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Applicability of Hydro-Geophysical Parameter Estimation in a Basement Complex Environment: Case Study of the University of Ibadan Campus, Southwestern Nigeria

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Abstract: The use of surface resistivity measurements in estimating aquifer hydraulic properties like hydraulic conductivity (K) and transmissivity (T) have been explored for various sedimentary environments with little emphasis on a basement complex environment. In an attempt to explore the applicability of this approach, surficial resistivity measurements involving Vertical Electrical Sounding (VES) using the Schlumberger electrode array were carried out at ten drilled and pump tested borehole points in a typical basement complex terrain of southwestern Nigeria comprising granite gneiss, quartzite/quartz schist and banded gneiss. Depth to basement as revealed by the processed VES data ranged between 3.8-25.5 m with a mean of 12.0 m. The pumping test result showed K-values to vary between 0.006-0.41 m day^{-1} (mean: 0.12 m day^{-1}) while those from the geoelectric measurements varied between 0.0055-0.323 m day^{-1} (mean: 0.13 m day^{-1}). t-values on the other hand varied between 0.4-17.0 m^2 day^{-1} (mean: 5.3 m^2 day^{-1}) from the pumping test analysis and 0.044-4.7 m^2 day^{-1} (mean: 1.5 m^2 day^{-1}) from surficial resistivity measurements. The correlation between the geophysically and hydro-geologically estimated hydraulic properties showed R = 0.78 for the K-values and R = 0.73 for the t-values. This to an extent shows the applicability of this approach in a basement complex area.

Key words: Hydraulic properties, basement complex, surficial resistivity measurements, hydraulic conductivity, transmissivity

INTRODUCTION

Fluid Transmissivity (T) and hydraulic conductivity are important in groundwater and hydrocarbon exploration as both provide a good knowledge of the potential of the porous media to transmit fluid within them. Pumping tests and well-log data analysis have been the conventional ways of deducing these properties but these operations could be very tedious, time consuming and expensive to carry out as there could be limitation in the numbers of boreholes available in the study area.

In recent times, the application of surficial resistivity measurements in estimating aquifer hydraulic properties have gained much emphasis as it helped to overcome the problems of cost and time consumption associated with the hydrogeological method. The approach is based on the established relationship between fluid Transmissivity (T) and transverse resistance (R_t) which both provide a good knowledge of the potential of the porous media to transmit fluid within them (Salem, 1999).

The applicability of this approach has been explored mostly for the sedimentary environments with little or no emphasis on basement complex terrains. Such researches in the sedimentary environment include that of Okoro *et al*. (2010), Ekwe *et al*. (2006, 2010) and Mbonu *et al*. (1991). Ayolabi *et al*. (2010) on the other hand only estimated the Dar-Zarrouk parameters for a basement complex terrain of Ajebo area in Southwestern Nigeria while K'Orowe *et al*. (2011) employed a modified Bernabe and Revil Model alongside formation bulk resistivity and formation factor to estimate K and T for Jangaon Sub-Watershed in India.

This study is targeted at exploring and validating the applicability of surface resistivity measurements in estimating the hydraulic properties K and T for a typical basement complex terrain of the University of Ibadan Campus, Southwestern Nigeria.

MATERIALS AND METHODS

Site description and geological setting: The University of Ibadan Campus covering an area extent of about 5 km^2 lies between latitudes 7°26.00'N and 7°27.25'N and longitudes 3°53.00'E and 3°54.20'E within Oyo State, Southwestern Nigeria (Fig. 1). Just like the other parts of the tropical belt of Nigeria, Ibadan is characterized with two distinct climatic conditions, the dry and wet season. The previous is characterized by the dry cold North-Eastern wind while the latter is characterized by the wet humid and moisture laden Southwestern wind and runs from April to middle

