INVESTIGATION OF RELATIONSHIPS BETWEEN GEOELECTRIC AND HYDRAULIC PARAMETERS IN A QUATERNARY ALLUVIAL AQUIFER IN YENAGOA, SOUTHERN NIGERIA

Okiongbo, K. S.[1] and Oborie, E.[2]
[1]Geophysics Unit, Department of Physics, Niger Delta University, Wilberforce Island, Bayelsa State, Nigeria
[2]Department of Geology, Niger Delta University, Wilberforce Island, Bayelsa State, Nigeria
(Corresponding Author: okenlani@yahoo.com)
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ABSTRACT

In an attempt to establish empirical electric-hydraulic relationships for the purpose of analyzing surface resistivity soundings, geoelectrical soundings using the Schlumberger array were carried out in Yenagoa and environs. Fourteen (14) VES stations were occupied across the study area. The field data were interpreted using Interpex IX1D computer software and the aquifer resistivity (ϱ) at each location was estimated. The hydraulic conductivity (K) determined from a reference borehole was combined with the normalized electrical conductivity (σ') to estimate a constant $K\sigma'$. This constant was integrated with the Dar Zarrouk parameters and used to estimate the hydraulic conductivity and transmissivity values at other VES locations where K values were unknown. The results showed that the hydraulic conductivity varied from 11.3 – 120.9 m/day while the transmissivity varied from 218.8 – 2849.9 m^2/day. Correlation of geoelectric and hydraulic parameters of the aquifer showed that the hydraulic conductivity (*K*) exhibited better correlation with the apparent formation factor (F_a) than transmissivity (*T*). Transmissivity was linearly related to normalized transverse resistance (T^i_R) via the equation $T = 0.018T^i_R + 301.6$ while the hydraulic conductivity was related to the aquifer resistivity (ρ) through the equation $K = 0.141\rho+413$. These empirical equations could be used to predict the hydraulic parameters in groundwater studies in the area.

Keywords: Hydraulic Conductivity, Transmissivity, Aquifer, Transverse Resistance, Apparent Formation Factor

INTRODUCTION

Correlations between hydraulic and geoelectric parameters have been studied by many authors (Kelly, 1977; Niwas and Singhal, 1981; Onuoha and Mbazi, 1988; Mbonu *et al*., 1981). These correlations are important because empirical/semi-empircal relations derived from such relationships could be used to extrapolate aquifer parameters using surface resistivity measurements.

Physical characteristics of aquifers such as hydraulic conductivity, transmissivity and storativity that control groundwater flow and transport are very important properties and are usually estimated for groundwater flow model calibration. These parameters are also important properties for the assessment of contaminated land, and for safe construction of civil engineering structures. Conventional methods for the estimation of these aquifer properties require the application of field hydrogeological methods such as pump tests which involve measurement of the rise and fall of water level with respect to time. The water-level fluctuations with time are then interpreted to arrive at aquifer parameters. Sometimes, laboratory experiments such as permeameter measurements are conducted to obtain small-scale estimates of porosity, hydraulic conductivity and tortuosity. These measurements, however, are time-consuming and costly. Pumping test and permeameter measurements in the laboratory are based on the Physics of fluid flow in porous media (de Lima and Niwas, 2000). In the electrical geophysical method, the flow of electrical current through the rock is used to determine the resistivities and thicknesses of different geological formations which have a resistivity contrast. The two flows, groundwater flow and electrical current, are though different in principle, and are governed by different physical laws, have an obvious analogy. This is because the physical conditions (tortuosity and porosity) that control the electric current flow (and electrical resistivity) also control the lateral flow of the water (hydraulic conductivity) in porous media (de Lima and Niwas, 2000). Exploiting this similarity, attempts have been made by many researchers to obtain estimates of hydraulic parameters using resistivity data (Bussian, 1983; Kumar *et al.*, 2001; Singh, 2005).

Studies from different geological settings revealed contrasting empirical models for the estimation of hydraulic conductivity (*K*) from resistivity data. Direct and inverse relationship between the log of resistivity (ϱ) and the log of *K* have been reported, depending on the subsurface material (Huntley, 1986). In the case of relatively clay-free sand and silt, an inverse relation between the log of resistivity (ϱ) and the log of *K* was reported due to the mutual dependence of ϱ and *K* on porosity (Heigold *et al.*, 1979). Hydraulic conductivity increases with porosity (ϕ) but ϱ decreases (Archie, 1942). In the case of clay-containing material, a direct relationship between the log of resistivity (ϱ) and the log of *K* is reported due to the mutual dependence of ϱ and *K* on clay content (Kosinski and Kelly, 1981). Hydraulic conductivity decreases with clay content, as does ϱ due to surface conduction in clays. Although valuable in a particular setting, it is apparent that a general model between *K* and ϱ does not exist (Purvance and Andricevic, 2000). Though empirically established electrical-hydraulic relationships often work reasonably well, however, they are usually only applicable to the specific study site or to sites with similar characteristics (Huntley, 1986; Purvance and Andricevic, 2000).

