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Aquifer Mapping and Characterization in the Complex Transition Zone of Ijebu Ode, Southwestern Nigeria

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Abstract

Vertical electrical soundings (VES) and geophysical logs were employed to map and characterize the aquifer units in the Northwestern zone of Ijebu Ode, Southwestern Nigeria with a view to appraise the groundwater potential of the area. Sixteen Schlumberger soundings (VES) having maximum current electrode separation of 900 m were acquired and interpreted through partial curve matching and computer iteration. Gamma ray and resistivity logs acquired in a drilled hole were interpreted for aquifer characteristics. All but one sounding (VES 9), indicated signatures that are diagnostic of poor hydrogeological characteristics. Four layers were interpreted within 80 m depth. The first layer composed of topsoil (dry clay) which ranges in thickness from 0.8 to 1.5 m. Sandy clay (53 – 1895 Ωm) with varying thickness (0.8 – 34.5 m) constitute the second layer. Thick sand (2.4 – 55.3 m) having high resistivity (1208 – 7350 Ωm) make up the third layer. Resistive basement (3155 – 39529 Ωm) occurring at depth of 3 – 63 m constitute the fourth layer. The low resistivity sand (1023 Ωm) located beneath VES 9 was identified to be the saturated aquifer. The saturated aquifer has 8 – 10% clay content and 40% porosity. The aquifer is 100% saturated with fresh water having resistivity of 122 Ωm and TDS value of 53 ppm. This study showed that the area was of low groundwater potential and highlights the significance of combined surface and subsurface geophysical investigations for groundwater in area where groundwater occurrence is erratic.

Keywords: *Aquifer, Geophysical logging, Transition zone, Electrical resistivity, Ijebu Ode*

Rezumat. Cartarea și caracterizarea acviferului din zona complexă de tranziție Ijebu Ode, sud-vestul Nigeriei

Pentru cartarea și caracterizarea stratelor acvifere din nord-vestul zonei Ijebu Ode, situată în partea de sud-vest a Nigeriei, s-a folosit sondarea electrica verticala(VES) și forajele geofizice, cu scopul evaluării potențialului subteran din zonă. Au fost realizate saisprezece sondări Schlumberger (VES) cu o separație maximă a curentului electrod la 900 m, și ulterior interpretate cu ajutorul curvelor parțiale și a iterației computerizate. Pentru interpretarea caracteristicilor acviferului, s-au folosit razele gamma și sondările de rezistivitate obținute într-un foraj. Cu excepția unei singure forări (VES 9), toate celelalte au indicat o slabă calitate hidrogeologică. Patru strate au fost interpretate până la o adâncime de 80 m. Primul strat, compus în principal din argilă uscată, are o grosime ce variază între 0,8 și 1,5 m. Argila nisipoasă (53-1895 Ωm) cu o grosime variabilă (0,8-34,5 m) formează cel de al doilea strat, urmat de un strat gros de nisip (2,4 – 55,3 m) cu rezistivitate ridicată (1208 – 7350 Ωm). Stratul al patrulea reprezintă un soclu de rezistivitate (3155 – 39.529 Ωm), întâlnit la o adâncime de 3-63 m. Nisipul cu un nivel redus de rezistivitate (1023 Ωm), localizat sub VES 9 a fost identificat ca fiind acvifer saturat. Acviferul saturat are un conținut de argilă de 8-10% și porozitate 40%. Acviferul este saturat 100% cu apă dulce, având o rezistivitate de 122 Ωm și valoare TDS de 53 ppm. Studiul de față demonstrează că zona dispune de un potențial redus al rezervelor de apă subterană și evidențiază importanța investigațiilor geofizice combinate, de suprafață și subteran, pentru determinarea rezervelor de apă subterană în zonele unde aceasta este sporadică.

Cuvinte-cheie: *acvifer, sondare geofizică, zonă de tranziție, rezistivitate electrică, Ijebu Ode*

Introduction

Groundwater is water, which originates from the infiltration of fluids through the soil and accumulates below the earth's surface in a porous layer and permeable rock called the aquifer. Tyson (1993) and Pearce (2006) described water as "the defining crises of the twenty-first century". The study location (Fig. 1), Aco residential Estate in Ijebu Ode lies within a hydrogeologically complex and problematic transition zone, between the Precambrian Basement rocks and Cretaceous sediments of Dahomey Basin, Southwestern Nigeria. It was desired to have reliable supply of portable water in this estate as public water supply is non-existent in the region. Groundwater exploitation is then the next alternative. But groundwater accessibility has been a major challenge to the people of Ijebu Ode who rely on groundwater for domestic, industrial and irrigational purposes. The area is plagued with acute groundwater development challenges as evident in numerous abortive and low groundwater yielding boreholes in the area. Some of the boreholes drilled within the estate produce water only during rainy season. A number of completed houses in the estate are largely uninhabited due to paucity of potable water. Previous workers such as Osinowo and Olayinka (2012) reported that complex co-occurrence of different rock types in this transition zone made groundwater development in the area very challenging. Where Potable water is not commonly found, its provision will limit the setting up settlements to the places where supply exist (Shankar 1994 and Huisman 1966). Consequently, there is an urgent need to assess the groundwater potential of the area for possible groundwater development.

