Evaluation of Sea water Intrusion in Freshwater Aquifers in a Lagoon Coast: A Case Study of the University of Lagos Lagoon, Akoka, Nigeria

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ABSTRACT: A geophysical technique has been employed to investigate seawater intrusion into freshwater aquifers in the coastal environment of the Lagos lagoon at the University of Lagos campus, Akoka, south-western Nigeria. Electrical resistivity method employing the Schlumberger array was used to acquire data for six vertical electrical soundings to investigate the vertical extent of seawater intrusion. The study revealed that the subsurface in contact with the lagoon was invaded by saline oceanic seawater. The Schlumberger electrode array which utilized current electrode half spacing from 1m to 500m was used to acquire both resistivity and induced polarization data in the proximity of the Lagos lagoon. Typical curve types reported for coastal areas such as the KQ, KQQ, and HKQ were observed in the investigated area and 4-6 geoelectric layers were delineated at an average depth of 71m. The subsurface lithology comprised of fine through medium grained sand to coarse sand intercalated in most cases with sandy clay and clayey sand. The resistivity of the intruded saline water was found to range between 1.8-37.2 Ωm at a depth interval of 0.7-79 m and the thickness of saline layers was found to be greater in the proximity of the coastline. The result of the investigation revealed that even under non-pumping conditions, the study area suffers from acute saline water intrusion and could be aggravated if there is groundwater abstraction. Ways to check the seawater intrusion problem through artificial recharge have been proposed in the study. [New York Science Journal. 2009;2(3):32-42] (ISSN: 1554-0200).

Keywords: Geoelectric sections, resistivity, seawater intrusion.

1. Introduction

Over time, there has been heavy reliance on groundwater resources to supplement surface freshwater supplies for use in domestic, industrial and agricultural requirements. Most times, however, groundwater resources are preferable to surface water resources on the basis of easier protection from pollution and better dependability during drought periods. It has also been found that groundwater supplies are more economic in purification aspects than alternative water supplies, specifically surface water resources.

Coastal sedimentary basins the world over have been inundated by saline oceanic seawater intrusion which leads to the invasion of wells drilled to the subsurface to yield freshwater by saline water, and Nigeria has not been an exception. Saltwater intrusion in coastal aquifers in Nigeria have been a source of public grievance as several wells drilled to the groundwater table were abandoned only a few months after due to saline water intrusion. Even in some areas, freshwater supplies from groundwater sources have been impossible due to saline water dominating aquifers. Saltwater intrusion is a natural process that occurs in virtually all coastal aquifers, it is not only a national phenomenon, but a global crisis.

In characterizing the extent of this occurrence, attempted studies have been directed particularly to coastal areas in contact with seas, but rather few studies have been conducted to evaluate the possibility of the occurrence via a lagoon. Even most studies in this regard attribute the seawater as being relict and neglect the obvious impact of the saline water bodies. With a maritime area of about 46,500 km^2 and a coastline of 853km parallel to the Atlantic ocean, Lagos, is essentially a maritime state backed up by numerous rivers, lakes, creeks, swamps and lagoons; in an attempt to evaluate the possibility of seawater intrusion to the subsurface via the lagoon, this study was conducted.

The investigation of seawater intrusion in freshwater aquifers has been based on geophysical techniques especially the electrical resistivity and electromagnetic methods which relies on resistivity contrasts as the seawater intruded zone is approached, (Goldman *et al.,* 1989; Fitterman and Deszcz-Pan, 2001; Kontar and Ozorovich, 2006; Khalil, 2006; Al-sayed and El-Qady, 2007); their studies were carried out in the proximity of seas. The presence of seawater causes groundwater to be considerably saline, hence the aquifer resistivity is reduced considerably, and the resistivity method can delineate the boundaries of the body of saline water. The fact that a resistivity contrast exists at the interface between fresh and saline water is sharp, the resistivity method has proved useful.

A geochemical study can also be used to determine the possibility of seawater intrusion and this has been used by Lee and Song, 2007. However, for enhanced results, a combination of geophysical and geochemical analysis have proved useful, (Hwang *et al.,* 2004).

