Geohydrological Parameters Estimation from Electrical Resistivity Applications to the Dahomey Basin of Nigeria

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BIOGRAPHY

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SUMMARY

An alternative approach of estimating geohydrological parameters using the electrical resistivity method in investigating aquifer hydrological properties is presented in this research. The application of electrical resistivity to the Dahomey Basin was aimed at delineating the depth to water level, vadose and lithological compositions and aquifer transmissivity. 1D and 2D resistivity data inversion results showed that vadose sediment compositions include porous sandstones, limestones, shales and topsoils. Depth to water level was derived from the inversion. Transverse conductance from the study correlated with the aquifer transmissivity. This study has shown that important geohydrological parameters can be estimated from electrical resistivity which will assist in making informed decisions on expensive pump testing exercises.

Keywords: Electrical resistivity, Vertical Electrical Sounding, Dahomey Basin, Aquifer transmissivity, Transverse conductance.

INTRODUCTION

Knowledge of aquifer parameters is an essential aspect of geohydrological investigation. Traditionally, gaining understanding of the hydrological parameters of an aquifer is usually through pump testing exercises which are quite technical and expensive to conduct. An alternative way to simplify this process is using the geophysical approach. Fluid transmissivity, transverse resistance, longitudinal conductance, hydraulic conductivity and aquifer depth are fundamental properties used in describing subsurface hydrology (Soupios et al., 2007). These parameters can be estimated from geoelectrical resistivity of the geophysical methods.
Geoelectrical resistivity has increasingly been used in groundwater prospecting since the twentieth century (El-Waheidi et al., 1992; Hallenbach, 1953; Koefoed, 1979; Kosinski and Kelly, 1981; Matias, 2002; Mhamdi et al., 2006). The geoelectrical understanding of the earth materials is used in predicting subsurface contaminant transport, groundwater flow and general aquifer characteristics (Frohlich et al., 1996; Heigold et al., 1979; Urish, 1981).

Therefore, the objectives of the geophysical electrical resistivity applications in this research is to determine the depth of vadose zones, delineation of water tables, lithological delineation and characteristics, layer transmissivity and inference on hydrogeological implications.

METHOD AND RESULTS

The geoelectrical investigation of a lateral hydrogeological environment requires direct contact of the equipment with the ground. Vertical Electrical Sounding (VES) was employed because of its relative practical and methodological advantages. VES is one of the best direct current (DC) resistivity methods adapted to determine resistivity of layered rock with depth.

The VES electrical resistivity method was chosen because it provides detailed information of vertical succession of individual thicknesses, resistivity and their different conducting zones (Ernstson and Kirsch, 2006; Sorensen et al., 2005). Eighteen VES sounding surveys were performed in this research. 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, was confirmed to be best suited for this investigation. This is because of its sensitivity to shallow variation which is the target in unsaturated zone characterisation above an unconfined aquifer (Ernstson and Kirsch, 2006). Dahlin and Zhou's (2004) recommendations on the use of Schlumberger and pole–dipole array was followed because of their high data density and gradient, but also because it is less sensitive to noise than the Wenner gamma array.

The equipment used included the resistivity meter (Model SSR-MP-ATS) which has been tested for its ability to probe up to 500 metres 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. The amount of current introduced was monitored and regulated throughout the field data acquisition. Stainless steel rods were used for both current and potential electrodes and good insulation of the cables was ensured to prevent leakages. VES traverses were zoned according to the geological formations of the Dahomey Basin (Figure 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. The sounding location was picked based on the following criteria:

- Near wells of known lithology and groundwater table.
- Near horizontal space for electrode spreading.
- Considerable distance from conductive materials on the ground surface and electrical overhead cables.
- Avoidance of topographic effect during spreading such as hills, gorges or generally difficult terrains. The assumption of a nearly horizontal layering was employed during the interpretation which was further aided by the identified well logs and water levels.

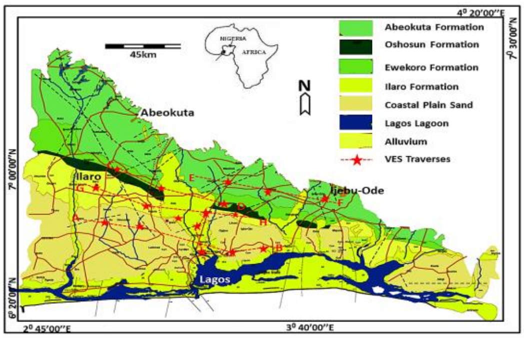


Figure 1. Eighteen VES points zoned along the Dahomey Basin geological formation and connected into a resistivity transverse

Generated data was inverted to 1D and 2D resistivity images using the IPI2WIN software (Bobachev, 2003). 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 zones.

