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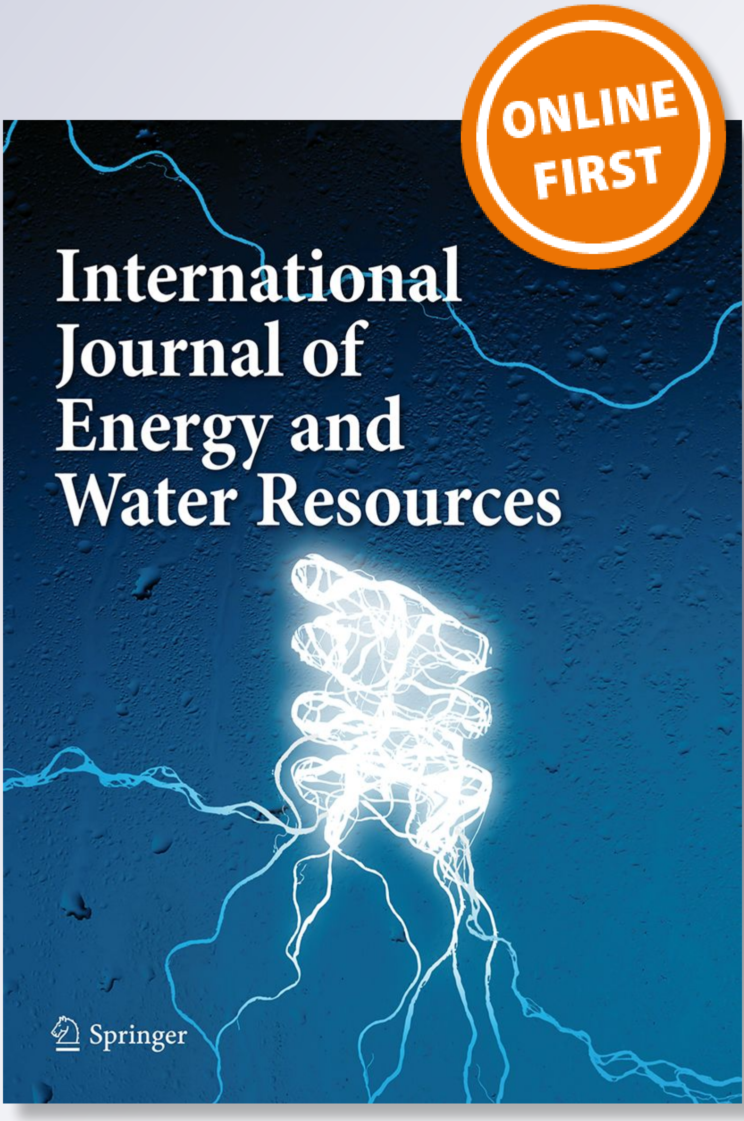

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ORIGINAL ARTICLE

Hydro-geophysical mapping of occurrences and lateral continuity of aquifers in coastal and landward parts of Ikorodu, Lagos, Southwestern Nigeria

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Abstract
Hydro-geophysical investigation of groundwater resource of Ikorodu area, SE Lagos was carried out using vertical electrical sounding (VES), lithologic, resistivity, and gamma ray logs. This was with the aim of evaluating the lateral and vertical variations of lithologic sequence and also delineates the aquifers within the subsurface. Fifty (53) VES of which six (6) traverse lines were selected and their geo-electric logs along these profiles were correlated to highlight the extent of continuity of different layers and evaluate their hydrogeological significance in the study are. The field data were curve-matched and computer iterated. Both modelled VES curves and borehole logs showed the alternation of subsurface layers of clay, sandy clay, "upper" sand, "lower" sand, and ferrugenized sand. The resistivities (Ω m) of these layers are: 3.3–93.9, 102.6–155.5, 219.9–1140, 250.6–1020.2, and 1428.8–6141, while the thicknesses in metres are: 0.5–62.6, 0.5–30.9, 1.4–34, 15–112.4, and 6.2–60.1, respectively. Lithologic, geo-electric, and gamma ray logs revealed the occurrence of confined/semi-confined and unconfined aquifers/semi-unconfined which correspond to lower and upper sands, respectively. Domestic water needs are largely supplied by two aquiferous horizons—the upper and the lower sands. While the upper sand supports only shallow hand-dug wells exclusively around the coastal area, the lower sand provides groundwater supply in the landward area. The present study has provided some useful insights in the understanding of the groundwater resource in the area which is useful for groundwater management.

Keywords Curve types · Groundwater management · Logs · Vertical electrical sounding

Introduction

In the last few years, groundwater appraisal in southwestern Nigeria has occupied the front burner of geological discourse due to growing urban population, epileptic or unavailable municipal water supply, contamination, and pollution problems (Olayinka et al. 1999; Olorunfemi et al. 1999; Abimbola et al. 1999; Ehinola 2002). In many of the urban and rural areas, there are little (or lack of) qualitative and quantitative data on groundwater occurrence invaluable to future groundwater development, policy formulation, and environmental auditing. Ikorodu and its environs located in the eastern part of Lagos southwest Nigeria have existed for long with inadequate municipal water supply. Currently, less than 5% of the inhabitants have regular access to municipal water supply. The shortage of municipal water supply is further aggravated by the progressive population explosion in the communities, coupled with the emergence of many large-scale industries in recent years as a result of unavailability of land in 'main' Lagos. These have led to the sudden emergence of wells and boreholes in every part of the town to address the shortage of municipal supply in the area. Many problems have been reported ranging from poor water quality, especially around the lagoon and swampy parts (Olatunji et al. 2005) as well as many cases of unsuccessful wells and boreholes. Other notable

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problems reported in areas with similar geography and geology include rapidly changing facies, occurrence of thick clay layer, and intrusion of saline water in some coastal communities (Ako et al. 2005). To forestall the incessant failure of boreholes and understand the nature of the subsurface lithological facies, there is need for proper delineation of the aquifers within the subsurface. Authors such as Aluko et al. (2017), Bayewu et al. (2017), and Omali (2014) have used geophysical methods to delineate groundwater aquifer in sedimentary and basement terrains in Nigeria, while Oloruntola et al. (2017) studied the groundwater occurrence and aquifer vulnerability using geophysical and borehole logs in a typical sedimentary terrain of southwestern Nigeria. Bayewu et al. (2018) conducted a similar research in a basement terrain of southwestern Nigeria using only geophysical tool. Ige et al. (2018) evaluated aquifer hydraulic characteristics in the Southern Bida Basin using geophysical and pumping test data and revealed that the groundwater potential of an aquifer is influenced by the thickness of the aquifer as well as the hydraulic conductivity. Potentialities of the aquifers in the Southern Bida basin according to the authors were between low (1–10 m^2/day), medium (10–100 m^2/day), and high (> 100 m^2/day) based on Krasny (1993) transmissivity values from pumping test data. The present study area is situated within the Dahomey basin which is stratigraphically made up of Abeokuta Group, Imo Group, Ilaro Formation, Coastal Plain Sands, and Recent Alluvium (Omatsola and Adegoke 1981). The recent alluvium deposits, the Coastal Plain Sands, and Ilaro Formations are the major aquifers in the basin (Longe et al. 1987). Three different aquifers were identified by Longe et al. (1987) within 200 m depth in parts of the areas underlain by the Coastal Plain Sand Formation. The first is the water table aquifer (average thickness of 8 m), while the second (10–25 m thick) and third (10–35 m) aquifers are confined with hydraulic conductivity (permeability) values in the range of 7.5–245.8 m/s. The varying hydraulic properties of aquifers in the basin have been interpreted as indication of the heterogeneity of the aquifers (Longe et al. 1987). Fatoba et al. (2014) derived the range of values of hydraulic conductivity of 0.8–65 m/day and 13–310 m^2/day for the coastal aquifers of Lagos using geoelectrical sounding, while Salami and Olorunfemi (2014) delineated two aquifers in the Dahomey sedimentary basin in the central parts of Ogun State using pumping test and geoelectrical sounding, whose hydraulic conductivities and range of aquifer thickness are averagely 2.34 m/day, 30–380 m, and 6.34 m/day, 10–900 m, respectively. The authors, therefore, classified the aquifers in the central parts of Ogun State as having high groundwater potential based on the hydraulic conductivity and thickness. The potentiality of an aquifer is strongly influenced by the aquifer thickness, as shown by Ige et al. (2018). Oloruntola et al. (2017) employed geophysical method to classify aquifers within the Coastal Plain Sand Formation around Magodo area, adjacent the present study area based on the thickness of the aquifers as high (> 30 m), medium (15–30 m) and low (< 15 m) potentials. It is thus very paramount to conduct geophysical explorations before undertaking a water drilling project to minimize the possibility of abortive holes that could lead to financial loss and maximize available resources. This present research is, therefore, aimed at studying lateral and vertical variations of the subsurface lithological facies, provides the groundwater potential in terms of the aquifer thickness, and delineates the aquifer types in the area.

