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Integrated Geophysical and Geochemical Investigations of Saline Water Intrusion in a Coastal Alluvial Terrain, Southwestern Nigeria

K. D. Oyeyemi[1]*, A. P. Aizebeokhai[1] and M. A. Oladunjoye[2]

[1]Applied Geophysics Programme, College of Science and Technology,
Covenant University, Nigeria
[2]Department of Geology, University of Ibadan, Nigeria
Email: kdoyeyemi@yahoo.com, kehinde.oyeyemi@covenantuniversity.edu.ng

ABSTRACT

Deterioration of water quality in the coastal areas of Lagos due to saltwater infiltration into the freshwater aquifer has become a major concern. Geophysical techniques involving 2D electrical resistivity tomography (ERT) using Wenner and dipole-dipole arrays were incorporated with geochemical evaluation using ICP-OES and 1C analytic methods to study the extent of saline water intrusion and its environmental impacts. The resistivity data were acquired with minimum electrode spacing of 5m (Traverses 1, 2, and 3) and 6 m (Traverse 4). Data level of 8 (maximum electrode spacing of 40.0 m) was achieved in each of the profiles; dipole length with n-factor of 6 was employed for the dipole-dipole array. The depth of inverse models from the geoelectrical resistivity data obtained in the area revealed significant impact of the saline water on delineated aquifers with very low resistivity values uniquely below $4.0\Omega m$. ERT results also show the lateral invasion and up-coning of saline water within the aquifer systems. Results of the physiochemical analysis indicate that the water is alkaline with pH values range 8.6-8.9. The salinity is also high with the total dissolved solids TDS values and chloride concentration ranges 10405 – 12005 (mg/L) and 432 – 724 (mg/L) respectively. The water has very high electrical conductivity (EC) values range 2005-3013 µS/cm and very Hard with 121 to 180 mg/L range of total hardness thereby falling below the minimum permissible standard of the Indian standard institution (ISI), European union (EU) and world health organization (WHO) for portable water consumption.

Keywords: Coastal aquifer; Water quality; Saline water intrusion; ERT; Geochemical analyses

1. Introduction

Nigeria has a coastline that is about 1000km long with the Atlantic Ocean, bordering eight states including Lagos, Ogun, Ondo, Delta, Bayelsa, Rivers, Akwa-Ibom and Cross River. Lagos maritime is backed up by numerous rivers, creeks, swamps and lagoon. The maritime area of Lagos is about 46,500 Km and coastline of 853 Km parallel to the Atlantic Ocean. There has always been massive influx of people from other parts of Nigeria to Lagos metropolis (rural-to-urban migration) causing increase in the population of Lagos, moving from ten to fifteen million in the recent times, and there is annual population increase of 3 % (UNDP, 2006). Therefore due to population explosion within Lagos metropolis, there is a corresponding acute shortage in pipe borne water provided by the government to meet the daily demand of the people. Therefore, most of the residents depend on borehole water both for domestic and industrial usage.

Longe et al. (1987) estimated over 10 million gallons of water being extracted via boreholes from the multi-layered aquifers existing in the area per day. However, most of the boreholes drilled in the coastal area of Lagos in most cases are later abandoned after few months due to severe saltwater intrusion into the aquifers. Owing to this endemic environmental pollution, potable water supply to inhabitants in some of the communities in the coastal belt of Lagos has been a major problem. Saltwater contamination of freshwater aquifer has been acclaimed all over the world to pose a threat to the sustainable development and economic wellbeing of dwellers in any coastal area (Urish and Frohlich, 1990; Frohlich et al., 1994; Choudhury et al., 2001; Kalpan et al., 2001; Frohlich and Urish, 2002).

