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A Hydrogeophysical Appraisals for Surficial Aquifer Potentials of Sedimentary Basin of SW Nigeria

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Abstract: This study presents the use of geoelectrical method in assessing the surficial aquifer potentials of the multi-layered sedimentary basin of South Western Nigeria. The 18 Vertical Electrical Sounding (VES) covering the sedimentary basin was conducted using the schlumberger electrode array. Methodology and data evaluation includes zoning the basin according to their geological formations and rock types. Field resistivity data were inverted into one and two dimensions with IPI2Win Software. The inversion were done to obtain both lateral and vertical layer distribution of beds in the vadose zone, depth to water levels, identification of lithological types and thicknesses and presence of aquifers. Four to six lithological layers were delineated general for the basin from the interpretation of the data inversions. Results showed that vadose sediment compositions include porous sandstones, limestones, shales and topsoils. Transverse conductance from the study correlated with the aquifer transmissivity which suggest possibility of good yield. This study has shown the importance of surface resistivity in aquifer parameters and potentials estimations.

Key words: Electrical resistivity, aquifer transmissivity, vertical electrical sounding, transverse conductance, hydrogeophysics, limestones

INTRODUCTION

Resistivity is a basic physics principle centred on an inverse of electrical conductivity measured through electromagnetic induction, Direct Current (DC) resistivity and induces polarisation methods (Binley and Kemna, 2005). Geoelectrical resistivity has been around and used in groundwater prospecting, since, the beginning of the 20th century (Hallenbach, 1953; Koefoed, 1979; Kosinski and Kelly, 1981; El-Waheidi *et al*., 1992; Matias, 2002; Mhamdi *et al*., 2006). Earth surface investigation using geoelectrical method gives a better understanding of the Earth materials and compositions, its possible subsurface contaminant transport mechanisms, groundwater flow and general aquifer characteristics (Heigold *et al*., 1979; Urish, 1981; Frohlich *et al*., 1996).

Vertical Electrical Sounding (VES) is one of the best Direct Current (DC) surficial and near-Earth surface hydrogeophysical methods developed and adapted to determine resistivity of layered rock with depth. Although, VES as continuously been modified into other advanced techniques such as continuous vertical electrical sounding (Van Overmeeren and Ritsema, 1988; Dahlin and Zhou, 2004). VES usage in developing country has continued to be the main available tool for hydrogeophysical investigations.

Other improvements to VES is the Pulled Array Continuous Electrical Sounding (PACES) developed in Denmark (Sorensen *et al*., 2005). This was based on direct current on surface with the aim to meet higher productivity, reliability detailed and dense sampling demand. Therefore, one of the advantages of VES and its modifications includes the ability to cover longer profile with lesser crew (with the use of 4-10 electrode arrays measuring continuous sounding data) and maintain constant current of 30 mA for safety and quick data processing.

Fluid transmissivity, transverse resistance, longitudinal conductance, hydraulic conductivity and aquifer depth are fundamental properties used in describing subsurface hydrology using hydrogeophysical approaches (Soupios *et al*., 2007). These properties can be estimated from surficial application of geoelectrical resistivity of the geophysical methods. Therefore, the objectives of the study is to investigate the surficial multi-layered aquifer potential in this research and to determine other hydrogeophysical parameters such as the depth of vadose zones, delineation of water tables, lithological delineation and characteristics, hydraulic characteristics and inference on the general hydrogeological conditions. Surficial aquifers are shallow aquifer with potential for urban usage. They are mostly situated within unconsolidated sediments and prone to contamination. They can be tapped with large diameter hand dug wells or typical machine boring holes. They are therefore, important for the inhabitant of the study area.

MATERIALS AND METHODS

The 18 geoelectrical soundings was performed for this experiment. For effectiveness, it is best geoelectrical soundings equipment makes deep direct contact with the ground surface which usually are lateral was observed in this research. As pointed out earlier, the VES was employed because of its relative practical and methodological advantages. Most importantly, VES selection was based on its most availability in the study area. The VES is noted to provide detailed information of vertical succession of individual thicknesses, resistivity and their different conducting zones (Sorensen *et al*., 2005; Ernston and Kirsch, 2006).