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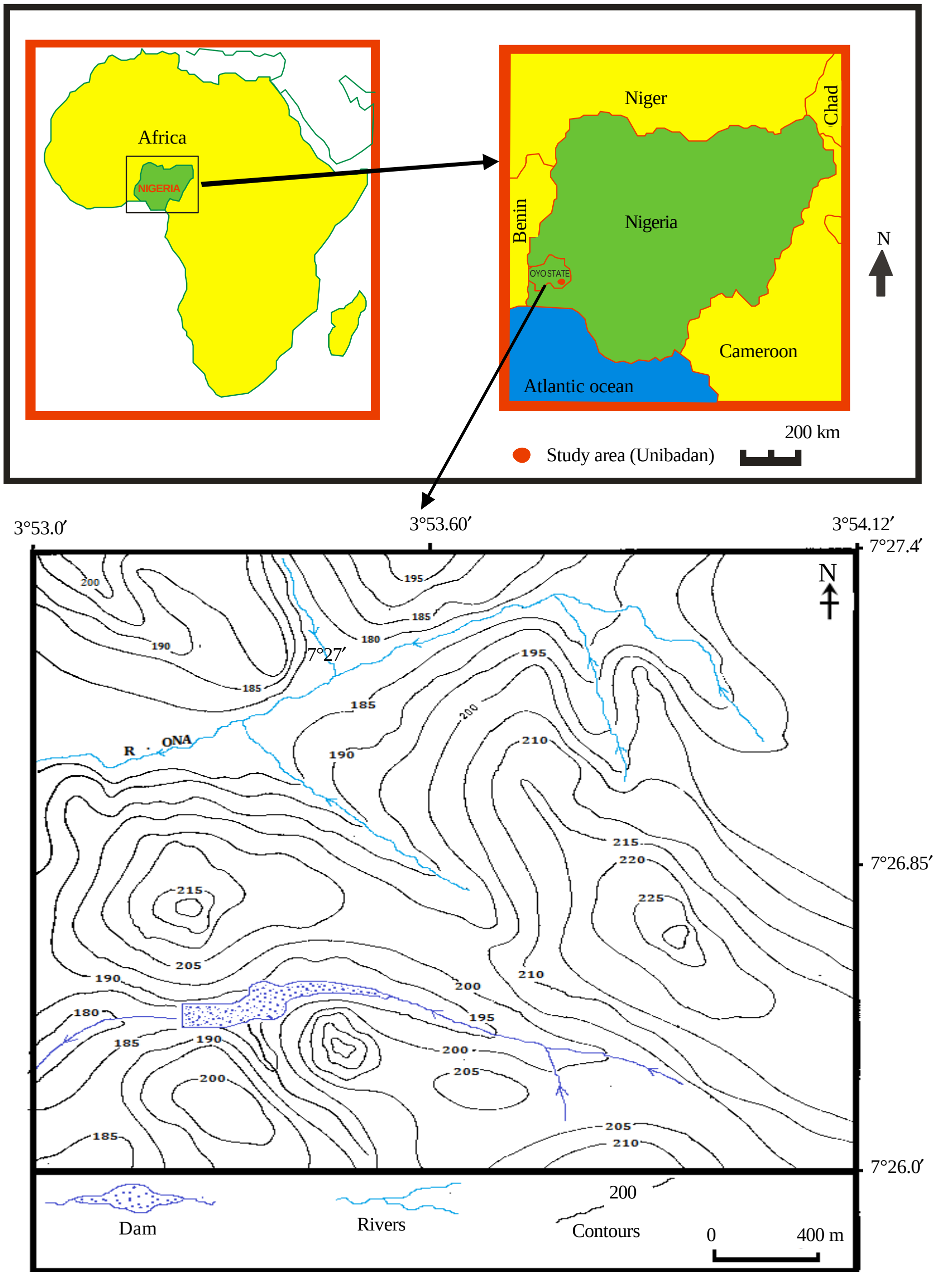

Fig. 1: Maps showing the location and physiography of the study area

October and early November. The rainfall and temperature of the area is about 1258.9 mm and 26.6°C on an average, respectively. The entire campus is underlain by the Precambrian basement rocks comprising augen gneiss, banded gneiss and quartzite/quartz schist with minor quartzitic and quartzo-feldspathic veins (Fig. 2). Available isotopic dating shows that this basement has beesubjected to various tectonic activities of different orogenies ranging from Liberian (2700±200 Ma), Eburnean (2200±200 Ma) to Pan-Africa (600±150 Ma) with that of Pan-Africa being the most pervasive and oriented most rocks of this area in a N-S trending direction (Odeyemi, 1981; Ajibade and Fitches, 1988). Hydrogeologically, the area lies within the category of hard rock environment where the aquiferous units comprise the weathered residual overburden (regolith) and the fractured bedrock (Greenbaum, 1985; Beeson and Jonesa, 1988).

