replacement of freshwater in coastal aquifers with saltwater due to the movement of a mass of saltwater in the freshwater aquifer. Seawater penetration is a natural process that occurs in all coastal aquifers and is only restricted to coastal areas (Kalisa et al., 2016). Generally, in Lagos like most other coastal area in the world, there has been a major reliance on the groundwater resources as the source of potable water for domestic and industrial purposes, so as to compensate for inadequate of pipe borne water. The narrow border between inland and marine coastal environment systems is highly vulnerable to the effects of human development activities (Steyl and Dennis 2010). Coastal aquifers deteriorate due to hydraulic contact with the sea, resulting in sea penetration (Chitea et al., 2011). The salinization of coastal aquifers has also become a major problem and has caused significant economic losses, leading to a deterioration in the quality of freshwater aquifers. Excessive extraction of groundwater with significantly less regeneration also contributes to this problem. The extent of saltwater intrusion is influenced by natural geological conditions, the hydraulic

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gradient, the rate of groundwater extraction and its replenishment (Choudhury et al., 2001; PulidoLeboeuf 2004; Batayneh, 2006). The salinization of aquifers makes them unusable for drinking (Khublaryan et al., 2008). Due to the natural process, seawater moves and mixes with fresh groundwater in coastal aquifers due to the difference in density that exists between bodies of water with different salinity. The geological formation determines the intrusion of saltwater and the degree of intrusion can vary from a few meters to kilometers (Himi et al., 2010).

Research has already been carried out in various countries of the world using different methods dealing with the penetration of the sea into coastal aquifers. Several authors use geochemical and geophysical studies to delineate the interface between fresh and saltwater (e.g., Adeoti et al., 2010, Mondal et al., 2013, Bouderbala, 2014, Tosin et al., 2015). Some specific ions such as Cl^-, Na^{2+}, Mg^{2+}, SO_4^{2-}, and Br^- are enriched by seawater intrusion and can be used as markers of its influence (Milnes and Renard 2004; Capaccioni et al., 2005; Zouhri et al., 2008; Mondal et al., 2010). Moreover, ionic ratios such as Cl^-/HCO_3^-, Ca^{2+}/Na^+, Na^+/Cl^-, Br^-/Cl^-, and Mg^{2+}/Ca^{2+} can be effectively used to evaluate the degree of seawater intrusion (El Moujabber et al., 2006, Ben Moussa et al., 2011). Some studies have introduced both geophysical approaches to obtain a more comprehensive picture of this phenomenon (Store et al. 2000; Cimino et al. 2008; Nielsen et al. 2007; Kouzana et al. 2010). This research aims to identify the groundwater salinization and to determine its extent in the coastal aquifer of Ikoyi using hydrogeochemical and geophysical methods. This knowledge will contribute to water planning strategies and methods of groundwater management.

2. Site Description and Geology of the Study Area

The area geographically falls within latitude 06^0 26' 59.48" N between 06^0 27' 01.52" N and longitude 03^0 25' 59.62" E to 03^0 26' 02.48" E which lies in the coastal area of Lagos, Nigeria. Available information indicates that Lagos which falls within Dahomey basin lies on the stratified series of sedimentary rocks made up of silt, clay and sand of various sizes and composition. The Dahomey Basin which extends into western Nigeria as far as the Okitipupa Hill or Ilesha Spur and as far west as the Volta Delta complex in Ghana, consists of an extensive wedge of Cretaceous, Paleocene and Neocene sediments which thicken markedly from the onshore margin of the basin (where the predominantly clastics Cretaceous sediments rest on Basement complex) into the offshore where thick finer grained Cenozoic sediments obscure the Cretaceous rocks developed in Leptogeoclinal basins (Whiteman, 1982). The Cretaceous rocks which rest unconformably on the Basement complex and west of the Okitipupa high consist mainly of coarse grained clastics known as Abeokuta formation in western Nigeria and “Maestrichtian

Sableux" (Slansky, 1962) in Benin (Dahomey). Omatsola and Adegoke (1981) subdivided the cretaceous sequence into three: Ise, Afowo and Araromi formations under Abeokuta group. The Upper Cretaceous (largely Maestrichtian) rocks, at outcrop and as far as the present-day shore, are predominantly of sandy facies and probably were laid down during the first post-Santonian sedimentary cycle (Murat,1972). The oldest of the Cenozoic formations exposed in the Nigeria section of the Dahomey Basin is the Akinbo shale and the youngest is the Benin formation and the alluvial deposits. The Cenozoic formations cropping out in the Nigeria section of the Dahomey include: Akinbo Shale; Ewekoro Formation; Oshoshun Formation; Ilaro Formation and alluvium Coastal Plain Sands. The Cenozoic formations are poorly exposed and difficult to map because of thick tropical vegetation and superficial deposits.