Oyedele (2001) combined a geophysical and geochemical analyses to show the presence of seawater intrusion in Victoria Island and Iwaya in Lagos state, south-western Nigeria. He suggested that the freshwater/saltwater interface (FWSWI) is relatively shallow and water withdrawals are from depths close to the FWSWI. And he contends that excessive groundwater withdrawals can increase the incidence of seawater intrusion.

Adepelumi *et al.* (2008) in an attempt to demarcate possible areas for groundwater development in the Lekki area of Lagos state, obtained resistivity results which revealed a dominant trend of decreasing resistivity with depth, indicating an increase in salinity with depth. They however traced the presence of the salinity to excessive groundwater pumping and the reduction of groundwater gradients. They established the inherent presence of saline water in the subsurface of their area of investigation as being trapped during the transgressive, and the regressive movement of the ancient sea during the quaternary times when some sediments were contemporaneously deposited under marine condition. They inferred that the saline water found at a shallow depth (10-30 m) was probably trapped during marine transgression and/or it migrated from depth by differential pressure-gradient. One can infer the source of saline water in the subsurface as connate according to the referenced report. They, however, did not particularly cite the influence of the lagoon which surrounded their study area. Their analysis is based on Kingston *et al* (1983) who suggested that prior to the fluctuation of the sea level in Lagos area, series of miogeoclinal depressions were formed at the edge of the rifting Atlantic Ocean. These depression zones were later filled with seawater where the sediments were deposited. It can be inferred that the saltwater was trapped during the period of marine deposition. The possibility of seawater intrusion by the tidal movement of saline seawater presently was not examined. And this study attempts to bridge that gap.

The Lagos lagoon coast bordering the University of Lagos to the east on the lagoon front overlooking the university guest houses, senate building, University library, human resources development board offices and the faculty of engineering are the focus of the study. It lies on latitude 6°30′40′′N and 3°24′52′′E longitude. It lies on marshland of vast mangrove and freshwater swamps, surrounding a small and much dissected table land consisting of freshwater swamp forest, mangrove swamp forest, sandy plain vegetation and rainforest vegetation (Ayolabi, 2004). The Lagos lagoon borders the university campus to the east and south. Bariga borders it to the north while Yaba lies towards the west. A canal runs along almost the whole of the western stretch of the university, while a marsh which has an open connection to the lagoon encompasses the whole of the northern stretch of the University, linking up with the canal in the west.

2. Hydrogeologic Setting of the Study Area

The study area is situated in Lagos State (figure 1) which is found within the Benin basin. The geology has no basement outcrop. It lies on the longitude 3^0E and latitude 7^0N with alternate wet and dry seasons. The Benin basin extends almost from Accra in Ghana, through the Republics of Togo and Benin to Nigeria where it separated from the Niger- Delta basin by Okitipupa ridge

(Ondo state) at the hinge of the Benin flank. The bottom of the sedimentary basin in the Benin basin consists of unfossilferous sandstones and gravels weathered from the underlying Precambrian basement. On top of these are marine shales, sandstones and limestones of Albian to santonian ages.

The area of investigation is low-lying with some depressions observed which are prone to flooding, as they are apparently below the surface of the lagoon.

The surface geology is made up of the Benin formation (Miocene to Recent) and the recent littoral alluvial deposits. The Benin formation consists of thick bodies of yellowish (ferruginous) and white sands (Jones and Hockey, 1964). It is friable, poorly sorted with intercalation of shale, clay lenses and sandy clay with lignite. The formation is overlain in many places by considerable thickness of red earth composed of iron-stained regolith formed by weathering and ferruginization of the rode (Onyeagocha, 1980). Multi-layer aquifers have been classified by Longe *et al.* (1987) into three types-the first encountered at a depth of 38m of average thickness of 8m and is not a major source of water supply and stands the risk of pollution because of its nearness to the surface. The aquifer probably belongs to the recent littoral/alluvial depth of 30m to 120m below sea level near the coast, it consists of an alternating sequence of sands and clay. The aquifer probably belongs to the continental Ilaro formation which is described as a sequence of predominantly coarse sandy estuarine deltaic and continental beds. The third aquifer is made up of alternating sequences in shape. This aquifer is the most productive and exploited region. It occurs between depths of 30-100 m below sea level in inland areas and 120-270 m near the coast. The thickness varies between 10 and 35 m. The aquifer most likely forms part of the Ilaro formation.