The extent of saltwater intrusion and percolation within the subsurface is influenced by the nature of geological formations present, hydraulic gradient, rate of withdrawal of ground water and its recharge. Several workers around the world have carried out various studies on saltwater intrusions into freshwater aquifer in coastal areas (e.g. Barret et al., 2002; Oteri and Atolagbe, 2003; Batayneh, 2006; Lee and Song, 2007; Adepelumi et al., 2008; Adeoti et al., 2010; Harikrishna et al., 2012). These include geophysical mapping of the interface between freshwater and saline water. Also, geochemical analyses of water samples from these areas have been conducted to investigate the quality of the freshwater with a view to evaluate their deterioration due to saline water intrusion. Therefore it is pertinent and essential to understand saline water intrusion within Lagos metropolis for adequate management of coastal aquifers and water resources. Therefore, within the purview of this research, geophysical and geochemical investigations were conducted to delineate possible saltwater intrusion in coastal alluvial aquifers, map the lateral and vertical extent of groundwater contamination, and assess the groundwater quality in coastal aquifers of Lagos.

2. Geologic and Hydrogeologic Setting of Study Area

Lagos is situated within the Dahomey basin and lies on the stratified series of sedimentary rocks made up of silt, clay and sand of various grain sizes and mineralogy. The Dahomey Basin extends into western Nigeria as far as the Okitipupa

Ridge or Ilesha Spur and as far west as the Volta Delta complex in Ghana. It 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). The Cretaceous sequence has been subdivided into three: Ise, Afowo and Araromi Formations under formerly termed Abeokuta Group (Jones and Hockey 1964; Omatsola and Adegoke, 1981). 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; Oshosun Formation; Ilaro Formation and alluvium Coastal Plain Sands. Table 1 summarized the lithostratigraphic units within the Dahomey basin.

The study area is located within Oworo area of Lagos, southwestern Nigeria, and the surface geology is made up of the Benin Formation (Miocene to Recent), recent Littoral alluvial, Lagoon and Coastal Plain Sand deposits (Longe et al., 1987). The formation of the alluvium deposits was perhaps influenced by the fluctuation of the sea-level during the Quaternary times. A common feature of the alluvium sediments found in the area is that they consist of mainly sands, littoral and lagoon sediments formed between an old barrier beach and a relatively younger barrier beach as well as coastal plain sands. The sediments range in size from coarse to medium grains, clean white loose sandy-soil that graded into one another towards the lagoon and near the mouth of the larger rivers.

The main aquifer in Lagos is the Coastal Plains Sands exploited through hand-dug wells and boreholes. This forms a multi-aquifer system consisting of three aquifer horizons separated by silty or clayey layers (Kampsax and Sshwed, 1977; Longe et al., 1987). The aquifer thickens from its outcrop area in the north of the city to the coast in the south and the sand percentage in the formation also changes from north to south (Longe et al., 1987). Abeokuta Formation constitutes a deep aquifer only within the northern parts of Lagos city (Ikeja area) where boreholes to the aquifer are about 750 m deep. The Ilaro and Ewekoro Formations are not key aquifers in Lagos as they are predominantly composed of shale/clay. The only source of hydraulic information on the Ilaro Formation was obtained at Lakowe where no fresh water horizon was intercepted. It has not been possible to differentiate the Ewekoro as a target aquifer in any boreholes or existing wells in the metropolis. The formation apparently represents a minor groundwater resource in Lagos.

3. Materials and Methods

Geophysical Investigation

Four parallel 2D electrical resistivity tomography (ERT) traverses (Traverses 1-4) were conducted using AGI SuperSting R8/IP8 Earth Resistivity meter, an 8 channel Memory Resistivity and IP Meter with inbuilt processor for 64 and 84 multi-electrodes system. For better horizontal and vertical resolution, two types of electrode array were deployed for the investigation – Wenner and dipole-dipole for the four profiles of about 400 meters length. The minimum electrode spacing of 5 m (Traverses 1-3) and 6 m (Traverse 4) were used for the data measurements, and a data level of 8 (maximum electrode spacing of 40.0 m) was achieved in each of the profiles. The dipole length with n-factor of 6 was employed for the dipole-dipole array. The choice of arrays for the survey was based on our desire to have good sensitivity to vertical and horizontal changes in the subsurface resistivity at both shallow and deeper depths, at the same time probe into the deeper depth and to have good vertical and horizontal data coverage under each ERT line. Wenner array was used for its ability to resolve vertical changes (horizontal structures), has a moderate depth of investigation though poor at horizontal coverage upon increasing the electrode spacing (Loke, 2000). To make up for this, we employed dipole-dipole with apparent resistivity of $\pi n(1+n)(2+n)aR$. The advantage of this array lies in the fact that it is good in mapping vertical structures, as well has a better horizontal data coverage than the Wenner (Loke, 2004).