Schlumberger's configurations which is closely associated with VES where current electrode A and B are spaced according to the depth of the underground layers intended to be investigated. Schlumberger array is sensitivity to shallow variation (Ernstson and Kirsch, 2006), a condition to observe particularly for detecting thin shallow surficial aquifers in a multi-layered sedimentary rock such as the study area. The research followed Dahlin and Zhou (2004) recommendations on the use of Schlumberger which is less sensitive to noise in data collection process and also because of its high data density and gradient.

The resistivity meter (Model SSR-MP-ATS) was used for data collection. The equipment advantages includes ability to probe up to 500 m into the Earth surface, provided the current and potential electrode followed a spacing that prevents faint detection of the current by the inner potential electrode. Other equipment include a stainless steel rods, electrical cables with good insulations, hammer and clip. Areas chosen for the geoelectrical soundings were nearly flat. The other criteria for chosen a sounding location was an area near a well of known lithology and groundwater table. This is for easy correlation and validation of the result. Finally, at location devoid of conductive materials underground such electrical cables of pipes.

VES traverses were zoned according to the geological formations of the sedimentary basin presented in Table 1. Traverse A-B was along the coastal plain sand, traverse C-D along the Ewekoro formation, traverse E-F along the Abeokuta formation and Traverse G-H along the Ilaro/Oshosun formation (Fig. 1). Zonation was used because it best detect variations when dealing with slight changes within same sedimentary rock (Linde *et al*., 2006). This approach allows direct comparison with borehole logs.

Derived field data were inverted to 1D and 2D resistivity images using the IPI2Win Software (Bobachev *et al*., 2002). The inversion was done to interpret the primary resistivity data recorded from the field with the aim of obtaining both a lateral and vertical layer distribution of beds in the vadose and aquiferous