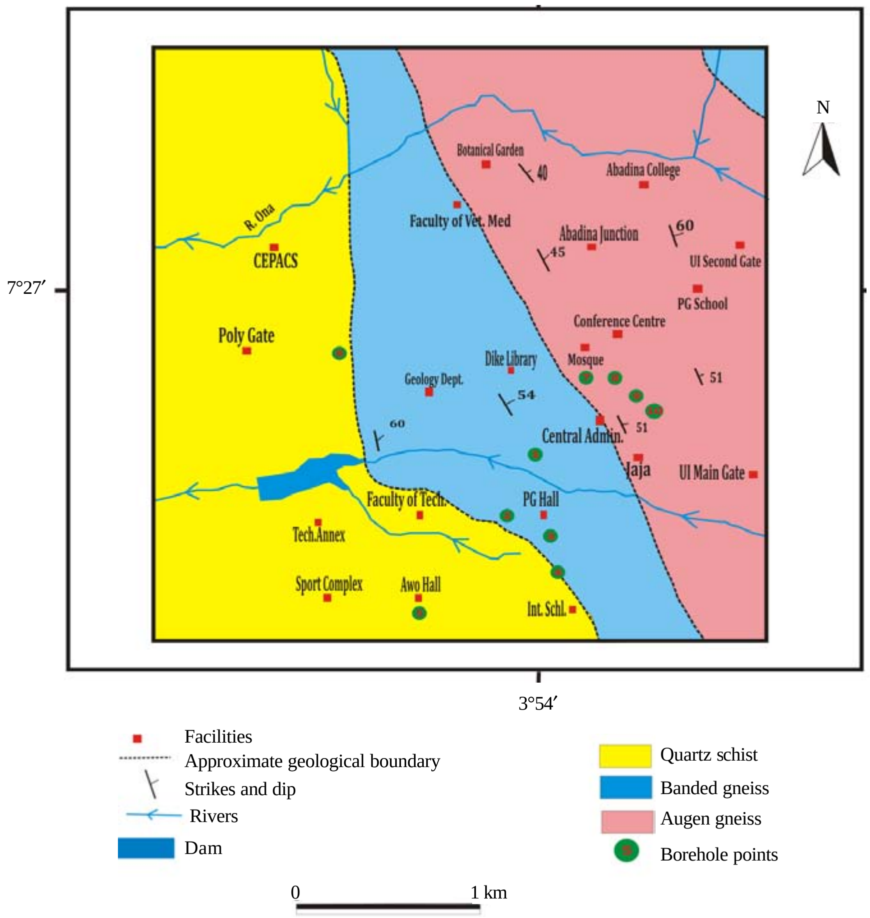

Fig. 2: Geological map of the University of Ibadan

These aquifers are formed by the *in situ* weathering of the basement rocks and their ability to store water depends of their area extent, size and aperture while their capability to allow its movement and abstraction chiefly depends on their hydraulic characteristics (Wright, 1992). The University and its surrounding community rely mostly on underground water supply from boreholes as their major source of potable water supply for use in the hostels, laboratories, staff quarters and offices.

Data acquisition and processing: Ten vertical electrical soundings were carried out close to the borehole points (Fig. 2) using the Schlumberger electrode array configuration. The obtained VES data were interpreted using partial curve matching technique and computer iteration program. The curve matching was done using a two-three layer master curve while the computer iteration modeling was done using WinResist Software which enabled accurate estimation of the thickness and electrical resistivity of the aquifers at an RMS error <5.0.

Pumping test operation as carried out by Alichi involved the pumping out of groundwater from drilled boreholes (Fig. 2) and measuring the response of the aquifer in terms of water level before and after pumping, discharge rate and pumping duration. Obtained data were analyzed using the Cooper Jr. and Jacob (1946) straight line method where drawn down was plotted with an arithmetic scale on y-axis against logarithm time scale on the x-axis.

Dar-Zarrouk parameters: Basic parameters such as layer resistivity (ρ_i) and layer thickness (h_i) which describes the geo-electric section are derived from the geoelectric data and are later used to compute other fundamental parameter such as the transverse resistance, transverse resistivity, longitudinal conductivity, longitudinal resistivity and electric anisotropy which have been referred to as Dar-Zarrouk parameters by Maillet (1947):

$$\text{Aquifer thickness} - h_a = \sum h_i\,(\text{m}) \tag{1}$$

$$\text{Aquifer resistivity}\,(\rho_a) - \rho_{L=\frac{ha}{S}} = \frac{\sum hi}{\sum \frac{hi}{\rho i}}\,(\Omega\text{m}) \tag{2}$$

Longitudinal conductance (S):

$$S=n\sum i=1\left(\frac{h_i}{\rho_i}\right),\quad S=\frac{h_1}{\rho_1}+\frac{h_2}{\rho_2}+\frac{h_3}{\rho_3}...\frac{h_n}{\rho_n}(\Omega^{-1}) \tag{3}$$

Transverse Resistance (R):

$$R=h_1\rho_1+h_2\rho_2+h_3\rho_3...h_n\rho_n(\Omega m^2) \tag{4}$$

Average transverse resistivity (ρ_t):

$$\rho_t=\frac{R}{h}=\frac{\sum h_i\rho_i}{\sum h_i}(\Omega m) \tag{5}$$

Longitudinal resistivity (ρ_L):

$$\rho_L=\frac{h_a}{S}=\frac{\sum h_i}{\sum \frac{h_i}{\rho_i}}(\Omega m) \tag{6}$$

Electric anisotropy (I):

$$I=(\frac{\rho_L}{\rho_t})^{1/2} \tag{7}$$

Electric current and groundwater flow direction: The direction of groundwater flow and electrical current flow is defined by the aquifer position relative to the non-producing strata of the concerned area and it is worth considering so as to know which of "S" or "R" best defines the aquifer resistivity. Kelly and Frohlich (1985) defined two principal conditions based on the flow of groundwater and electrical current within the aquifer: the transverse and longitudinal case. Transverse case occurs when the aquifer rests on a thickness of less permeable material rather than directly on bedrock. In this condition, the direction of water flow is horizontal while that of the electric current flow is vertical. Longitudinal case on the other hand occurs when the aquifer is sandwiched in between resistive unsaturated zone and resistive bedrock where the groundwater flow as well as the electrical flow is horizontal (Fig. 3).

Kelly and Frohlich (1985) revealed that unlike "R", "S" is never a good representation of the aquifer transmissivity (T_{aq}) because "S" is a ratio of thickness to resistivity (Eq. 3) rather than their product as in "R" (Eq. 4). This means that "R" which is a measure of the ability of the aquifer to transmit current through its entire thickness will correlate well with T_{aq} (the ability of the aquifer to transmit water through its entire thickness) rather than Niwas and Singhal (1981) had also emphasized the use of transverse resistance rather the resistivity used by Kelly (1977) to correlate hydraulic properties.