3. Methodology and Data Processing

The hydrogeochemistry of the Ikoyi aquifer has been considered in terms of the major ionic constituents Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}, Cl^{-}, SO_4^{2-}, HCO_3^{-}, NO_3^{-} and of the physical parameters (pH, EC and temperature). The physicochemical parameters have been collected from 6 (six) boreholes. Samples from all boreholes were collected in 75 cl bottles, following the standard guidelines (Schoenleber 2005). The samples were analyzed immediately for hydrogen ion concentration (pH), temperature (T^0C) and electrical conductivity (EC). Other parameters were later analyzed in the laboratory. A water sample was taken in vials to be analyzed in the laboratory according to the norms. The analytical methods used are summarized in Table 1, and the water samples collected from 6 (six) boreholes in various parts of Ikoyi and analysed for their chemical compositions.

Table 1: Physicochemical methods used for analyzing groundwater

Element	Analysis Method
Ca^{2+}, Mg^{2+}, Na^{+} and K^{+}	Atomic absorption spectrometry
Cl^{-} and HCO_3^{-}	Volumetric methods
SO_4^{2-}	Spectrophotometer
NO_3^{-}	Colorimetric method
pH, EC and temperature	WTW universal conductivity meter

In all, twenty (15) vertical electrical soundings (VES) and four (3) traverses were carried out within the study area. The electrical resistivity method consists of measuring the potential at the surface, which results from a known current flowing into the ground (Bhattacharya and Patra 1968; VanNorstrand and Cook 1966; Ritz et al. 1999). A pair of current electrodes, A and B, and a pair of potential electrodes, M and N, is used. The apparent resistivity ρ_a is given by.

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$$\rho_a = \frac{K\Delta V}{I}$$

where K denotes a geometric coefficient dependent upon the electrode array, ΔV denotes the measured potential difference and I denote the current intensity. The ERI technique consists of using a multi-core cable with as many electrodes plugged into the ground at specific spacing, according to a sequence of readings predefined and stored in the internal memory of the equipment. The various combinations of transmitting (A, B) and receiving (M, N) pairs of electrodes construct the mixed sounding/profiling section, with a maximum investigation depth that mainly depends on the total length of the cable (Figure 3&4). In electrical methods, the spatial resolution and depth of investigation is linked to the distance between electrodes. In a first approximation, for Schlumberger and Wenner arrays, the maximum depth of investigation is of the order of 20 % of the total length of the cable and the total length of the resistivity profile.

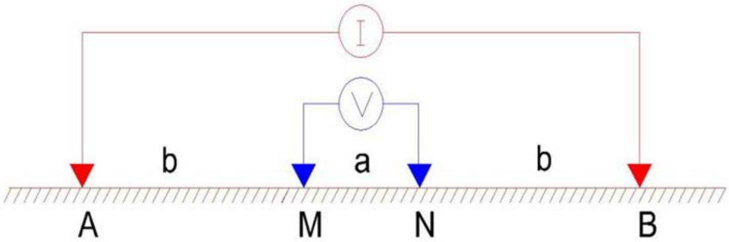

Figure 3: Electrode Configuration of the Schlumberger Array (Milson, 1996)

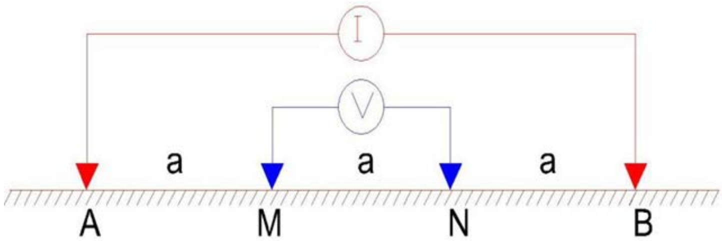

Figure 4: Electrode Configuration of the Wenner Array (Milson, 1996)

The Schlumberger array current electrode separation (AB) varied from a minimum of 2 to 620 m while measurements were made at sequences of electrodes at 10, 20, 30, 40, 50 and 60 m at maximum length of 200 m for the Wenner array.

