Delineation of Saltwater Intrusion into the Freshwater Aquifer of Lekki Peninsula, Lagos, Nigeria

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Abstract

Recently, the deterioration of water quality in the coastal zones of Lekki Peninsula area of Lagos due to saltwater infiltration into the freshwater aquifer has become a major concern. With the aim of providing valuable information on the hydrogeologic system of the aquifers, the subsurface lithology and delineating the groundwater salinity, vertical electrical resistivity (VES) sounding survey was carried out utilizing surface Schlumberger electrode arrays and electrode spacing varying between 1 to 150 m. The DC resistivity surveys reveal significant variations in subsurface resistivity within the coastal sediments. The VES resistivity curves obtained also show a dominant trend of decreasing resistivity with depth (thus increasing salinity). In general, the presence of four distinct resistivity zones were delineated viz: the unconsolidated dry sand (A) having resistivity values ranging between 125 to 1,028 Ohm-m represent the first layer; the fresh water-saturated soil (zone B) having resistivity values which correspond to 32-256 Ohm-m is the second layer; the third layer (zone C) is interpreted as the mixing (transition) zone of fresh with brackish groundwater. The resistivity of this layer ranges from 4 to 32 Ohm-m; while layer four (zone D) is characterized with resistivities values generally below 4 Ohm-m reflecting an aquifer possibly containing brine. The rock matrix, salinity and water saturation are the major factors controlling the resistivity of the formation. Moreover, this investigation shows that saline water intrusion into the aquifers can be accurately mapped using surface DC resistivity method.

Keywords: Resistivity, Coastal, Saline water, Aquifer, Nigeria

Introduction

Saline intrusion into coastal aquifers has become a major concern (Batayneh, 2006) because it constitutes the commonest of all the pollutants in freshwater, therefore, understanding of saline intrusion is essential for the management of coastal water resources (Ginzburg and Levanon, 1976). Various workers around the world have carried out geophysical survey to demarcate the interface between freshwater and saline water. For example, Lee and Song (2007) investigated the saltwater intrusion problem in the coastal area of South Korea, they observed that salinization of fresh groundwater is highly associated with groundwater withdrawal. Also, Barret et al (2002) successfully used DC resistivity method to map perched water tables containing saline-water and freshwater lenses in southern Australia. Nowroozi et al, (1999) mapped the saltwater/freshwater interface in the geological setting of the Eastern Shore of Virginia. Furthermore,, Frohlich and Urish (2002) showed that the deterioration of freshwater quality due to natural seawater infiltration affects the balanced life of the narrow coastal strip of Rhodes Island, USA. In-addition, Urish and Frohlich (1990) and Frohlich et al., (1994) observed that the discharge of a large volume of groundwater may allow saltwater intrusion into the freshwater aquifers, and this potential saltwater contamination poses a threat to the sustainable development and economic well being of any coastal area. In Southeastern Nigeria, Oteri (1988) delineated the depth to the top of the freshwater sands underlying the saline water sands to vary from 77 to 947 m below ground level. Choudhury et al., (2001) reported that saline water intrusions into coastal aquifers have resulted in acute environmental problems in the past. They further confirm that the extent of saline water intrusion is influenced by the nature of geological formations present, hydraulic gradient, rate of withdrawal of ground water and its recharge.

Owing to massive influx of people from other parts of Nigeria to Lagos metropolis (rural-to-urban migration), the population of Lagos has increased from ten to fifteen million in the recent times, and there is annual population increase of 3 % (UNDP, 2006). There is a concomitant acute water shortage to meet the daily demand of the people. Therefore, most of the residents depend on borehole water both for domestic and industrial usage. According to the estimate of Longe et al. (1987), over 10 million gallons of water are extracted from the multi-layer aquifers existing in the area per day. However, most of the boreholes drilled in the coastal area of Lagos were abandoned due to saltwater intrusion into the aquifers. Due to the severe saltwater intrusion into the aquifer, potable water supply to inhabitants in some of the communities in the coastal belt of Lagos has been a major problem. Therefore, geophysical survey was carried out to mapped possible saltwater intrusion, and fresh water interface in Lekki area of Lagos. Three parallel traverses each having 600 m length was established across the survey area. The traverses were separated from each other by 150 m. Subsequently, twenty-nine vertical electrical resistivity sounding (VES) points using Schlumberger configuration were occupied on the traverses (Fig. 1).