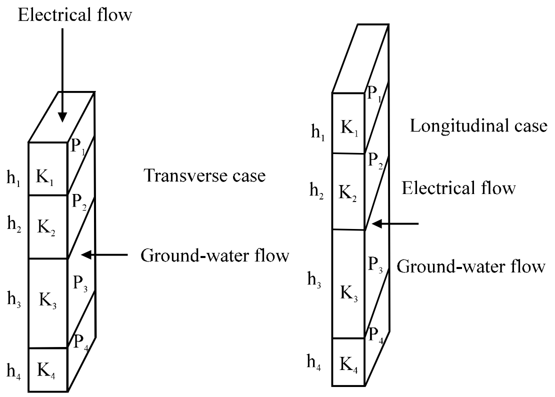

Fig. 3: Layered models of electrical and groundwater flow (Kelly and Frohlich, 1985)

A basement complex area follows a longitudinal case where the aquiferous weathered regolith and fractured bedrock are sandwiched in between resistive top layer and resistive fresh bedrock (Olayinka and Mbachi, 1992). The aquifer resistivity which is the minimum resistivity can be obtained by reducing several layers in the isolated case into a single resistivity which stands as the governing resistivity (Bhattacharya and Patra, 1968; Kosinski, 1978; Zhody, 1965). The aquifer thickness (h_a) is taken as the sum of the individual layer thickens (h_i) and the aquifer resistivity (ρ_a) is the longitudinal resistivity (ρ_L) (Reiter, 1981; Kossinski and Kelly, 1981; Kelly and Frohlich, 1985).

Hydro-geophysical estimations: Rock tortousity and porosity control the electric current flow as well as the groundwater flow and by inference the electrical conductivity and the hydraulic conductivity of the geologic medium. Based on this inference, a great number of empirical relationships used in correlating geoelectric parameters and hydraulic parameters have been developed (Kelly, 1977; Kossinski and Kelly, 1981; Niwas and Singhal, 1981; Onuoha and Ezeh, 1988; Mbonu *et al.*, 1991; Huntley, 1986). Niwas and Singhal (1981) established an analytical relationship between aquifer transmissivity and transverse resistance as well as between transmissivity and longitudinal conductance. From Darcy's law, the fluid discharge Q is given as:

$$Q=KIA \tag{8}$$

While from Ohms law:

$$\hat{j} = \sigma E \tag{9}$$

Where:

K = Hydraulic conductivity
I = Hydraulic gradient
A = Cross sectional area perpendicular to the direction of flow
$\hat{j}$ = Current density
E = Electric field intensity
σ = Electrical conductivity inverse of resistivity

Assuming a unit cross-sectional area and thickness (h), Niwas and Singhal (1981) combined Eq. 8 and 9 to get:

$$T = K\sigma R = KS/\sigma \tag{10}$$

Where:

R = Transverse resistance
S = Longitudinal conductance

Both R and S are referred to as Dar-Zarrouk parameters and are designated by:

$$S = h/\rho \text{ and } R = h\rho \tag{11}$$

Where:

h = The thickness of the individual layers
ρ = Resistivity of the individual layers

The idea is that in areas of similar geologic setting and water quality, the product $K\sigma$ has been found to remain constant (Niwas and Singhal, 1981; Onuoha and Ezeh, 1988; Onu, 1995; Ekwe *et al*., 2006, 2010; Mbonu *et al*., 1991). Hence, having (K_{PT}) from the pumping test and (σ) from the interpreted geoelectric data, researchers can calculate constant "A" ($K_{PT}\sigma$) for each of the rock types. Since, assumed constant for a particular rock type researchers have:

$$\text{Constant}\,\text{"}A\text{"} = \frac{(K_{PT}\sigma)_1 + (K_{PT}\sigma)_2 + (K_{PT}\sigma)_3 + \ldots + (K_{PT}\sigma)_n}{n} \tag{12}$$

where, Av. $K_{PT}\sigma$ is constant (A) (Niwas and Singhal, 1981). Then:

$$K_{cal} = A/\sigma \text{ and } T_{cal} = K_{cal}\sigma R \tag{13}$$

Where:

A = Constant (Siemen/day)
K_{PT} = Hydraulic conductivity from pumping test
K_{cal} = Calculated hydraulic conductivity (m/day) of each sounded point
T_{cal} = Calculated hydraulic conductivity (m/day)
σ = Aquifer conductivity (inverse of aquifer resistivity)
R = Transverse resistance given as $h\rho a$ where, h = Aquifer thickness and ρa = Aquifer resistivity from the geosounding data
S = Longitudinal conductivity given as $h/\rho a$. R and S are both referred to as Dar Zarrouk parameters.

RESULTS AND DISCUSSION

Pumping test: Pumping test results as derived by Alichi (2007) for the study area were used for this study (Table 1). Drawdown-time measurements from boreholes were analyzed to estimate their respective transmissivity (T) using the Cooper Jr. and Jacob (1946) Straight Line Method where drawdown measurements are plotted on an arithmetic scale on the Y-axis against a logarithm time scale on the x-axis.

VES result: Results of the processed and interpreted VES data showed three to four layer geo-electric layers (Fig. 4a-f) with curve types varying between Q, H, HK and QH being a function of the resistivities, layers thicknesses and the electrode configuration (Zohdy, 1976).

Individual layer resistivity and thickness varied between 8-561 Ωm and 0.3-22.7 m, respectively (Table 2). Encountered typical lithologies while drilling were also correlated with the geoelectric layers obtained from the VES interpretation (Fig. 5a-c).