For this reason, electrical resistivity soundings were carried out. The results were test drilled and justified with stratigraphic and electrical logs obtained from the drill hole. Until recently, low monetary value of water has precluded the use of modern logging techniques in groundwater investigation irrespective of their benefits (Maliva *et al.* 2009). Electric logging that involved measurement of natural-gamma ray and formation resistivity was employed. Driscoll (1986), Keys (1997), and Kobr *et al.* (2005) reviewed the applications of borehole geophysical logging to groundwater investigation. In addition, the electrical resistivity method, using Schlumberger array of Vertical Electrical Sounding (VES) technique, was adopted. The technique employs fast, effective and versatile procedure which makes the characterization of subsurface geology possible (Ako 1989; Mbonu *et al.* 1991 and Ojo *et al.* 2007, Oyedele and Oladele 2011, Salami and Olorunfemi 2014).

This study aimed at characterizing the groundwater potential of Aco Estate, Ijebu-Ode area of Ogun state, Southwest, Nigeria using Vertical Electrical Sounding and borehole geophysical logging. This study provided guide for future groundwater development in the study area as means of reducing incidences of abortive and low yield borehole.

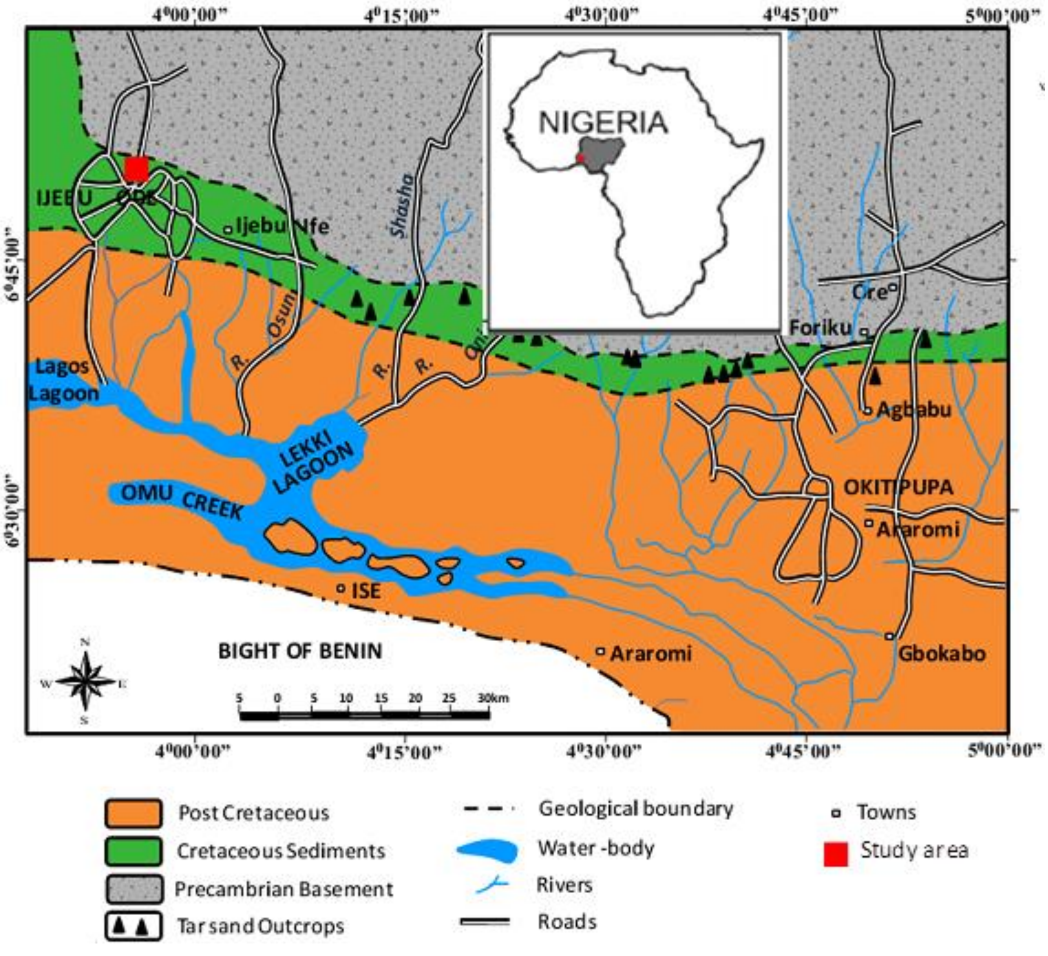

Fig. 1: Geologic map of the Ijebu-Ode zone and study area (processed after Enu, 1985). Inset: Map of Africa

Description of study area

Aco Estate is located in Ijebu Ode, Southwestern Nigeria (Fig. 1). It lies between longitude E003°53'11.01" to E003°53'39.96" and latitude N06°51'01.59" to N06°51'18.54". The elevation varies between 138.6 to 69.4 m above the sea level. Aco Estate is a developing residential estate with few completed buildings. The area is characterized by hot, humid tropical climate with rainy season which last from March/ April to October/ November and dry season which last for the rest of the year October/ November. An average annual rainfall of about 1300 mm and an annual potential evapo-transpiration of about 188 mm are prevalent (Akanni 1992). It is characterized by slightly dense vegetation and many big perennial rivers with mostly dendritic drainage pattern (Akanni 1992). The geologic units of the area are made up of crystalline rocks of the Basement Complex and sedimentary rocks of Eastern Dahomey Basin (Fig. 1). The basin stratigraphy is dominated by sand and shale alternation with minor proportion of limestones and clays (Omatsola and Adegoke, 1981). The stratigraphy of the eastern Dahomey basin is represented in Table 1.

