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Application of vertical electrical soundings to characterize aquifer potential in Ota, Southwestern Nigeria

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A knowledge of hydrogeophysical parameters of aquifers is essential for groundwater resource assessment, development and management. Traditionally, these parameters are estimated using pumping test carried out in boreholes or wells; but this is often costly and time consuming. Surface geophysical measurements can provide a cost effective and efficient estimates of these parameters. In the present work, geoelectrical resistivity data has been used to characterize and evaluate the aquifer potential at Covenant University, Ota, southwestern Nigeria. Some thirty-five vertical electrical soundings (VESs) were conducted using Schlumberger array with a maximun half-current electrode spacing (AB/2) of 240 m. The geoelectrical parameters obtained were used to estimate longitudinal conductance and transverse resistance of the delineated aquifer. Both the longitudinal conductance and transverse resistance, which qualitatively reflects the hydraulic properties of the aquifer, indicate that the aquifer unit is characterized with high values of hydraulic parameters; consequently a good groundwater potential. Thus, groundwater resource development and management in the area can be effectively planned based on these parameters.

Key words: Hydrogeophysics, geoelectrical parameters, resistivity survey, aquifer potential.

INTRODUCTION

Geophysical methods are increasingly becoming relevant in hydrological applications (Hubbard et al., 1997; Rubin and Hubbard, 2005; Vereecken et al., 2006). Conventional hydrogeologic investigation requires estimates of hydraulic parameters using traditional approaches such as pumping test, slug test and laboratory analyses of core samples. Pumping tests can produce reliable estimates of hydraulic parameters, but the estimates are largely volumetric averages. Laboratory analyses can provide information at a very fine scale, but there are many questions about the reliability of the hydraulic parameters estimates obtained with those analyses. Slug test has the most potential of the traditional approaches for detailed characterization of the variability of hydraulic parameters, but most sites do not have the extensive well network required for effective application of this approach (Butler, 2005). These traditional methods are time-consuming and invasive.

Non-invasive (or minimally invasive) geophysical methods can be used to characterize an image flow and transport processes within the subsurface. Spatial and temporal patterns of hydrological states can be retrieved from the geophysical parameters; thus, estimates of the hydrological and petro-physical parameters that determine flow and transport processes can be made. Geoelectrical resistivity technique is one of the most

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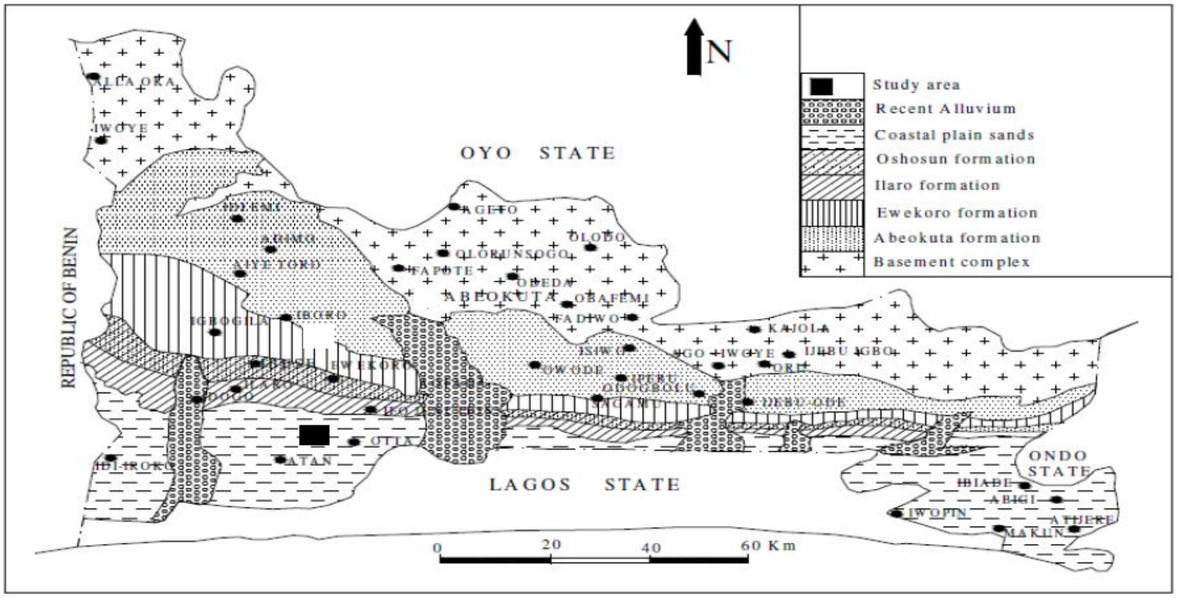