The objective of this study was to determine the relationship between aquifer hydraulic properties and Vertical Electrical Sounding (VES) derived resistivity in the unconsolidated alluvial sediments of Yenagoa and environs.

Study Area

The study area lies between latitudes 04° 23.3´ and 04° 38.2´ North of the equator and longitudes 006° 05´ and 00 6° 025´ East of the prime meridian within the coastal area of the Niger Delta (Fig. 1).

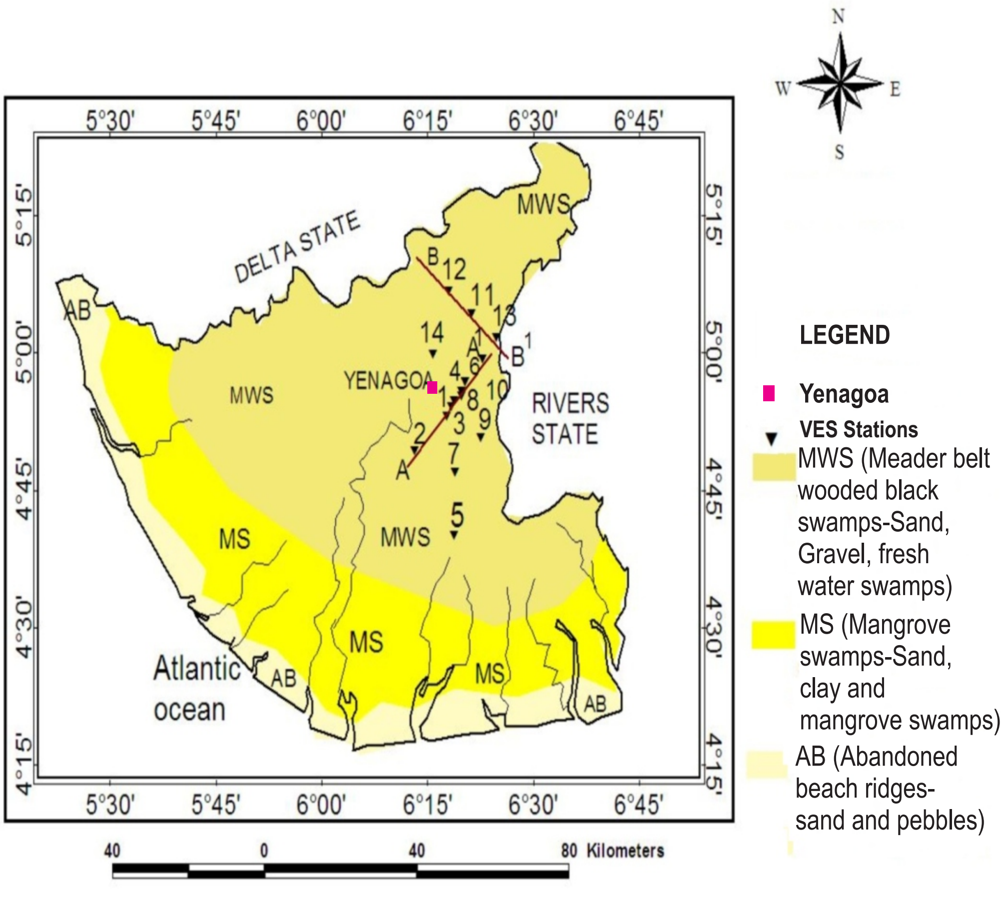

Fig.1. Map of Bayelsa State Showing the Study Area and the VES Stations

The area is a peneplain, intersected by numerous creeks, rivers and lakes (e.g Epie Creek, Ikoli River, Oxbow lake). The study area has surface elevation ranging between 40 and 50 m above mean sea level and covers an area of about 100 km^2. It is located within the tropical equatorial climate region with a temperature range of 23 – 38°C. The geomorphology of the area is monotonously flat and the regional slope is towards the south. Average annual rainfall is about 3000 mm and this serves as the major source of groundwater recharge.

The study area is underlain by the deposits of the Quaternary Coastal Plain Sands, which result from the sediment laden discharges of the River Niger that is spread on the delta by its various tributaries. These sediments are generally an admixture of medium to coarse-grained sands, sandy clays, silts and clays. The deposits constitute the shallow unconfined aquifer that is exploited by shallow (< 30m) boreholes and hand dug wells that serve as the primary water supply source for many semi-urban and urban communities in the area and in the Niger Delta region in general (Amajor 1991). Water table in large sections of the Niger Delta is close to the surface but subject to spatial and seasonal variations. In the study area, the water table is about 3 – 4 m during the dry season (Ekine and Osobonye, 1996). During the wet season, the water table rises considerably, in some cases, to the ground surface. Based on the results of hydrogeochemical analysis, the electrical conductivity (EC) of the groundwater varies between 102 – 2028 μS/cm. Total dissolved solids (TDS) varies between 51 and 1410 mg/L. Okiongbo and Douglas (2013) reported that the concentration of major ions in the groundwater is within acceptable limits except in some few cases.