The acquired vertical electrical sounding (VES) data were processed both quantitatively and qualitatively. The quantitative interpretation of the depth sounding curves was carried out using the partial curve matching technique (Bhattacharya and Patra, 1968). In order to do this, the VES data were plotted on a transparent paper. The partial curve matching technique involved the use of a standard two (2) layer master curves and four (4) auxiliary type curves (H, K, A, and Q). This procedure required segment-by-segment curve matching starting from the position with shorter electrode spacing and moving towards those with longer spacing. The results of the VES curves obtained from the partial curve matching were then used to constrain the interpretation by the computer using inversion software known as WinResist Software. This invariably reduces overestimation of depths in the curve matching. The result of the computer iteration shows the quantitative analysis to know the resistivity, thickness and depth. The qualitative interpretation of the depth sounding curves was carried out based on individual geo-electric characteristics on the number of layers represented by the four types of the auxiliary curves (A, H, K, and Q) and also from the profiles and maps involves inspection for patterns/anomaly signatures that are diagnostic of the target.

The acquired Wenner apparent resistivity datasets were tomographically inverted to obtain true electrical resistivity distribution of the study area using the ‘‘RES2DINV’’ finite-difference software, based on the smoothness-constrained least squares inversion by a quasi-Newton optimization method (Loke and Barker 1996). An initial 2D electrical resistivity model is generated, from which a response is calculated and compared to the measured apparent resistivity values of the field data. The optimization method then attunes the resistivity value of the model block iteratively until the calculated apparent resistivity values of the model are in close agreement with the measured values of the field data. The absolute error provides a measure of the differences between the model response and the measured data which is an indication of the quality of the model obtained. Using this scheme, 2D inverted models of true resistivity variation of sub-surface geological formations for the study area have been computed. The RES2DINV software offers two inversion options robust inversion (Loke et al. 2003) and smoothness-constrained least squares inversion (Loke and Dahlin 2002). It has been reported by Dahlin and Zhou (2004) that the robust inversion is better than the smoothness-constrained least squares inversion. In situations where the subsurface geology comprises a number of almost homogeneous regions but with sharp boundaries between different regions, the robust inversion scheme attempts to find a model that minimizes absolute changes in the model resistivity values (also known as L1 norm or blocky inversion method), thereby giving appreciably superior results. The smoothness-constrained optimization method (also known as L2 norm) on the other hand tries to minimize the squares of the spatial changes (or roughness) of the model resistivity values and tends to construct a model with a smooth variation of resistivity values. This approach is used only if the subsurface resistivity varies in a smooth or gradational manner.

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4. Results and discussion

The 2D Electrical Resistivity models of traverse 1 – 3 are shown in Figure 5. Typical resistivity curves of VES 1 – 15 are shown in Figures 6 to 8. The summary of the interpreted VES results and physiochemical analysis are presented in Tables 1 and 2 respectively.

(i) 2D model.