Table 1: Regional stratigraphic setting of the Eastern Dahomey basin (Idowu et al. 1993)

Age		**Formation**			**Lithology**
		Ako et al., 1980	Omatsola and Adegoke, 1981		
Tertiary	Eocene	Ilaro Formation	Ilaro Formation		Sandstone
	Paleocene	Oshosun Formation	Oshosun Formation		Shale
		Ewekoro Formation	Ewekoro Formation		Limestone
Cretaceous	Maastrichtian		**Abeokuta Group**	Araromi Formation	Shale
	Turonian			Afowo Formation	Sandstone/ shale
	Berremian			Ise Formation	Sandstone

Methodology

Geophysical survey

The electrical resistivity method utilizing the Schlumberger Vertical Electrical Soundings (VES) technique was used for the surface groundwater exploration. The PASI 16-GL Resistivity Meter was used for the data acquisition. Sixteen (16) VES stations (Fig. 2) were occupied with maximum current electrode spacing (AB) of 900 m. The VES data obtained were manually plotted against their respective current-electrode spacing values (AB/2) on a log-log scale. The VES Curves were interpreted quantitatively by the partial curve matching technique and computer assisted 1-D forward modelling using WIN-RESIST computer iteration program to obtain the geoelectric parameters of the subsurface.

Geologic logging

Location of VES 9 was test drilled. Test drilling involved drilling small diameter hole (BH) that furnishes information on substrata in a vertical line from the subsurface. BH is positioned at Latitude N06°51'09.10" and Longitude E003°53'17.50". Geologic log was constructed from the drill-cutting samples collected at frequent intervals during the drilling of the well. It furnished a description of the geologic character and the thickness of each stratum encountered as a function of depth. It enabled delineation of aquifers from aquitards.

Geophysical logging and Lithologic identification

Geophysical logging of the subsurface geologic lithologic units penetrated by BH was accomplished by lowering a set sondes that contain water-tight gamma ray and resistivity instruments into BH and taking measurements at constant interval. The well was logged to depth of 63.0 m. Shale was differentiated from sand by establishing a shale baseline. Established "oil-field" geophysical-log interpretation methods were applied to the analysis of formations to identify freshwater aquifer. The primary application of natural-gamma logging is in identifying lithology. Clayey formations (shale, clay) emit more rays than gravels and sands. It therefore, differentiates between sand and clay. Resistivity logging is useful for determination of aquifer parameters, evaluation of quality of formation water and identification of the position of the water table.

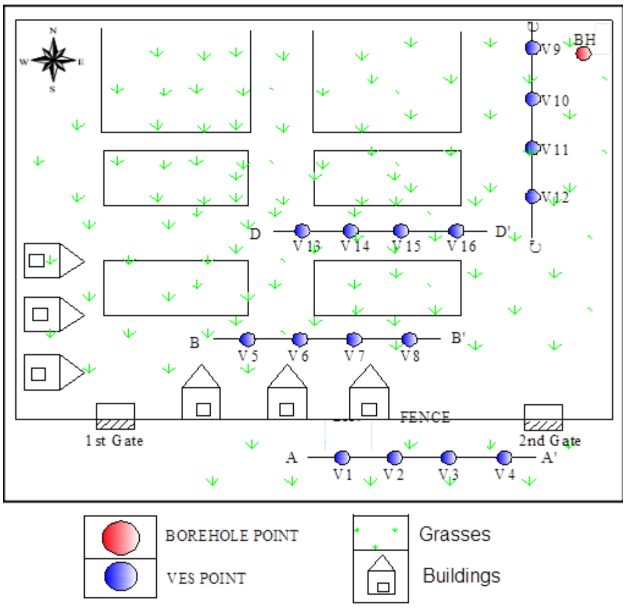

Fig. 2: Location of Vertical Electrical Soundings and geologic logging test

Estimation of clay content from the gamma logs

The clay content at certain was estimated from the Gamma Ray Index (I_{GR}). The I_{GR} was calculated from the Gamma Ray log using Eq. (1) by (Schlumberger, 1989):

$$I_{GR} = \frac{(GR_{\log} - GR_{\min})}{(GR_{\max} - GR_{\min})}$$

Where:

I_{GR} = Gamma Ray Index
GR_{log} = gamma ray reading from shaly sand
GR_{min} = gamma ray minimum from clean sand
GR_{log} = gamma ray maximum from shale

The calculated volumes of shale were expressed in percentage.

Determination of porosity

Porosity was roughly estimated from resistivity measurements using the Humble formula (Winsauer *et al.,*1952) in equation 2 in the absence of independent porosity device such as an acoustic log, a density log, or a neutron log.

$$F = \frac{0.62}{\emptyset^{2.15}}$$

Where F= Formation factor, Ø = porosity

Formation factor F was established using relationship established between the lithological descriptions and the formation factor (TNO 1976, Ecknis 1934).