The study area

Ikorodu (Fig. 1) lies between latitudes 6. 53°N and 6.69°N by longitudes 3.44°E and 3.67°E, covering an area of 419.9 km^2. The area is located within the sedimentary basin of southwestern Nigeria. The proximity of Ikorodu (about 25 km) to central Lagos (Ikeja) has recently led to the massive influx of people and industry to the area due to the availability of relatively cheap land and labour. The climate is characterized by alternate wet and dry seasons, within the tropical rain forest belt. Precipitation in the study area is usually in the form of rainfall. The amount of rainfall ranges between 750 and 1000 mm in the rainy season (March and October) and 250 mm and 500 mm in the dry season between November and March (Akanni 1992). Ikorodu area is characterized by considerable variation in topography. Some parts of Ikorodu are characterized by steep gradients which are completely absent in the Lagos and Badagry areas (Udo 1970). The topography of the lagoon side varies from areas, where the land rises very gently from the edge of the water to areas with markedly steep rise in relief around the lagoon such as Ijede. Geologically, the present study area belongs to the Coastal Plain Sands, which is made up 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 aquifers are essentially made of sands, gravels, or a mixture of the two (Longe et al. 1987). The field work was conducted in Ikorodu, Lagos in 2007.

Materials and methods

Fifty-three (53) vertical electrical soundings (VES) with AB/2 of between 250 and 500 m as dictated by availability of space for electrode spread were carried out across the area. The study was carried out with the aid of Syscal Junior Terrameter, measuring tapes, current and potential electrodes, hammers, compass/clinometer, and Garmin Global Positioning System (GPS). The Schlumberger array was used

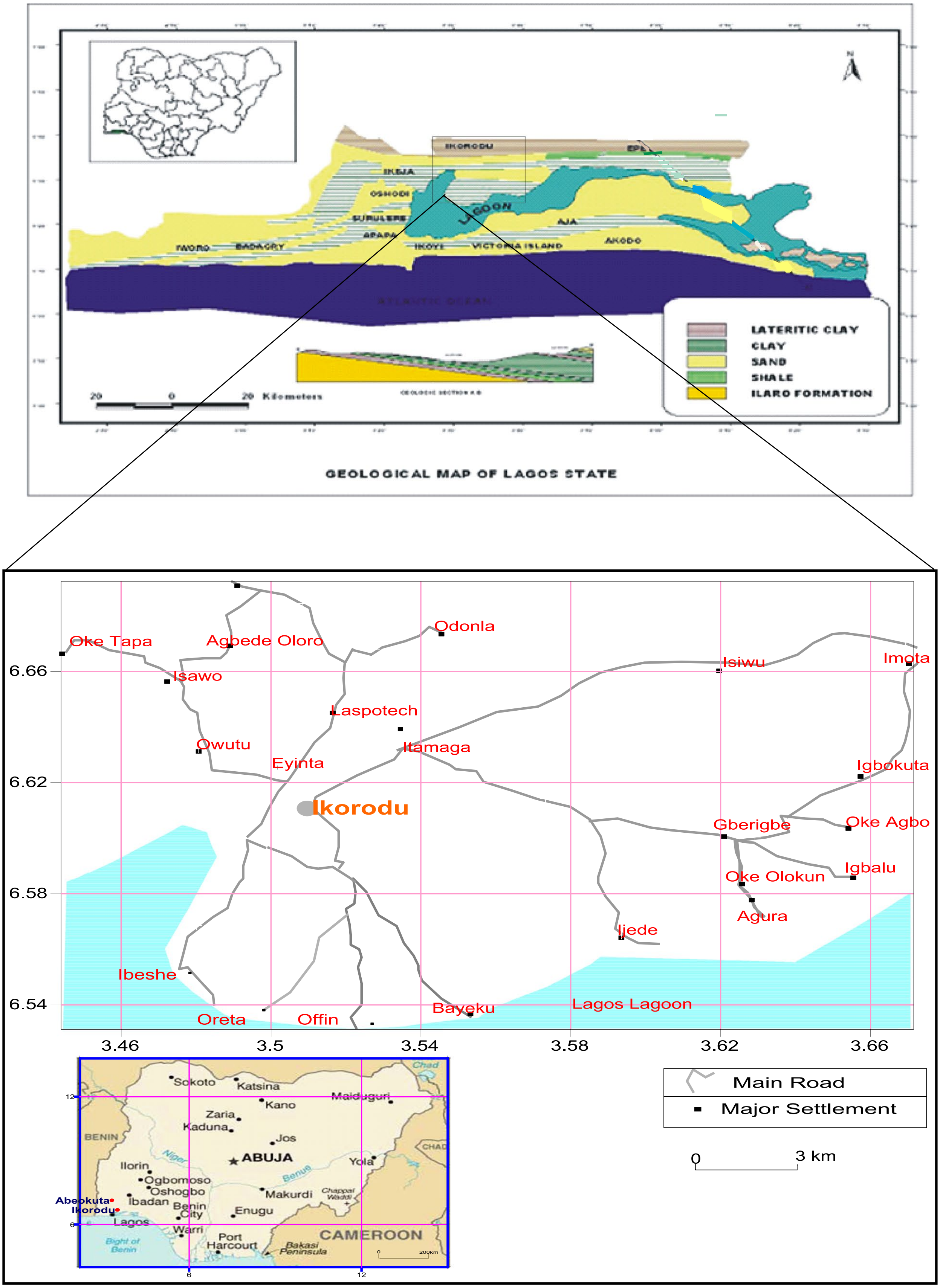


Fig. 1 Geological map of Lagos State (Olatunji 2006) (inset: location map of Ikorodu and map of Nigeria showing Ikorodu)