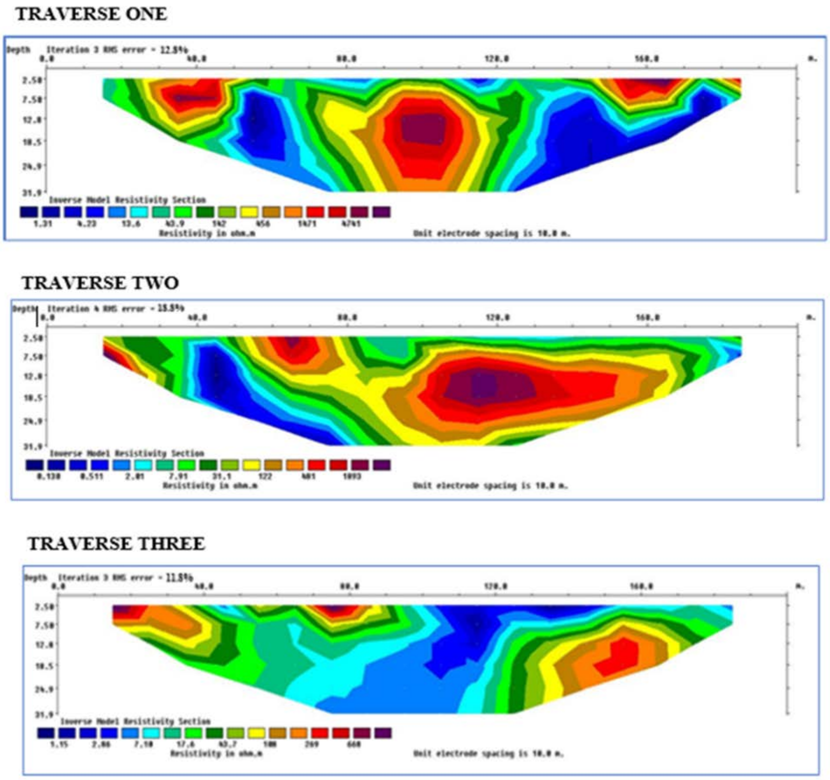

Figure 5: 2D Electrical Resistivity Imaging.

The 2D resistivity structures are presented as pseudo and inverted sections in a colour coded format representing minimum and maximum values respectively.

A total spread of 200 m was surveyed and a depth of 31.9 m was probed with resistivity values ranging from 0.130 to 4741 Ωm across the traverses as shown in Figure 6. Three to four resistivity structures were delineated which are representative of clay, clayey sand, saline layer (clay) and sand. The clay has resistivity values ranging from 13.6 to 43.9 Ωm at depth range of 2.5 to 31.9 m across the traverses. The clayey sand has resistivity value of 108 Ωm with corresponding depth of 2.5 to 24.9 m in traverse 3. The clay infiltrated with saline water has resistivity values ranging from 0.130 to 7.91 Ωm with corresponding depth of 2.5 to 31.9 m across the traverses. These indicate zone of saline water intrusion (polluted subsurface aquifer). The sand has resistivity

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values ranging from 122 to 4741 Ωm having corresponding depth of 2.5 to 31.9 m across the traverses.

(ii) 1D model

The following sounding curves types were interpreted: KQH, QHKH and QQH (Table 2) for VES 1 to VES 15 respectively. From the quantitative interpretation five to six distinct layers were identified. The layers are: topsoil, clayey sand, clay, saline clayey sand, saline clay and sand. The resistivity of the topsoil varies from 38.2 Ωm to 155.3 Ohm-m. The resistivity of the sand varies from 100.8 Ωm to 115.8 Ωm. The resistivity of clayey sand varies from 56.6 Ωm to 90.1 Ωm. The resistivity of clay varies from 12.7 Ωm to 41.2 Ωm. The resistivity of the saline layer (saline clayey sand/clay) varies from 2.1 Ωm to 51.2 Ωm. The depth of saline clay interface varies from 25.7 m to 72.6 m. The depth to the saline clayey sand interface varies from 25.7 - 72.6 m