The Lekki-Peninsula is located in the south-eastern part of Lagos State. It lies between Latitudes $6^0$27' and $6^0$27'30''N and Longitudes $3^0$27' and $3^0$30'E in South-Western Nigeria. The study area is situated within the Western Nigeria coastal creeks and lagoons (Pugh, 1954) developed by barrier beaches associated with sand deposition. It forms part of the Lagos lagoon system known to be the largest of the four Lagoon system of the Gulf of Guinea Coast (Adepelumi and Olorunfemi, 2000). The survey area covers approximately 280,000 m^2 (Fig. 1), and was earmarked for immediate development by the Lagos government. Although there are various geophysical techniques that are commonly employed for groundwater investigation in coastal environment, however, electrical resistivity methods are the most unique because of their ability to detect increases in the conductivity of an aquifer that result from increases in pore-water conductivity (Abdul Nassir, et al., 2000; Ebraheem et al., 1997). Coupled with the fact that electrical conductivity of an aquifer is controlled primarily by the amount of pore spaces (that is, the porosity), and by the salinity of the water in the pore spaces; therefore, increase in either the porosity or the concentration of dissolved ions will result in increase in the conductivity of the groundwater (Stewart, 1999). Electrical resistivity method was chosen for this work based on the results obtained by previous of workers like Van Overmeeren (1989), Goldman et al., (1991) and Nowroozi et al. (1999) that confirmed the existence of distinct resistivity contrast between freshwater and saline-waters in coastal aquifers of Yemen, Isreal and Virginia, USA.

The thrust of this research is to delineate the possible saline-water contaminated zones; the saline-water/freshwater interface; and to ascertain the nature of subsurface geological formations. The main objective was to demarcate areas for groundwater development that is not susceptible to saline-water intrusion risk.

Geology and Physiography

The Lekki-Peninsula is located within the Western Nigeria Coastal Zone – a zone of coastal creeks and lagoons (Pugh, 1954) developed by barrier beaches associated with sand deposition. It is situated within the Nigerian sector of the Benin-basin and near the eastern margin of the basin. The geological formations of the study area composed of sediments laid down under fluviate, lascustrine and marine environments. These sediments grade into one another and vary widely in lateral extent and thickness (Adepelumi and Olorunfemi, 2000). The surface geology of the study area is made up of the Benin Formation (Miocene to Recent), recent littoral alluvial, lagoon and coastal plain sand deposits (Longe et al, 1987). The fluctuation of the sea-level during the Quaternary times affected the formation of the alluvium deposits. 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 coarsed to medium grained, clean white loose sandy-soil that graded into one another towards the lagoon and near the mouth of the larger rivers.

However, lithostratigraphic information from boreholes in and around Lekki-Peninsula reveals that typical section of the stratigraphy consists of unconsolidated dry and wet sand, and organic clay deposit. The deposits are sometimes interbedded in places with sandy-clay or clayey-sand and mud with occasional varying proportion of vegetable remains and peat. The environment of deposition of these sediments was suggested to be near-shore littoral and lagoonal (Longe et al, 1987).

The Lekki-Peninsula area comprises of five geomorphological sub-units comprising of: The abandoned beach ridge complex; the coastal creeks and lagoons; the swamp flats; the forested river floodplain and the active barrier beach complex (Adegoke et al, 1980). The topography is generally low lying and flat with several points at sea-level. This makes the area prone to periodic flooding. The survey area runs almost parallel to the coast. It is separated from the Gulf of Guinea by a narrow old barrier beach sand and a relatively younger barrier beach sand. This configuration is related to the direction of the south-westerly prevalent wind, tidal and wave current from the Atlantic Ocean.

The coastal landscape in the Lekki-Peninsula area contains multi-layer aquifers that are harnessed through hand-dug wells with very shallow depth extent Longe et al, (1987) delineated three major aquifer zones in the region, and they suggested that the aquifers belong to the recent littoral and alluvium deposit, and the Benin Formation. The first aquifer is a water table aquifer that is prone to pollution because of its nearness to the ground source. The second and third are confined aquifers made up of an alternating sequences of sand and clay. They are harnessed through boreholes and are the basis of mini-water works in Lagos area. These aquifers belong to the continental Ilaro Formation. The third aquifer is the most productive and most exploited horizon. Groundwater exists under confined to semi-confined condition within the sandy horizon which is sandwiched between the clay horizons. The water water table ranges in depth from 2.0 to 15.0 m below ground level (b.g.l). In-addition, the study area is well drained by rivers and streams which flow in a southerly direction through the creeks into the lagoon and the Atlantic Ocean. The total annual rainfall in the area ranges from 1200 to 2100 mm, the major portion of which occurred between June and October.

Methodology

DC Resistivity data acquisition, processing and inversion

In this work, a total of Twenty-nine (29) Vertical Electrical sounding (VES) data was acquired on the established three traverses labeled A-A”, B-B” and C-C”. The traverses are each 600 m in length, while the traverses are separated by a distance of 150 m (Fig. 1). The ABEM SAS 1000C terrameter was used for the resistivity measurement. Throughout the survey, the half-current electrode separation (AB/2) varying from 1 to 150 m was used.

The field resistivity data was interpreted using the 1-D inversion program of Pirttijärvi (2005). The curves were interpreted with a minimum number of layers that are deemed necessary, and that are qualitatively recognizable on the field curves. It is possible that more layers than the recognizable ones are present, which we then declare as being electrically suppressed. We only add suppressed layers if borings or models from adjacent soundings suggest their existence and if they produce an acceptable fit. Also, the degree of uncertainty of the computed model parameters and the goodness of fit in the curve fitting algorithm are expressed in terms of residual error (RMS). The resistivity of the different layers and the corresponding thickness are reproduced by a number of iterations until the model parameters of all the VES curves are totally resolved with minimum residual error. At this stage, the final subsurface 1-D resistivity image that best explains the data is obtained. Typical resistivity sounding curve obtained after it has been subjected to the processing procedure explained above is shown in Figures 2.