In the Benin basin, salt water intrusion into recent sediments aquifers occurs beneath a freshwater lens in a belt stretching from the coastline to a distance of 5km in some places. Saltwater intrusion has also been found to occur in the confined aquifers of the coastal plain sands in a zone stretching from Apapa to Lekki within Lagos metropolis (Oteri and Atolagbe, 2003).

Lagoons are common features on the Guinea coast of West Africa. The Lagos lagoon with a surface area of 6354.798km^2 is open, tidal and brackish, and is the largest of the eight lagoons in southwestern Nigeria. The Lagos lagoon, a water body in the heart of the metropolis, cuts across the southern part of the metropolis, linking the Atlantic Ocean (in the west and south) and the Lekki lagoon (in the east). The Lagos lagoon consists of three main segments, Lagos harbour, the metropolitan and Epe division segment.

The bottom water of the lagoon has high temperatures which were relatively constant throughout the year. The temperatures varied between 32.7^{o}C in December 2002 at the entrance of the Ogun river near Ikorodu and 27^{o}C in 2003. During the rains (April to November) the influx of river water and heavy cloud cover in the sky resulted in a gradual fall of the temperatures to a minimum of 26^{o}C.

There is differential salinity in the lagoon due to the effect of the Atlantic Ocean. The bottom deposits ranged from coarse shelly sand around the mouth of Lagos harbour through various grades of muddy sand to mud. Sandy mud or muddy deposits occurred in the central areas with muddy sand or sand being attributed to the fast water currents in the area. The seabed in the metropolitan areas is relatively higher and increases towards the Epe segment of the lagoon. The seabed has been distorted by semi and large scale mining especially towards the Ikorodu area of the lagoon.

All the water bodies dominating Lagos State, the Lagos lagoon inclusive, others have a common connection to the Atlantic Ocean via the commodore channel (see figure 1). Thus some of the hydrologic conditions prevailing in the Gulf of Guinea are reflected to some extent in the Lagos lagoon, going by the definition put forward earlier.

The entire Gulf of Guinea is highly stratified with a thin surface layer of fresh tropical water overlying high salinity subtropical water (because of density difference). An additional contribution of saline water comes from subducted subtropical water from the Atlantic Ocean.

This saline water communicates with the Lagos lagoon via the Commodore channel largely dependent on the direction of the tides.

3. Data Acquisition and Processing

In this work, a total of six VES points were occupied along selected traverses namely AA', BB' and CC'. The traverses AA' and CC' were taken parallel to the shoreline of the lagoon stretching westward, while the traverse BB' was taken perpendicular to the shoreline. The Schlumberger electrode array was utilized for the data acquisition which was done with the ABEM terrameter SAS 1000. The current electrode half spacing for the survey ranged from 1 to 500m in successive steps.

The field data were curve matched using the conventional curve matching technique and the layer parameters obtained were used as an input model for a fast computer iteration and modelling software known as RESIST©. The application of this software is a standard procedure for obtaining a fairly accurate estimate of the subsurface resistivity distribution.

The addition of Induced Polarization (IP) data to a resistivity investigation improves the analysis of resistivity data in three ways: (1).Some of the ambiguities encountered in resolving thin stratigraphic layers while modeling electrical resistivity data can be reduced by the analysis of IP data, (2).IP data can be used to distinguish geologic layers which do not respond well to an electrical resistivity survey; and (3).The measurement of another physical parameter (electrical chargeability) can be used to enhance a hydrogeologic interpretation such as discriminating equally electrically conductive targets such as saline, electrolytic or metallic-ion contaminant plumes from clay layers.

The interpreted data were contoured in order to observe the resistivity, thickness, and depth of saline layers and the freshwater/saltwater interface (FWSWI). The SURFER© 8 software was used in producing the maps.

4. Discussion of Results

The analysis of resistivity data revealed the presence of four to five geoelectric layers along profiles AA' and BB' while six geoelectric layers characterized profile CC'. Typical curve types characteristic of saline water intruded zones were observed such as AKQ, KQH, KQ and KQQ. The curves were found to descend gently indicating a conductivity decrease which can be explained in terms of the seawater intrusion into subsurface formations. The descending segment of the VES curves are characterized by a steeply low resistivity zone (figure 2). The IP curves were interpreted thus: the electrode-depth ratio was used to estimate the depths at various electrode spacings. Chargeabilities of < 50msec were interpreted as sand, while those >50msec or negative were interpreted as clay; fluctuations in the IP profile was not unconnected with the clay and sand mixture. These were interpreted as sandy clay or clayey sand depending on the degree of fluctuation.