MATERIALS AND METHOD

Fourteen (14) geoelectrical soundings using the Schlumberger array with a maximum current electrode half-spacings (AB/2) ranging between 100 and 200 m were carried out across the study area (Fig 1) with the ABEM SAS 3000 Terrameter Resistivity Meter. The positions and surface elevations of the VES locations were also recorded during the survey with a GPS receiver. The calculated apparent resistivity data were inverted using the Interpex, 1-D inversion software. All depths were constrained with the lithological log from the nearest borehole. The model parameters for each VES station are presented in Table 1. All the VES stations were located close to pre-existing water boreholes. Groundwater samples were collected from the boreholes. These groundwater samples were analysed for the Electrical Conductivity (EC). The electrical conductivity of the groundwater and the VES interpretation results, were used to determine the apparent formation factors using Archie (1942) equation. Pump test was carried out on the existing borehole at Okaka close to VES station 8 to determine the hydraulic conductivity. The pumping test data were interpreted using Jacob's straight line method (Fetter, 1994) following the formula:

$$T = \frac{2.3Q}{4\pi\Delta s}, \quad K = \frac{T}{H} \tag{1}$$

Where T is the transmissivity in m^2/s, Q is the rate of discharge in m^3/s, Δs is the slope in m, K is the hydraulic conductivity in m/s, and H is the saturated thickness in metre obtained from the borehole data. The transmissivity and hydraulic conductivity values obtained were 187.6 m^2/day and 28.0 m/day respectively.

Archie's law (Archie, 1942) relates the bulb resistivity of a fully saturated granular medium to its porosity and the resistivity of the fluid within the pores according to equation:

$$\rho_b = \alpha\rho_w\phi^{-m} \tag{2}$$

where ϱ_b is the bulk resistivity, ϱ_w is the resistivity of the saturating water, ϕ is the porosity of the medium, and the dimensionless coefficients α and m (cementation factor and coefficient of saturation) depend on the rock type. The ratio $\frac{\rho_b}{\rho_w}$ is called the Formation Factor, F. This is the true Formation Factor when the formation is a clay-free, clean sand. If the aquifer is a clayey or shaly sand, then the Formation Factor becomes apparent (F_a).

The transverse unit resistance (T_R) and the longitudinal conductance (L_C) (both are Dar-Zarrouk parameters) are defined as follows:

$$L_C = \frac{h}{\rho} \quad (3)$$

$$T_R = \rho \times h \quad (4)$$

where h is the thickness of the aquifer and ϱ is the resistivity of the aquifer.

The groundwater flow through an aquifer is governed by the transmissivity *T,* which is expressed as:

$$T = Kh \quad (5)$$

where *K* is the hydraulic conductivity. Niwas and Singhal (1981) determined analytically the relationship between transmissivity and transverse resistance on one hand and the transmissivity and longitudinal conductance on the other. Niwas and Singhal (1985) modified these relationships by using a modified aquifer resistivity (ϱ'), known as normalized aquifer resistivity (Kosinski and Kelly, 1981) to incorporate variations in the quality of groundwater. However, the modification factor is the ratio of the average pore water resistivity and ($\bar{\rho}_w$) the pore water resistivity (ϱ_w) at the measuring point. The normalized aquifer resistivity (ϱ') is defined as

$$\rho' = \rho \frac{\bar{\rho}_w}{\rho_w} \quad (6)$$

Thus, the hydraulic and electric parameters were combined to give a relationship between transmissivity (*T*) and normalized transverse resistance (T'_R) as follows:

Divide equation 5 by equation 4

$$\frac{T}{T_R} = \frac{Kh}{\rho h} = \frac{K}{\rho}$$

$$T = \frac{KT_R}{\rho} = K\sigma T_R \quad (7)$$

For normalized Transverse resistance (T'_R)

$$T'_R = \varrho' h \quad (8)$$

Therefore,

$$T = \frac{KT'_R}{\rho'} = K\sigma' T'_R \quad (9)$$

where ϱ' and σ' are normalized resistivity and conductivity respectively.

$$\text{If } \frac{K}{\rho'} = \alpha \text{ or } \alpha = K\sigma' \quad (10)$$

Then

$$T = \alpha\, T'_R \quad (11)$$

The relationship between transmissivity (*T*) and normalized longitudinal conductance (L'_C) can be established thus:

Divide equation 5 by equation 3

$$\frac{T}{L_C} = \frac{Kh\rho}{h},$$

hence

$$T = K\rho L_C$$

For normalized longitudinal conductance

$$T = K\rho' L'_C = (KL'_C)\rho' \quad (12)$$

where $L'_C = \frac{h}{\rho'}$

where

T = Aquifer transmissivity (m^2/s)

K = Hydraulic conductivity (m/s)

T_R = Transverse resistance of the aquifer (Ohm-m^2)

L_C = Longitudinal conductance (Ohm^{-1})

P' = normalized aquifer resistivity (Ohm-m)

The product KLc' was assumed to be constant at a reference point of the aquifer and therefore known. Thus, we define

$$b = KL'_C \quad (13)$$

Prior to the investigation of transmissivity variations throughout the aquifer, the appropriate *Kσ* constant was calculated. The *Kσ* product was expressed in terms of both transverse resistance (T_R) and longitudinal conductance (L_C). Mazac *et al.* (1985) observed that conditions where the transverse resistance is dominant occur when the aquifer rests on a thickness of less permeable material rather than directly on bedrock. Since the aquifer rests on less permeable clayey materials as shown in the sounding curves at all stations in the study area, it was more appropriate to estimate the transmissivity variations in this aquifer by means of the transverse resistance (Eq. 11) rather than the longitudinal conductance (Eq. 12).

The $a = K\sigma$ constant was calculated by using the *K* value from the pumping test (*K* = 28.0 m/day) and the modified electric conductance (σ') from each VES station. This constant has been combined with the normalized transverse resistance (T'_R) at the remaining stations to investigate the transmissivity variations throughout the study area. Hydraulic conductivity was computed using equation (10). Table 2 gives a summary of the interpreted results showing the aquifer thicknesses, resistivities, hydraulic conductivities, and transmissivities.

RESULTS AND DISCUSSION

The VES curves in the studied area are largely dominated by four layer KH and HK type (Figs. 2 & 3) with the occurrence of a limited number of three layer K type and five layer KHK and HKH types. Based on the correlation between the VES results and the lithological information from the borehole, three major subsurface layers are recognised. The topmost layer, consisting of calcareous loam mixed with organic matter (Amajor, 1991), is represented in the geoelectrical column by the upper two layers of which the upper one has a thickness of about 0.6 m and a resistivity of 189 Ωm. The underlying layer has a thickness of about 1.7 m with a resistivity of 349 Ωm and consists of silty sand (Fig. 2). The increase in the resistivity value from the surface downwards is attributed to the increase in grain size.