However, the nature of field data for the 29 VES data (See Fig. 2) indicates the influence of 2D effects due to near-surface inhomogeneities. Monteiro Santos et al (1997b) showed that such lateral inhomogeneities often give rise to very thin and low resistive false layers in VES curves, which are likely to be misinterpreted as water-bearing zones. In such cases, 1-D interpretation is not always able to properly present a realistic resitivity model because of the high degree of misfit between field data and model response. Therefore, in order to account for the near-surface inhomogeneities in the data; understand to what extent 1-D approximations represent the true subsurface resistivity structure, and also retrieve the subsurface geology that best fit the VES data; thus, 2-D inversion was carried out on the data. The 2-D resistivity cross-sections were created through an inversion process using the WinGLink Software (2007). The resistivity data acquired along each traverse was used as input into the 2-D inversion program. The 2-D subsurface resistivity structure existing beneath traverses A-A", B-B" and C-C" were revealed through the inversion process. According to Jupp and Vozoff (1975), inversion of the field observations is the standard procedure to obtain an estimate of the true resistivity distribution in the subsurface. The inversion method involves the estimation of the parameters of a postulated earth model from a set of observed data. It may be viewed as an attempt to fit the response of an idealized subsurface earth model to a finite set of observed data. In this work, a smoothness-constrained algorithm was used to invert the apparent resistivity data (Adepelumi et al, 2006). The algorithm used is iterative and fully automated. A reliable 2.5-D finite-element method was used for the calculation of the Jacobean matrix and the apparent resistivity. The inversion estimates a resistivity model by minimizing the difference between the observed and the calculated data. The roughness of the resistivity model is also minimized in the smoothness constrained inversion method by imposing a smoothness condition (Tsourlos et al., 1998). Figures 3-5 shows the inverted 2-D section of profiles A-A", B-B" and C-C".

The subsurface layer resistivities obtained by the inversion process are controlled by the resistivity of the pore water and the resistivity of the host rock (Burger, 1992). According Nowroozi et al, (1999) resistivity of water may vary from 0.2 to over 1000 Ohm-m depending on its ionic concentration and the amount of dissolved solids. Average seawater has a resistivity of 0.2 Ohm-m. Resistivity of natural water and sediments without clay may vary from 1 to 100 Ohm-m m while the resistivity of wet clays alone may vary from 1 to 120 Ohm-m. The resistivity of a layer saturated by saline water and some dissolved solids is in the range of 8 to 50 Ohm-m. Thus, a wide range of resistivity is often reported for a particular water saturated material.

Discussion of Results

Twenty-nine (29) VES stations were occupied in the Lekki Peninsula area of Lagos Nigeria (Fig. 1). The interpretation of the sounding curves shows that the following nine curve types exist, viz: AKQ, AQH, KHK, KKH, KQH, KQQ, HKQ, QQH and QQQ types. These curves are typical of what are obtainable in coastal environments of Nigeria. The AKQ and KQQ VES curves are the predominant curve types as they account for 38%, 21% and 11% respectively. Furthermore, all the twenty-nine depth soundings curves interpreted are characterized by a steep descent from the unsaturated to the saltwater saturated sediment. This decrease could be attributed to increase in porosity, hydraulic conductivity, fluid content, possibly conductivity arising from saline water intrusion from the nearby lagoon, and/or the presence of clay/peat. Figure 2 shows VES 5 sounding curve, a typical example of the VES curves obtained in the area. This curve indicate a distinct very low-resistivity zone of less than 4 Ohm-m below a saturated sand/sandy-clay aquifer layer occurring at a depth of 44 m. This layer possibly represent either saline sand or saline peat.

It is pertinent to point out that the resistivity curve types obtained in this study are comparable to the ones obtained by Choudhury, et al (2001) in the eastern and south eastern part of Kolkata metropolis of India which is a similar terrain to Lekki peninsula. From the quantitative interpretation results of all the resistivity curves, four distinct geologic layers were identified. These layers are: 1) Dry and unconsolidated sand, 2) Wet sand, 3) Sandy-clay/Clay, 4) Peat which constitute the bedrock. Majority of the VES curves were fitted with five layers instead of four delineated. This discrepancy is explained in terms of geolectrical suppression of one of the layers since the lithology obtained from two existing borehole in the study area shows the existence of this layer (Table 1).