Estimation of formation water resistivity (Rw)

The Formation water resistivity was computed from Eq. (3) by Asquith *et al.,* (2004): $R_{w} = \frac{R_o}{F}$

$$R_{w} = \frac{R_o}{F}$$

Where R_O is the formation resistivity obtained from log.

Determination of formation water saturation

Water saturation (*S*w), using the Archie's (1942) water saturation equation was computed from Eq. (4):

$$S_w^n = F \bullet R_w/R_t,$$

where *n* is the saturation exponent assumed to be 2.

Estimation of Total Dissolved Solids (TDS) of formation water

The total dissolved solids (TDS) in ppm of the formation were calculated from water resistivity using Eq. (5) by Turcan (1966) and Estepp (1998):

TDS = 0.64 * EC = 0.64 * 10,000/Rw

EC =electrical conductivity of the formation water in micromhos/cm

Results and discussion

Subsurface stratigraphy

The stratigraphy of the area (Fig. 3) is composed mainly of clay and sand. The lithologic unit from the surface to 18.0 m depth is predominantly clay and sandy clay varieties. From the depth of 18.0 m to 64.0 m is constituted by sand which grades from silt to fine grain sand. These sand units will constitute the potential aquifers in the study area.

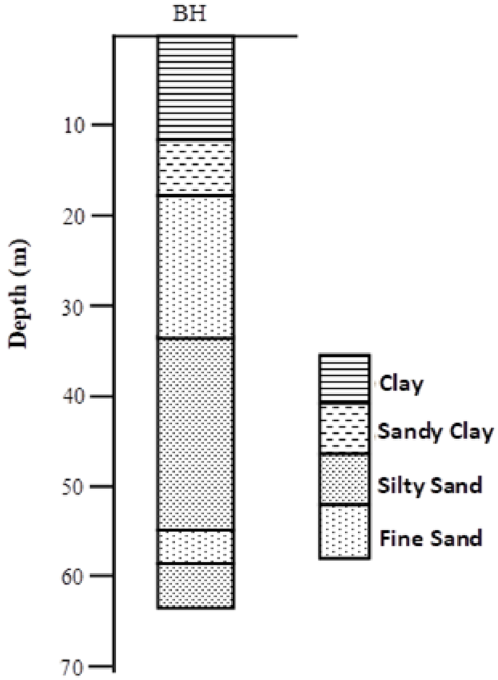

Fig. 3: Stratigraphic log of drill at the north-eastern part of the study area

Geoelectric characteristics

The interpreted VES curves in the study area are characterized by three to four geoelectric layers in form of A, AA, AK, HA, and KH type curves (Fig. 4). The results of interpreted VES curves are summarized in Table 2. Figures 5a - d show the geoelectric sections constructed from the interpreted VES data. Four lithologic units that included the topsoil, sandy clay, sand (dry sand and saturated sand) and fresh basement were depicted on the 2-D sections. The first layer is composed of topsoil (dry clay) which ranges in thickness from 0.8 to 1.5 m. Sandy clay (53 – 1895 Ωm) that was 0.8 – 34.5 m thick constitute the second layer. The sandy clay unit is typically of poor hydrogeological characteristics. Thick sand package (2.4 – 55.3 m) underlain the sandy clay and formed the third geo-electric layer. The high resistivity response of the thick sand (1208 – 7350 Ωm) indicated a high degree of dryness and could therefore not supply groundwater. However, beneath the dry sand is a package of sand beneath location of VES 9 believed to be saturated with water due to its lower resistivity response (1023 Ωm). Thickness of this water bearing sand could not be determined because of electrical current termination within this layer. The fourth layer was the highly resistive basement (3155 – 39529 Ωm) occurring at depths ranging from 3 – 63 m.