Geo-electrical and hydraulic estimations: The estimation results showed the aquifer thickness to vary between 3.8-15.6 m (mean: 8.3 m) within the banded gneiss, 4.8-25.5 m (mean: 15.2 m) within the quartzite and 11.8-14.5 m (mean: 13.3 m) within the augen gneiss. The hydraulic conductivity ranged from 0.04-0.17 m day^{-1} (mean: 0.08 m day^{-1}), 0.0087-0.0055 m day^{-1} (mean: 0.0071 m day^{-1}) and 0.138-0.323 m day^{-1} (mean: 0.23 m day^{-1}) within the banded gneiss, quartzite

Table 1: Some of the pumping test data for the boreholes

Locations	Rock type	Depth (m)	Borehole discharge (m^3 day^{-1})	Hydraulic conductivity (K)	Trans-missivity (T)
Bello Hall	BGN	64	81.6	0.012	0.80
New PG Hall 1	BGN	87	79.2	0.011	0.60
New PG Hall 2	BGN	60	69.1	0.024	1.50
Idia Hall	BGN	60	86.4	0.193	10.44
Awo Hall	QZT	65	79.2	0.008	0.50
Lisabi Crescent	QZT	60	62.8	0.006	0.40
Tedder Hall 1	AUG	50	138.2	0.080	3.90
Tedder Hall 2	AUG	68	57.6	0.130	4.10
Melamby Hall 1	AUG	50	138.2	0.410	17.00
Melamby Hall 2	AUG	58	138.2	0.333	14.00

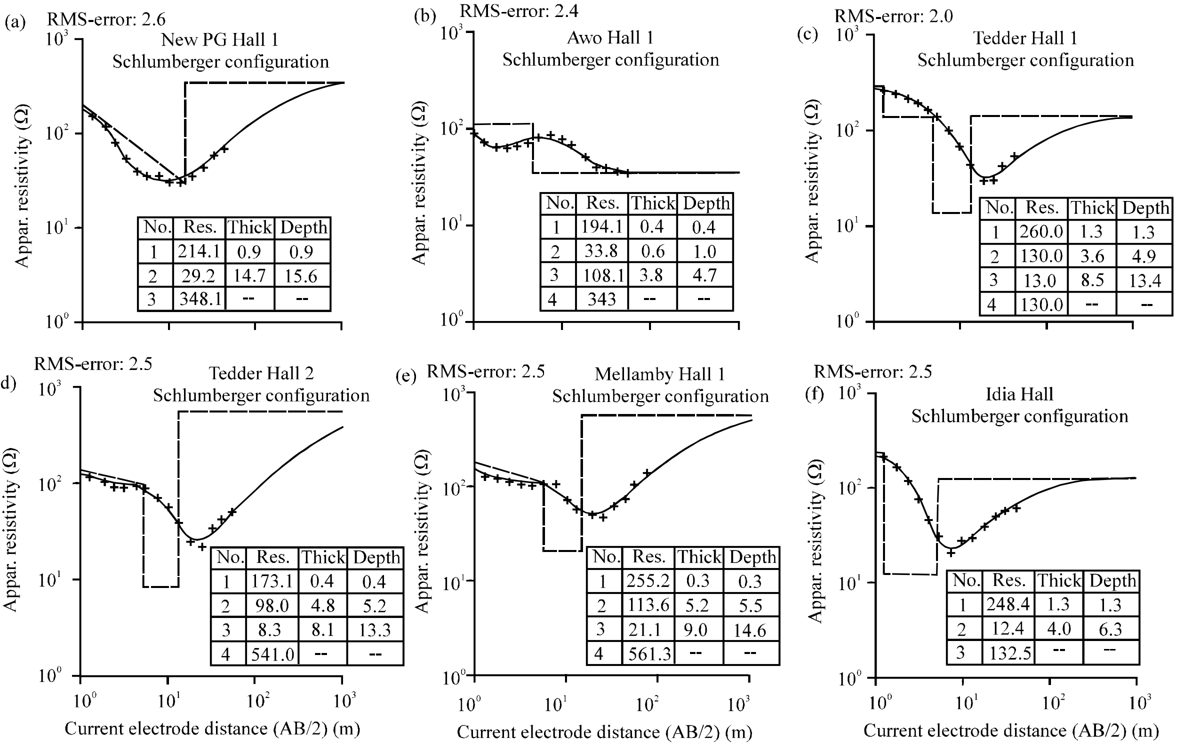

Fig. 4: a-f) Typical VES curves obtained from some points in the study area

Table 2: Results of the interpreted VES

Locations	Longitudes	Latitudes	Elevation (m)	ρ (Ωm)	h (m)	Curve
Bello Hall	3.8991	7.4433	219	123/60/15/80	0.8/2.0/7.9	QH
New PG Hall 1	3.8959	7.4379	210	220/29/330	0.9/9	H
New PG Hall 2	3.8952	7.4390	191	120/63/28	1.6/3.6	Q
Idia Hall	3.8963	7.4374	213	240/17/252	1.3/2.5	H
Awo Hall	3.8933	7.4357	220	195/33/109/34	0.4/1.0/4.8	HK
Lisabi Crescent	3.8910	7.4477	224	320/160/48/336	0.5/2.3/22.7	QH
Tedder Hall 1	3.8997	7.4460	231	260/130/13/130	1.3/3.6/8.5	QH
Tedder Hall 2	3.9001	7.4465	224	173/98/8/541	0.4/4.8/8.1	QH
Melamby Hall 1	3.9011	7.4461	215	255/114/21/561	0.3/5.2/9.0	QH
Melamby Hall 2	3.9013	7.4459	223	480/96/19/384	0.4/1.6/9.8	QH