Figure 1. Geological map of Ogun State showing the study area (after Badmus and Olatinsu, 2010).

common geophysical tools used for hydrological investigations. The technique has been widely used in groundwater exploration to determine depth to water-table, aquifer geometry and groundwater quality by analyzing measured apparent resistivity field data. Numerical inversion techniques are often used to obtain the inverse model of the electrical resistivity distribution of the subsurface from the measured apparent resistivity data. This is achieved by solving the nonlinear and mixed-determined inverse problem whose solution is inherently non-unique and sometimes unstable. Typically, the resolution of the inversion result differs spatially, so that some regions may be well resolved while others are prone to exhibit artefacts and interpretation errors (Day-Lewis et al., 2005; Aizebeokhai, 2009).

In general, the inverse geophysical models can be used to estimate the hydraulic properties of aquifer by using analytical relationships between hydraulic parameters and geoelectrical parameters (Niwas and de Lima, 2003). In the present work, some thirty-five vertical electrical soundings (VESs) were conducted in Covenant University campus, Ota, southwestern Nigeria. The survey was carried out between the months of April and May, 2013 as part of the preliminary investigations to evaluate groundwater resource potential in the area. Schlumberger array was used in conducting the measurements with a maximum half-current electrode spacing (AB/2) of 240 m. The geoelectrical parameters obtained from the survey, which characterized the aquifer unit, were used to estimate the longitudinal conductance and transverse resistance of the delineated aquifer. The longitudinal conductance and transverse resistance of a porous medium characterise the hydraulic properties (conductivity and transmissivity) of the medium. The electrical resistivity (or its inverse conductivity) of a porous medium does not directly gives information about the hydraulic conductivity of the medium since the bulk electrical resistivity primarily depends on porosity, water saturation and dissolved ions.

Study area

The study area (Figure 1) falls within the eastern Dahomey (or Benin) Basin of southwestern Nigeria which stretches along the continental margin of the Gulf of Guinea. The area is generally a gently sloping low-lying area characterized by two major climatic seasons namely, dry season spanning from November to March and raining (or wet) season between April and October. Occasional rainfalls are usually witnessed within the dry season, particularly along the region adjoining the coast. Mean annual rainfall is greater than 2000 mm and forms the major source of groundwater recharge in the area.

In general, the rocks are Late Cretaceous to Early Tertiary in age (Jones and Hockey, 1964; Omatsola and Adegoke, 1981; Billman, 1992; Olabode, 2006). The stratigraphy of the basin has been grouped into Abeokuta Group, Imo Group, Oshoshun, Ilaro and Benin Formations (Figure 2). The Cretaceous Abeokuta Group consists of Ise, Afowo and Araromi Formations, and mainly composed of poorly sorted ferruginized grit, siltstone and mudstone with shale-clay layers. Overlying the Abeokuta Group is the Imo Group which is subdivided into the limestone-dominated Ewekoro Formation and the shale-dominated Akinbo Formation. The Akinbo Formation

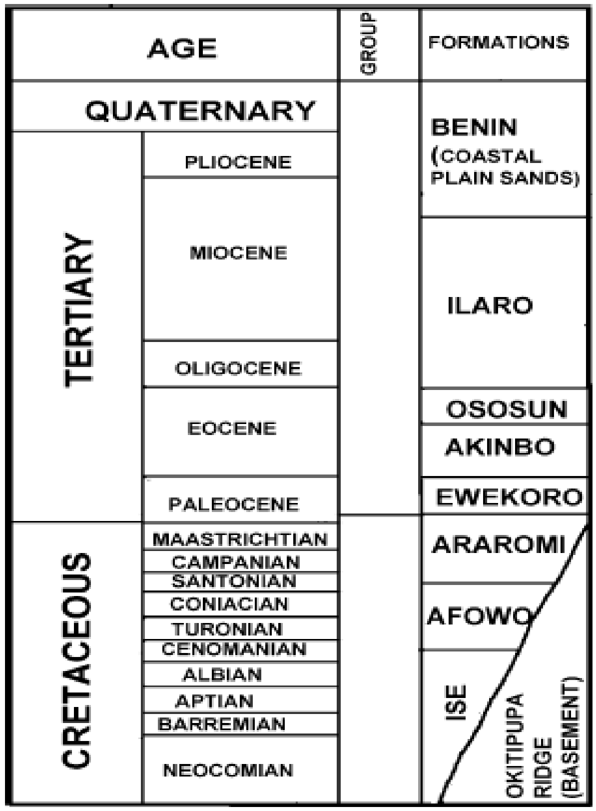

Figure 2. Simplified Cretaceous and Tertiary stratigraphy of the Nigeria part of Dahomey Basin (after Jones and Hockey 1964; Omatsola and Adegoke 1981; Billman 1992).