Table 1 Electrode configuration for VES readings

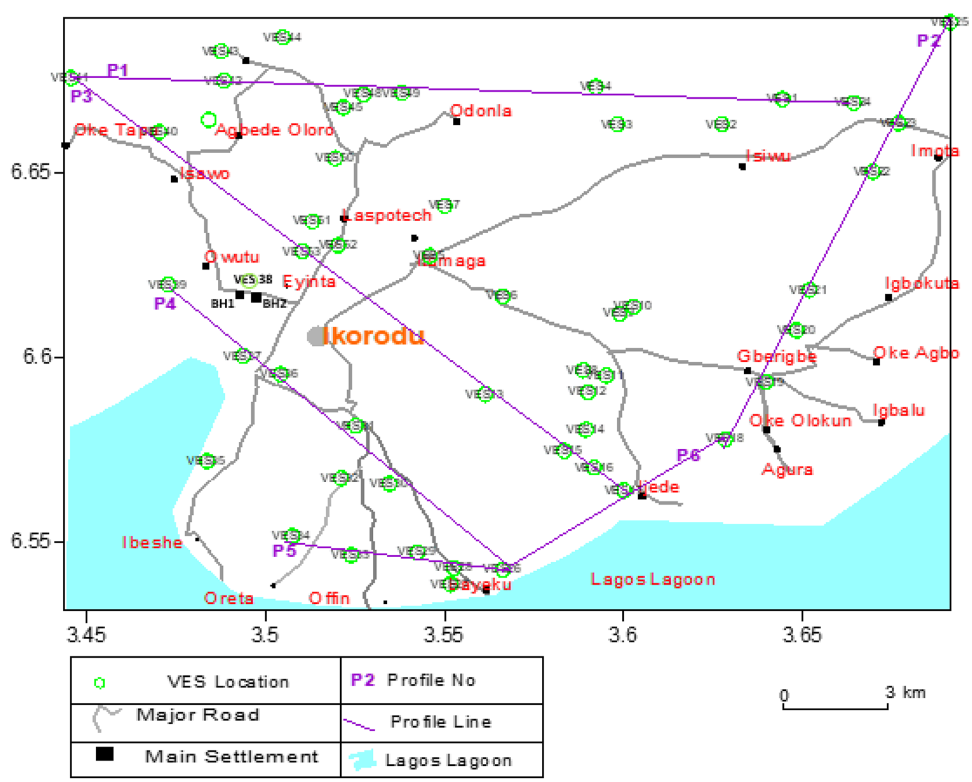
AB/2 (m)	1–6	6–15	15–40	40–100	100–200	200–300	300–500
MN/2 (m)	0.25	0.50	1.00	2.50	5.00	20.00	30.00

following the configuration in Table 1 and also ensuring that the landward areas and regions around the Lagos lagoon were all well covered (Fig. 2). By injecting low-frequency electrical current (*I*) into the ground with two current electrodes, the resultant voltage (*V*) between two potential electrodes was measured. The current was made to penetrate deeper into the subsurface by stepwise increasing the distance between the outer electrodes. The values of apparent resistivity were obtained by multiplying the resistance (*V*/*I*) displayed by the terrameter with appropriate geometric factor (*K*). The VES data were processed by partial curve-matching technique and further computer-assisted 1D forward modelling with the aid of the Winresist software (version 1.0) to obtain true resistivity, thickness, and depths. The outcome of curve matching provided starting models for computer modelling which gave the final accepted geo-electric structures. The iteration process was done between 1 and 30 times before achieving a perfect match, after which the computer displayed the result of the iteration in the form of a curve and layer parameters. It was ensured that the root mean square (r.m.s) error was not more than 5% in all the iterated curves. The interpretation of the VES results was done based on the correlation (Fig. 3) between VES 38 and adjacent lithologic and gamma ray logs (BH1 and BH2) which were gotten from the Local Government Waterworks, Lagos State. These borehole logs helped to constrain the VES interpretation by assigning a range of resistivity values for lithologies (Table 2). Six VES traverse lines (Fig. 2) were selected and their geo-electric logs along these profiles were correlated to highlight the extent of continuity of different layers and evaluate their hydrogeological significance in the study area (Fig. 4).

Results and discussion

The representatives of the typical VES curves of the area are presented in Figs. 5 and 6. The sounding curves obtained in Ikorodu area vary from the three-layer type curves to six-layer type curves that include AK, AKH, HK, HKHK, HA, AKQ, KQQ, KHAK, HKHA, QH, K, and HK. The AK and KH curve types together jointly constitute about 70% of the curve types and are mostly dominant in the landward area compared with the area around the Lagos lagoon. The many varieties of the curves obtained in this area can be attributed to the alternation of clay and sand sequences which is evident in the borehole logs and VES results. This cyclicity of sedimentation

Fig. 2 Vertical electrical sounding (VES) points and borehole locations in Ikorodu area



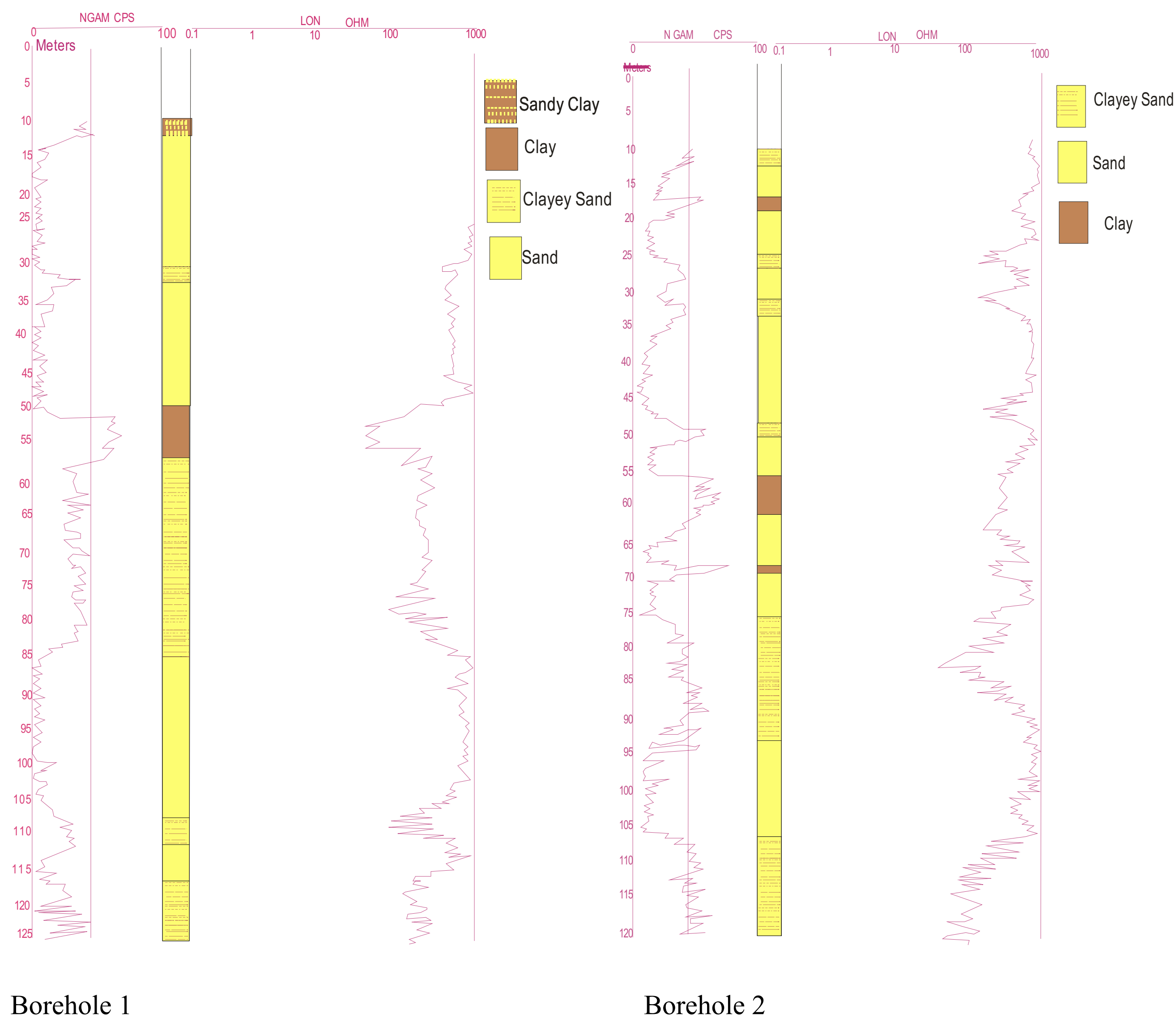


Fig. 3 Gamma ray and resistivity logs of borehole 1 and 2 in Ikorodu area

Table 2 Range of resistivity values for lithologies in the study area

Clay	Sandy clay	Sand/sandy soil	Ferrugenized sand
< 100 Ω m	100–200 Ω m	200–1200 Ω m	> 1200 Ω m