Table 3: Summary of the estimated geoelectric and hydraulic parameters

Locations	Rock	H (m)	r°	S	ρ_L	σ	R	ρ_T	ρ_B	K_{PT}	$K_{PT}\sigma$	Av. $K_{PT}\sigma$	K_{cal}	T_{cal}
Bello Hall 2	BGN	10.7	0.68	0.570	18.89	0.053	202.10	31.49	80.0	0.012	0.00064	0.002300	0.0440	0.467
NPGH 1	BGN	15.6	0.84	0.510	30.52	0.033	476.15	39.67	330.0	0.011	0.00036	0.002300	0.0701	1.101
NPGH 2	BGN	5.2	0.38	0.071	73.31	0.014	381.20	80.19	28.0	0.024	0.00034	0.002300	0.1652	0.880
Idia Hall	BGN	3.8	0.88	0.154	24.64	0.041	93.60	93.16	252.0	0.193	0.00790	0.002300	0.0564	0.217
Awo Hall 1	QZT	4.8	0.52	0.055	87.28	0.012	418.90	105.90	34.4	0.008	0.00010	0.000105	0.0087	0.044
Lisabi Crescent	QZT	25.5	0.75	0.489	52.16	0.019	1330.20	63.44	336.0	0.006	0.00010	0.000105	0.0055	0.140
Tedder Hall 1	AUG	13.4	0.82	0.687	19.52	0.051	261.50	68.40	130.0	0.080	0.00410	0.010700	0.2088	2.800
Tedder Hall 2	AUG	13.3	0.97	1.030	12.95	0.077	172.20	45.63	541.0	0.130	0.01001	0.010700	0.1380	1.830
Melamby Hall 1	AUG	14.5	0.93	0.476	30.49	0.033	442.20	59.05	561.3	0.410	0.01350	0.010700	0.3230	4.710
Melamby Hall 2	AUG	11.8	0.91	0.533	22.13	0.045	261.10	45.07	384.0	0.333	0.01500	0.010700	0.2367	2.780

H = Aquifer thickness, r° = Reflection coefficient, S = Longitudinal conductance, ρ_L = Longitudinal resistivity, σ = Electrical conductance, R = Transverse resistance, ρ_T = Transverse resistivity, ρ_B = Basement resistivity, K_{PT} = Hydraulic conductivity from pumping test, K_{cal} = Calculated hydraulic conductivity, T_{cal} = Calculated transmissivity

and granite gneiss while transmissivity varied from 0.2-1.1 m^2 day^{-1} (mean: 0.67 m^2day^{-1}), 0.04-0.14 m^2 day^{-1} (mean: 0.092 m^2 day^{-1}) and 1.8-4.7 m^2 day^{-1} (mean: 3.03 m^2 day^{-1}) within the rocks, respectively. Table 3 shows the values of the estimated geoelectric parameters for the study area. The result of the Pearson's

Table 4: Correlation coefficient of estimated parameters with borehole discharges

Factors	ρ_B(Ωm)	rc	Elev (m)	H (m)	ρ_L	BD (m)	K_{cal}	K_{PT}	T_{cal}	T_{PT}
PPM	0.2	0.4	0.32	-0.003	-0.4	-0.57	0.76	0.7	0.79	0.71