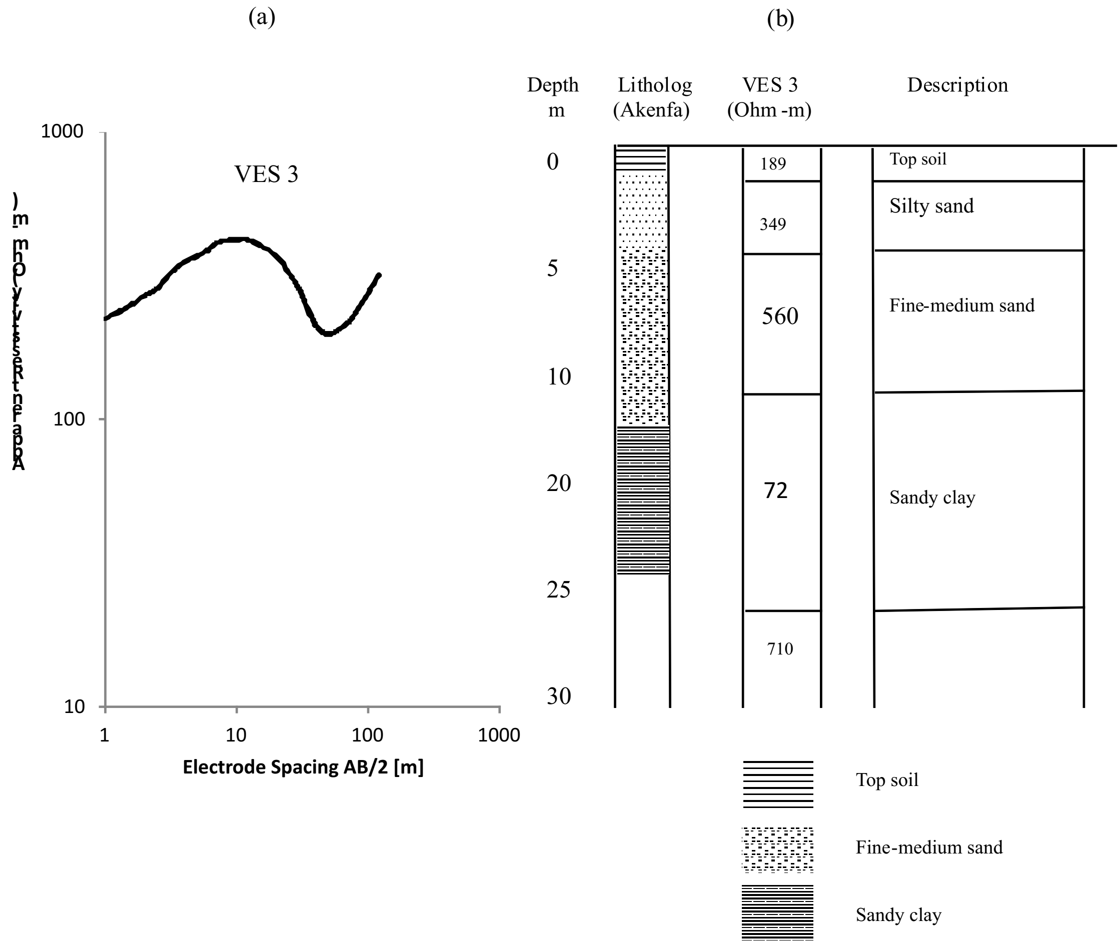

Fig. 2 (a) VES (VES 3) Curve and (b) Correlation of the VES Interpretation Results with the Lithology of the nearest Borehole

The third layer resistivity is 560 Ωm and the layer is interpreted to be the fresh water saturated alluvial sand aquifer. The borehole lithology log shows that the aquifer is composed of fine-medium grained sand. The fourth geoelectric layer extends from the base of the overlying alluvial aquifer to a depth of 27.7 m. This layer which has a relatively low resistivity (72 Ωm) is regarded as water saturated sandy clay. The fifth layer has a resistivity of 710 Ωm which is typical of sand.