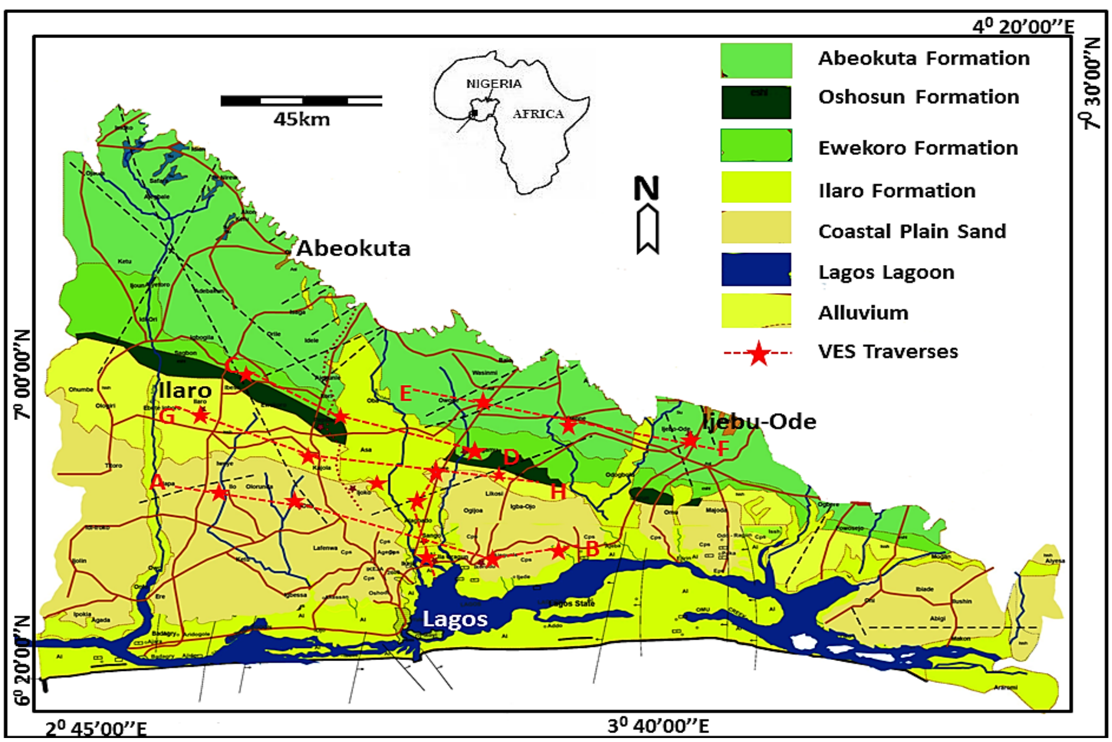

Fig. 1: Positions of the 18 VES points showing zonation followed along geological boundary in data acquisitions process

Table 1: Stratigraphic succession and lithology of rock type in study area

Age	Formations	Lithology
Recent	Alluvium	Sand
Pleistocene-Oligocene	Coastal plain sand	Sand, clay, silt
Eocene	Ilaro	Beach sand, mud, clay
Paleocene	Oshosun, Akinbo and Ewekoro	Silt, shale, clay, limestone and glauconite
Maastrichtian-Neocomian	Araromi, Afowo Ise	Sand, gravel, clay and limestone
Pan African	Basement rocks	Granite, schist, gneiss

zones. It does this by iterative mode by calculating at the end of each step the updated model layer thickness and resistivity. Secondly, by estimating the misfit function of between the observed and calculated data. This is validated with RMS relative error which were below 5% for this study.

The software was based on Newton algorithm (Bobachev *et al.*, 2002) with the main advantages for this study to include identification of lithological layer from different sounding points through the possibility of connecting VES points along the sounding profile. The data processes involve removal of spurious data and noise. Field VES data were plotted on a log paper and partial curve matching was carried out.

The obtained layer and resistivity values derived during curve matching were used as the initial background values for inversion of the data into a 1D image. From the inversion, lithology, layer depth, overall thickness of vadose zone overburden as well as the lithology and layer resistivity/conductivity were extracted and eventually were extracted. These extracted parameters were used in the lithological identification, vadose zone characterisation, aquifers transmissivity estimation and estimations of aquifer potentials.