The observed apparent resistivity data for the 2D profiles were further processed and inverted using RES2DINV inversion code. Griffiths and Baker (1993) stated that the computer program applied nonlinear optimization technique to evaluate automatically 2D resistivity inverse model of the subsurface for the observed apparent resistivity data. The program subdivides the subsurface into a number of rectangular blocks in accordance to the spread of the observed data as determined by the survey parameters comprising electrode configuration, electrode separations and positions, and data level (Loke and Baker, 1996). Least-squares inversion technique with standard least-squares constraint, which minimizes the square of the difference between the observed and the computed apparent resistivity values, was used to invert the 2D data. The least-squares equation was solved using the standard Gauss–Newton technique. Smoothness constraint to minimize large and unrealistic variations in the output models was applied to model perturbation vector only and appropriate damping factors were selected using trial and error methods.

Hydrogeochemical Study

Water samples from three boreholes and one hand-dug-well were collected within the area. Some sensitive hydrochemical parameters of water such as total dissolved solids (TDS), electrical conductivity (EC), temperature and pH were determined in situ on site using digital meters (water treatment works (WTW)-conductivity meter model L/92 and WTW- pH meter model pH/91). The WTW- pH meter was calibrated with pH solutions 4 and 7. Water samples of approximately 75 mL were collected for multi-element analysis; pressure filtered through 0.2 mm nuclepore membranes and 3 mL analytical grade HNO3 was added to bring the water acid solution to approximate pH of 2. The analysis of trace elements and cations in water were conducted using inductively coupled plasma optical emission spectrometry (ICP-OES) technique which is time saving due to simultaneous multi element determination over an unusually wide analytical range of 40-70 elements to very low detection limits of 0.001% (ppm to ppb or in many cases ppt); whereas the unacidified water samples were analysed for anions concentrations using the DIONEX DX-120 ion chromatography technique. All the analyses were carried out at the ACME laboratory, Ontario Canada. The samples were analysed for 73 constituents and physical properties. The Results were further compared with recommended standards to determine the extent of the pollution and the water quality.

4. Results and Discussion

Electrical Resistivity Tomography

The 2D inverse models of the subsurface resistivity distribution obtained from smoothness constrained inversion are presented in Figures 3, 4, 5, and 6 for both Wenner and dipole-dipole configurations of each traverse line. The 2D electrical resistivity tomography profiles measured with lateral extent of 400 m for both configurations and vertical extent ranging from 28.7 to 65.7 m for Wenner array, while 82.7 to 111.7 m for dipole-dipole array. The Wenner arrays have the inverse resistivity model values range from about 0.423-196 Ωm, 0.260- 1909 Ωm, 0.126-792 Ωm, and 0.453-143 Ωm, while that of the dipole-dipole arrays, the inverse resistivity model values range from 0.192-4100 Ωm, 0.270-66.2 Ωm, 0.170-2901 Ωm, and 0.0494 - 2496 Ωm for Traverses 1 - 4 respectively.

The 2D imaging of the subsurface variations in the resistivity/conductivity vividly reflect different lithologies and fluid content. The subsurface lithologies consist of top soil (predominantly sandy clay) with varying materials of low to medium resistivity value, clay, sandy clay/clayey sand and sand. The sandy clay/clayey sand and sand layers constitute the coastal aquifer units within the area with varying ground water yield as a result of variation in porosity and permeability. Some of the aquifer units characterised by low resistivity values were found to have been impacted by saline and/or brackish water suspected to be resulting from the increase in groundwater pumping or extraction for domestic and industrial use thereby causing drop in the level of the freshwater table, reducing its pressure for denser saltwater to flow further inland. The observed modes of the saline water invasion from the geoelectrical resistivity results in most cases are lateral (Traverses 1, 2, and 4) and up-coning (Traverse 3).