The correlation of the resistivity, IP (figure 3) and available borehole log in the study area revealed that the topsoil along traverse AA' is made up of fine to medium sand with characteristically low resistivity attributed to the overflow of saline oceanic seawater via the lagoon. The resistivity ranges between 11.5 Ωm to 43.7 Ωm with a thickness ranging from 0.7 m to 1.7 m. This layer is underlain by a medium sand bed which is the second geoelectric layer of resistivity 3.4 Ωm to 74.9 Ωm, and thickness of 2.2 m to 9.9 m. The third geoelectric layer beneath this traverse is a continuous sandy clay formation which grades into the fourth geoelectric layer beneath VES 1, 2, 3 and 4; and into the fifth geoelectric layer beneath VES 2. These layers are considered to suffer from acute seawater ingress, with formation resistivity of 7Ωm to 42.10 Ωm. The thickness of this layer ranges from 12 m to 70 m. (See figure 4). The fifth layer beneath VES 4 is a high resistivity coarse sand or clayey sand formation.

The geoelectric section along traverse BB' consists of VES 5. The topsoil is the first geoelectric layer with formation resistivitiy>100 Ωm and is made up of coarse sand. The second geoelectric layer, even though it is a relatively good freshwater aquifer; apart from its proximity to the surface and consequently, exposure to pollution, it's thickness of 0.9 m does not favour exploitation. The third geoelectric layer can be considered as the zone of rapidly mixing fresh and saline water. With a formation resistivity of 64.1 Ωm and thickness of 5.8m, it is comprised of medium sand/ sandy clay. The fourth geoelectric layer suffers from acute saline water intrusion due to the presence of seawater. With a resistivity of 1.8 Ωm and thickness of 12.8 m, it is composed of sandy clay. It is underlain by a coarse sand/clayey sand freshwater aquifer zone of unknown thickness and resistivity of 210.7 Ωm.

The geoelectric section along traverse CC' consists of VES 6. The topsoil is sand formation with a resistivity of 47.9 Ωm and 0.8 m thick. The second and third geoelectric layers which are coarse sand beds are freshwater bearing aquifers saturated by very good quality freshwater. The formation resistivities are 260.7 Ωm and 309.9 Ωm, and 1.2 m and 6 m thick respectively. The fourth geoelectric layer is composed clayey sand, saturated with good quality water. The resistivity of this layer is 89.7Ωm and it is 29.9m thick. The fifth geoelectric layer has a resistivity of 8 Ωm, and 34 m thick. The lithology which is composed of saline-water saturated clayey formation is underlain by coarse sand bed which bears very good quality water. This layer has a resistivity of 532.5 Ωm.

The interpreted data were subjected to processing using the SURFER 8 Golden software to produce the various contour maps. These show the lateral and horizontal extent of saline oceanic seawater intrusion. The study area shows evidence of subsurface formations by saline water intrusion. The depth of penetration of saline water intrusion increased from the lagoon coastline inwards.

Maps of isoresistivity surfaces for estimating depth to saline and freshwater zones at the locations occupied are shown in the figures below (figure 5a-f). The observed trend is that the thickness of the saline water formation is increasing towards the coast. In addition, the depth to the saline water zone is found to be relatively shallow near the coast compared to inland areas. The depth to the FWSWI varies from about 72 m near the coast to about 20m in inland areas. The resistivity of the freshwater aquifer is found to decrease as distance from the coast increases.

The isoresistivity contour map for saline water surfaces indicates that the resistivity of saline water tends to decrease towards the coast. Higher resistivity values are observed further away from the coast, i.e. at Tafawa Balewa way. It is expected however that this resistivity grades gradually through intermediate water to good quality water as distance from the coast keeps increasing. And the isoresistivity map for freshwater shows that reasonably good aquifers containing very good quality water can be found far away from the coastline. This is attributable to the high resistivity values which are observed as the distance from the coastline increases.