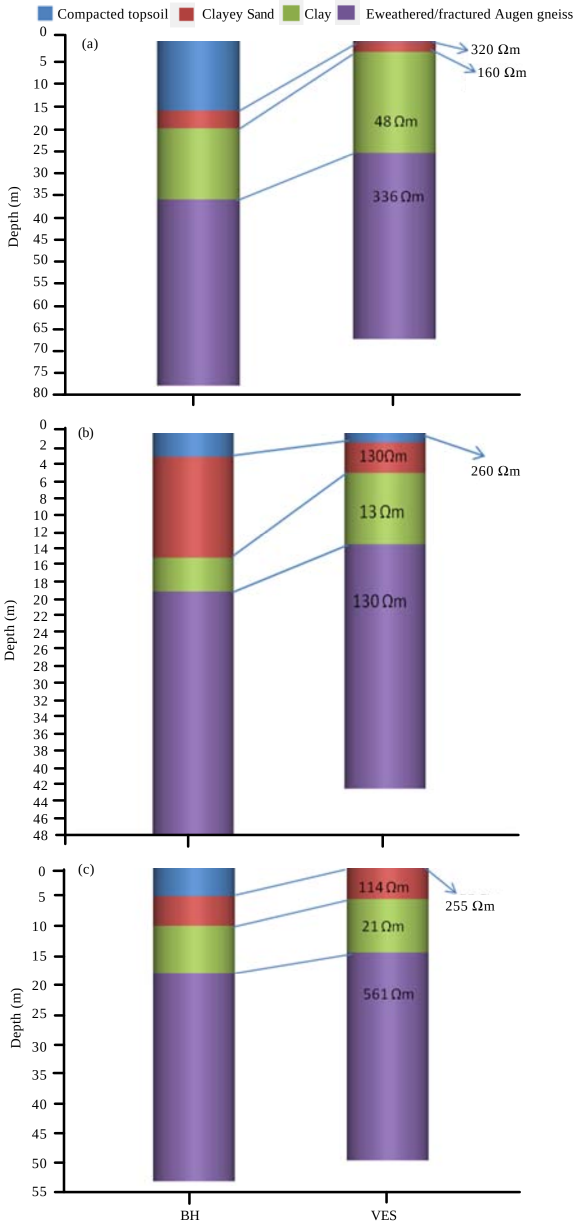

Fig. 5: a) Lithologic correlation for Lisabi Crescent; b) Lithologic correlation for Tedder Hall 1 and c) Lithologic correlation for Mellamby Hall 1

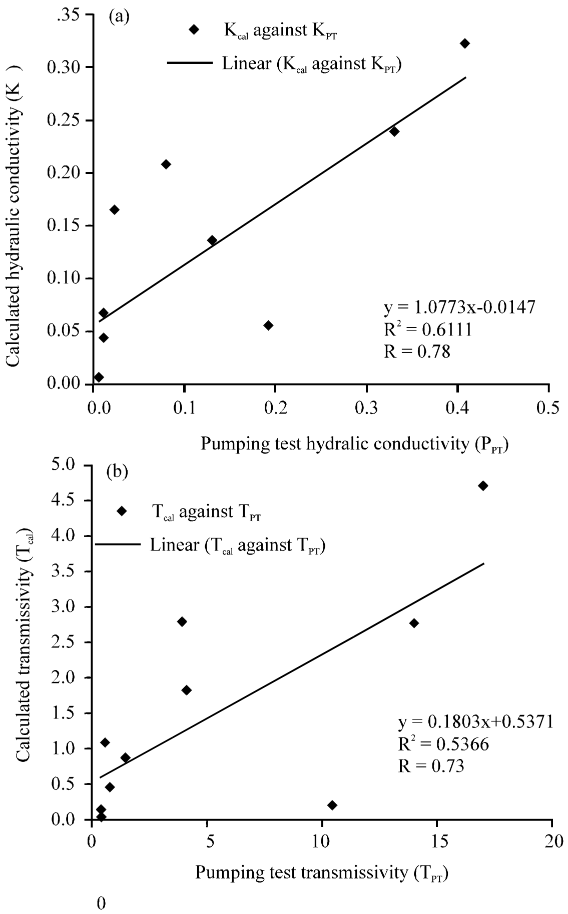

Fig. 6: a) Correlation between the pumping test derived and b) geo-electrically estimated K and t-values

Product Moment Correlation (PPM) operation carried out on the estimated parameters and borehole discharges as shown in Table 4 depicts that parameters like basement resistivity (ρ_B), reflection coefficient (r_c), surface elevation (Elev.) and aquifer thickness (H) are of little significance as to the borehole yield of the area while aquifer resistivity (ρ_L) and Borehole Depth (BD) shown no significance in contributing to the borehole yield of the area.

On the other hand, parameters like hydraulic conductivity (K) and transmissivity (T) both showed good significance in contributing to the borehole discharges in the study area. K and T values estimated from the pumping test operation and those estimated from the surficial resistivity measurements showed a correlation of R = 0.78 and 0.73 with each other, respectively (Fig. 6a, b).

Figure 7a-d are the contour plots showing the variation in the distribution of both pumping test derived and geo-electrically estimated hydraulic properties (Fig. 8 and 9).