is overlain by the Oshoshun Fomation and then Ilaro Formation which is predominantly a sequence of coarse sandy estuarine, deltaic and continental beds; the Ilaro Formation displays rapid lateral facies changes. Overlying the Ilaro Formation is the Benin Formation which is predominantly coastal plain sands and Tertiary alluvium deposits. The local geology is predominantly coastal plain sands which are underlain by a sequence of coarse sandy estuarine, deltaic and continental beds largely characterised by rapid changes in facies.

METHODOLOGY

Vertical electrical soundings

A total of thirty-five vertical electrical soundings (VES) were conducted within the study area so as to delineate the subsurface lithological configuration, depth to aquifer(s) and aquifer characteristics. An ABEM Terrameter (SAS 1000 series) was used for the apparent resistivity measurements. Schlumberger electrode configuration was adopted for the resistivity soundings due to its high lateral resolution. The maximum half-current electrode separation (AB/2) used ranges from 130 to 240 m, with an average of 180 m. The spread was sufficient for the effective depth of investigation anticipated. Most of the VESs were conducted along three main profiles (Figure 3). Care was taken to minimize electrode positioning error. A minimum stack of 3 and maximum of 6 were used for measurement. The root-mean squares error associated with the data measurement was minimal, generally less than 0.3%. Measurements with root-mean squares error up to 0.5% or more were repeated after re-checking electrodes contact.

The observed apparent resistivity data were processed by plotting the apparent resistivity values against half-current electrode spacing (AB/2 or half the spread length) at each station on a bi-logarithmic (log – log) graph sheets. Partial curve matching of the field curves with relevant Schlumberger developed master and auxiliary curves was carried out to obtain estimates of the number of layers and their respective resistivities and thicknesses. The geoelectric parameters obtained from this manual interpretation were then used as the initial models for the computer inversion using the Win-Resist code. This computer code uses iterative process by matching the computed data with the observed field data to obtain the inverse models. The iterative process is an attempt to reduce the root-mean squares errors and improve the goodness of fit between the measured data and computed data. The root-mean squares error observed in the inversion range between 1.4 and 2.8%.

Hydraulic parameters estimation

The relationship between the hydraulic conductivity K and geoelectrical resistivity ρ of an aquifer is strongly controlled by the nature of the aquifer substratum (Niwas and Singhal, 1985; Niwas