Table 1: Comparison of lithologies obtained from borehole and VES data

Lithology from borehole	Lithology from VES 5	Depth (m)
Unconsolidated dry sand	Unconsolidated dry sand	0 - 2.7
Wet sand	Wet sand	2.7 - 5.1
Clayey-sand	Missing/Suppressed layer	5.1 – 12.0
Sandy-clay	Sandy-clay	12.0 – 36.7
Peat	Peat	> 36.7

Three geoelectric sections running West-East direction were obtained from the inversion of the interpreted field resistivity data. The inversion of the interpreted field resistivity data was carried out with the aim of delineating the subsurface geologic sequence present in the study area, and determine their geoelectrical parameters (layer thicknesses and resistivities); and delineate the structural and geomorphological features present beneath the subsurface. The inverted 2-D geoelectrical sections along traverse A-A”, B-B’ and C-C” are shown in Figures 3 to 5. Ten VES points are situated on traverse A-A” (1, 2, 3, 4, 5, 6, 7, 8, 9 and 10), and on traverse B-B” (11, 12, 13, 14, 15, 16, 17, 18, 19 and 20) but traverse C-C” has only nine VES points (21, 22, 23, 24, 25, 26, 27, 28 and 29). However due to the water-logged nature of the eastern part of traverse C-C”, we could not acquire further VES data on this traverse. It should be noted that the interpreted 1-D vertical variation of resistivity values at each station is overlay on the geoelectric sections. It is evident that the interpreted resistivity sections has brought out the disposition of the saline/brackish water zones and the various subsurface lithology existing in the area. More importantly, the saline/brackish water is characterized by very low order of resistivity (less than 4 Ohm-m). Because the aquifers are hydraulically connected, it is thus envisaged that excessive pumping of groundwater from the overlying freshwater aquifer (zone B) would possibly lead to the saline/brackish water migrating upward under pressure and pollute the adjoining aquifer.

Figure 3 shows the inverted geoelectric section along traverse A-A”. The section spans a distance of approximately 600 m. From this section, four distinct layers characterized it. The topsoil is the dry and unconsolidated sand having apparent resistivity (ρ) values ranging between 248 Ohm-m and 2032 Ohm-m, and variable thickness (h) of 0.8 - 17.8 m; the second layer is composed of wet sand, and its resistivity ranges from 130 to 448 Ohm-m, while it has thickness that varies between

24.0 to 35.0 m; the third layer is the sandy-clay/clay formation whose resistivity value ranges between 8 and 130 Ohm-m, while its thickness ranges between 35 and 80 m. Peat constitutes the fourth layer which is the bedrock and its resistivity varies from 1 to 4 Ohm-m. Generally, the depth to top of the peat formation varies from about 35 to 95 m.

The inverted geoelectric section along traverse B-B" is shown in Figure 4. The traverse has the same length as traverse A-A". Four subsurface layers were delineated from this traverse. The first layer constitutes the topsoil. It is composed of dry and unconsolidated sand. Its resistivity values ranges between 255 Ohm-m and 1020 Ohm-m, while it has thickness that ranges from 3.0 to 20.0 m. The second layer is composed of wet sand. It has a layer resistivity values that range from 64 Ohm-m to 256 Ohm-m. Its thickness varies from 7.0 to 18.0 m. The third layer is sandy-clay/clay. It has resistivity values ranging between 8.10 to 64.0 Ohm-m. Their thickness varies between 10.0 and 45.0 m. The bedrock beneath this traverse constitutes the fourth layer and it is peat. Its depth of occurrence varies between 18 to 22 m.

The inverted geoelectric section of traverse C-C" is display in Figure 5. Also, a maximum of four layers were delineated from this section as it is in the previous sections (Figs. 3-4). The subsurface obtained on traverse C-C' also has the same resemblance to other traverses. The topmost layer is the unconsolidated dry sand that spans through the entire length of the traverse. The resistivity of the first layer is variable and it varies between 128 Ohm-m and 1012 Ohm-m, while its thickness ranges from 0.6 to 7.0 m. This layer is underlain by the wet sand having resistivity value ranging between 32 Ohm-m to 127 Ohm-m. Its thickness varies from 15.0 to 34.0 m. The ubiquitous third layer constituted by sandy-clay/clay is also present beneath this traverse. Its resistivity value ranges between 4 Ohm-m and 32 Ohm-m, while its thickness varies from 24 to 52.0 m. The third layer is underlain by peat which constitutes the fourth layer. The fourth layer has resistivity value in the range of 1 to 5 Ohm-m. The depth to the peat bedrock varies from about 48.0 m to 56.0 m.

From the geoelectric sections (Figs. 3-5), it is evident that two major saltwater intrusion zones exist beneath the survey area at 10-30 m, and 60-100 m. Salinity as inferred from low resistivity sections is generally high in the central part of the traverses. Two major factors are thought to contribute to the saline-water intrusion observed in the Lekki Peninsula area viz: 1) the excessive pumping of groundwater that has disturbed the hydrodynamic equilibrium in the aquifer (Lee and Song, 2007); and 2) the reduction of groundwater gradients which allows saline water to displace fresh water in the aquifer (Lee and Chang, 1974). When this happens, the groundwater quality deteriorates very rapidly, thereby leading to increase in the salinity of the groundwater. We infer that the sandy-clay formations (zone C) delineated possibly act as a barriers for migration of saline water. Mapping of the contamination zones would assist in the groundwater management policy as area less susceptible to saline water contamination will be develop. Also, a closer look at the geoelectric sections showed that the aquifers present in the study area are hydraulically connected. In-addition, as shown in figures 3 to 5, it is evident that the eastern and western parts of the survey area is devoid of significant saltwater/brackish contamination because the area is characterized with resistivity value greater than 200 Ohm-m. However, it is deduced that the presense of sandy-clay in this area possibly prevent upward migration of saltwater..