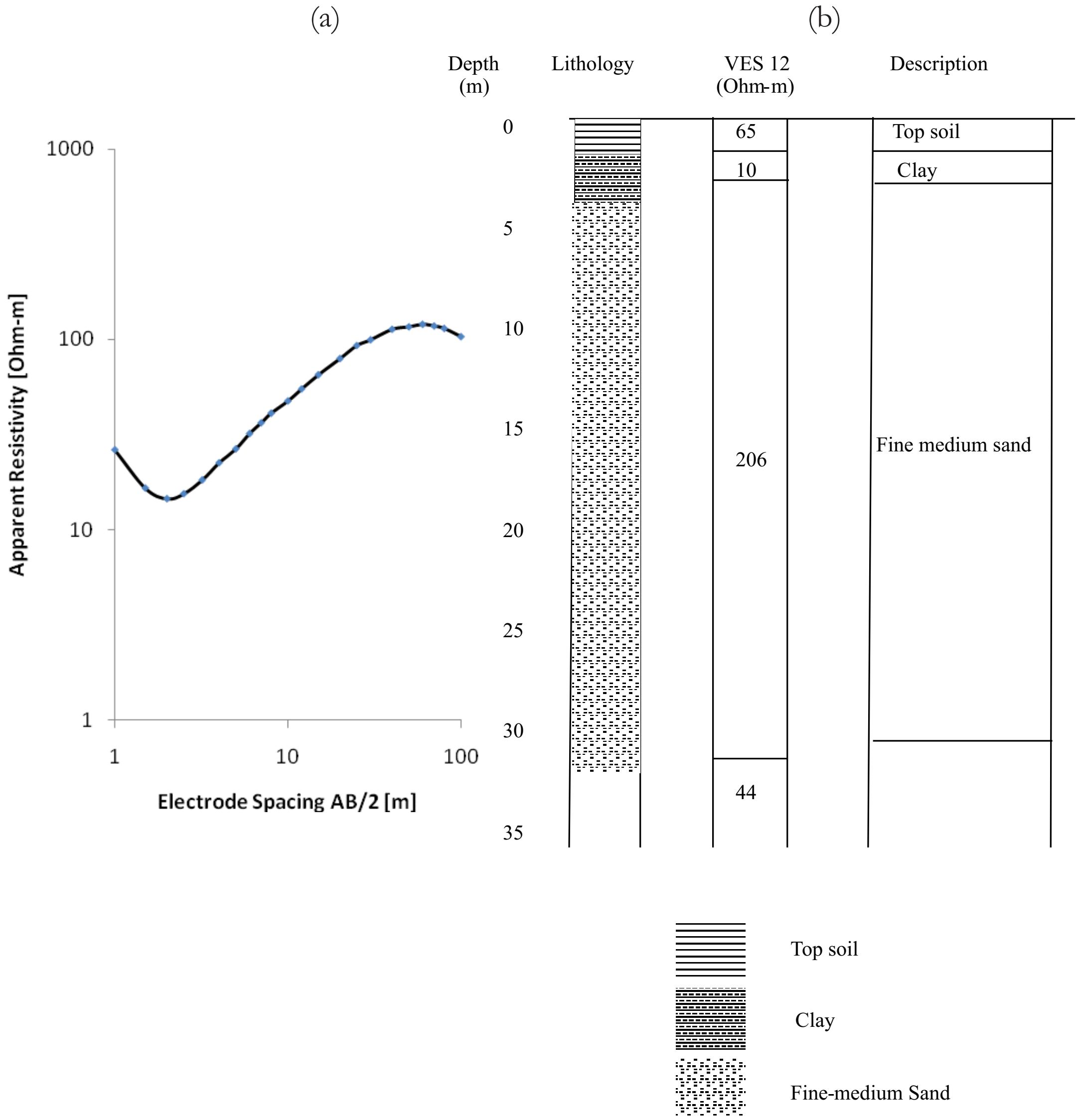

Fig. 3 (a) VES (VES 12) Curve and (b) Correlation of the VES (VES 12) Interpretation Results with the Lithology of the nearest Borehole.

Figure 3 shows the results obtained from VES-12 location. The first geoelectric layer extends from the ground surface to a depth of 0.4 m with layer resistivity of 65 Ωm. The second geoelectric layer extends to a depth of 2 m, with resistivity value of 10 Ωm. This layer corresponds to clay. The third geoelectric layer extends to a depth of about 33 m and has a layer resistivity of 206 Ωm. This layer corresponds to fine-medium grained sand.

The estimated hydraulic conductivity and transmissivity values using equations 10 and 11 respectively are presented in Table 1. The obtained results indicate that the transmissivity values are high over the entire area and vary from 218.8-5085 m^2/day. This is consistent with the findings of Amajor (1991) in the study area using pump test data. The hydraulic conductivity values range from 29.4-161.2 m/day. These results are realistic in view of the fact that the aquifer is composed of unconsolidated fine-medium-coarse sand (Mbonu *et al.,* 1991). Figures 4 and 5 show plots of hydraulic conductivity and transmissivity versus the apparent formation factor. The plots indicate an increase in hydraulic conductivity and transmissivity with increase in apparent formation factor. However, the estimated hydraulic conductivity (K) values exhibit better correlation with the apparent Formation Factor (F_a) than transmissivity (T) with apparent Formation Factor (F_a).

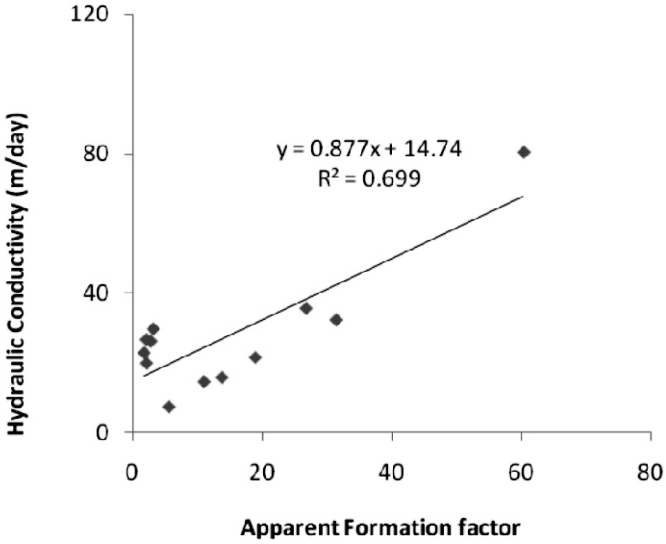

Fig. 4. Relation Between Hydraulic Conductivity and Apparent Formation Factor

Table 1. Geoelectrical Layer Parameters (Resistivity and Thickness) Obtained from the Interpretation of Geoelectrical Soundings

		Thicknesses (m)				Resistivity (Ωm)					
VES No	VES Location	h_1	h_2	h_3	h_4	ρ_1	ρ_2	ρ_3	ρ_4	ρ_5	RMS Error (%)
1	Tombia H/C	1.3	1.8	7.5	-	132	142	2399	59	-	1.3013
2	Azikoro	0.5	4.7	97.6	-	57	31	230	126	-	3.7510
3	Akenfa III	0.6	1.7	9.2	16.2	189	349	560	72	710	1.9129
4	Emeyal- Otueke Rd	0.6	3.1	14.9	48.4	58	58	222	86	213	1.4058
5	Dr Wessey- Igbogene	0.5	0.7	12.9	18.3	94	132	106	1456	12	2.2874
6	Dr Egirani-Emeyal II	1.4	13.2	25.6	-	72	15	664	149	-	2.7507
7	Tombia	0.4	0.5	14.0	-	40	453	1837	96	-	2.8559
8	WaterBoard	1.1	1.9	6.7	23.5	61	15	134	15	1640	5.2276
9	Otueke 5	0.5	4.3	9.9	-	11	20	193	4	-	1.4353
10	EJARS Farm-Elebele	0.5	1.9	10.2	-	38	20	263	13	-	4.3460
11	Agbobiri	0.5	8.2	54.7	-	105	64	280	50	-	1.1446
12	Ongolo	0.4	1.6	30.5	-	65	10	206	44	-	2.0981
13	Ogbia Sec Sch	1.0	3.0	8.2	-	192	177	367	127	-	1.2507
14	Otueke 4	1.3	3.8	12.3	-	11	20	193	4	-	1.4353