has been described by Longe et al. (1987) to be characteristic of near shore depositional environment. Furthermore, there are conspicuous variations in the thickness of the sand and clay layers across the study area. These differences could be as a result of the elevation differences as shown by the profiles (Figs. 7, 8, 9, 10, 11, 12) and as also supported by Udo (1970). In addition, Oladele et al. (2015) showed that the deep (about 10 km) basement beneath the basin is not topographically flat but characterized by a large Basement depression flanked by Basement highs (Omatsola and Adegoke 1981). This could as well possibly impact on the deposition patterns and consequent thickening and thinning of the aquifers across the study area as shown in the 3D model of the aquifer thickness distribution in the study area (Fig. 12).

The topography across the area is undulating (Figs. 7, 9) especially along profiles 1 and 3, gentle slope along profiles 2, 4 and 6 (Figs. 8, 10, 12) traversing from landward area southerly towards the Lagos lagoon and flat along profile 5 (Fig. 11) parallel and close to the lagoon.

Profile 1

Profile one consists of VES 41, VES 42, VES 48, VES 49, VES 4, VES 1, and VES 24 running from NW to

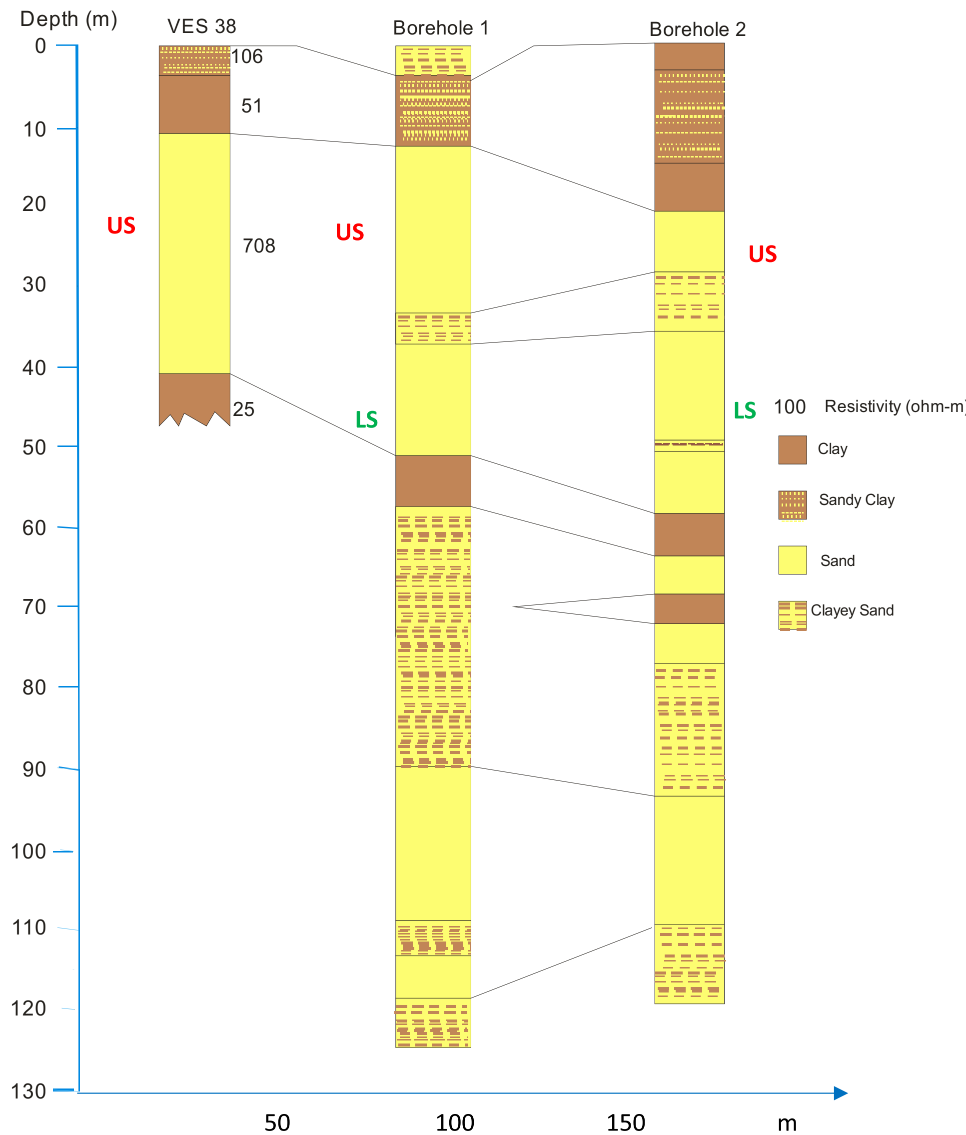


Fig. 4 Correlation of VES 38 and lithologic logs of adjacent boreholes 1 and 2

NE of the area. The curves are primarily of AK type ($r1 < r2 < r3 > r4$). The topography of the area is undulating (Fig. 7) with the highest points along the profile at VES 42 and VES 49. The first layer is characterized by clay in the western part and this grades gradually to sandy clay in the eastern area. The thickness of the horizon varies from 0.6 to 2 m and resistivity range of 28–150 Ω m. However, the first layer in location 41 is sandy. Underlying the first layer is a highly resistive sandy layer (probably ferrugenized) that grades gradually eastward to the sandy and clay horizon. The thickness of the resistive sand varies from 6.2 to 24.6 m. The sand which extends laterally from NW to NE varies in thickness from 3.3 to 49 m. The sand is exposed at location of VES 41 to the ground surface, but confined/semi-confined in many places towards the north-eastern part of the area.

Profile 2

The profile (Fig. 8) covers NNE–SSW of Ikorodu area, including VES 25, VES 23, VES 22, VES 21, VES 20, VES 19, and VES 18. The topography is gently sloping downward from VES 25 towards VES 18. The curves are mainly of AK type ($r1 < r2 < r3 > r4$), the commonest curve type in Ikorodu area. The top layer ranges from sandy clay (117–181 Ω m) to sand (394 Ω m). While the sand is exposed at VES 25, it is semi-confined in VES18, VES 19, and VES 21 and confined in VES 23. Underlying the sand is highly resistive ferrugenized sand (1437–6941), extending from VES 25, where it is very thick to VES 18, where it is relatively thin. Underlying the resistive sand is clay which grades intermittently to sandy clay with resistivity range of 22–143 Ω m.