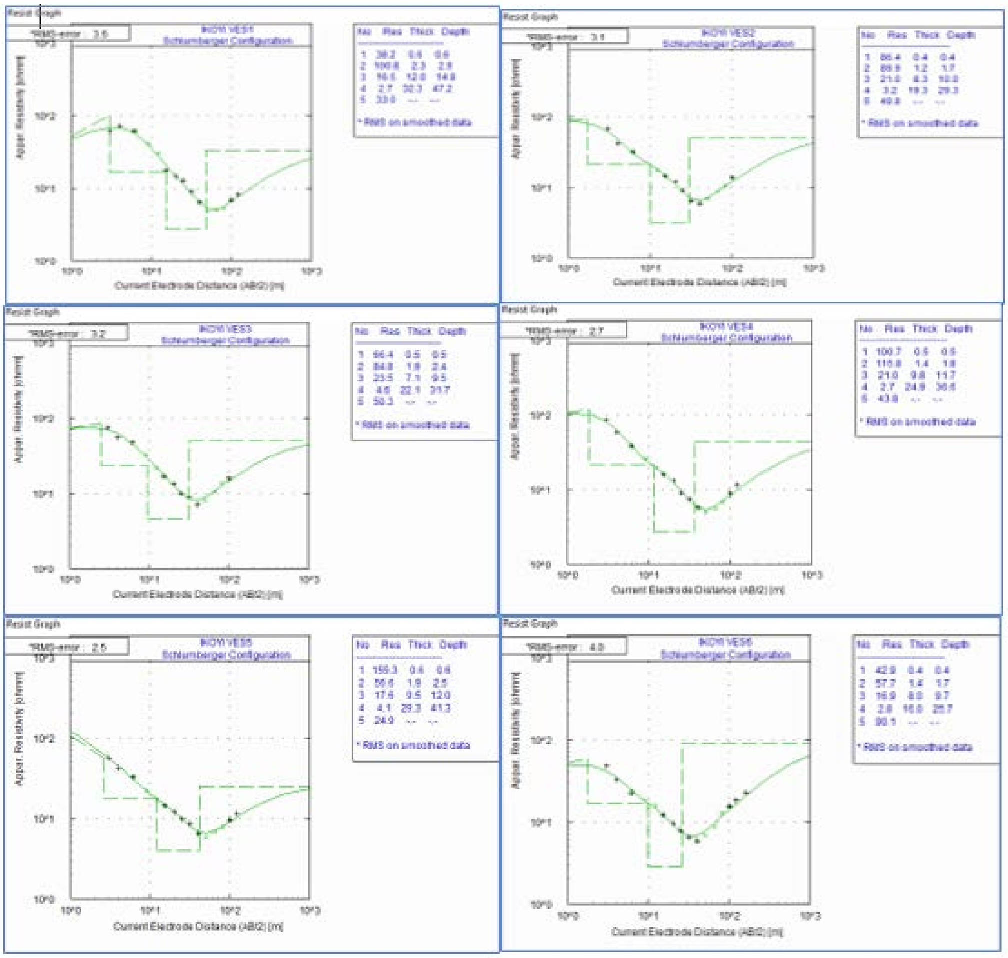

Figure 6: VES CURVES (1 to 6).

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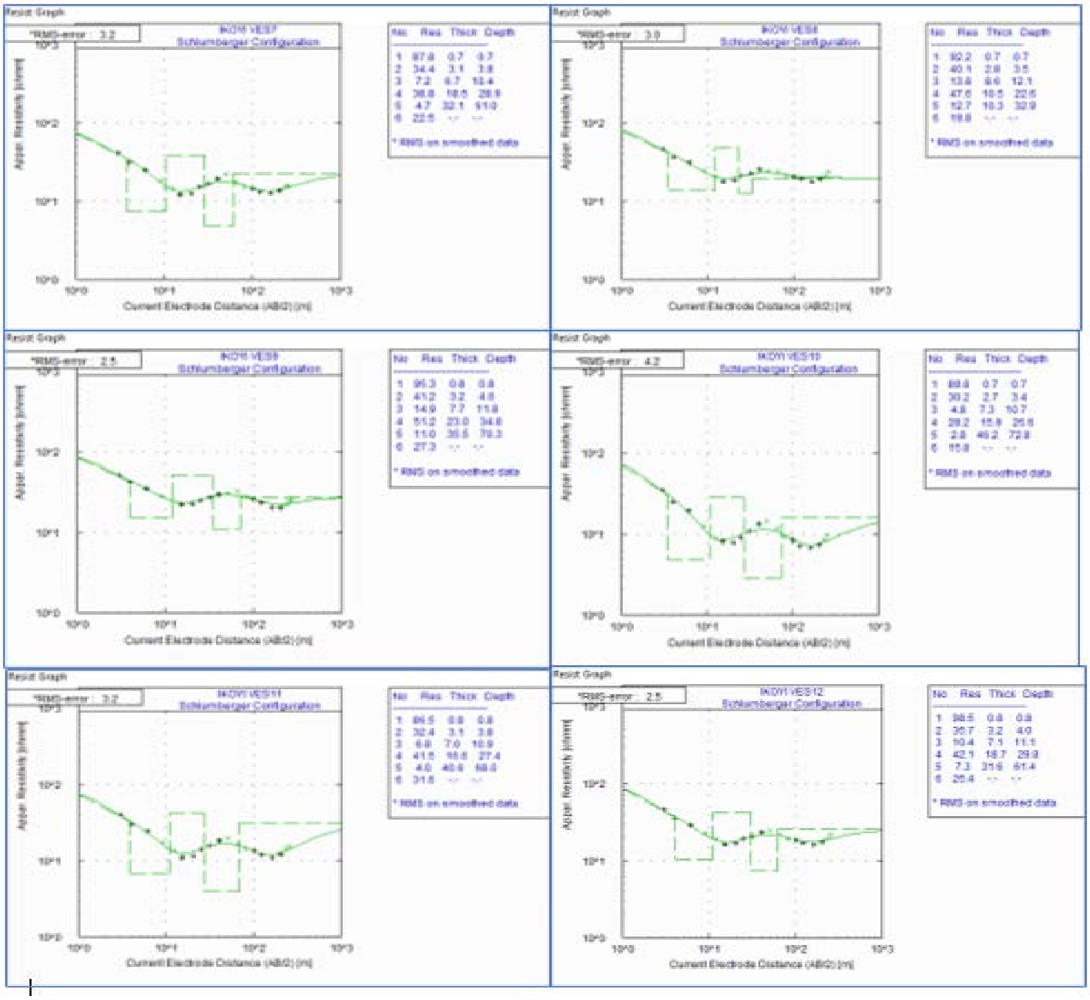