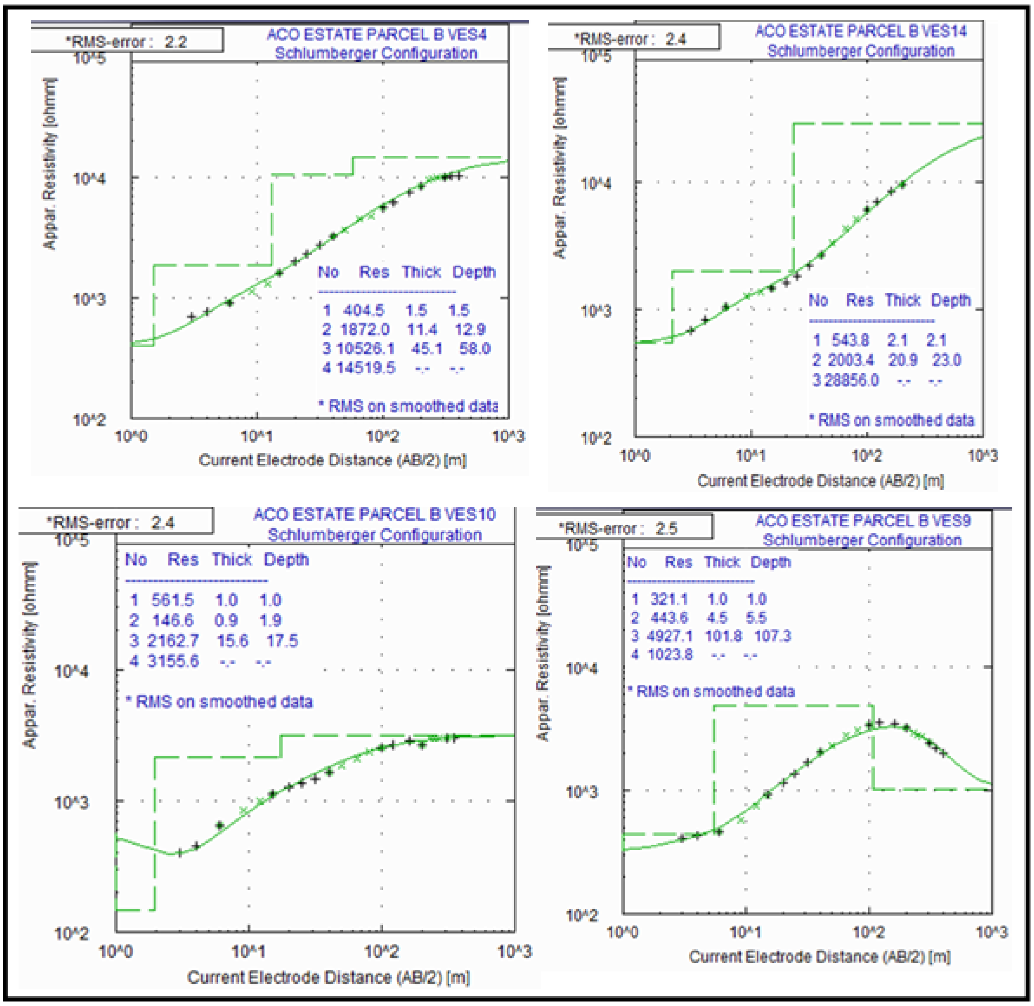

Fig. 4: Typical VES Curves and their interpretation models

Table 2: The results of the interpreted VES data

VES	Curve Type	No of Layer (s)	Resistivity (Ωm)	Thickness (m)	Depth (m)	Lithology
1	HA	4	354	0.9	0.9	Topsoil
			53	0.8	1.7	Sandy Clay
			4500	20.5	22.2	Sand (dry)
			7403	--	--	Fresh Basement
2	AA	4	321	1.0	1.0	Topsoil
			388	1.6	2.7	Sandy clay
			2984	22.7	25.4	Sand (dry)
			10268	--	--	Fresh Basement
3	KH	4	233	1.0	1.0	Topsoil
			8577	5.7	6.7	Sand (dry)
			2587	34.5	41.2	Sandy clay
			11154	---	---	Fresh Basement
4	A	3	404	1.5	1.5	Topsoil
			1898	11.0	12.5	Sandy Clay
			10106	---	---	Fresh Basement
5	A	3	267	1.4	1.4	Topsoil

			1409	16.2	17.7	Sandy Clay
			16584	---	---	Fresh Basement
6	A	3	188	0.8	0.8	Topsoil
			1208	14.5	15.2	Sandy Clay
			14416	---	---	Fresh Basement
7	A	3	214	1.1	1.1	Topsoil
			1377	10.9	12.0	Sandy Clay
			12606	---	---	Fresh Basement
8	A	3	238	1.1	1.1	Topsoil
			1135	7.9	8.9	Sandy Clay
			11837	---	---	Fresh Basement
9	AK	4	321	1.0	1.0	Topsoil
			443	4.5	5.5	Sandy clay
			4927	55.3	60.8	Sand (dry)
			1023	---	---	Sand (saturated)
10	HA	4	561	1.0	1.0	Topsoil
			146	0.9	1.9	Sandy clay
			2162	15.6	17.5	Sand (dry)
			3155	---	---	Fresh Basement
11	A	3	324	1.0	1.0	Topsoil
			1651	4.6	5.6	Sandy Clay
			4444	---	---	Fresh Basement
12	A	3	412	1.0	1.0	Topsoil
			3836	2.4	3.4	Sand (dry)
			7066	---	---	Fresh Basement
13	AA	4	466	1.0	1.0	Topsoil
			1895	14.6	16.6	Sandy Clay
			7350	47.3	62.8	Sand (dry)
			39529	---	---	Fresh Basement
14	A	3	543	2.1	2.1	Topsoil
			2003	20.9	23.0	Sandy Clay
			28868	---	---	Fresh Basement
15	A	3	616	0.9	0.9	Topsoil
			1240	11.6	12.5	Sandy Clay
			15624	--	--	Fresh Basement
16	A	3	304	1.0	1.0	Topsoil
			1895	20.1	21.1	Sandy Clay
			23743	---	---	Fresh Basement