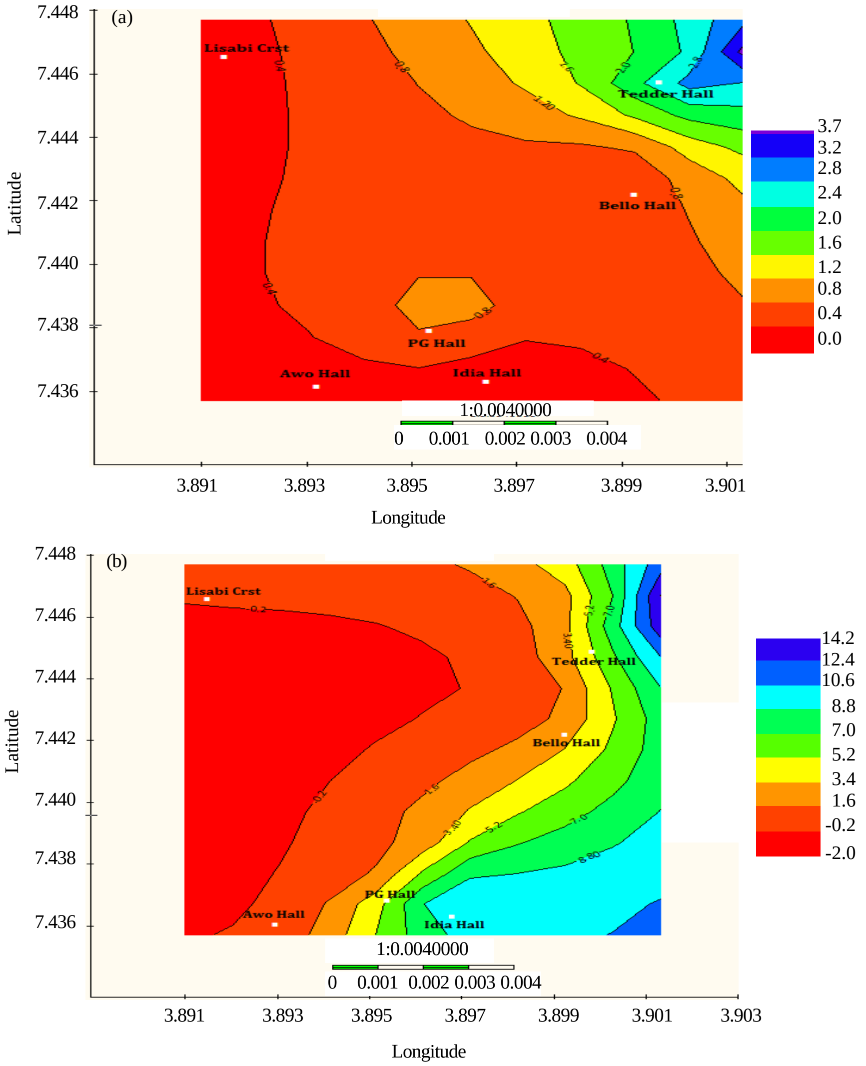

Fig. 7: a) Contour plots of the VES and b) pumping test derived t-values

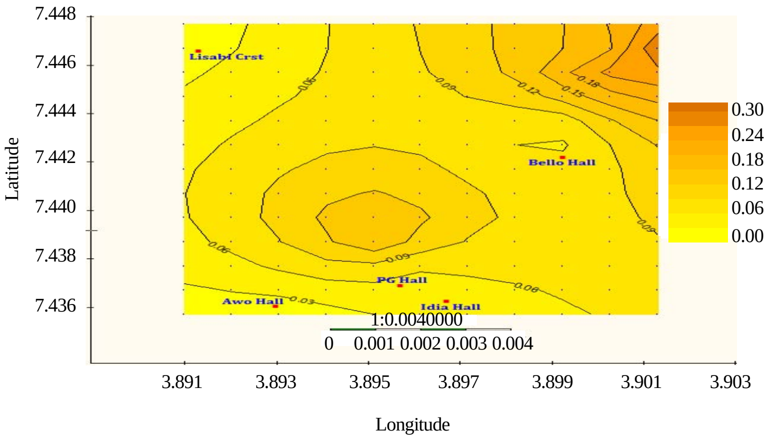

Fig. 8: Contour plots of the VES

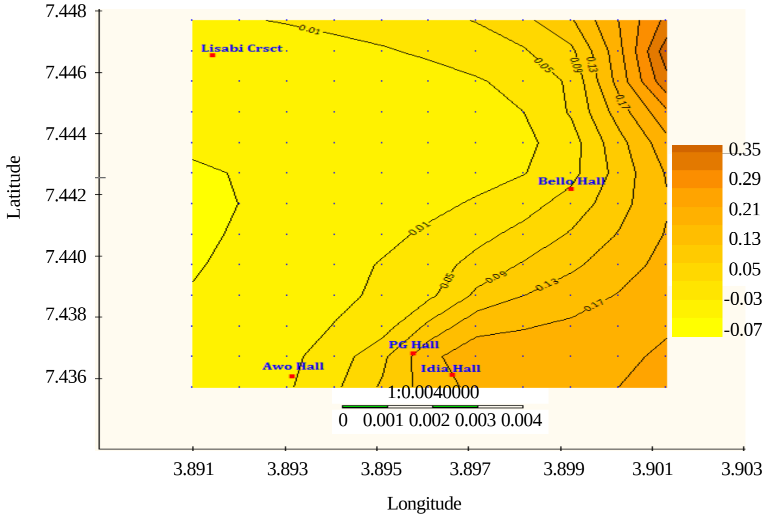

Fig. 9: Control plots of pumping test derived K-values

CONCLUSION

Vertical Electrical Sounding (VES) has provided an inexpensive and time saving technique for characterizing basement complex aquifers even for areas where drilled boreholes may not be available or feasible. Base on Pearson's product moment of correlation (R), the fair correlation between the geophysically and hydro-geologically estimated K and T values (R = 0.78 and R = 0.73, respectively) shows to an extent the applicability of this approach in a basement complex area while the better correlation of K_{PT}, K_{cal}, T_{PT} and T_{cal} with the borehole discharge than other aquifer parameters shows that hydraulic characteristics are much more important with regards to aquifer yields than other parameters like borehole depth, depth to basement, basement resistivity, reflection coefficient, aquifer thickness and resistivity. On a general note the low correlation values of K and T values with the borehole discharge can be attributed to the fact that there appears to be different factors controlling borehole discharges in a basement complex terrain. Based on the average estimated K (m/day) and T (m^2/day) values, the granite gneisses showed the best hydraulic potential followed by the banded gneiss and the quartzite/quartz schist. This conforms to what was reported by Bala *et al.* (2011) for a similar basement rocks in northern Nigeria.

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