Fig. 5 Typical AK curve in the Ikorodu area

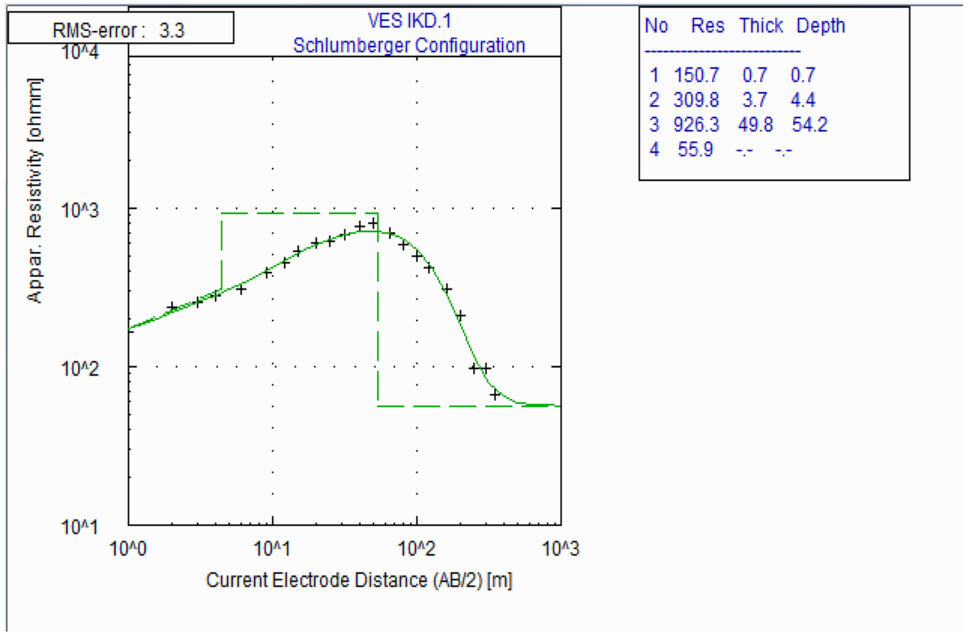
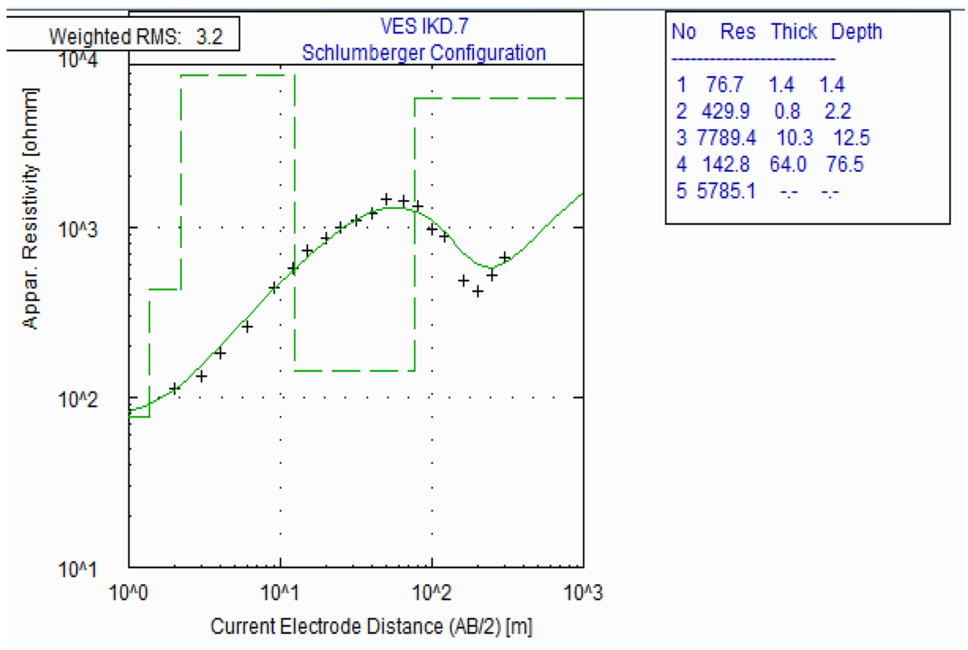


Fig. 6 Typical KH curve in Ikorodu area



Profile 3

This profile (Fig. 9) consists of VES 41, VES 40, VES 53, VES 13, VES 15, VES 16, and VES 17, covering NW–SE central section of the map. The curves are mostly of the AK type ($r1 < r2 < r3 > r4$). The topography along the profile is undulating with the highest point around VES 53. The first layer is essentially clayey in the central section with resistivity between 22 and 93 Ω m and thickness of 0.5–1.4 m. At the edges of the profile, the characteristics of the first layer vary from sand (363–499 Ω m) to sandy clay (141–160 Ω m). The highly resistive sand (1429–2809 Ω m) extends laterally throughout almost the entire profile with a sharp contact around VES 17. Beneath the resistive sand (ferrugenized sand) is a sandy horizon with resistivity of 275–416 Ω m, covering the central area of the profile, and clay to sandy clay (30–115 Ω m) at the flanks of the profile.