Electrical resistivity distributions indicate that salt water interfaces vary between 29.5 to 40.5 m depth within the area resulting from the saline water incursion extending to a depth of about 32.5 m (Traverse 1) and 40 m (Traverse 4) beneath the surface marked with very low resistivity value ranging from 0.0494 – 3.5 Ωm. The upwelling or upcoming of saline water observed on the Traverse 3 forming a cone structure from the deeper depth below the aquifer units is a saltwater wedge extending inland underneath the freshwater because of its higher density . Any water supply borehole or well established within this vicinity will draw from this saltwater cone and be contaminated. The water pollution experience within the study area is suspected to be principally due to the increase in the extraction or withdrawal of groundwater from the aquifer units over time leading to incursion and invasion of sea water from the Lagos metropolis lagoon into the aquifer system (Oteri and Atolagbe, 2003; Adepelumi et al., 2008; Adeoti et al., 2010; Harikrishna et al., 2012). This problem is particularly acute within the area that many boreholes which were producing fresh water after drilling become salty a few months later and therefore abandoned. Also, reports from several water borehole drilling companies around Lagos metropolis confirm that the groundwater within the confined aquifers units within the study area is corrosive; this is not unconnected with the severe environmental pollution of saline water intrusion into the aquifer system in the area. Therefore, it is imperative that adequate remediation measures should be adopted to mitigate the effect of saline water intrusion into coastal aquifer system within Lagos metropolis. There is need for government policy to regulate pumping rates of groundwater within the coastal areas. Another remediation approach include artificial or managed coastal aquifer recharge (Labregére, et al., 2006; Raicy, et al., 2012); which entails introduction of fresh water injection and salt water extraction techniques to prevent or retard the salinization process within coastal aquifer systems.

Hydrogeochemical Evaluation

Four water samples collected from the study area with one hand-dug shallow well and three Boreholes labeled OW1- OW 4 were analyzed and the results presented in Tables 2 - 4. The summary of the physicochemical elemental analysis of the water samples were compared with drinking water standards (ISI, 1995; EU, 1998; WHO, 2006) in Table 5. The measured acidity and alkalinity of water samples within the study area shows the pH values to be more than the maximum permissible limits for all standards considered (Table 5). According to Ezeigbo (1989), the water within the area could be considered alkaline. The electrical conductivity (EC) determines the degree of dissolved matters in water and pure water has a very low EC (Montgomery, 2002). Tables 4 - 5 reveal very high values of EC and chloride content within the water samples with that of the hand dug well (OW 2) being the highest. This attests to their high salinities and finally confirms saline water intrusion via lateral invasion and up-coning from the nearby Lagos lagoon as delineated from electrical resistivity tomography.

The obtained values for total dissolved solute (TDS) from the samples were too far above the minimum and maximum permissible levels proposed by WHO (2006) and ISI (1995). This suggests high concentration level of dissolved solids thereby falling within brackish and saline waters proposed by Todd (1980). Though hardness values obtained were significantly higher than the permissible limits of WHO (2006) in the shallow depth hand dug well, the values fall within the permissible range in borehole water samples. This perhaps is due to the greater depth of the yielding aquifer for the borehole water which may be temporary unpolluted by the saline water intrusion in the area. However using the classification of Sawyer and McCarthy (1967), all the inspected samples range from moderately hard to hard water.