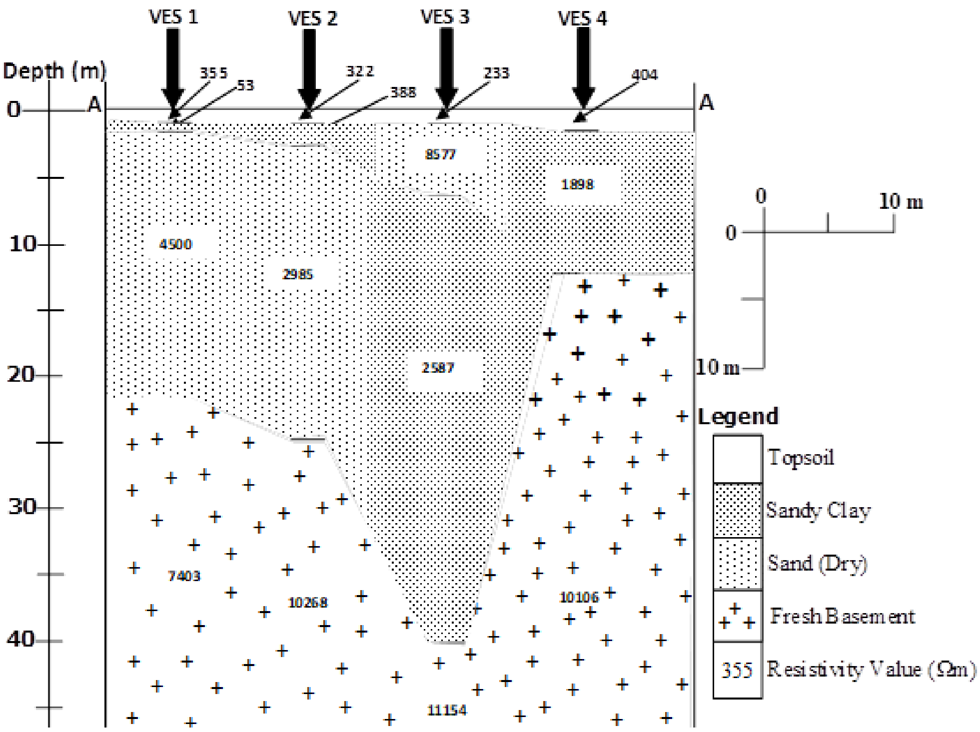

Fig. 5a: Geolectric sections along profile A - A'

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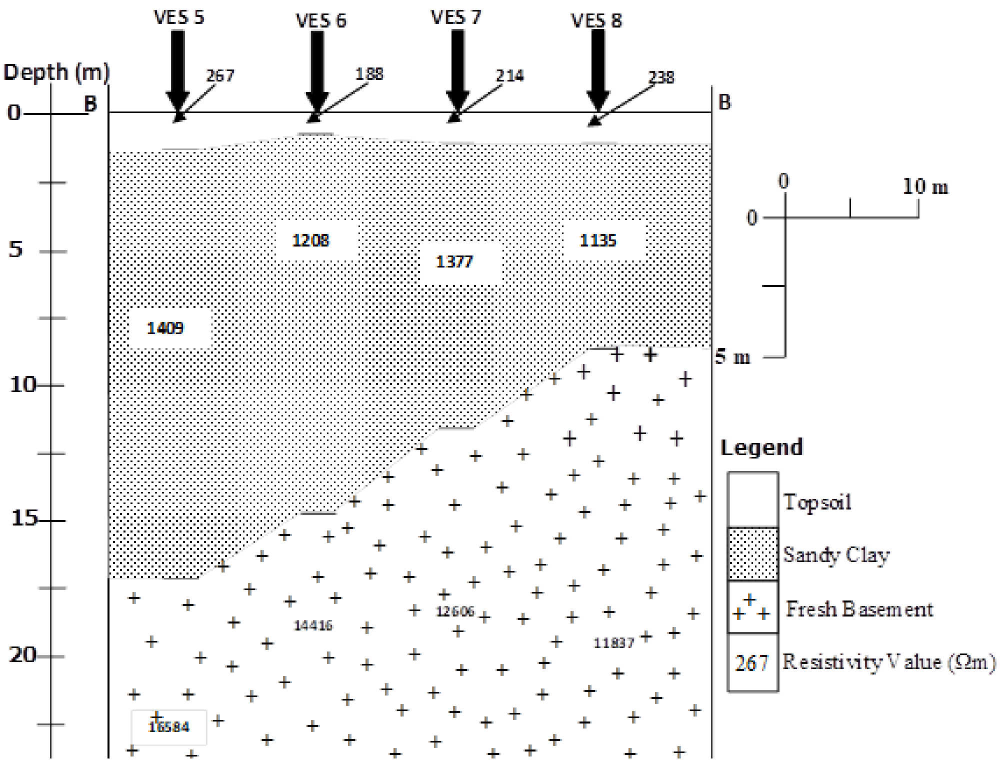

Fig. 5b: Geolectric sections along profile B - B'