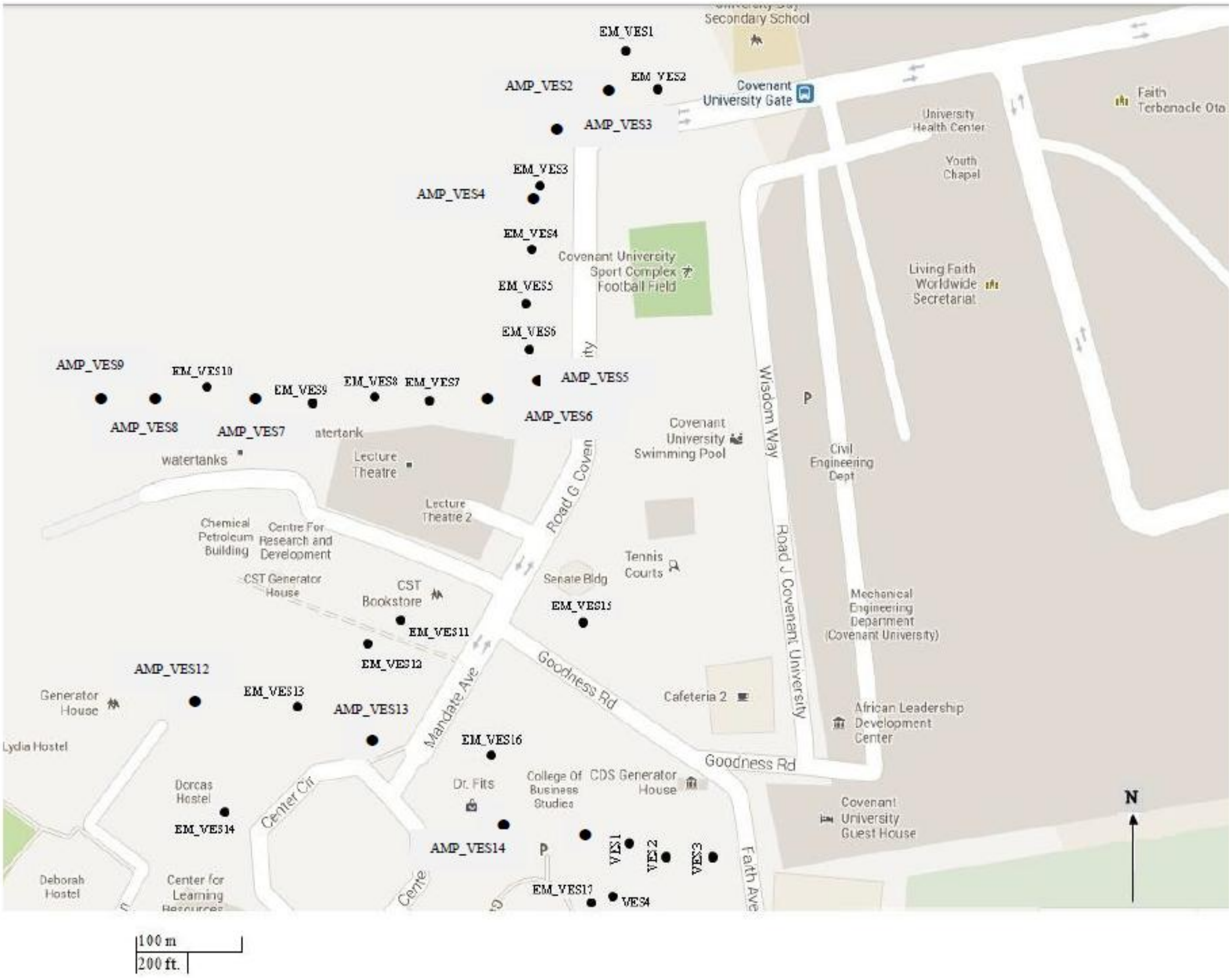

Figure 3. Map showing the study area and locations of VES points.

and de Lima, 2003). For a highly resistive substratum, both the current and the hydraulic flows are dominantly horizontal in a typical unit column of the aquifer, and the relationship between K and ρ, is inverse. If the substratum is highly conductive, the hydraulic flow will still be horizontal while the current flow in a characteristic unit column is dominantly vertical; thus, a direct relation exist between K and ρ. If the aquifer material is cut in the form of a vertical prism of the unit cross-section from top to bottom, fluid flow and current flow in the aquifer material obeys Darcy's law and Ohm's law respectively. Thus, for current and fluid flows in a lateral direction, the transmissivity of the aquifer is given as:

$$T = (K\rho)S \qquad (1)$$

where ρ is the bulk resistivity and S is the longitudinal unit conductance of the aquifer material with thickness b given by b/ρ. For a lateral hydraulic flow and current flowing transversely, the transmissivity of the aquifer becomes:

$$T = (K/\rho)R \qquad (2)$$

where R is the transverse unit resistance of the aquifer material given by $b\rho$. If the aquifer is saturated with water with uniform resistivity, then the product $K\rho$ or K/ρ would remain constant. Thus, the transmissivity of an aquifer is proportional to the longitudinal conductance for a highly resistive basement where electrical current tends to flow horizontally, and proportional to the transverse resistance for a highly conductive basement where electrical current tends to flow vertically (Niwas et al., 2011). The above equations may therefore be written as:

$$T = \alpha S; \quad \alpha = K\rho \qquad (3)$$

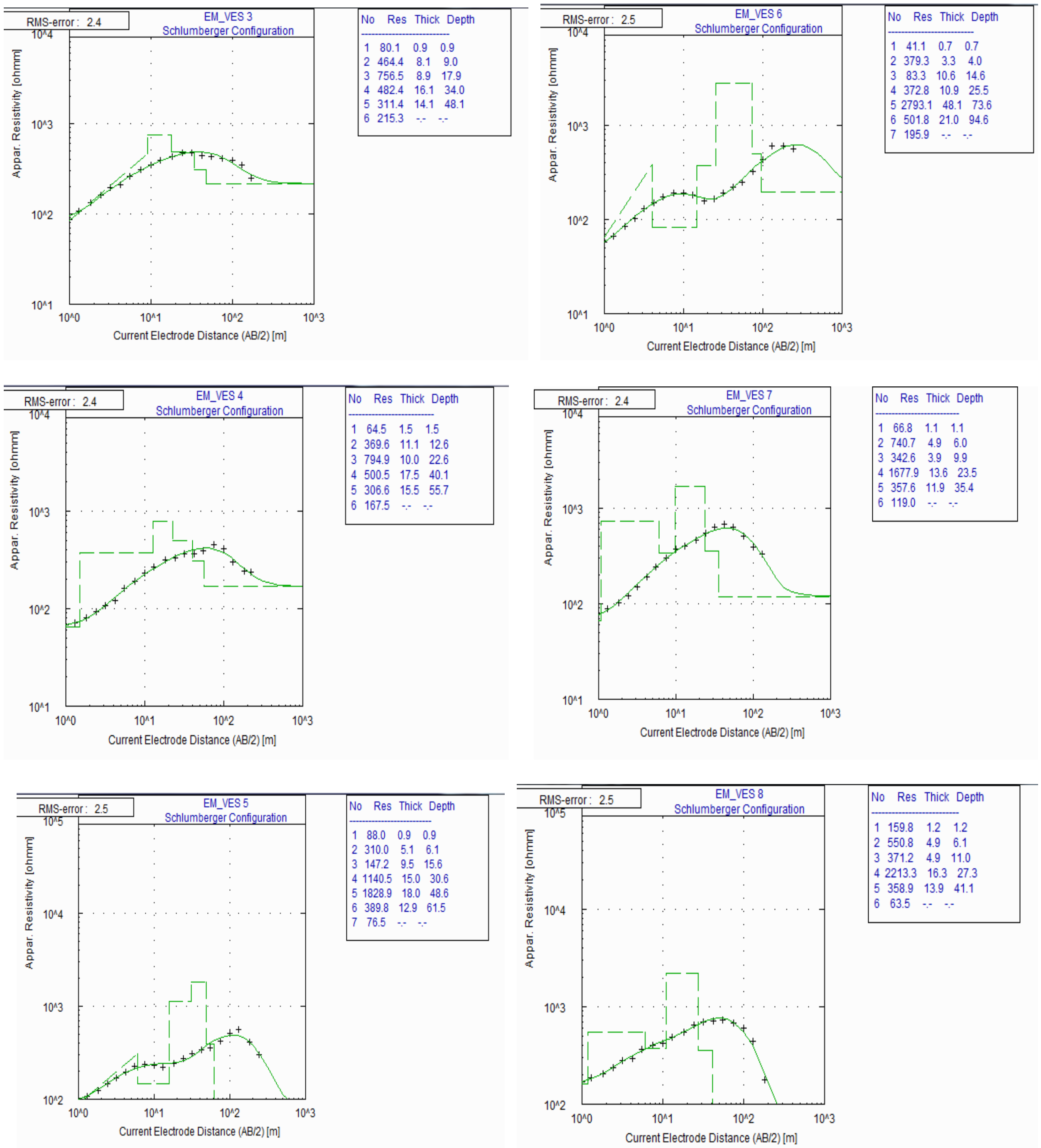

Figure 4. Representative of the iterated VES curves showing the inverse models of the geoelectrical parameters.

and

$$T = \beta R; \quad \beta = K / \rho \tag{4}$$

where α and β are constants of proportionality. From these relations, the model resistivity values obtained from the inversion process were used to estimate the longitudinal unit conductance and transverse unit resistance of the aquifer unit.

RESULTS AND DISCUSSION

Some representative of the output from the computer interpretation of the observed apparent resistivity data are presented in Figure 4. Five to seven layers were generally delineated from the iterated sounding curves. The geoelectrical parameters of the layers correlated for each Traverse are presented in Tables 1 to 3; the

Table 1. Geoelectrical parameters of the VES in Traverse 1.