The vadose zone thickness was delineated based on the sediments, geological information and geoelectrical results. During the inversion, the average depth to water table was measured using a groundwater level indicator and an available driller's log were correlated. From these correlations, the true resistivity, depths and thickness of the expected water-bearing zones were delineated.

Two important parameters derived from electrical resistivity are the longitudinal unit conductance (S, layer thickness over resistivity) and the transverse unit resistance (TR, layer thickness times resistivity). These two parameters in Eq. 1 define what is known as the Dar Zarrouk parameters (Maillet, 1947) as follows:

$$S = h/r \text{ and } TR = r.h \quad (1)$$

Where:

r = The resistivity of the layers (Ωm)
h = The thickness of the layers (m)

Aquifer Transmissivity (AT) (ability of a layer with permeability k, to transmit fluid through its entire thickness h) is calculated as show in Eq. 2:

$$AT = k.h \quad (2)$$

Where:

AT = The Aquifer Transmissivity (m^2/sec)
k = The hydraulic conductivity (m/sec)
h = The lithological thickness (m)

The k-values used were within the range presented in Domenico and Schwardz (1990) for clay (1×10^{-10} m/sec), sand (2×10^{-4} m/sec) and gravel (3×10^{-2} m/sec). The extracted TR parameters (Ω-m^2) is directly correlated to the transmissivity (m^2/day).

RESULTS AND DISCUSSION

The VES curves: The VES curve obtained from plotting the apparent resistivity against the corresponding half of electrode spacing (AB/2) gives curves types such as HAK, HKQ, AKQ, AK, AKH and QHA. Most of the obtained sounding curves were of the HAK type ($\rho_1>\rho_2<\rho_3<\rho_4>\rho_5$) as shown in Fig. 2a and the AKQ type ($\rho_1<\rho_2<\rho_3>\rho_4$) in Fig. 2. These curves types indicated four to five lithologies. The HAK curves rose steeply into positive slopes and such curves are a reflection of a highly resistive sedimentary rock at depth[20] which serves as underlying beds for unconfined aquifers. Table 2 shows the curve types, sequence and number of layers for the eighteen resistivity sounding curves.