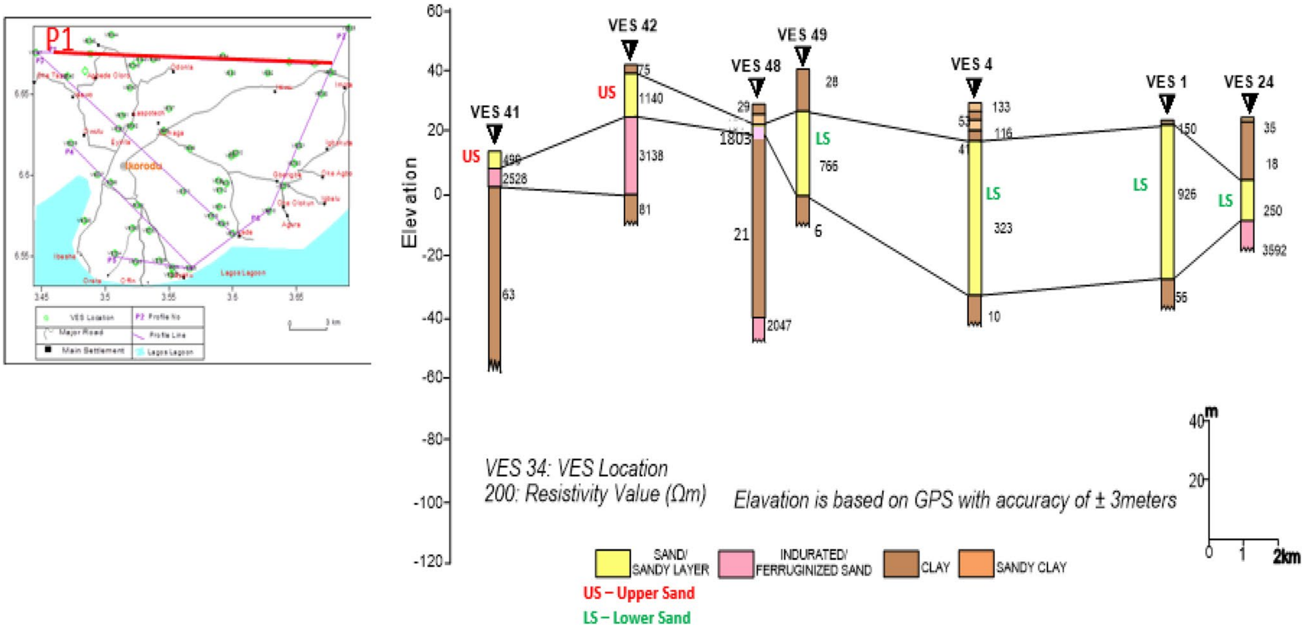


Fig. 7 Geo-electric section of VES locations along profile 1 in Ikorodu area

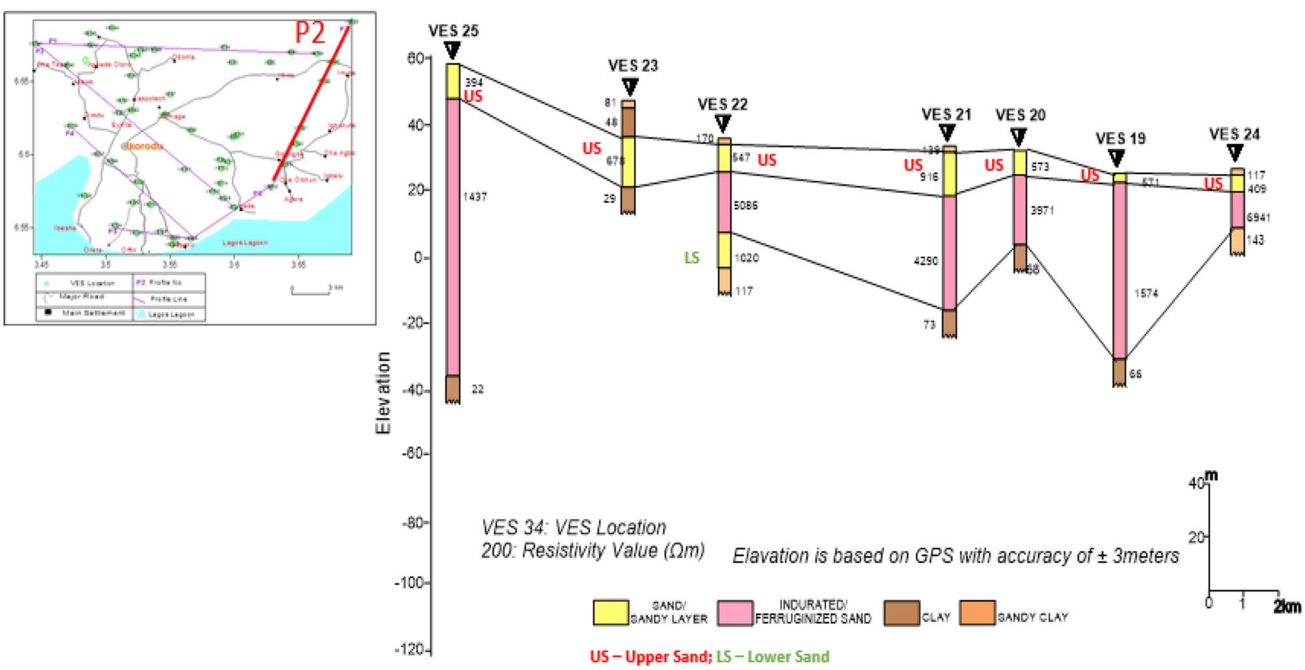


Fig. 8 Geo-electric section of VES locations along profile 2 in Ikorodu area

Profile 4

This covers VES 39, VES 37, VES 36, VES 31, VES 30, and VES 26, traversing the western to the southern part towards the Lagos lagoon (Fig. 10). Again, the AK curve type is the most dominant. The first layer varies from clay (50–74 Ω m) to sandy clay (140–144 Ω m) and sand in the central area of the profile. The resistive sand occurs sporadically along the profile beneath the first layer and grades abruptly into sandy layer (454–754 Ω m). The sand in the central area is semi-confined and exposed towards the Lagos lagoon. Beneath