The software was based on Newton Algorithm (Bobachev, 2003). The advantage of using the software is the identification of lithological layer and the possibility of connecting VES points along the sounding profile to produce a 2D image. 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 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. These extracted geohydrological parameters were used in the lithological identification, vadose zone characterisation and aquifers transmissivity estimation. The sounding point along the same geological zones was connected together using IPI-2D programs. The programme effectiveness in inhomogeneous horizontally layered media allows suppressing the distorting influence of near surface inhomogeneity, thereby increasing the accuracy of the interpretation.

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 and used to constrain the 2D resistivity model. From this correlation, 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 Equation 1 define what is known as the Dar Zarrouk Parameters (Maillet, 1974) as follows:

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

Where r is the resistivity of the layers (Ω-m) and h is 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 Equation 2:

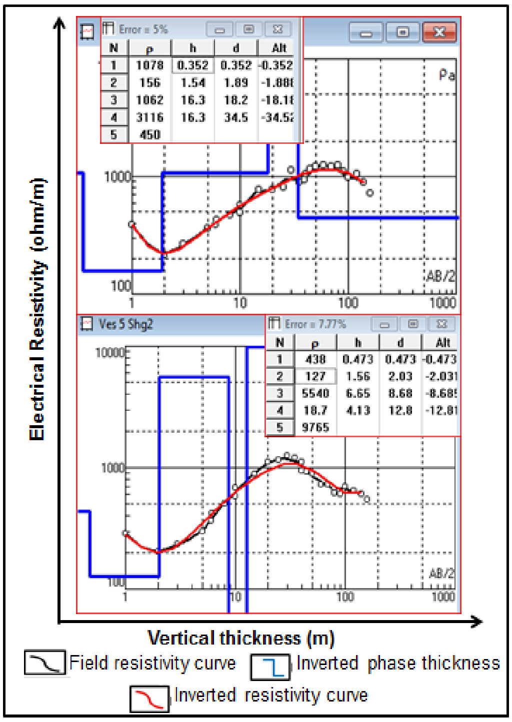
$$AT = k.h \qquad (2)$$

Where AT is the aquifer transmissivity (m^2/s), k is the hydraulic conductivity (in m/s) and h is the lithological thickness (m). The k-values used were within the range presented in Domineco and Schwartz (1990) for clay (1×10^{-10} m/s), sand (2×10^{-4} m/s) and gravel (3×10^{-2} m/s). The extracted TR parameters (Ω-m^2) is directly correlated to the transmissivity (m^2/day)

Geoelectrical Curves Delineation

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 ($\rho1 > \rho2 < \rho3 < \rho4 > \rho5$) as shown in Figure 2a, and the AKQ type ($\rho1 < \rho2 < \rho3 > \rho4$) in Figure 2b.

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 (Onuoha and Mbazi, 1988) which serves as underlying beds for unconfined aquifers. Table 1 shows the curve types, sequence and number of layers for the eighteen resistivity sounding curves.



Error = 5%

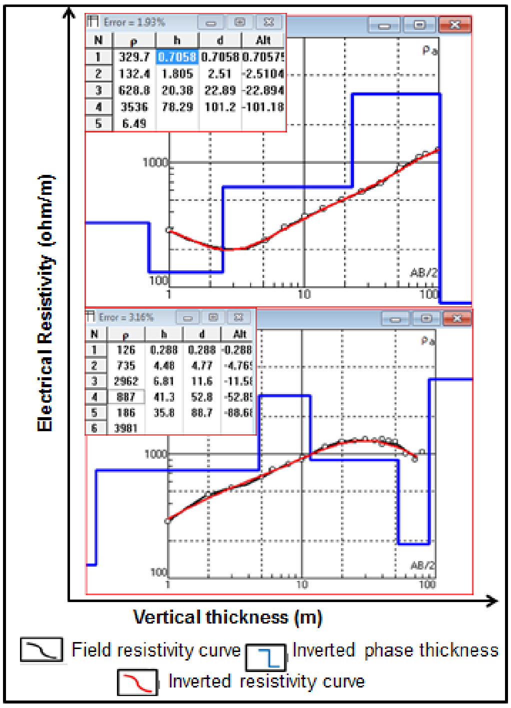
N	ρ	h	d	Alt
1	1078	0.352	0.352	-0.352
2	156	1.54	1.89	-1.888
3	1062	16.3	18.2	-18.18
4	3116	16.3	34.5	-34.52
5	450			

Ves 5 Shg2

Error = 7.77%

N	ρ	h	d	Alt
1	438	0.473	0.473	-0.473
2	127	1.56	2.03	-2.031
3	5540	6.65	8.68	-8.685
4	18.7	4.13	12.8	-12.81
5	9765			

Figure 2a. 1D resistivity inversion showing thickness and number of lithologies



Error = 1.93%

N	ρ	h	d	Alt
1	329.7	0.7058	0.7058	0.70575
2	132.4	1.805	2.51	-2.5104
3	628.0	20.38	22.89	-22.894
4	3536	78.29	101.2	-101.18
5	6.49			