Geoelectrical reconstruction of lithological sections: The geoelectrical data were re-interpreted into a lithological logs and water table estimated in this logs. The reconstruction was done by interpreting the resistivity values from each layer curves, the resistivity and thickness of the individual layers.

It was noted that different layer exhibit same resistivity. The interpretation was solved by understanding the deeper knowledge of the underlying geology, particularly using documented stratigraphy data and drillers geological logs. The results from the reconstructed geological logs is presented in Fig. 3.

Water table estimation and aquifer potentials: Water table with the vadose thickness estimated from the data and compared along their transverses and zonation (i.e., geological depositions and boundaries). The results

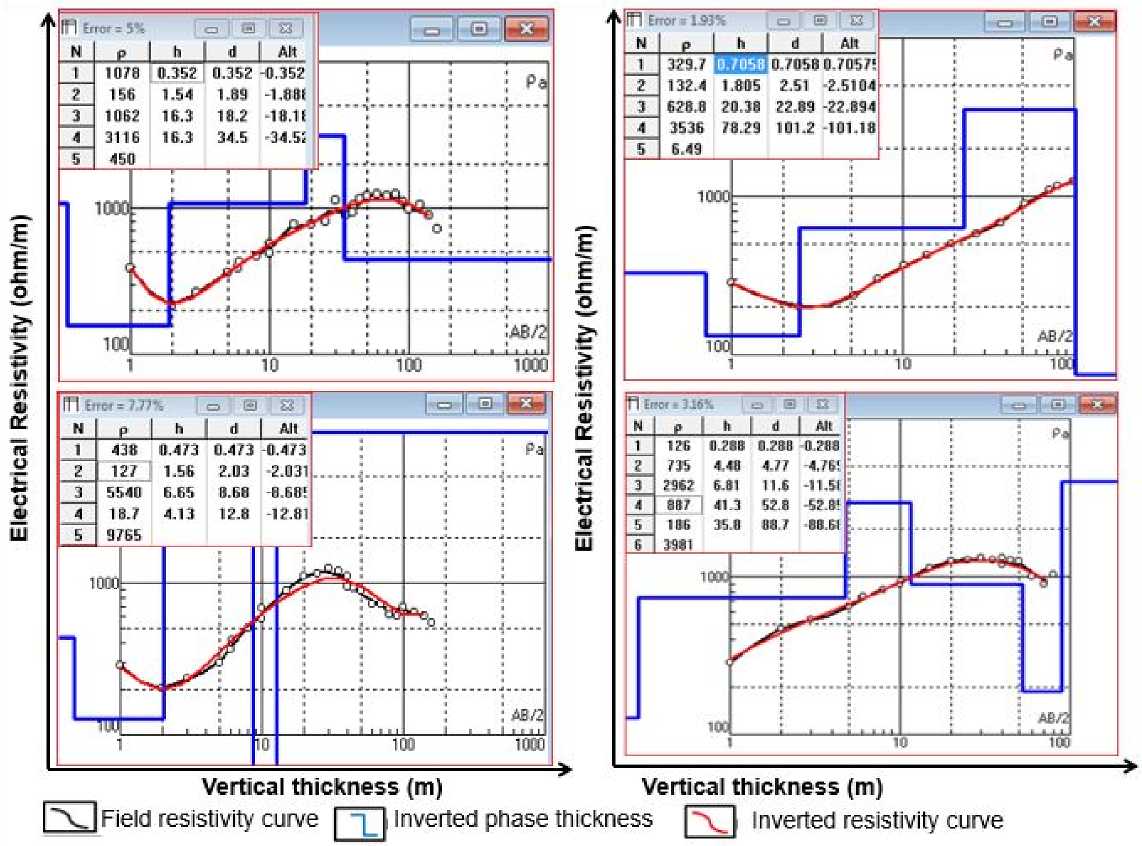

Fig. 2: 1D resistivity inversion showing thickness and number of lithologies

Table 2: Interpreted resistivity values for the 18 VES curves

Sounding number	Curve types	Layer sequence	No. of layers	Location
1	AK	ρ1<ρ2<ρ3<ρ4>ρ5	5	Iperu
2	AK	ρ1<ρ2<ρ3>ρ4	4	Ikenne
3	AKQ	ρ1<ρ2<ρ3>ρ4>ρ5	5	Ijebu-Ode
4	KQKQ	ρ1>ρ2>ρ3<ρ4>ρ5<ρ6	6	Ijoko
5	QHA(K)	ρ1>ρ2ρ3<ρ4>ρ5	5	Shagamu
6	HAK	ρ1>ρ2<ρ3<ρ4>ρ5	5	Shagamu
7	HAK	ρ1>ρ2<ρ3<ρ4>ρ5	5	Papalanto
8	HAK	ρ1>ρ2<ρ3<ρ4>ρ5	4	Ibeshe
9	AKH	ρ1<ρ2<ρ3<ρ4>ρ5<ρ6	6	Ibafo
10	QHA	ρ1>ρ2>ρ3>ρ4<ρ5<ρ6	6	Mowe
11	HKQ	ρ1>ρ2<ρ3<ρ4>ρ5	5	Ilaro
12	HAK	ρ1>ρ2<ρ3<ρ4>ρ5	4	Aje
13	QH	ρ1>ρ2>ρ3<ρ4	4	Arepo
14	HAK	ρ1>ρ2<ρ3<ρ4>ρ5	4	Otta
15	AK	ρ1<ρ2<ρ3<ρ4	4	Agbado
16	QHK	ρ1>ρ2>ρ3>ρ4<ρ5>ρ6	6	Ikorodu
17	AKQ	ρ1<ρ2<ρ3>ρ4>ρ5	5	Agbowa
18	AKH	ρ1<ρ2<ρ3<ρ4>ρ5<ρ6	6	Ofada

showed an estimated vadose thickness of 22-25 m for the Ilaro formation, 25-40 m for the Ewekoro formation, 35-70 m for the Abeokuta formation, 2-5 m for the alluvium formation and 10-21 m for the coastal plain sands. These has been summarised in Table 3 with the VES number compared with the estimated vadose zone, estimated water table from resistivity and validated with actual water table measurement taking at wells nearest to points of electrical sounding.

Aquifer parameter estimations: An indirect method for estimation of the aquifer yield potential in terms of water