Layer	1			2			3			4			5			6			7		
Lithology	Top Soil (Sandy Clay)			Lateritic Clay			Lateritic Clay (Compacted)			Clayey/Silty Sand			Laterite (Confining Bed)			Sand (Main Aquifer)			Shale/Clay		
Location	Resistivity (Ωm)	Thickness (m)	Bottom Depth (m)	Resistivity (Ωm)	Thickness (m)	Bottom Depth (m)	Resistivity (Ωm)	Thickness (m)	Bottom Depth (m)	Resistivity (Ωm)	Thickness (m)	Bottom Depth (m)	Resistivity (Ωm)	Thickness (m)	Bottom Depth (m)	Resistivity (Ωm)	Thickness (m)	Bottom Depth (m)	Resistivity (Ωm)	Thickness (m)	Bottom Depth (m)
EM_VES 3	80.1	0.9	0.9	464.4	8.1	9.0	756.5	8.9	17.9	482.4	16.1	34.0			34.0	311.4	14.1	48.1	215.3		
AMP-VES 3	70.8	0.9	0.9	548.8	8.7	9.6	709.5	9.4	19.1	459.0	16.2	35.2			35.2	306.8	15.2	50.4	220.8		
EM_VES 4	64.5	1.5	1.5	369.6	11.1	12.6	794.9	10.0	22.6	500.5	17.5	40.1			40.1	306.6	15.5	55.7	167.5		
AMP-VES 4	41.4	1.1	1.1	405.4	12.4	13.4	443.7	8.7	22.1	304.5	15.4	37.5			37.5	258.4	15.3	52.8	171.5		
EM_VES 5	88.0	0.9	0.9	310.0	5.2	6.1	147.2	9.5	15.6	1140.5	15.0	30.6	1828.9	18.0	48.6	389.8	12.9	61.5	76.5		
AMP-VES 5	37.0	0.7	0.7	446.4	3.6	4.3	76.0	10.5	14.8	422.5	11.6	26.4	4641.6	32.5	58.8	437.1	21.9	80.8	239.4		
EM_VES 6	41.1	0.7	0.7	379.3	3.3	4.0	83.3	10.6	14.6	372.8	10.9	25.5	2793.1	48.1	73.6	501.8	21.0	94.6	195.9		

Table 2. Geoelectrical model parameters of the VES in Traverse 2.

Layer	1			2			3			4			5			6			7		
Lithology	Top Soil (Sandy Clay)			Lateritic Clay			Lateritic Clay (Compacted)			Clayey/Silty Sand			Laterite (Confining Bed)			Sand (Main Aquifer)			Shale/Clay		
Location	Resistivity (Ωm)	Thickness (m)	Bottom Depth (m)	Resistivity (Ωm)	Thickness (m)	Bottom Depth (m)	Resistivity (Ωm)	Thickness (m)	Bottom Depth (m)	Resistivity (Ωm)	Thickness (m)	Bottom Depth (m)	Resistivity (Ωm)	Thickness (m)	Bottom Depth (m)	Resistivity (Ωm)	Thickness (m)	Bottom Depth (m)	Resistivity(Ωm)	Thickness (m)	Bottom Depth (m)
EM_VES 7	66.8	1.1	1.1	740.7	4.9	6.0	342.6	3.9	9.9			9.9	1677.9	13.6	23.5	357.6	11.9	35.4	119.0		
AMP-VES 6	86.9	1.1	1.1	750.7	5.0	6.1	353.2	4.0	10.1			10.1	1726.8	13.4	23.5	347.0	11.9	35.4	118.1		
EM_VES 8	159.8	1.2	1.2	550.8	4.9	6.1	371.2	4.9	11.0			11.0	2213.3	16.3	27.3	358.9	13.9	41.1	63.5		
EM_VES 9	70.8	1.2	1.2	684.4	5.9	7.1	440.1	5.4	12.4			12.4	2659.8	19.5	32.0	368.3	14.9	46.9	91.6		
AMP-VES 7	100.0	0.5	0.5	489.0	3.0	3.5	284.0	3.3	6.9	656.6	5.5	12.4	2770.8	14.2	26.6	341.0	13.1	39.7	25.7		
AMP-VES 8	47.3	0.8	0.8	621.3	4.9	5.7	1033.7	5.4	11.1	979.2	7.6	18.6	2864.2	15.3	34.0	363.8	11.9	45.9	54.1		
EM_VES 10	80.3	1.5	1.5	979.1	4.8	6.3	1509.8	6.9	13.2	738.7	7.7	20.9	2219.9	14.9	35.8	368.0	12.3	48.1	134.7		
AMP-VES 9	72.3	0.9	0.9	509.7	5.2	6.2	1350.8	6.3	12.5	976.4	6.1	18.6	2422.0	14.5	33.1	346.4	11.7	44.7	128.5		

geoelectric parameters are largely consistent among the interpreted sounding curves. The lithologies of the interpreted layers were inferred based on the local geology and available information.

The resistivity of the top soil (sandy clay) varies

Table 3. Geoelectrical model parameters of the VES in Traverse 3.