The depth to saline water surfaces is shallower in the proximity of the lagoon. With an increase in the distance from the coastline, the depth to saline water surfaces increases to about > 22 m. The traverse taken at Tafawa Balewa way was at a higher elevation than those occupied at the Lagoon Front and Oduduwa Drive in which the water and ground level were approximately the same. The explanation then was that the salts are transported when there is overflow, moved further by wind action, settle gravitationally and are pushed down the subsurface by meteoric water. In the case of Tafawa Balewa way, the saline water hits the wall of the adjoining ground carrying some sediments, salts inclusive. Further lagoon water hitting the walls transports the salts further until they meet an impermeable layer which traps the salts.

The thicknesses of saline water zones are greater in the proximity of the lagoon. Less thick beds are found away from the lagoon. The thickness of saline water intrusion is lowest at Oduduwa Drive because it is dominated by freshwater aquifers and the most we can find is intermediate water of rapidly mixing fresh and saline water.

The salinity problem may exist due to upward movement of water and salts from groundwater. For coastal aquifers, the influence of seas, oceans, and lagoons are predominant. Since it is a saline problem, the validity of including lagoons in the picture have been emphasized.

The salt enrichment process of the subsurface is spread over to thousands of millions years, during which the determining parameters of rainfall, hydrology and other climatic factors have not remained constant. Much as we do not want to envisage relict seawater, whether or not it occurs, or the salinity can be attributed to saline surface water intrusion shall become apparent at the end of this treatise.

One of the potential causes of subsurface salinity which does not require too geologically long a time, has been reported by Achari *et al.* (2005) was the inundation of an entire barrier by the surface influx of seawater where the tsunami impact on groundwater quality was assessed. They proferred an explanation for the process that led to groundwater salinization thus: when seawater ingressed over the surface, by waves with heights ranging from 4 to 7 m, it carried along some dissolved salts, which were lodged in the soil. The salts brought by the mighty waves sink into the soil and with the first rains of the year, the absorbed salts leach down to the groundwater aquifer and contaminated it. When the dry summer months advance, evaporation causes the salt to accumulate in the subsurface, pending recharge (by the sea, which brings in more salts anyway). Rainfall recharge pushes the saltwater, further down in an attempt to establish hydrodynamic equilibrium capillary rise in rainless months push the salts up. In all, the soil salinity is significant for a considerably long time and is a continuous process.

Table 1: Summary of Interpretation

VES No	Geoelectric Layers	Resistivity (Ωm)	Thickness (m)	Depth (m)	Curve Type	Probable Lithology	Inferred Interpretation
1	1	37.50	1.2	1.2	KQ	Fine to medium sand	Topsoil
	2	58.30	9.9	11.1		Medium sand	Intermediate quality water
	3	33.33	101.0	112.2		Sandy clay	Saline water
	4	9.00	-	-		Sandy clay	Saline water
2	1	41.50	1.7	1.7	KQQ	Fine to medium sand	Topsoil
	2	74.90	6.5	8.2		Medium sand	Intermediate quality water
	3	37.20	12.5	20.8		Sandy clay	Saline water
	4	34.50	58.4	79.2		Sandy clay	Saline water
	5	7.60	-	-		Sandy clay	Saline water
3	1	43.7	1.6	1.6	KQ	Fine to medium sand	Topsoil
	2	56.9	9.1	10.7		Medium sand	Intermediate quality water
	3	42.1	59.2	69.9		Sandy clay	Saline water
	4	12.70	-	-		Sandy clay	Saline water
4	1	11.5	0.7	0.7	HKH	Fine to medium sand	Topsoil
	2	3.6	2.2	2.8		Sandy clay	Saline water
	3	61.6	16.6	18.8		Medium sand/Sandy clay	Intermediate quality water
	4	7.0	52.4	71.2		Sandy clay	Saline water
	5	514.1	-	-		Coarse sand/ Clayey sand	Very good quality water
	1	101.00	0.7	0.7		Coarse sand	Topsoil
	2	131.60	0.9	1.6		Coarse sand	Very good quality water