Figure 7: VES CURVES (7 to 12).

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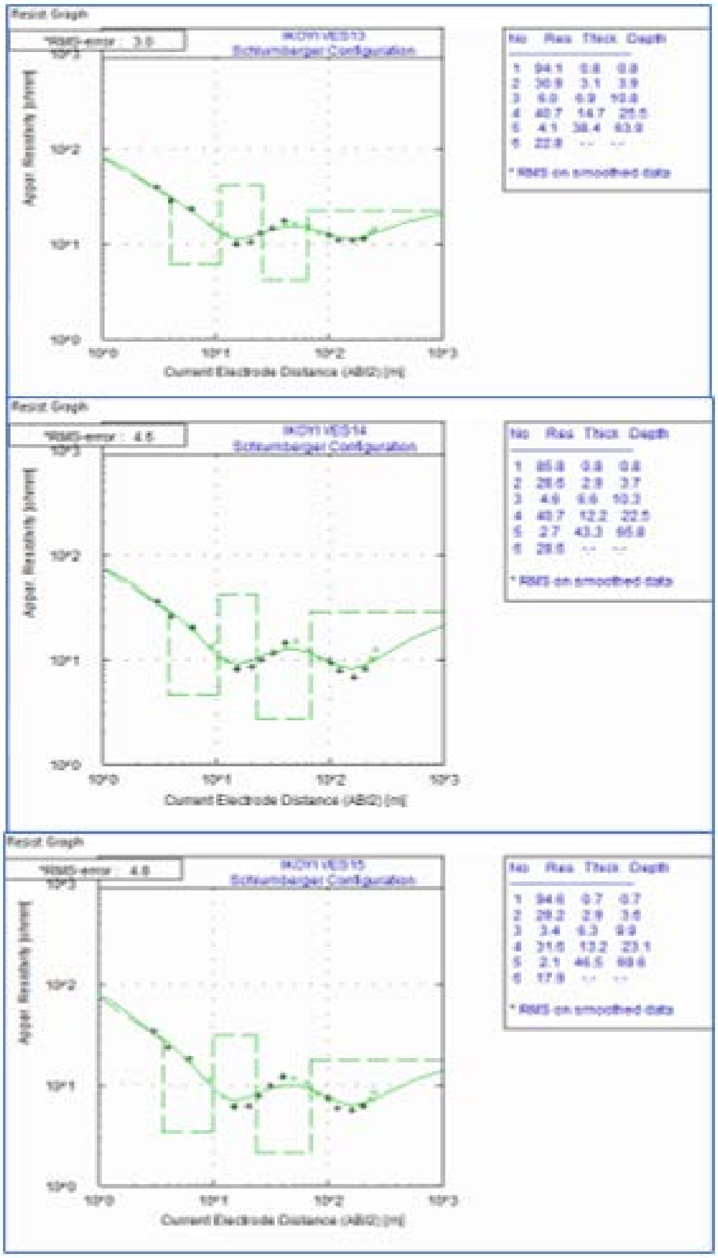

Figure 8: VES CURVES (13 to 15).