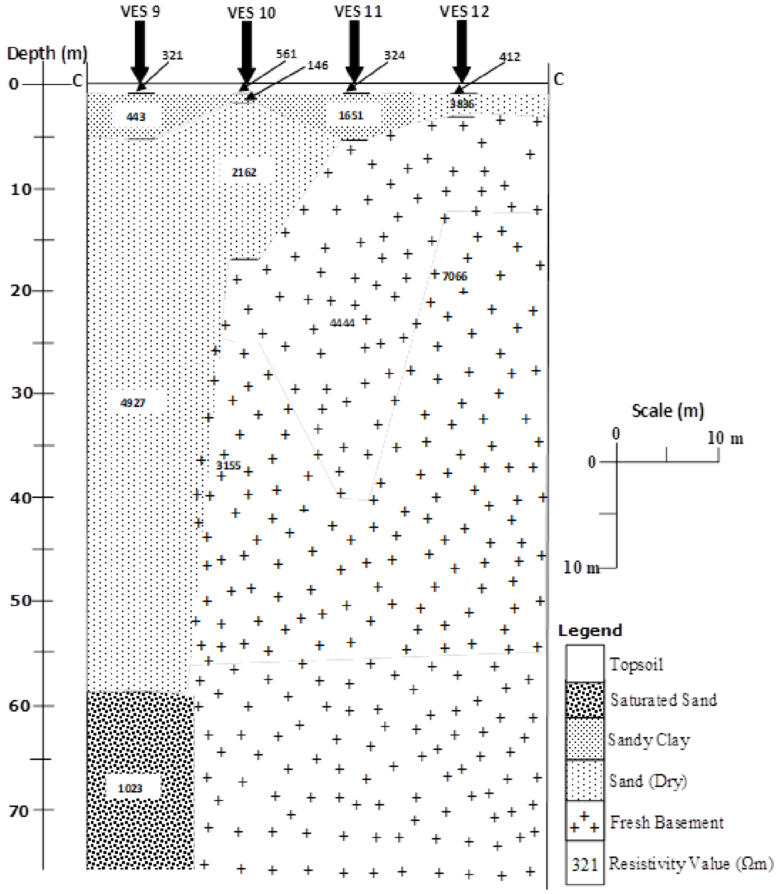

Fig. 5c Geoelectric sections along profile C - C'

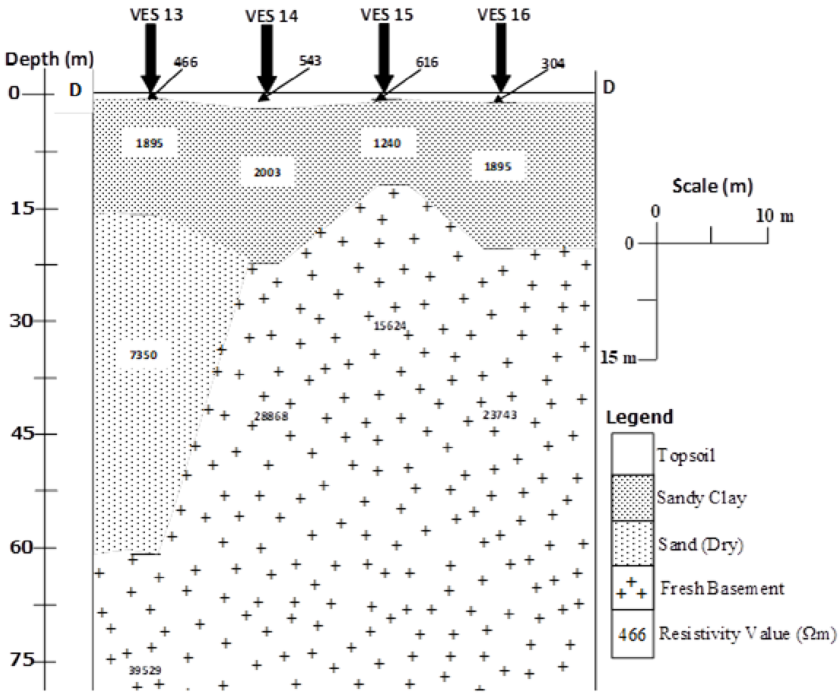

Fig. 5d: Geoelectric sections along profile D - D'

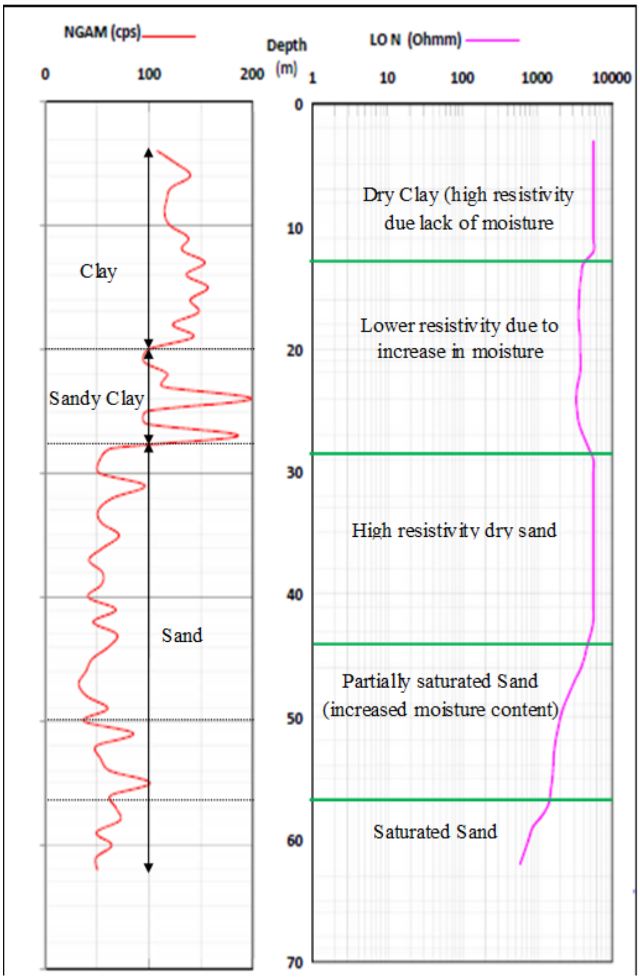

Fig. 6: Interpreted gamma ray and resistivity logs showing a sequence of clay, sandy clay and sand