5	3	64.1	5.8	7.4	KQH	Sandy clay	Intermediate quality water
	4	1.8	12.8	20.2	-	Sandy clay	Seawater/ very saline water
	5	210.7	-	-		Coarse sand/ Clayey sand	Very good quality water
6	1	47.9	0.8	0.8	AKQH	Fine to medium sand	Topsoil
	2	260.7	1.2	2.0		Coarse sand/ Clayey sand	Very good quality water
	3	309.9	6.0	8.0		Coarse sand/ Clayey sand	Very good quality water
	4	89.7	29.9	37.9		Clayey sand	Good quality water
	5	8.0	34.0	71.9		Clay	Saline water
	6	532.5	-	-		Coarse sand/ Clayey sand	Very good quality water

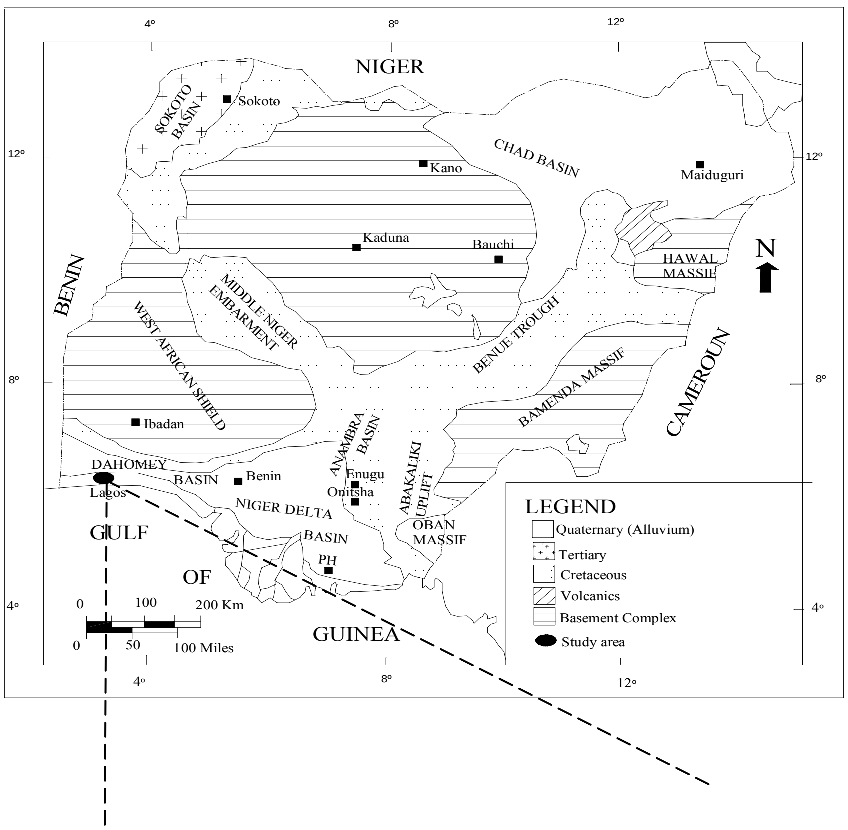
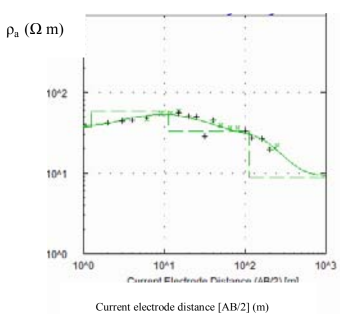
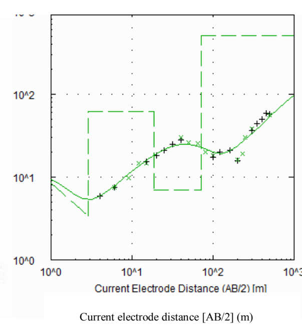


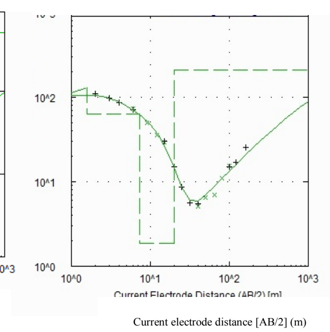
Figure 1: Geological map of Nigeria showing the location of the study area. Inset is the image of Lagos state showing the distribution of lagoon water up to the study area.