Furthermore, it is observed that all the geoelectric sections (Figs. 3-5) are characterized by distinct bedrock depressions. On traverse A-A”, this depression is located between VES 5 and VES 8, while on traverse B-B”, it exist between VES 18 and VES 20, and on traverse C-C”, it is discernable between VES 24 and VES 27. These depression zones could possibly be part of the miogeoclinal depressions formed at the edge of the rifting Atlantic Ocean during the Quaternary times (Kingston et al (1983) and/or ancient buried river/stream channels or creek.

The occurrence of the saline water contamination in the study area could be explained plausibly in terms of the occurrence of trapped saline-water within the aquifer. This saltwater were possibly 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. Prior to the fluctuation of the sea-level in Lagos area, Kingston et al (1983) suggested that series of miogeoclinal depressions were formed at the edge of the rifting Atlantic Ocean. These depressions zones were later filled with sea water where the sediments were deposited. We interpret the resistivity of the formation found in zone C to be due to the combined effect of formation resistivity and the pore fluid resistivity. Thus, it is inferred that the saline-water found at the shallow depth (10-30 m) was probably trapped during marine transgression and/or it migrated from depth by differential pressure-gradient.

Conclusions

Surface electrical resistivity surveys was conducted in the Lekki Peninsula area of Nigeria, with the aim of providing valuable information on the hydrogeologic system of the shallow alluvial aquifer, and delineating the salinity of groundwater and its subsurface configuration. The resistivity result reveals a dominant trend of decreasing resistivity with depth which indicates increase of salinity with depth. The differences in resistivity are associated with the various lithologic types and variations in water saturation. The presence of four distinct zones of resistivity values characterizing the survey area was delineated viz: (1) the topmost layer is the unconsolidated dry sand (A) having resistivity values ranging between 125 to 1,028 Ohm-m; (2) the underlying zone (B), corresponds with fresh water-saturated soil which has resistivity values of 32-256 Ohm-m; (3) a mixing (transition) zone (C) of fresh with brackish groundwater whose resistivity values ranges from 4 to 32 Ohm-m; and (4) layer four (D) is characterized with resistivities values generally below 4 Ohm-m. This zone reflects an aquifer containing saltwater only whose depth varies across the traverse. Distinct zones of saline water contamination have been delineated both in the near-surface (10-30 m), and deeper subsurface (60-100 m). However, the subsurface geology generally shows a sandy-clay formation (C) which largely prevents saline water intrusion into the overlying freshwater zone (B) which is devoid of any significant saline water contamination. Two major factors are thought to contribute to saline water intrusion observed in the study area, viz: the excessive pumping of groundwater that has disturbed the hydrodynamic equilibrium in the aquifer; and the reduction of groundwater gradients which allows saline-water to displace fresh water in the aquifer. Also, this investigation has also delineated the areas where ground water development can be undertaken, as well as the vulnerable zones where ground water withdrawal should be restricted. Through this study, it was confirm that the Schlumberger sounding resistivity method is an efficient tool for investigating the saltwater-freshwater interface in a coastal environment.

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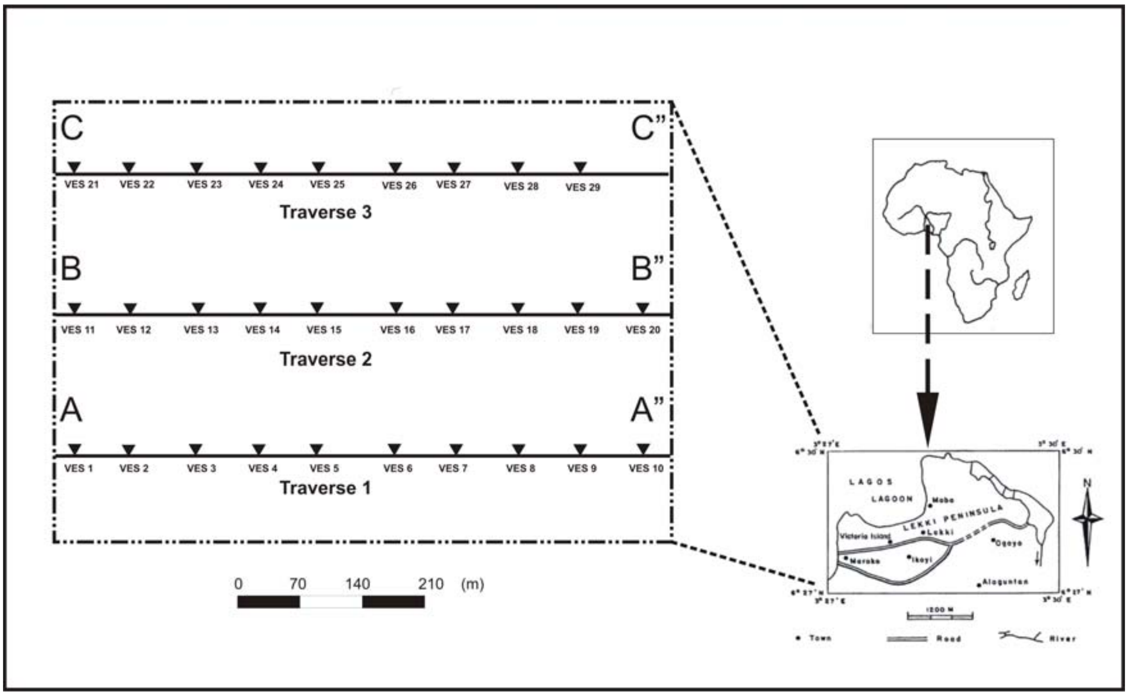