Geophysical logs interpretation and estimation of petrophysical parameters

Interpreted geophysical logs (Fig. 6) revealed a sequence of clay, sandy clay and sand. The layer from depth of 4.0 - 20.0 m is denoted as clay due to the high gamma response (100 – 150 API). High resistivity response (5500 Ωm) of this clay implied absence of moisture content. Thus, this layer constitutes an aquitard of no groundwater potential. Sandy clay underlies the clay unit down to 29 m depth. Serration of the gamma ray indicated presence of sand streak in the clay unit. Reduction in the resistivity of sandy clay (3000 Ωm) and lower part of the overlying clay may be due to relative increase in moisture content. This unit is viewed as not significant for groundwater development due to low fluid content. Sand underlies the sandy clay to 63 m depth. This sand may vary in size from silty to fine grained as portrayed by serrated gamma ray signature and evident in the lithologic log.

The upper part of the sand down to 44 m was interpreted as dry sand due to high resistivity response (3500 – 6000 Ωm). The middle section of the sand (44 – 56 m) is characterized by reduced resistivity response (1000 – 3500 Ωm) indicative of partial saturation condition or increased clay content. This layer might not be reliable for groundwater accumulation. The lowermost section of the log (56 – >63 m) indicated low resistivity response sand (600 – 1000 Ωm) interpreted as water saturated aquifer. Calculated clay content in the saturated sand aquifer ranges from 8 – 10% while the porosity of 40% was estimated. The aquifer was 100% saturated with fresh water that was characterized by resistivity of 122 Ωm and TDS value of 53 ppm. These properties indicated high quality water accumulation in a highly porous aquiferous unit that could furnish water in economic quantity.

Basement topography

Depth to basement varies from 12.5 m to 62.8 m (Figures 5a-d) where sand-basement interface were determined and would be deeper where the interface was not imaged such as beneath VES 9. Depressions exist in the basement beneath locations of 3, 5, 9 and 13. There is possibility that these basement depressions could host groundwater especially during the raining season when they are recharged by percolating rain water.

Reasons for high rate of failed boreholes

The high rate of failed boreholes in the study area could be explained from the results of this study. The existence of thick column of clay at shallow subsurface would have contributed the spate of failure of shallow borehole and hand dug wells around the study area when such clay inadvertently was the target of groundwater abstraction. Clay by nature has low permeability in spite of its high porosity and thus cannot ensure sustainable groundwater yield. Furthermore, the presence of thick column of impermeable clay at near surface connotes poor infiltration of the surface water during the rainy season which translates to inadequate recharge of the underlying aquifer. Moreover, the existence of very thin sediment package/shallow basement and situation in which weathered/fractured basement is non-existent combined to produce insignificantly thick overburden column which considerably diminished the prospect for economic groundwater occurrence. In addition, the occurrence of thick but dry sand, though porous and permeable, that was not recharged presented hydrogeological dilemma in which an aquiferous unit is bereft of groundwater. This condition is partly responsible for paucity of groundwater in the study area.

Borehole site selection and optimum borehole depth

The study area is generally of low groundwater potential as evident in the prevalence of A AA and type curves in the population of interpreted VES curves. However, the low resistivity sand column delineated underneath VES 9 at 60.8 m depth and interpreted as water saturated sand was envisaged to be of very high groundwater potential and capable of yielding groundwater in economic quantity. A borehole that would terminate at the base of the saturated sand (> 61 m) beneath VES 9 point is recommended for groundwater development in Aco Estate. Alternatively, the test hole can be re-entered and developed into groundwater abstraction borehole.

Conclusion

The groundwater potential of part of Ijebu Ode, infamous for failed boreholes, has been investigated using combined surface and subsurface geophysical methods. The subsurface sequence is characterized by clayey top soil, sandy clay, sand (dry and saturated) and fresh basement. Generally, the VES stations in the area have very poor hydrogeological characteristics. Eighty percent of the VES interpreted are A/AA type curves which are typical geoelectric signatures that are diagnostic of low groundwater potential units. The high rate of failed boreholes in the study area was possibly due to presence of thick column of impermeable clay at shallow subsurface, the existence of very thin overburden in some locations, occurrence of dry aquiferous sand unit d rugose basement architecture. The combination of these unfavourable hydrogeological conditions culminated to dearth of groundwater in the study area. However, VES 9 point was recommended for drilling to the base (> 61 m) of water saturated sand unit. Due to favourable aquifer properties, this sand is envisaged to be of very high groundwater potential and capable of furnishing groundwater in economic quantity. This study demonstrated the importance of integrating geophysical and logging tests in mapping and characterizing aquifer in a typical complex geologic terrain.

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