Layer	1			2			3			4			5			6			7		
Lithology	Top Soil (Sandy Clay)			Lateritic Clay			Lateritic Clay (Compacted)			Clayey/Silty Sand			Laterite (Confining Bed)			Sand (Main Aquifer)			Shale/Clay		
Location	Resistivity (Ωm)	Thickness (m)	Bottom Depth (m)	Resistivity (Ωm)	Thickness (m)	Bottom Depth (m)	Resistivity (Ωm)	Thickness (m)	Bottom Depth (m)	Resistivity (Ωm)	Thickness (m)	Bottom Depth (m)	Resistivity (Ωm)	Thickness (m)	Bottom Depth (m)	Resistivity(Ω m)	Thickness (m)	Bottom Depth (m)	Resistivity (Ωm)	Thickness (m)	Bottom Depth (m)
AMP-VES 12	397.7	0.8	0.8	452.7	3.7	4.5	339.8	4.7	9.2			9.2	1361.7	12.3	21.5	354.8	12.6	34.1	123.5		
EM_VES 13	314.8	0.9	0.9	543.7	4.5	5.4	354.0	5.3	10.7			10.7	1000.9	11.9	22.6	345.9	11.6	34.2	88.0		
AMP-VES 13	413.1	1.2	1.2	566.7	5.3	6.5	483.6	7.8	14.3			14.3	787.7	8.2	22.6	245.1	15.0	37.6	473.1		
EM_VES 15	223.9	0.7	0.7	615.5	3.1	3.9	495.5	4.4	8.3			8.3	1223.2	14.4	22.7	297.3	11.5	34.1	87.9		
AMP-VES 14	306.8	0.6	0.6	606.3	2.2	2.8	344.5	3.4	6.4			6.4	2138.3	11.4	17.7	276.1	10.4	28.1	64.0		
EM_VES 16	181.5	0.8	0.8	547.4	3.3	4.1	456.1	4.1	8.2			8.2	4170.7	15.5	23.7	345.6	11.5	35.2	22.9		
VES 3	502.0	0.8	0.8	835.0	3.2	4.0	571.3	6.2	10.2			10.2	2165.0	21.0	31.2	350.0	12.0	43.2	120.0		
VES 1	418.7	0.6	0.6	814.9	5.4	6.0	156.8	6.1	12.1	288.9	4.3	16.4	4221.5	11.0	27.4	346.0	11.3	38.7	48.2		
VES 4	234.1	0.6	0.6	909.2	3.3	3.9	291.2	4.9	8.8	711.1	7.2	16.0	2150.2	18.2	34.2	345.3	11.6	45.8	103.2		

from $41.1\Omega m$ to $502.0\Omega m$ with mean resistivity of $156.81\Omega m$; the thickness of this layer ranges from 0.5 – 1.5 m. The resistivity of the top soil largely depends on clay volume, moisture content and degree of compaction. The resistivity of the underlying geoelectric layer range from $310.0\,\Omega m$ to $909.2\,\Omega m$ with thickness ranging from 2.2 – 13.0 m, while those of the third geoelectric layer are $76.0 - 1509.8\,\Omega m$ and $3.3 - 10.6\,m$. The second and third layers are laterally continous and are basically the same lithologic unit, lateritic clay, with different degree of compaction and water saturation. The variability in the resistivity and thickness of these units are shown in Tables 1 to 3. These layers are largely impermeable, especially in areas where they are compacted, and percolation through these layers relatively poor and slow. Consequently, the top soil and possibly the second layer occasionally form parched aquifer; and most parts of the areas are usually flooded due to poor percolation of the underlying layers (Aizebeokhai et al., 2010).

The fourth geoelectric layer, an intercallation of silt, sand and clay, was delineated in all the soundings in Traverse 1 and some of the soundings in Traverses 2 and 3. The range of model resistivity of this layer is $288.9 - 1140.5\,\Omega m$ with thickness ranging from 4.3 – 17.5 m. This layer is thought to be laterally discontions continous based on the geoeletric layers delineated. However, it may be masked in some cases due to the resistivity contrast between the third and fifth geoelectric layers. Underlying this geoelectric layer is a very high resistive substratum with resitivity ranging from $787.7 - 4641.6\,\Omega m$ and thickness ranging between 8.2 and 48.1 m.

The sixth geoelectric layer delineated is the main aquifer unit which consists of unconsolidated coarse grain sands. The aquifer unit is confined by the overlying high resistive unit, the depth to the aquifer delineated from the geoelectric parameters ranges from 17.7-73.6 m (Table 4). Its resistivity, ranging between $245.1\Omega m$ and $583.1\Omega m$, and thickness ranging between $10.4\,m$ and $21.9\,m$, are more uniform among the geoelectric layers delineated (Table 4). Underlying the aquifer unit is a high conductive clay/shale layer with model resistivity ranging between $22.9\,\Omega m$ and $239.4\,\Omega m$. The resistivity of this unit is also largely uniform.