Figure 1: Location map of the survey area at Lekki Peninsula, Lagos Nigeria.

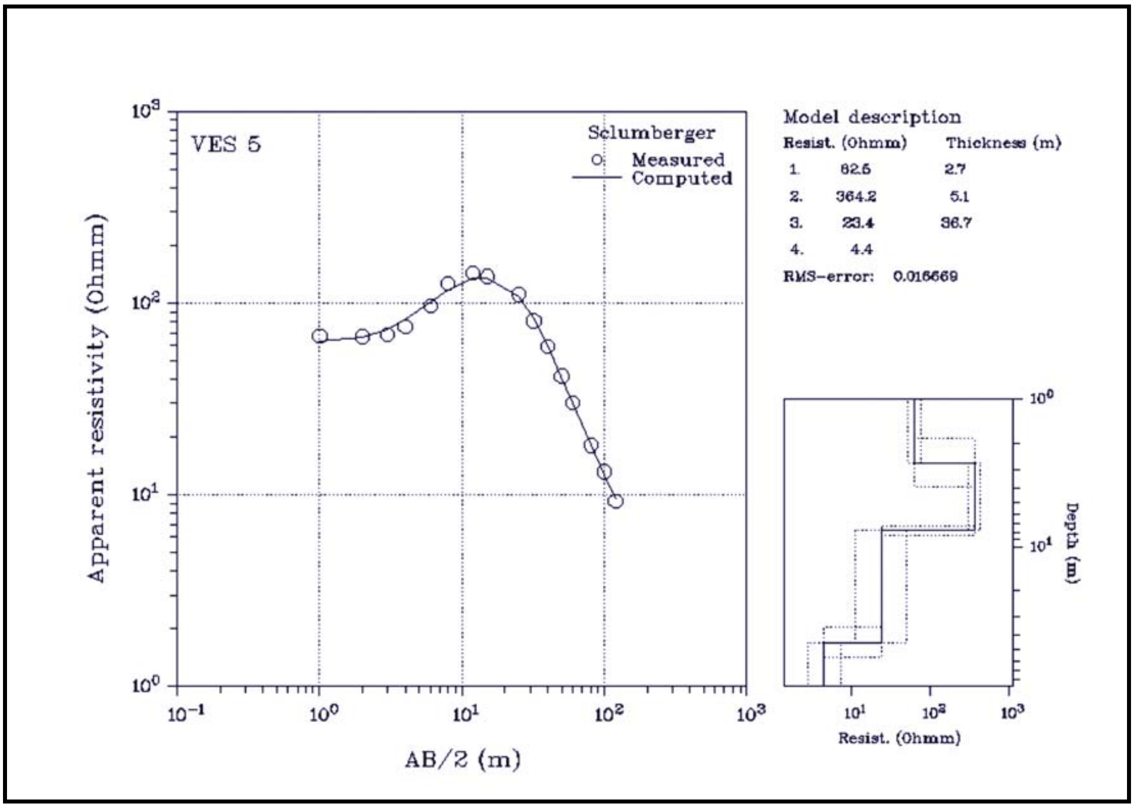

Figure 2: The interpreted 1D resistivity data of VES 5.