Table 2. Aquifer Electrical and Hydraulic Parameters Estimated from Vertical Electrical Sounding Data

VES No	VES Location	h (m)	ρ (Ohm-m)	ρw (Ohm-m)	σ'	ρ'	K_o (m/day)	TR (Ohm-m²)	TR' (Ohm-m²)	α=Kσ'	α=Kσ'	$K_c=\alpha\rho'$ (m/day)	T (m²/day)
1.0	Tombia H/C	9.4	1856	76	0.0006	1624		17448	15269	0.017	0.03	48.7	490
2.0	Azikro	97.6	230	9	0.0006	1781		22468	173796	0.016		53.4	5085
3.0	Akenfa III	11.1	481	30	0.0009	1086		5338	12052	0.026		32.6	578
4.0	Emeyal - Otueke	14.9	222	20	0.0014	736		3302	10962	0.038		22.1	776
5.0	Dr Wessey Pre.	18.3	1456	54	0.0006	1789		26637	32741	0.016		53.7	953
6.0	Emey Dr Egirani	25.6	664	11	0.0002	4029		16986	103139	0.007		120.9	1334
7.0	Tombia	16.6	1594	133	0.0013	798		26452	13253	0.035		24.0	865
8.0	WaterBoard	6.7	134	24	0.0027	375	28.0	900	2514	0.075		11.3	349
9.0	Otueke 5	16.7	111	39	0.0053	188		1845	3143	0.149	0.15	28.2	870
10.0	Ejars Farm Elebele	10.2	263	92	0.0052	192		2684	1954	0.146		28.7	531
11.0	Agbobiri	54.7	280	83	0.0045	224		15294	12260	0.125		33.6	2850
12.0	Ongolo-Okaka	30.5	206	65	0.0047	213		6289	6512	0.131		32.0	1589
13.0	Ogbia Sec Sch	8.1	364	170	0.0070	143		2948	1162	0.195		21.5	422
14.0	Otueke 4	4.2	265	108	0.0061	165		1113	691	0.170		24.7	219

h=Aquifer thickness (m), ρ= aquifer resistivity (Ohm-m), ρ' = normalized aquifer resistivity (Ohm-m), ρ_w= pore water resistivity (Ohm-m), K_o= hydraulic conductivity from pump test data (m/day), T_R = transverse resistance (Ohm-m^2), T_R' = normalized transverse resistance (Ohm-m^2), K_c = Computed hydraulic conductivity (m/day), T = transmissivity (m^2/day)

Pfannkuch's (1969) model provides the theoretical basis for the observed relationship between hydraulic conductivity and apparent formation factor and suggested that in addition to porosity and tortuosity, there is a mutual dependence of apparent formation factor and hydraulic conductivity on grain size.

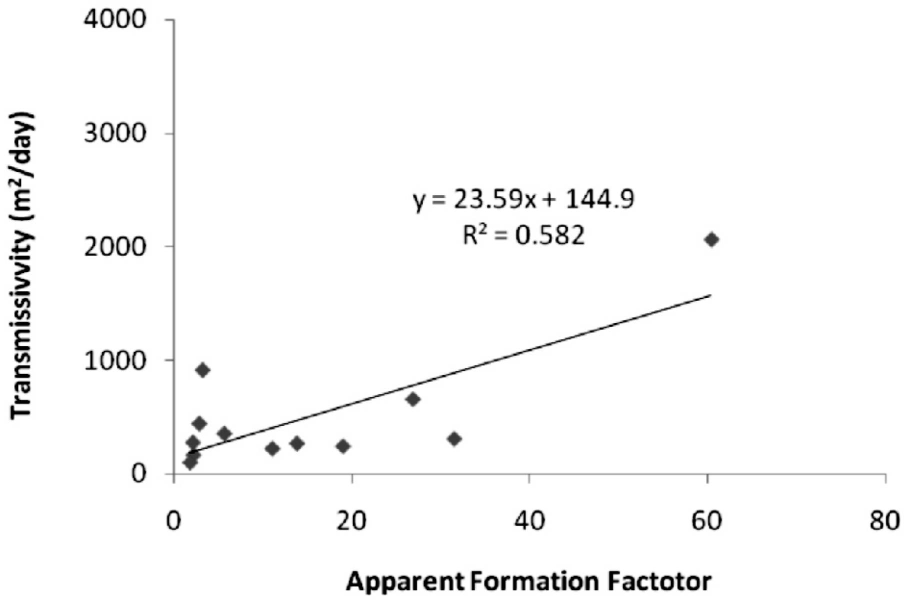

Fig.5. Relationship Between Transmissivity and Apparent Formation Factor

Frohlich and Kelly (1985) observed that if the aquifer is characterised by a high resistivity in a typical K type curve, the transverse resistance is a unique parameter and can directly be correlated with the hydraulic transmissivity. Correlation between transmissivity (*T*) and normalized transverse resistance (T_R') is presented in Figure 6. The regression line fitted to these data indicates the following relationship.