The geoelectric parameters of the aquifer were used to compute the longitudinal conductance and transverse resistance of the aquifer unit (Table 4). These parameters are indicative of the spatial

Table 4. Hydraulic parameters estimated from inverse model resistivity parameters.

S/N	Location	Depth to Aquifer (m)	Aquifer Thickness (m)	Aquifer Resistivity (Ωm)	Longitudinal Conductance (Ω^{-1})	Transverse Resistance (Ωm^2)
1	AMP-VES 2	28.6	12.3	583.1	0.0211	7172.13
2	EM_VES 3	34.0	14.1	311.4	0.0453	4390.74
3	AMP-VES 3	35.2	15.2	306.8	0.0495	4663.36
4	EM_VES 4	40.1	15.5	306.6	0.0506	4752.30
5	AMP-VES 4	37.5	15.3	258.4	0.0592	3953.52
6	EM_VES 5	48.6	12.9	389.8	0.0331	5028.42
7	AMP-VES 5	58.8	21.9	437.1	0.0501	9572.49
8	EM_VES 6	73.6	21.0	501.8	0.0418	10537.80
9	EM_VES 7	23.5	11.9	357.6	0.0333	4255.44
10	AMP-VES 6	23.5	11.9	347.0	0.0343	4129.30
11	EM_VES 8	27.3	13.9	358.9	0.0387	4988.71
12	EM_VES 9	32.0	14.9	368.3	0.0405	5487.67
13	AMP-VES 7	26.6	13.1	341.0	0.0384	4467.10
14	AMP-VES 8	34.0	11.9	363.8	0.0327	4329.22
15	EM_VES 10	35.8	12.3	368.0	0.0334	4526.40
16	AMP-VES 9	33.1	11.7	346.4	0.0338	4052.88
17	AMP-VES 12	21.5	12.6	354.8	0.0355	4470.48
18	EM_VES 13	22.6	11.6	345.9	0.0335	4012.44
19	AMP-VES 13	22.6	15.0	245.1	0.0612	3676.50
20	EM_VES 15	22.7	11.5	297.3	0.0387	3418.95
21	AMP-VES 14	17.7	10.4	276.1	0.0377	2871.44
22	EM_VES 16	23.7	11.5	345.6	0.0333	3974.40
23	VES 1	27.4	11.3	346.0	0.0332	3909.80
24	VES 3	31.2	12.0	350.0	0.0343	4200.00
25	VES 4	34.2	11.6	345.3	0.0336	4005.48

variability of the hydraulic properties (hydraulic conductivity and transmissivity) of the aquifer units. Zones with high longitudinal conductance are generally characterized as areas with low permeability with high clay volume, consequently low hydraulic conducvity. Similarly, areas with low value of longitudinal conductance corresponds to high permeability and hydraulic conductivity. The computed longitudinal conductance for the delineated aquifer unit is generally low, ranging between $0.0211\ \Omega^{-1}$ and $0.0612\ \Omega^{-1}$. This shows that the confined aquifer is characterized with high hydraulic parameters with high permeability and low clay volume. Thus, the aquifer unit is characterized with high hydraulic conductivity and high transmisivity as indicated by the computed longitudinal conductance.

Moreover, many hydrological studies have shown that the transverse resistance parameter can be used to effectively characterize aquifer properties. The transverse resistance of an aquifer increases with increasing transmissivity and yield. The distribution of the transverse resistance range between $2871.44\,\Omega m^2$ and $10537.80\,\Omega m^2$ in the area is presented in Table 4. High values of transverse resistance are generally observed, indicating high transmissivity and high yield of the aquifer units.

Conclusion

Vertical electrical soundings have been used to delineate and characterize the aquifer unit as part of the preliminary investigations to assess groundwater resource potential and development at Covenant University, Ota, southwestern Nigeria. The geoelectrical parameters obtained were used to estimate the longitudinal conductance, and transverse resistance which are reflective of the hydraulic properties of the aquifer were estimated using geoelectric parameters obtained by inverting observed apparent resistivity data. The computed longitudinal conductance indicates high permeabilty and low clay volume in the aquifer unit and thus high hydraulic conductivity for the delineated aquifer unit. Similarly, the computed transverse resistance shows that the aquifer unit is characterized with high transmissivity and yield. Thus, groundwater resource development and management can be effectively planned for.

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