Conclusion

Combined geophysical and geochemical investigations have been used to study the subsurface geology and delineate the extent of the incursion of saline water into the coastal alluvial aquifer units within the study area. The inferred lithologies from the 2D ERT imaging include the top soil which is mainly sandy clay, clay, sandy clay/clayey sand and sand. Sandy clay/clayey sand and sand units constitute the delineated coastal aquifer systems within the area. The inversion of the fresh water aquifer units within the area by saline water is perhaps due to increase in groundwater extraction; hydraulic connection between freshwater and seawater thereby allowing saltwater to push further inland beneath the freshwater. The saline water intrusion mechanisms are both lateral and up-coning. The results of the hydrogeochemical studies of the obtained water samples from major boreholes and hand dug well within the area confirm them to be alkaline with very high electrical conductivities and chloride contents. The observed high concentration level of total dissolved solids of the water samples above the permissible limits proposed by world health organization (WHO, 2006) and Indian Standard Institution (ISI, 1995) further categorize them to be within the brackish and saline waters. These among others, constitute major reasons for the failure and abandonments of several boreholes and hand-dug wells within the area. Effective remediation measures including introduction of artificial recharge of fresh water and salt water extraction techniques are to be adopted; formulation of adequate policy by relevant government agency towards regulation of groundwater pumping rate in coastal areas in order to mitigate intrusion of saline water into the aquifer systems are therefore recommended.