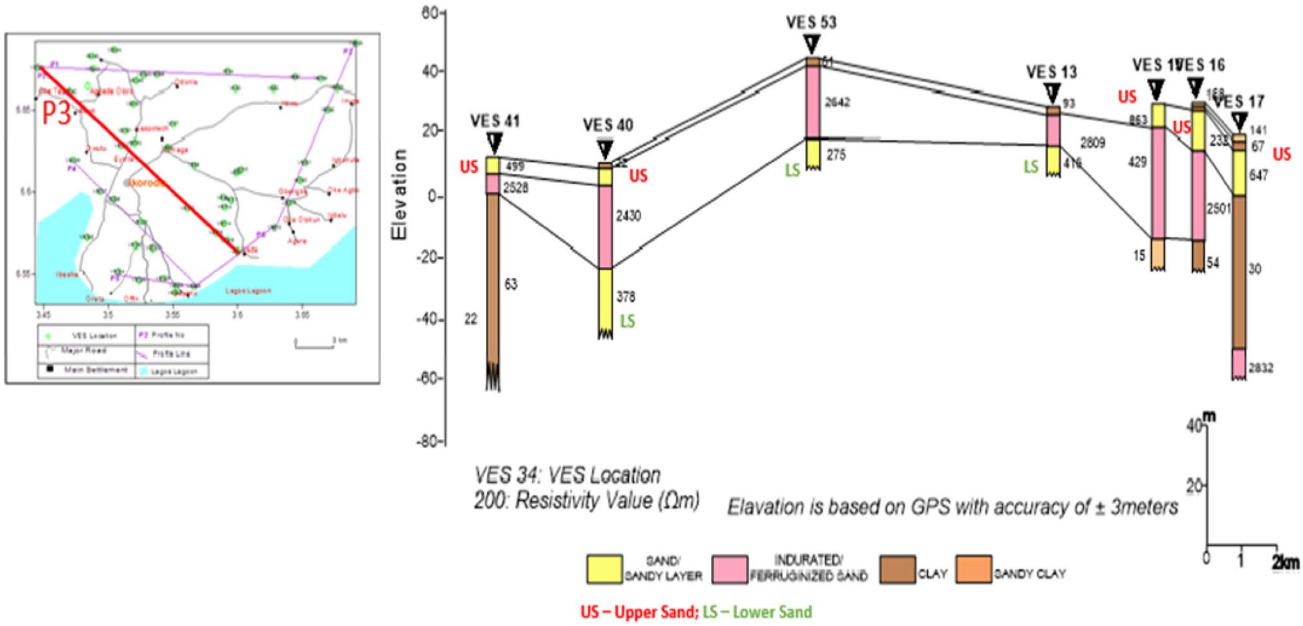


Fig. 9 Geo-electric section of VES locations along profile 3 in Ikorodu area

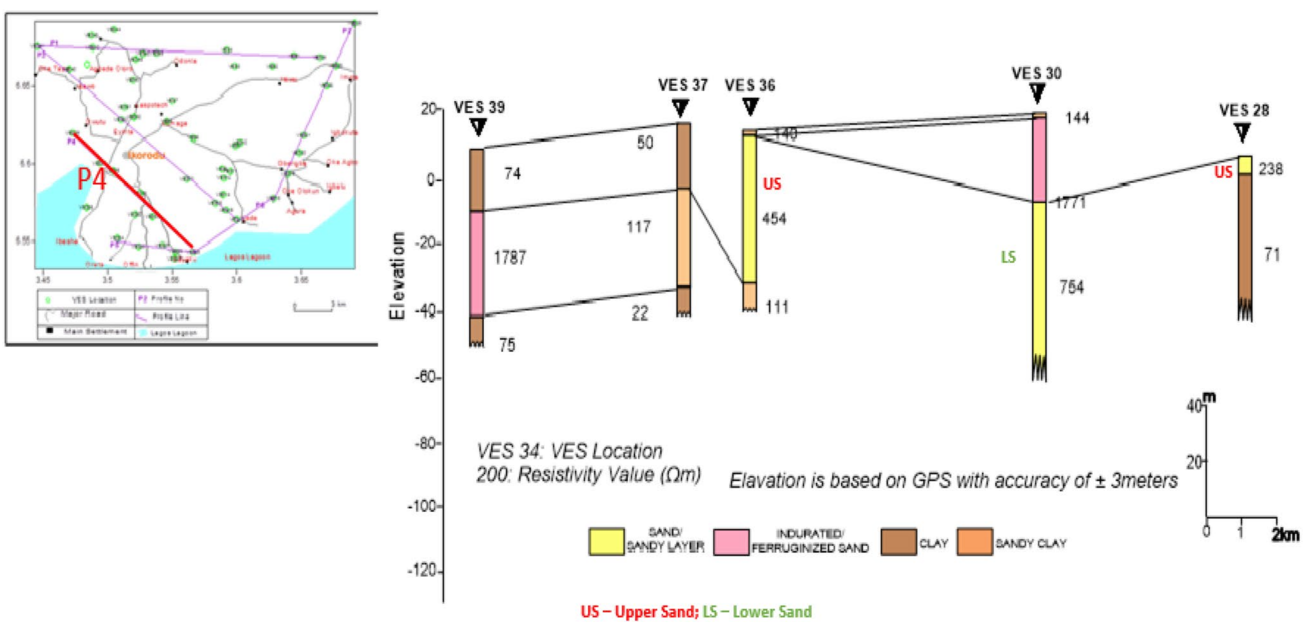


Fig. 10 Geo-electric section of VES locations along profile 4 in Ikorodu area

this horizon is a clayey layer (22–75 Ω m) with lenses of sandy clay around VES 36.

Profile 5

This is a profile of the area closest to the Lagos lagoon from west to east. It consists of VES 33, VES 29, VES 28, and VES 26, with a relatively flat relief (Fig. 11). Although along this profile, there is no principal curve type, the lagoon area is mainly the HK type ($r1 > r2 < r3 > r4$). The first layer, a sandy horizon has a resistivity of 219–700 Ω m with a thickness of 1.3–8.5 m. This layer is exposed to the surface almost entirely in the lagoon area and is linked to the confined upper sand in the landward area, as shown in profiles 2, 4, and 6. Underlying this sand is a thick clay layer (8–71 Ω m) which is thin in the central

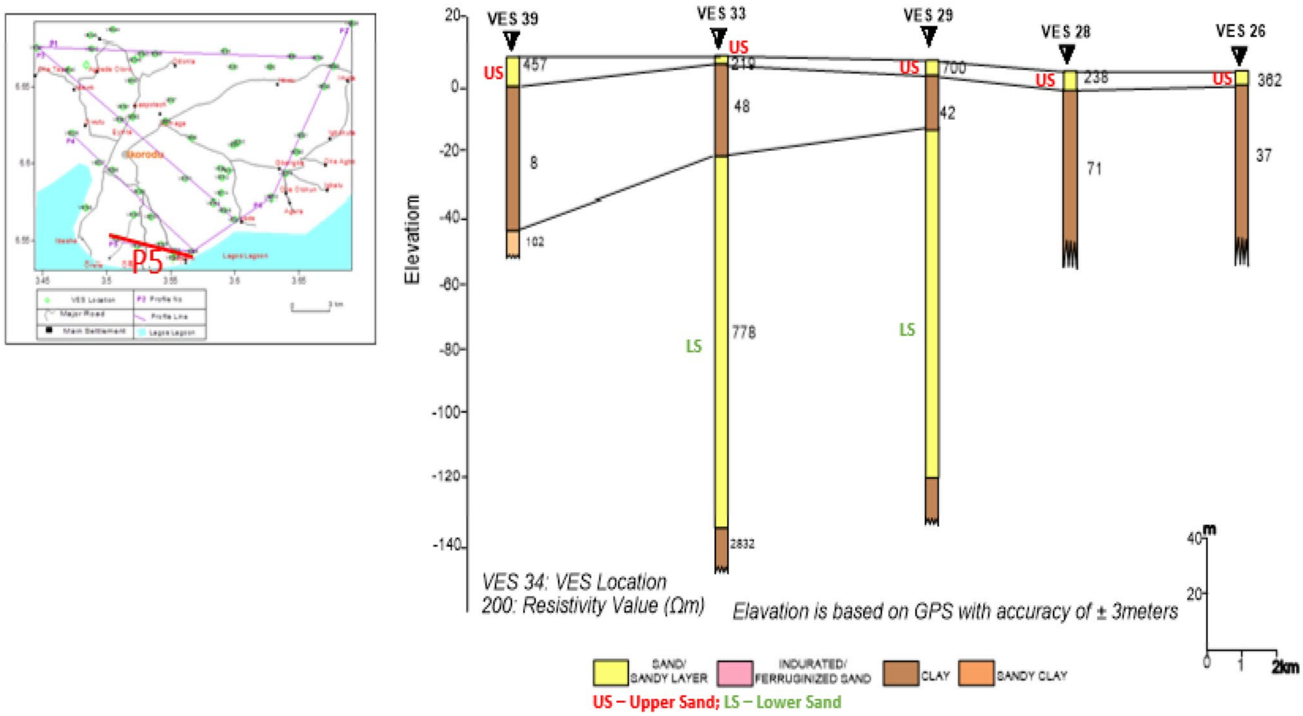
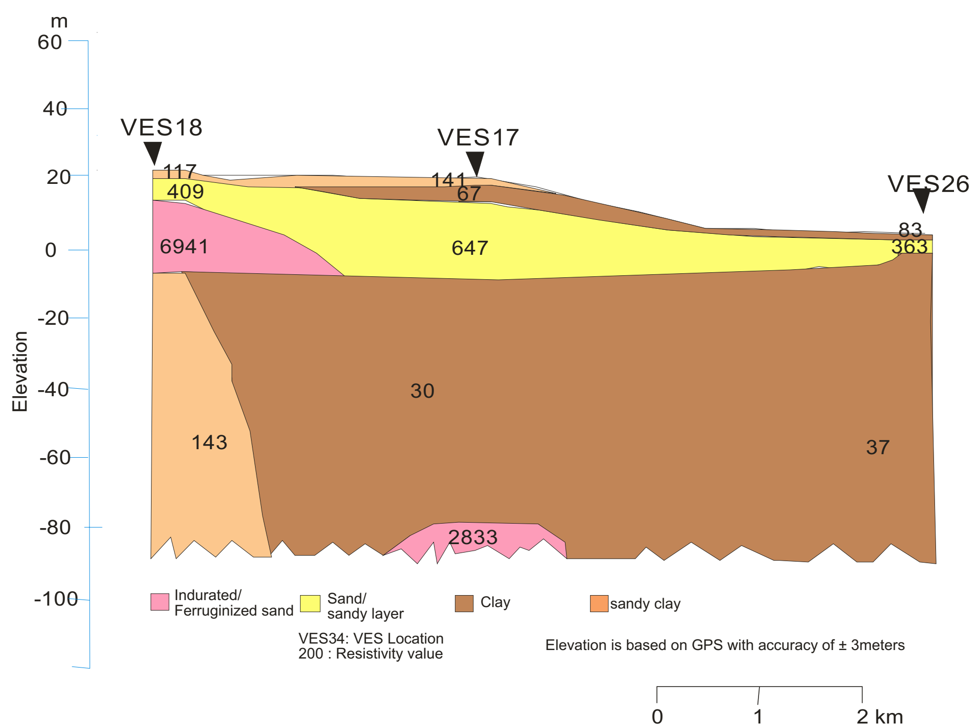


Fig. 11 Geo-electric section of VES locations adjacent to the Lagos lagoon (profile 5) in Ikorodu area

Fig. 12 Geo-electric section of VES locations along profile 6 in Ikorodu area



area and thicker at the flanks of the area. Below, this layer is a very thick sand (322–778 Ω m), which corresponds to the confined sand in the landward area extends laterally throughout almost the entire profile with a sharp contact around VES 17. Beneath the resistive sand (ferrugenized sand) is a sandy horizon with resistivity of 275–416 Ω m, covering the central area of the profile, and clay to sandy clay (30–115 Ω m) at the flanks of the profile. The sandy layer is underlain by clay (16–61 Ω m) invariably sandwiching the lower sand in the area.