a.Iterated curve for VES 1

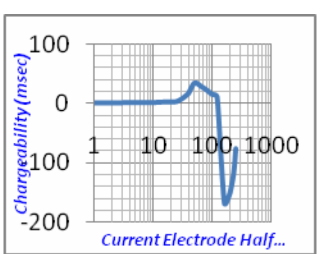


b.Iterated curve for VES 4

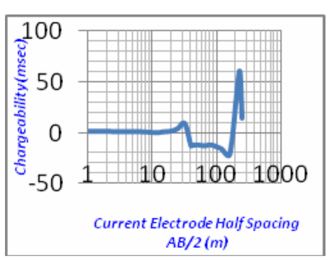


c. Iterated curve for VES 5.

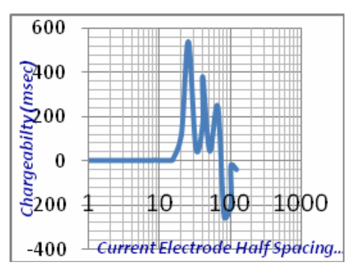
Figure 2a-c: Representative samples of computer iterated resistivity curves



a.IP curve for VES 1



b.IP curve for VES 3



c.IP curve for VES 5

Figure 3a-c: Representative samples of induced polarization curves.

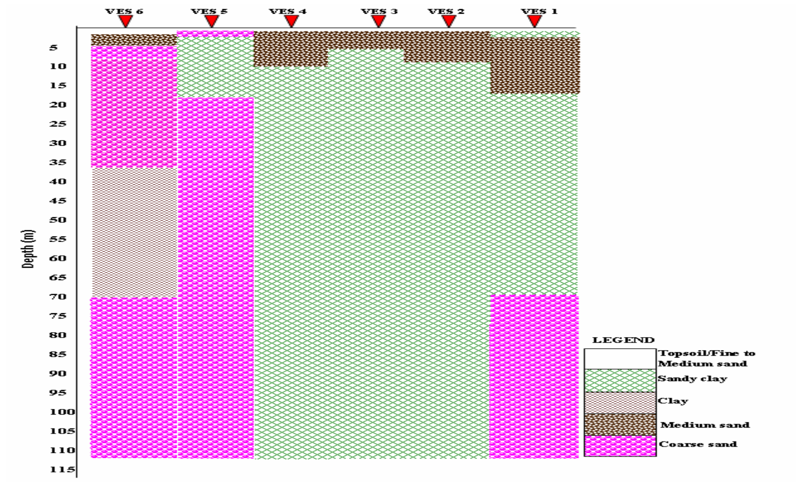
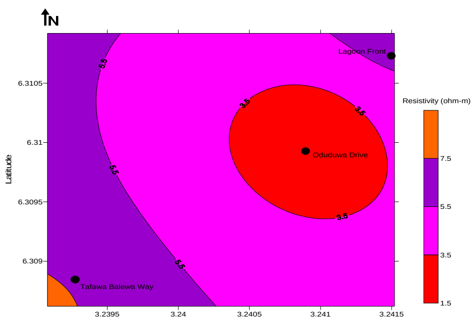
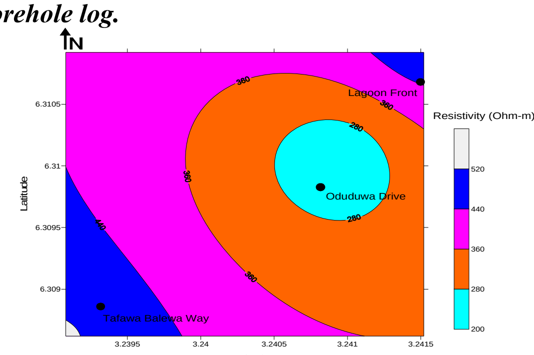


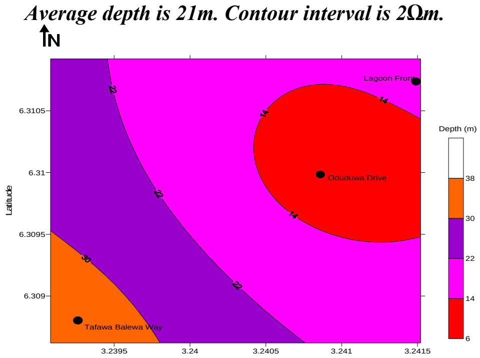
Figure 4: Subsurface conceptualisation of the study area inferred from the VES and IP interpretation correlated with the available borehole log.