$T = 0.018T_R' + 301.6$ ($R^2 = 0.83$)

The slope of the line is positive which indicates an increase in *T* with an increase in T_R'. This is in agreement with an earlier work done by Frohlich and Kelly (1985). The observed scatter is attributed to hydraulic and electrical anisotropies, as well as lithological and mineralogical variations, grain size, and size and shape of the pores and pore channels (Salem, 1999).

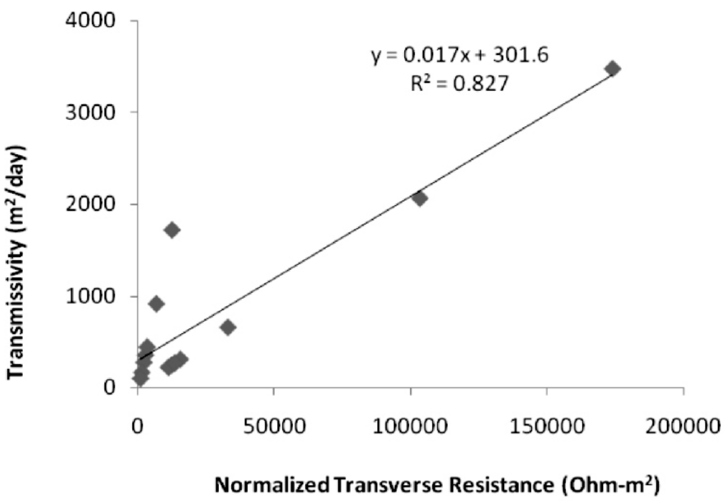

Fig. 6. Relation Between Transmissivity and Modified Transverse Resistance

Figure 7 shows a linear relationship between hydraulic conductivity (*K*) and resistivity of the aquifer materials. This is consistent with the observation of Kelly, (1977) and Niwas and Singhal, (1981) that in aquifer materials composed of gravel, coarse sand and sand with clay, the hydraulic conductivity increases with resistivity.

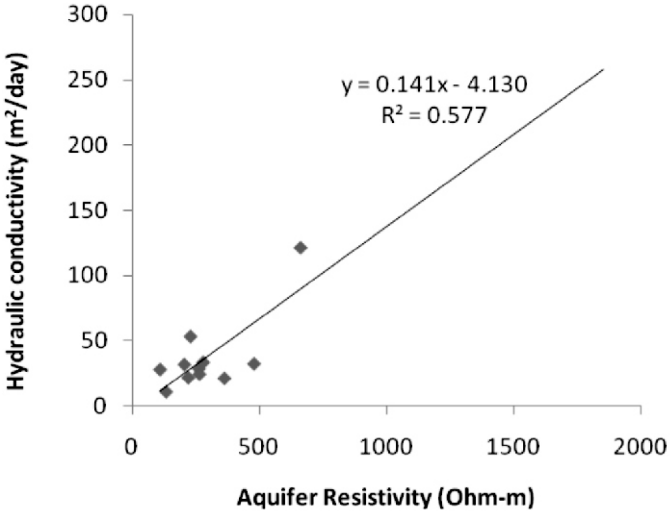

Fig.7. Relation Between Hydraulic Conductivity and Resistivity

The regression line fitted to these data is of the form:

$K = 0.141\rho - 4.13$ (R^2=0.58)

CONCLUSION

The purpose of this study was to investigate relationships between hydraulic and geoelectric parameters in an alluvial aquifer. The practical applicability of the method lies in the fact that the hydraulic conductivity must be known for any reference point in the area, then it can be possible to get a fairly good idea of the hydraulic parameters of the aquifer in other locations from geoelectrical soundings. The obtained results indicate that the transmissivity values are high over the entire area and vary from 218.8-5085 m^2/day. The hydraulic conductivities range from 29.4-161.2 m/day. Computed hydraulic conductivity (*K*) values exhibit better correlation with the apparent formation factor (F_a) than transmissivity (*T*). This study also shows a direct relationship between transmissivity and normalized transverse resistance. Hydraulic conductivity was found to be linearly related with aquifer resistivity. Because of the inhomogenity of the alluvial deposits, it would be unreasonable to expect unique results from geoelectrics. However, the empirical relations obtained in this study can be used to predict the hydraulic parameters as preliminary information for further management of groundwater supply in the area.

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