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Table 2: Summary of interpreted VES curves with inferred lithology

VES No	LAYERS	RESISTIVITY (Ωm)	THICKNESS (m)	DEPTH (m)	CURVE TYPE	LITHOLOGY
1	1	38.2	0.6	0.6	KQH	Topsoil
	2	100.8	2.3	2.9		Sand
	3	16.5	12.0	14.9		Clay
	4	2.7	32.3	47.2		Clay (Saline)
	5	33.0	----	----		Clayey Sand (Saline)
2	1	86.4	0.4	0.4	KQH	Topsoil
	2	89.9	1.2	1.7		Clayey Sand
	3	21.0	8.3	10.0		Clay
	4	3.2	19.3	29.3		Clay (Saline)
	5	49.8	----	----		Clayey Sand (Saline)
3	1	66.4	0.5	0.5	KQH	Topsoil
	2	84.8	1.9	2.4		Clayey Sand
	3	23.5	7.1	9.5		Clay
	4	4.6	22.1	31.7		Clay (Saline)
	5	50.2	----	----		Clayey Sand (Saline)
4	1	100.7	0.5	0.5	KQH	Topsoil
	2	115.8	1.4	1.8		Sand
	3	21.0	9.8	11.9		Clay
	4	2.7	24.9	36.6		Clay (Saline)
	5	43.8	----	----		Clayey Sand (Saline)
5	1	155.3	0.6	0.6	QQH	Topsoil
	2	56.6	1.9	2.5		Clayey Sand
	3	17.6	9.5	12.0		Clay
	4	4.1	29.3	41.3		Clay (Saline)
	5	24.9	----	----		Clayey Sand (Saline)
6	1	42.9	0.4	0.4	KQH	Topsoil
	2	57.7	1.4	1.7		Clayey Sand
	3	16.9	8.0	9.7		Clay
	4	2.8	16.0	25.7		Clayey Sand (Saline)
	5	90.1	----	----		Clayey Sand
7	1	87.8	0.7	0.7	QHKH	Topsoil
	2	34.4	3.1	3.8		Clay
	3	7.2	6.7	10.4		Clay (Saline)
	4	38.8	18.5	28.9		Clayey Sand (Saline)
	5	4.7	32.1	61.0		Clay (Saline)
	6	22.5	----	----		Clayey Sand (Saline)
8	1	92.2	0.7	0.7	QHKH	Topsoil
	2	40.1	2.8	3.5		Clay
	3	13.8	8.6	12.1		Clay
	4	47.7	10.3	22.6		Clayey Sand (Saline)
	5	12.7	10.3	32.9		Clay
	6	19.8	----	----		Clayey Sand (Saline)
9	1	95.3	0.8	0.8		Topsoil

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	2	41.2	3.2	4.0	QHKH	Clay
	3	14.9	7.7	11.8		Clay
	4	51.2	23.0	34.8		Clayey Sand
	5	11.0	35.5	70.3		Clay (Saline)
	6	27.3	----	----		Clayey Sand (Saline)
10	1	89.8	0.7	0.7	QHKH	Topsoil
	2	30.2	2.7	3.4		Clay
	3	4.8	7.3	10.7		Clay (Saline)
	4	28.2	15.9	26.6		Clayey Sand (Saline)
	5	2.8	46.2	72.8		Clay (Saline)
	6	15.8	----	----		Clayey Sand (Saline)
11	1	86.5	0.8	0.8	QHKH	Topsoil
	2	32.4	3.1	3.8		Clay
	3	6.8	7.0	10.9		Clay (Saline)
	4	41.5	16.6	27.4		Clayey Sand (Saline)
	5	4.0	40.6	68.0		Clay (Saline)
	6	31.6	----	----		Clayey Sand (Saline)
12	1	98.6	0.8	0.8	QHKH	Topsoil
	2	35.7	3.2	4.0		Clay
	3	10.4	7.1	11.1		Clay (Saline)
	4	42.1	18.7	29.8		Clayey Sand (Saline)
	5	7.3	31.6	61.4		Clay (Saline)
	6	25.4	----	----		Clayey Sand (Saline)
13	1	94.1	0.8	0.8	QHKH	Topsoil
	2	30.9	3.1	3.9		Clay
	3	6.0	6.9	10.8		Clay (Saline)
	4	40.7	14.7	25.5		Clayey Sand (Saline)
	5	4.1	38.4	63.9		Clay (Saline)
	6	22.8	----	----		Clayey Sand (Saline)
14	1	85.8	0.8	0.8	QHKH	Topsoil
	2	28.6	2.9	3.7		Clay
	3	4.6	6.6	10.3		Clay (Saline)
	4	40.7	12.2	22.5		Clayey Sand (Saline)
	5	2.7	43.3	65.8		Clay (Saline)
	6	28.6	----	----		Clayey Sand (Saline)
15	1	94.6	0.7	0.7	QHKH	Topsoil
	2	28.2	2.9	3.6		Clay
	3	3.4	6.3	9.9		Clay (Saline)
	4	31.6	13.2	23.1		Clayey Sand (Saline)
	5	2.1	46.5	69.6		Clay (Saline)
	6	17.9	----	----		Clayey Sand (Saline)