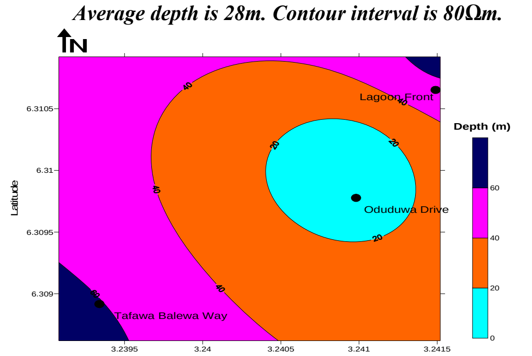
a.Isoresistivity map for saline water horizon (2-46Ωm). Average depth is 21m. Contour interval is 2Ωm.



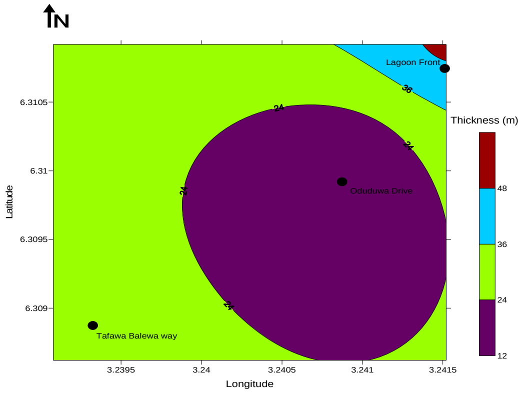
b.Isoresistivity map of freshwater aquifer. Average depth is 28m. Contour interval is 80Ωm.



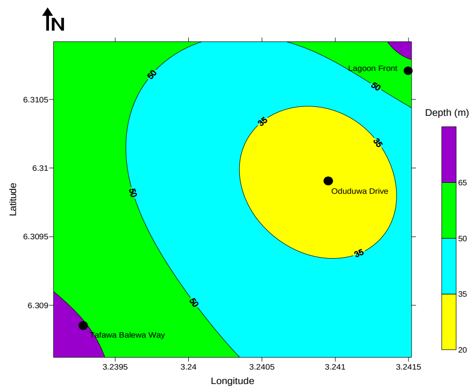
c.Depth to saline water isoresistivity surface. Contour interval is 8m.



d. Depth to freshwater aquifers. Contour interval is 20m.



e.Isopach map of saline beds. Contour interval is 10m.



f. Contour map of depth to freshwater/saltwater interface Average depth is 54m. Contour interval is 15m.

Figure 5a-f: Isoresistivity, isopach and depth maps of the study area.

5. Conclusion

In evaluating seawater intrusion into coastal aquifers of lagoonal environments, six vertical electrical sounding measurements were conducted at selected stations at the University of Lagos, Akoka; to acquire both resistivity and IP data. From the one dimensional interpretation of the acquired data, it was found that saline water intrusion which is characteristic of seawater penetrated the subsurface in contact with the lagoon. The depth of the intrusion increased as distance from the coastline increased. In addition, typical curve types which are characteristic of coastal Nigeria sedimentary basin such as the KQ, KQQ, KQH, HKQ and AKQH were observed in the study area.

The astonishing rapidity with which saline water inundates the subsurface has been elucidated and elaborated. The study shows that the area suffers from acute saline water intrusion. It also attempted to look at the origin of the salts as being due to the deposition of sediments during flow towards land areas and the influence of meteoric water which serves to push some of these sediments down the subsurface. The study however, is not a radical departure from the view that saline water found its way into the aquifers due to an upwelling of saline water, whose origin is connate. Infiltration ponds whose water are natural floodwaters can be used to recharge coastal aquifers so that the rate of withdrawal is balanced by the rate of freshwater recharge.

Seawater intrusion is a natural phenomenon in coastal aquifers. Whether we like it or not, it occurs. Ways in which this happens have been examined. However, it becomes problematic when man withdraws water close to coastal areas. So in attempting to minimize the problem, monitoring its expansion and retreat, a geophysical approach has been proposed.

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