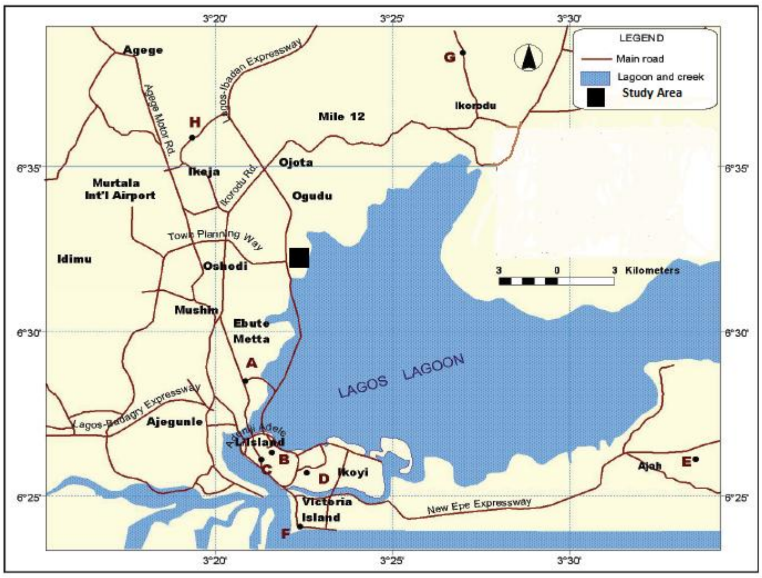


Fig. 1: Lagos metropolis showing the study area

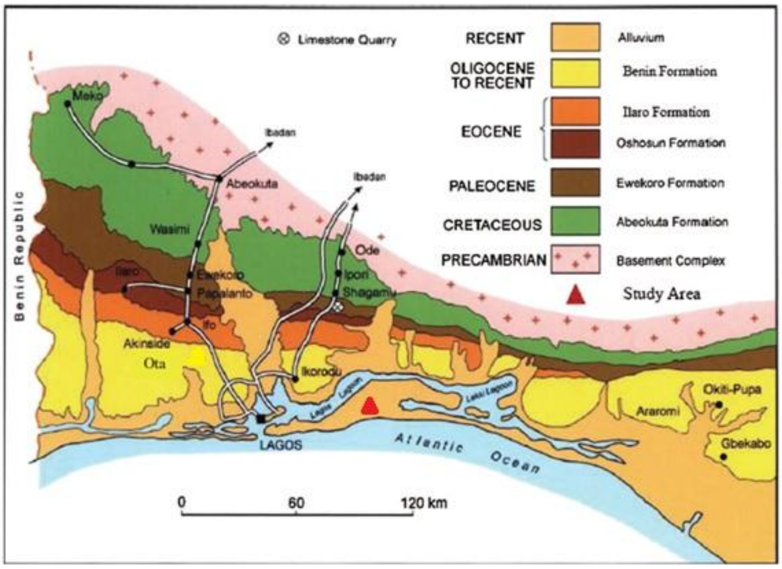
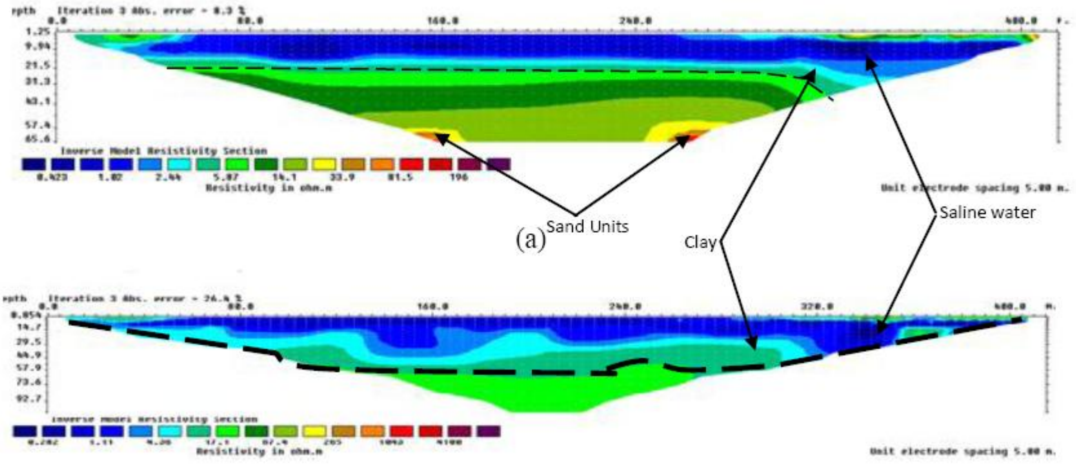
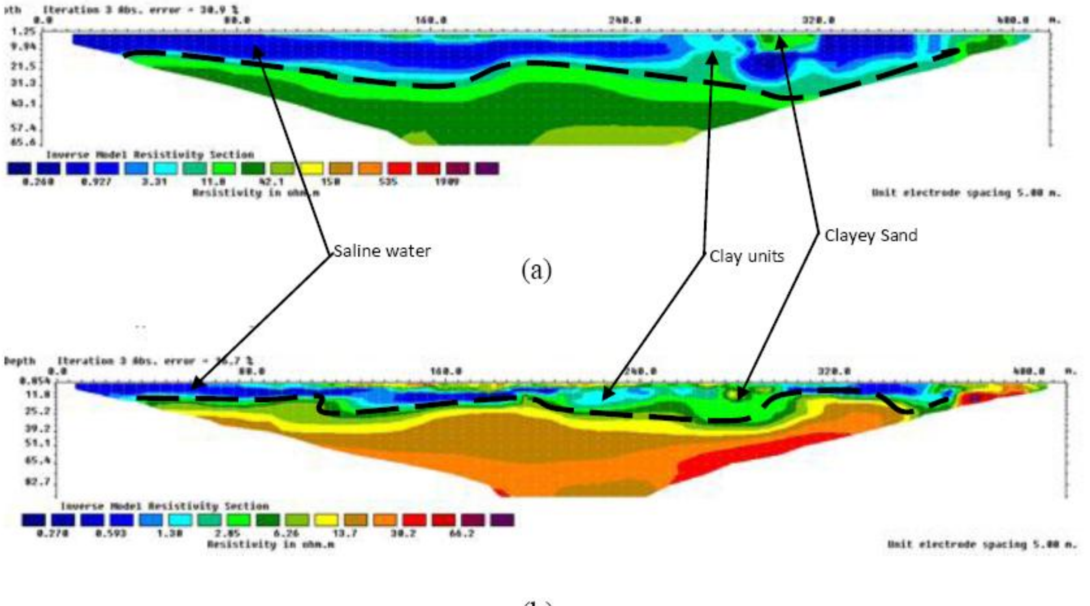


Fig. 2: Geological map of the Nigerian part of the Dahomey embayment (modified after Gebhardt et al. 2010)



(b)