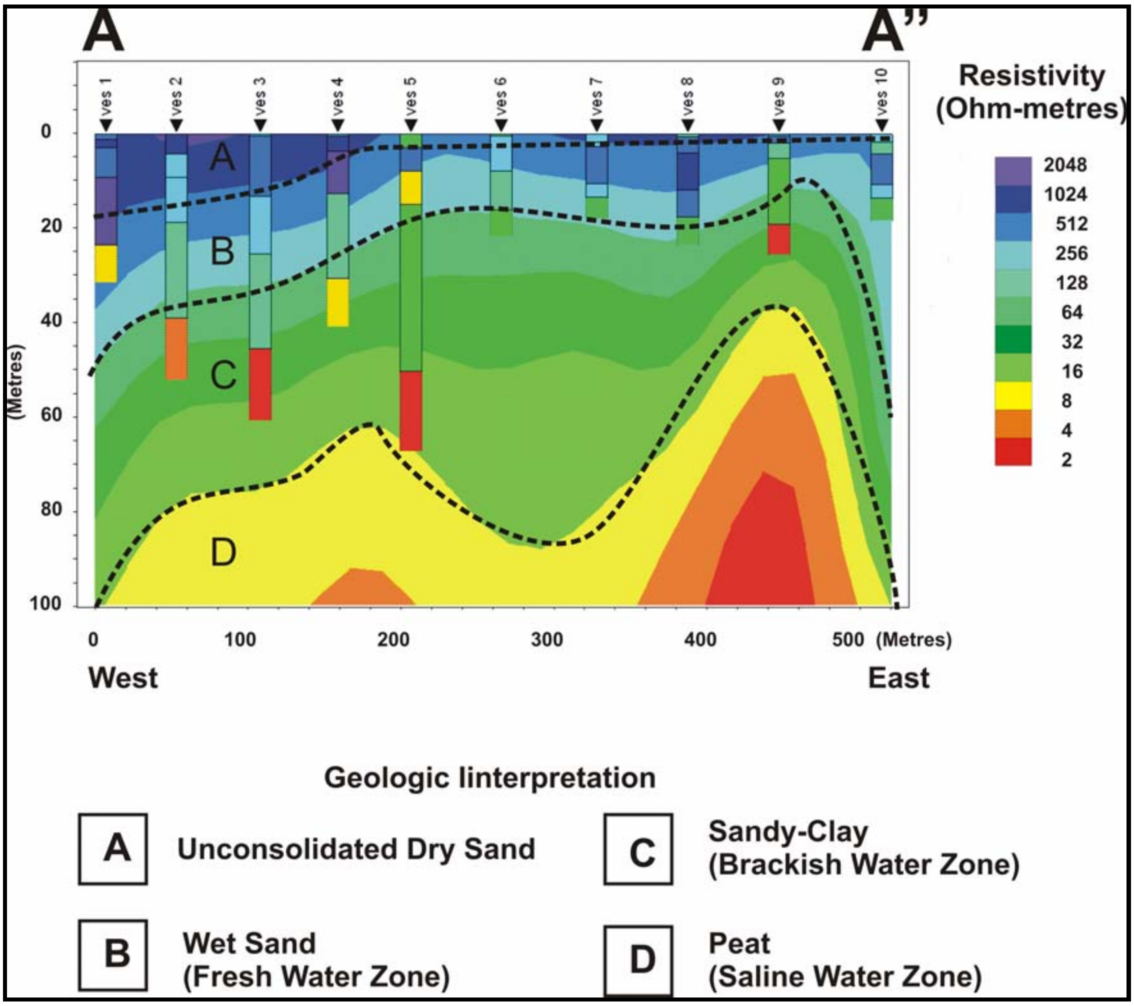

Figure 3: Interpreted 2D resistivity section of the subsurface beneath traverse A-A”