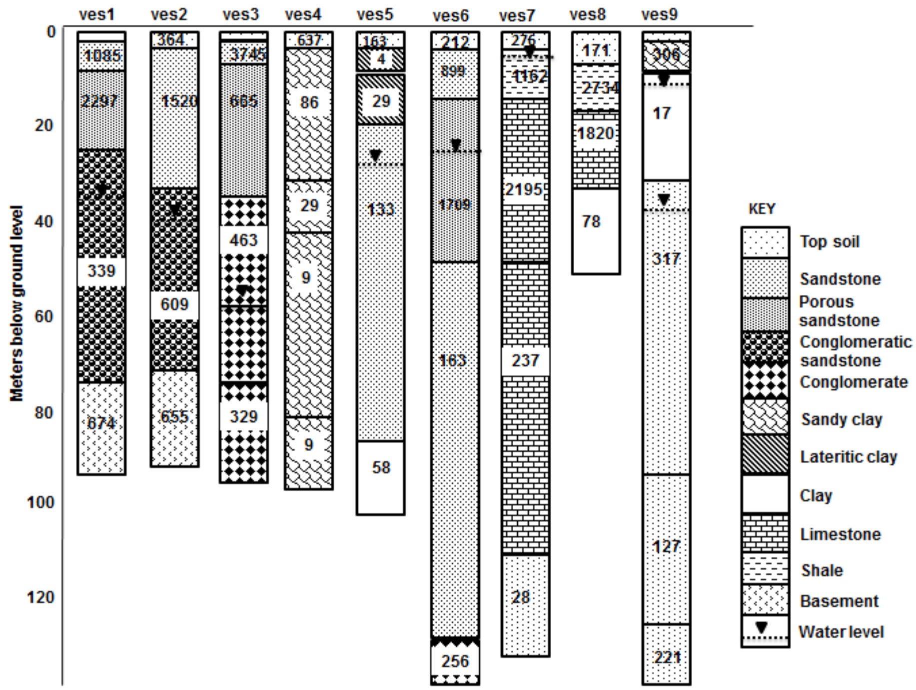

Fig. 3: Reconstructed lithological logs and water table estimation from geoelectrical resistivity

Table 3: Interpreted resistivity values of formation from the sedimentary basin

VES No.	Vadose resistivity range (Ωm)	Estimated resistivity depth to water table (m)	Actual measured water table (m)	Vadose zone thickness (m)
5, 6, 11, 12	4-2385	22-25	21	20
7, 8	171-2734	25-40	2-4, 35	30
1, 2, 3	268-3754	35-70	45-90	65
14,15,16,17	165-3512	10-21	7-25	22
9, 10, 13 18	11-438	2-4	3-6	3

Table 4: Comparison of study area resistivity against documented resistivity values in Ωm

Rocks and their resistivity values	Study area	Telford *et al*. (1995)	Milsom (2003)
Clay/Shale	17-83	1-90	100-200
Sandstone	133-3745	1-1000	200-8000
Fresh water sand	133-308	50-1000	-
Limestone	237-2195	10-10000	500-10000
Dry sand/Loose sand	899-3745	2000-100000	500-50000
Gravel/Conglomerate	339-609		100-600
Top soil	67-637		50-100

supply is through estimation of the transmissivity. Correlation of the derived aquifer transmissivity from traverse resistance to calculated aquifer transmissivity using known hydraulic conductivity values is shown in Fig. 5. The results showed that the transverse resistivity (Ωm^2) directly correlate to the aquifer transmissivity (m^2/day). Since, transverse resistance has been directly related to transmissivity, it suggest an increase in one means potential increase in the other.

Geoelectrical application in this study has shown the presence of multiple aquifers present in the study area. The lithological units as interpreted from the VES data included: topsoil, sandy clay, conglomeratic sandstone, limestone, dry porous sandstone, basement rocks and lateritic clay. Figure 3 shows the reconstructed lithological logs for VES 1-9. The topsoils are basically sandstone consisting of lateritic sand/clay and alluvium. Topsoil resistivity ranged from 67-275 Ωm. Sandstone resistivity values ranged from 133-308 Ωm for the section filled with groundwater and from 899-3 745 Ωm for the dry porous sandstones. Limestone resistivity values ranged from 237-2 195 Ωm while clay showed values below 100 Ωm. For comparison purposes, the resistivity interpretation is compared with documented resistivity standards in Table 4.

Estimated lithological transmissivity shows the surficial aquifer zones to be of high yield zones, especially, for the Ilaro/Oshun formations and CPS with VES 5, 11, 12 and VES 14-17, respectively. An increase in aquifer transmissivity and transverse resistance parameters suggest that the fluid potential (indicated by transmissivity) of the lithologies and aquifer in the basin increases considerably as the transverse resistance increases. This correlate with actual pump test result of 10-54 m^3/h between the CPS and Ilaro/Oshsun formation reported by Offodile (2014). It can further be deduced that the correlation has shown the influence of hydraulic and electric anisotropies as well as variations in mineralogy, sizes of grains, lithology, sizes and shape of the pores and pore channels (Soupios *et al*., 2007).