(iii) Physicochemical.

The chemical analysis of water samples showed that the pH varies from 7.05 to 8.42, total dissolved solids vary from 1786 to 2116 mg/L and electrical conductivity varies from 2106 to 2656 µS/cm. The anions and cation concentrations such as Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}, Cl^{-} and $HCO3^{-}$ ranges from 158

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to 185 mg/L, 36 to 48 mg/L, 222 to 287 mg/L, 3.2 to 3.8 mg/L, 10.86 to 20.87 mg/L and 2.33 to 3.88 mg/L respectively. The ratio of Cl/HCO3$^-$ ion ranges from 4.05 to 7.67. Some of these values do not fall within WHO standard for portable water. More so, the palatability of the water around the study area is unacceptable. The analysis showed that the clayey sand and clay are polluted based on geophysical and physicochemical.

Table 3: Observed wells information, chemical analysis, Cl$^-$/HCO3$^-$ ion ratio, palatability of drinking water (WHO 2017)

Sample nos.	PH	EC (μs/cm)	TDS (mg/L)	Ca^{2+} (mg/L)	Mg^{2+} (mg/L)	Na^+ (mg/L)	K^+ (mg/L)	Cl^- (mg/L)	HCO3$^-$ (mg/L)	Cl/HCO3$^-$ (range)	Palatability class
1	7.85	2345	2116	169	36	222	3.2	18.42	3.88	4.75	Unacceptable
2	8.42	2177	1876	178	42	257	3.5	20.87	2.72	7.67	Unacceptable
3	7.76	2146	1884	185	45	248	3.2	10.86	2.68	4.05	Unacceptable
4	7.05	2656	2148	176	38	254	3.8	12.72	2.33	5.46	Unacceptable
5	7.62	2106	1786	158	48	254	3.8	11.86	2.68	4.43	Unacceptable
6	8.06	2238	2088	178	46	287	3.6	20.54	3.36	6.11	Unacceptable

5. Conclusion

Geophysical investigation involving electrical resistivity method in Ikoyi area, Lagos State Nigeria, was used to study saline water intrusion problem in the area. Three 2D Wenner electrical resistivity imaging and fifteen vertical electrical sounding (VES) data were acquired in the study area. The subsurface structure composed mainly of alternation of clay, clayey sand (saline) and clay (saline). The interpreted results show saline water plumes where they occur in different part of the area investigated. The 1D and 2D results revealed a very high degree indicating saline water intrusion between depth interval of 2.5 and 72.6 m in the study area. Freshwater aquifers where not delineated due to the availability of space within the area of study. The physicochemical analysis revealed high degree of electrical conductivity, total dissolved solids and in the anions and cation concentrations. The palatability of the water around the study area is unacceptable. The analysis showed that the clayey sand and clay are polluted based on geophysical and physicochemical results. These results showed the effectiveness and usefulness of electrical resistivity method in mapping saline water intrusion problem in coastal areas. It is necessary to carry out integrated geophysical survey involving electrical resistivity and induced polarization methods prior to drilling in the study area.

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