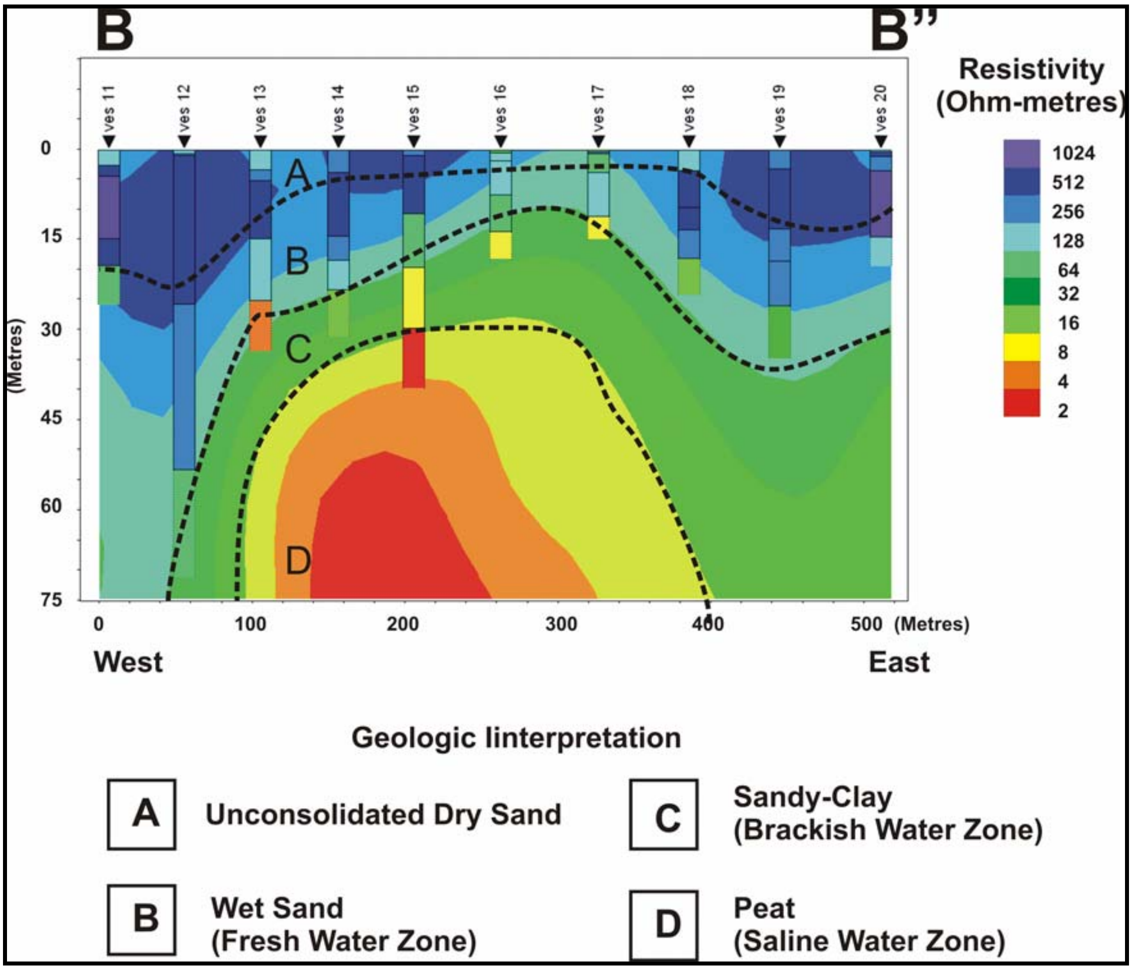

Figure 4:Interpreted 2D resistivity section of the subsurface beneath traverse B-B".

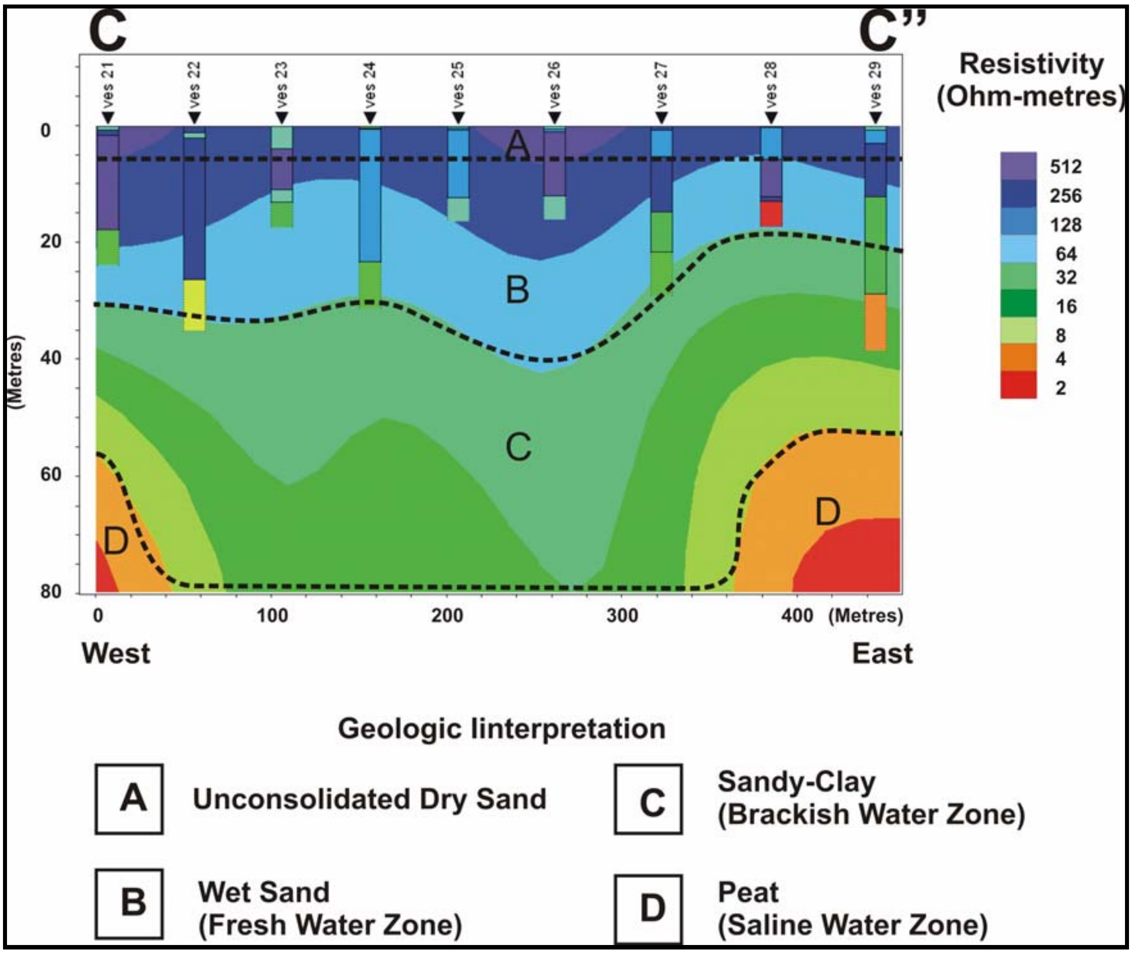

Figure 5: Interpreted 2D resistivity section of the subsurface beneath traverse C-C"