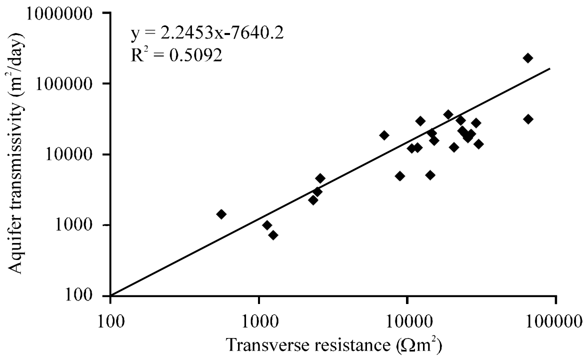

Fig. 5: Correlated plot of aquifer transmissivity with transverse conductance

Major constraint to interpretation of VES data in hydraulic parameters estimations, aquifer potential prediction and of the vadose thickness delineation from resistivity inversion is the bulk resistivity layer interpretation. However, experimental evidence has shown that the bulk electrical resistivity of a rock increases with increasing electrical resistivity of the saturating fluid (Frohlich and Parke, 1989). This general assumption was noted to be correct for this study. The complete summary of the hydrogeological implications of each layers resistivity, vadose overall thickness, lithological unit which serves as the aquifer and the hydrogeological implications is presented in Table 5. The porous sandstones are non-aquifer bearing. This is due to loose unconsolidated particles. However, they are good aquifer potential materials. The aquifer bearing rocks in the area are the sand, sandy clay and conglomeratic sandstone.

Table 5: Summarised interpretation of apparent resistivity and hydrogeological implications

Location	VES points	Curve type	No. of layers	Resistivity (ρ = Ωm)	Thickness (m)	Depth (m)	Lithological units	Hydrogeological implication
Iperu	1	AK	5	268	0.92	0.92	Top soil	Non-aquiferous
				1 085	7.48	8.40	Porous sandstone	Non-aquiferous
				2 297	16.48	24.88	Porous sandstone	Non-aquiferous
				339	49.89	74.77	Sandstone/ Conglomeratic sandstone	Aquiferous
				674			Basement	Non-aquiferous
Ikenne	2	AK	4	364	1.46	1.46	Top soil	Non-aquiferous
				1 520	30.57	32.03	Sandstone	Non-aquiferous
				609	39.93	71.96	Sandstone/ Conglomeratic sandstone	Aquiferous
				655			Basement	Aquiferous
Ijebu-Ode	3	AKQ	5	419	0.62	0.62	Top soil	Non-aquiferous
				3 745	1.72	2.34	Porous sandstone	Non-aquiferous
				665	32.52	34.86	Sandstone	Aquiferous
				463	39.91	74.77	Conglomerate	Aquiferous
				329			Conglomerate	Aquiferous
Ijoko	4	KQKQ	5	637	1.69	1.69	Top soil	Non-aquiferous
				86	30.60	32.29	Sandy clay	Non-aquiferous
				29	9.62	41.91	Sandy clay	Non-aquiferous
				9	20.26	62.17	Sandy clay	Non-aquiferous
				5			Sandy clay	Non-aquiferous
Shagamu	5	QHA(K)	5	163	0.45	0.45	Top soil	Non-aquiferous
				4	3.61	4.06	Lateritic clay	Non-aquiferous
				29	14.05	18.11	Lateritic clay	Non-aquiferous
				133	69.03	87.14	Sandstone	Aquiferous
				58			Clay	Non-aquiferous
Shagamu	6	HAK	5	212	3.47	3.47	Top soil	Non-aquiferous
				899	11.89	15.36	Sandstone	Non-aquiferous
				1709	32.30	47.66	Porous sandstone	Non-aquiferous
				163	84.64	132.30	Sandstone	Aquiferous
				256			Conglomerate	Aquiferous
Papalanto	7	HAK	5	276	3.47	3.47	Top soil	Non-aquiferous
				1162	11.50	14.97	Shale	Aquiclude
				2195	32.31	47.28	Limestone	Non-aquiferous
				237	69.12	116.40	Limestone	Aquiferous
				28			Sandstone	Aquiferous