Profile 6

Profile 6 consists of VES 18, VES 17, and VES 26 providing a third dimension for profile 2 (Fig. 10). The topography along the profile is gentle between VES 18 and 17, but steep between 17 and 26. The first layer, overlying the sand described earlier in profile 2, grades between sandy clay (141 Ω m) and clay (83 Ω m). The sand (upper sand) has a resistivity of 363–647 Ω m in the area. Beneath this layer, the highly resistive sands (6941 Ω m) described in profile 2 as extending from north-eastern part to the southern area, gradually thins out towards VES 17. The sands are underlain by sandy clay that grades abruptly to a thick clay horizon (30–37 Ω m) towards the lagoon. The highly resistive sand re-appears below the clay to sandy clay horizon around VES 17.

A combination of profiles 1, 3, 4, and 5 reveal that generally in Ikorodu area, the lower, mostly confined sand occurs continuously in the central area of the profiles, revealing that the sand occurs at a shallower elevation in the central area along the NE–SW trend. The flanks of the profiles all have thicker clay horizons and the sand was not encountered in many parts of the flanks of the area, suggesting that the sandy layer occurs at greater depth at the flanks. These situations are partly due to differences in elevation, or could be structural as the basin has been described by a number of authors to be structurally controlled.

Aquifers in Ikorodu Area

As shown in the preceding discussions, the aquifer in Ikorodu area can be classified into two, namely:

1. The upper sand (mostly unconfined/semi-unconfined).
2. The lower sand (mostly confined/semi-confined).

The upper sand (mostly unconfined/Semi-unconfined)

The upper sand is exposed to the surface in almost all areas close to the Lagos lagoon and in some of the landward areas, due to elevation differences and effect of erosion that has carved out the area to the present rugged undulating topography. The upper sand, as shown in Figs. 5, 6, 7, 8, 9, and 10, is recharged mostly by precipitation in areas, where it is exposed to the surface. Although it is present in virtually all parts of Ikorodu, it has little hydrogeological significance in the landward area due to the relatively high elevation (20–60 m above sea level) in comparison with the elevation in the coastal area (< 10 m). It has thickness range between 1.4 and 34 m and, therefore, has low-to-high groundwater potential rating based on Oloruntola et al. (2017) aquifer potential classification scheme. In the coastal area, it has very high groundwater potential as water flows from the landward area towards the coast due to the hydraulic gradient between the areas. It supplies water to shallow wells in the coastal area all year round due to the availability of recharge through precipitation and perennial surface water bodies.

The lower sand (mostly confined/semi-confined)

The lower sand occurs at greater depth than the upper sand with a depth range of between 20 and 80 m in the central area. It is shown in Figs. 5, 6, 7, 8, 9, and 10. It is generally thicker than the upper sands and mostly sandwiched between two confining or semi-confining layers by clay, resistive sand (feruginized), or sandy clay. It has thickness range between 15 and 112. 4 m and, therefore, has medium-to-high groundwater potential rating based on Oloruntola et al. (2017) aquifer potential classification scheme. The sand is in hydraulic continuity throughout the area, especially in the central NE–SW area, where it is encountered in all the profiles. The confined aquifer supplies water to the deep wells and boreholes used mostly for domestic purposes in the study area. The depth of occurrence of the lower sand correlates strongly with the lithological logs and geophysical logs of wells in the area. In addition, it perfectly coincides with the estimated depth of some functional boreholes in the area, based on information supplied by the inhabitants (Fig. 13).

Conclusion

A combination of vertical electrical resistivity, lithologic, and gamma ray logs has been employed to study the occurrences and lateral continuity of aquifers within the Coastal Plain Sand Formation of Dahomey Basin in Ikorodu area, SE Lagos. Six VES traverses covering the entire area and two borehole logs showed that the formation consists of alternating sand, clay, sandy clay, and ferrugenized sands. The VES curves vary from three-layer type curves to six-layer type curves, showing alternation and cyclicity of the lithologies that have been described as characteristic of near shore depositional environment. The aquifers are mainly the sandy soils that occur at varying depths and thicknesses that are likely due to the variations in elevations from the landward parts to areas near the coast in the study area and the structural disposition of the basin. Two aquifer zones were delineated based on their depths of occurrence—the upper mostly unconfined aquifer/semi-unconfined which supports only shallow hand-dug wells exclusively around the coastal area and the lower confined/semi-unconfined aquifer that provides groundwater in the landward area. While the upper

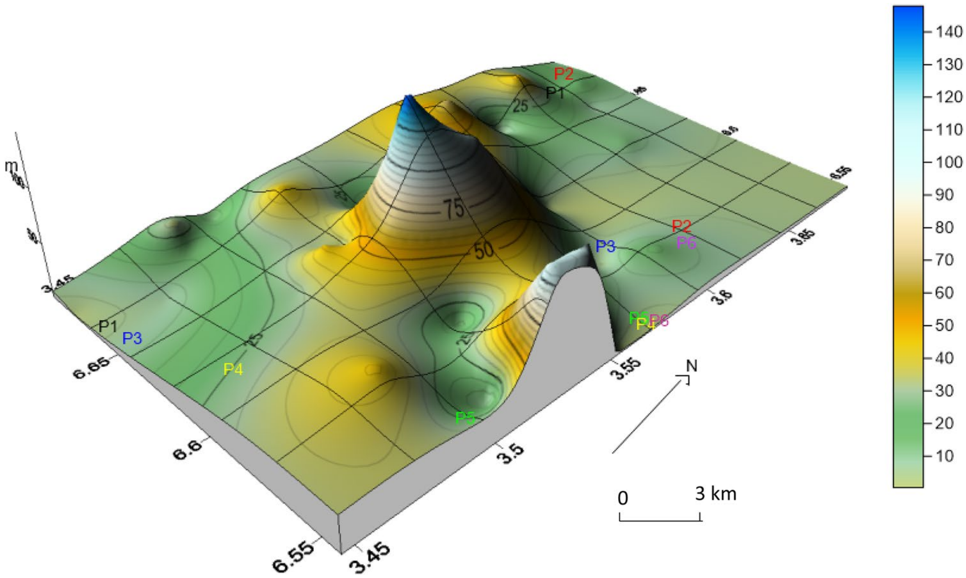


Fig. 13 3D model of aquifer thickness and distribution in the study area

sand generally has low-to-high groundwater potential, the lower sand has medium-to-high groundwater potential. The present study has provided some useful insights in the understanding of the groundwater resource in the area that can aid in further hydrogeological studies and groundwater management.

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