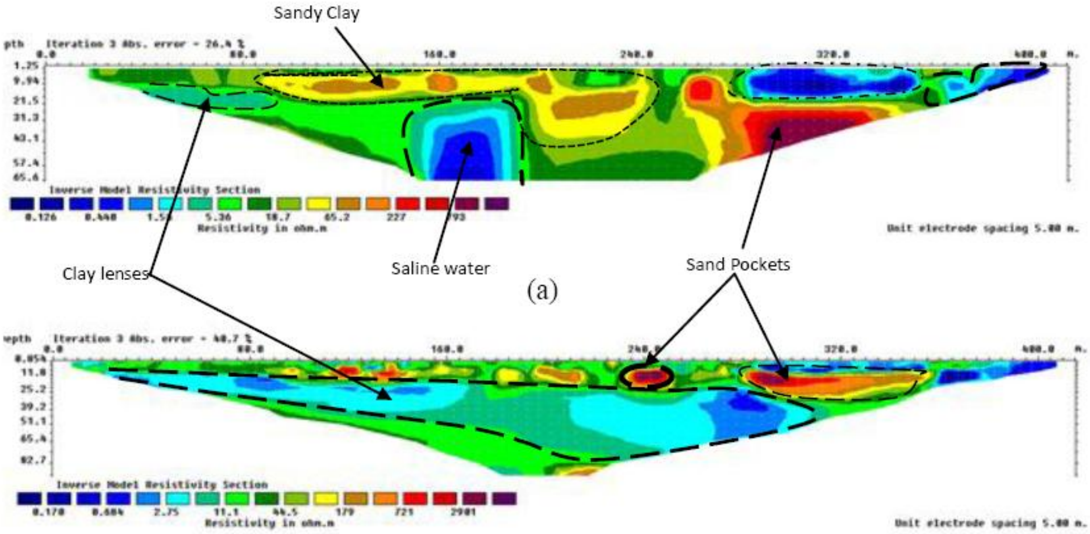
Fig. 3: Model resistivity inversion for Traverse 1 using (a) Wenner and (b) dipole-dipole arrays



(a)

(b)

Fig. 4: Model resistivity inversion for Traverse 2 using (a) Wenner and (b) dipole-dipole arrays



(a)

(b)

Fig. 5: Model resistivity inversion for Traverse 3 using (a) Wenner and (b) dipole-dipole arrays