Table 5: Continue

Location	VES points	Curve type	No. of layers	Resistivity (ρ = Ωm)	Thickness (m)	Depth (m)	Lithological units	Hydrogeological implication
Ibeshe	8	HAK	4	171	6.34	6.34	Top soil	Non
				2734	10.50	16.84	Shale	Aquiclude
				1820	18.76	35.60	Limestone	Non-aquiferous
				78			Clay	Non-aquiferous
Ibafo	9	AKH	6	106	1.34	1.34	Top soil	Non-aquiferous
				306	6.71	8.05	Clayey sand	Aquiferous
				17	22.06	30.11	Clay	Non-aquiferous
				317	64.60	94.71	Sand	Aquiferous
				127	43.10	137.81	Sand	Aquiferous
				221			Sand	Aquiferous
Mowe	10	QHA	6	151	3.34	3.34	Top soil	Aquiferous
				20	2.29	5.63	Clay	Aquitard
				11	5.86	11.49	Clay	Aquitard
				196	10.98	22.47	Sand	Aquiferous
				691	72.97	95.44	Sandstone	Aquiferous
				374			Sandstone	Aquiferous
Ilaro	11	HKQ	4	56	2.29	2.29	Top soil	
				1916	21.75	24.04	Porous sandstone	Non-aquiferous
				233	46.50	70.54	Sandstone	Aquiferous
				231			Sandstone	Aquiferous
Aje	12	HAK	4	67	2.31	2.31	Top soil	
				2385	18.76	21.07	Porous sandstone	Non-aquiferous
				508	29.55	50.62	Sandstone	Aquiferous
				208			Sandstone	Aquiferous
Arepo	13	HA	4	150	2.54	2.54	Top soil	
				438	43.78	46.32	Sandstone	Non-aquiferous
				284	28.59	74.91	Sandclay	Aquiferous
				76			Clay	Aquitard
Otta	14	HAK	4	165	2.61	2.61	Top soil	
				450	42.71	45.32	Sandstone	Non-aquiferous
				303	28.98	74.3	Sandstone	Aquiferous
				83			Clay	Aquitard
Agbado	15	AK	4	587	11.50	11.5	Top soil	Non-aquiferous
				3000	16.96	28.46	Porous sandstone	Non-aquiferous
				297	37.64	66.10	Sandstone	Aquiferous
				270			Sandclay	Aquiferous
Ikorodu	16	QHK	6	428	2.32	2.32	Top soil	Non-aquiferous
				199	2.85	5.17	Sandy clay	Aquiclude
				2619	10.17	15.34	Porous sandstone	Aquiclude
				172	9.96	25.30	Sandy clay	Aquiferous
				105	11.65	36.95	Sandy clay	Aquiferous
				29				
Agbowa	17	AKQ	5	406	2.11	2.11	Top soil	Non-aquiferous
				3512	5.18	7.29	Porous Sandstone	Non-aquiferous
				363	5.28	12.57	Sandstone	Aquiferous
				21	53.31	65.88	Clay	Aquitard
				44			Clay	Aquitard

CONCLUSION

The study discussed the use of electrical resistivity to determine the surficial aquifer potentials of the sedimentary basin of South Western Nigeria. Groundwater is situated in unconsolidated sediment of sand, sandy clay, conglomeratic sandstones and limestone. The estimated depth to water table compared perfectly with the observed wells in the study areas and the vadose thickness. Electrical resistivity inversion allows the delineation of the multi-aquiferous layers and their geological compositions. The estimated transmissivity showed a wide range of values due to inhomogeneity and diverse geological materials. A considerable distance of VES points to each other is a limitation in this study and should be largely minimised as possible. The importance of this study findings are contribution to knowledge and existing literature on the study area, in updating hydrogeological and aquifer maps and guides on the hydrogeological parameters such as depth of borehole drilling, rate of groundwater pumping, types of drilling bits to use while drilling, lithologies to be drilled and expected.

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