Error = 3.16%

N	ρ	h	d	Alt
1	126	0.288	0.288	-0.288
2	735	4.48	4.77	-4.765
3	2962	6.81	11.6	-11.58
4	887	41.3	52.8	-52.85
5	186	35.8	88.7	-88.66
6	3981			

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

VES No.	Curve types	Layer sequence	Number of layer
1	AK	ρ1<ρ2<ρ3<ρ4>ρ5	5
2	AK	ρ1<ρ2<ρ3>ρ4	4
3	AKQ	ρ1<ρ2<ρ3>ρ4>ρ5	5
4	KQKQ	ρ1>ρ2>ρ3<ρ4>ρ5< ρ6	6
5	QHA(K)	ρ1>ρ2>ρ3< ρ4 > ρ5	5
6	HAK	ρ1>ρ2<ρ3<ρ4>ρ5	5
7	HAK	ρ1>ρ2<ρ3<ρ4>ρ5	5
8	HAK	ρ1>ρ2<ρ3<ρ4>ρ5	4
9	AKH	ρ1<ρ2<ρ3<ρ4>ρ5<ρ6	6
10	QHA	ρ1>ρ2>ρ3>ρ4<ρ5<ρ6	6
11	HKQ	ρ1>ρ2<ρ3<ρ4>ρ5	5
12	HAK	ρ1>ρ2<ρ3<ρ4>ρ5	4
13	QH	ρ1>ρ2>ρ3<ρ4	4
14	HAK	ρ1>ρ2< ρ3<ρ4> ρ5	4
15	AK	ρ1<ρ2<ρ3<ρ4	4
16	QHK	ρ1>ρ2>ρ3> ρ4<ρ5> ρ6	6
17	AKQ	ρ1<ρ2<ρ3>ρ4>ρ5	5
18	AKH	ρ1<ρ2<ρ3<ρ4>ρ5<ρ6	6

Table 1. Interpreted resistivity values for the 18 VES curves

Lithological Sections

The geoelectrical section was used to determine the resistivity and thickness of the individual layers. The lithological units as interpreted from the VES data included: topsoil, sandy clay, conglomeratic sandstone, limestone, dry porous sandstone, basement rocks and lateritic clay. 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.

Vadose and Water Table Delineation

The vadose thickness and water table was estimated from the 2D models and compared along their transverses and zonation (i.e. geological depositions and boundaries) as shown in Figure 3. The results 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. The major constraint from 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).

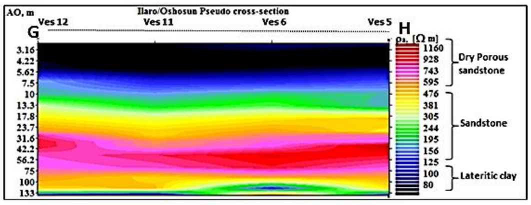


Figure 3. Pseudo sections of resistivity transverse along the Ilaro Formation.

Table 2 shows the comparison of the estimated vadose thicknesses from resistivity inversion, measured water table in the basin and vadose zone thicknesses.

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	171–2 734	25–40	2–4, 35	30
1, 2, 3	268–3 754	35–70	45–90	65
14,15,16,17	165–3 512	10–21	7–25	22
9,10, 13 18	11–438	2–4	3–6	3

Table 2. Interpreted resistivity values of formation from the sedimentary basin

Aquifer Transmissivity

Correlation of the derived aquifer transmissivity from traverse resistance to calculated aquifer transmissivity using known hydraulic conductivity values, is shown in Figure 5. The results showed that the transverse resistivity (Ω-m^2) directly correlated to the aquifer transmissivity (m^2/day). An increase in both parameters suggest that the fluid potential (indicated by transmissivity) of the lithologies and aquifer in the basin increases considerably as the transverse resistance increases.

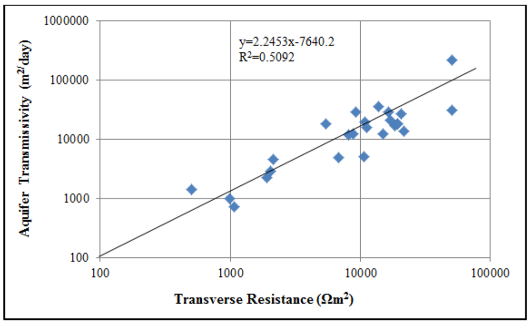


Figure 5. Correlated plot of aquifer transmissivity with transverse conductance

CONCLUSIONS

The research has shown an alternative way of estimating geohydrological parameters from electrical resistivity applications. This is a cost-effective method as compared to drilling of wells to carry out pump testing to determine hydraulic parameters which is often an expensive exercise. 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.

Based on this research important geohydrological parameters such a depth of borehole drilling, rate of groundwater pumping, types of drilling bits to use, expected lithologies can be predicted. This will assist in planning a geohydrological field exercise.

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