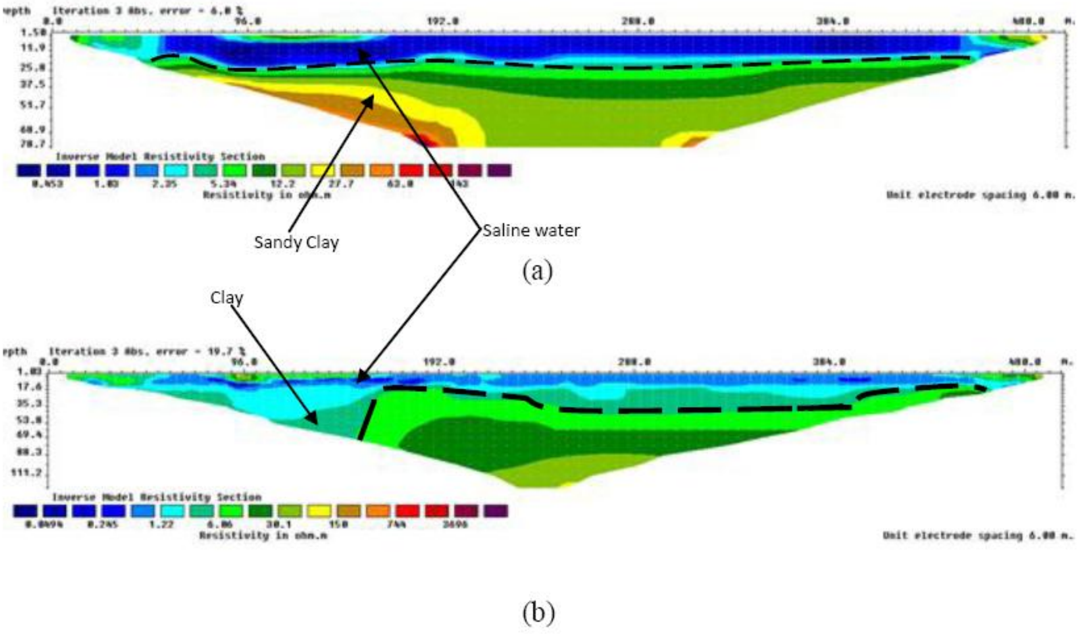


Fig. 6: Model resistivity inversion for Traverse 4 using (a) Wenner and (b) dipole-dipole arrays

Table 1: The stratigraphic column of within Dahomey Basin

Omatsola and Adegoke (1981)			**Agagu (1985)**	
Formation	**Age**	**Formation**	**Age**	**Formation**
Alluvium			**Recent**	**Alluvium**
Coastal Plain Sand Ilaro Ewekoro	Pleistocene-Oligocene Eocene Palaeocene	Coastal Plain Sand Ilaro Oshosun Akinbo Fm	Pleistocene-Oligocene Eocene Palaeocene	Coastal Plain Sand Ilaro Oshosun Akinbo Ewekoro
Abeokuta	Maastrichtian-Neocomian	Araromi Afowo Ise	Maastrichtian-Neocomian	Araromi Afowo Ise
Precambrian Crystalline Basement Rocks				

Table 2: Sampling number, code and GPS coordinates

Sampling No	Code	Water Source	Elevation (m)	Northing	Easting
1	OW 1	Borehole	69	$N07°08.150'$	$E003°21.251'$
2	OW 2	Hand-dug well	73	$N07°07.750'$	$E003°21.450'$
3	OW 3	Borehole	74	$N07°07.400'$	$E003°22.600'$
4	OW 4	Borehole	77	$N07°08.600'$	$E003°23.900'$

Table 3: The physicochemical results

Code	pH	$(SO_4)^{2-}$mg/L	HCO_3mg/L	Ca^{2+} mg/L	Total Hardness mg/L	Fe^{2+} mg/L
OW1	8.6	14.2	78.5	15.5	121	0.06
OW2	8.7	33.8	248	7.5	180	0.01
OW3	8.6	43.1	131.7	40.72	130	0.4
OW4	8.9	24	143.8	41.8	123	0.02

Table 4: The physicochemical results (Contd.)

Code	Cl^- mg/L	Na^+ mg/L	K^+ mg/L	Mg^{2+} mg/L	EC (µS/cm)	TDS (mg/L)	P^+ mg/L
OW1	432	19.9	20.5	7.4	2005	10405	<0.02
OW2	724	9.5	4.2	1.9	3013	12004	<0.02
OW3	409	35.2	6.7	5.3	3000	11000	0.04
OW4	446	35.3	7.3	5	3000	12006	<0.02

Table 5: Summary of the physicochemical results compare to the WHO, EU and ISI drinking water standards

	Drinking water standards			Water from the study area	
Measured Parameters	WHO, 2006	ISI, 1995	EU, 1998	Range	Mean
pH	7-8.5	6.5-8.5	NA	8.6-8.9	8.7
EC (µS/cm)	250	NA	250-500	2005-3013	2754.5
TDS (mg/L)	500	500	NA	10405-12006	11353.75
TH (mg/L)	150	300	100-500	121-180	138.5
Ca^{2+} (mg/L)	75	75	NA	7.5-41.8	26.38
Mg^{2+} (mg/L)	50	30	30-250	1.9-7.4	4.9
Na^+ (mg/L)	120	NA	200	9.5-35.5	24.98
K^+ (mg/L)	12	NA	NA	4.2-20.5	9.68
Fe^{2+} (mg/L)	0.3	0.3	0.2	0.01-0.40	0.12
HCO_3^-	300	600	NA	78.5-248	147.8
SO_4^{2-}	200	200	250	14.2-43.1	26.28
Cl^-	250	250	250	432-724	502.75

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