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THE LIMITING FACTOR RELATIONSHIP BETWEEN GEOELECTRIC AND HYDRAULIC PARAMETERS – A CASE STUDY

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ABSTRACT

The limiting factor relationship between geoelectric and hydraulic parameters of parts of the West Chad Basin, northeastern Nigeria was appraised in this present study. The objectives of study included the estimation of the aquifer hydraulic parameters of the Pleistocene aged alluvium Formation from both the geoelectric and pumping test datasets with a view to determining empirical and limiting factor relationships and groundwater conditions. 106 geoelectric sounding and seventeen pumping test datasets were analyzed with RESIST Software and time – drawdown plots respectively. The concept of Dar-Zarrouk parameters was used to determine aquifer hydraulic parameters. The range of values from results included the following; derived transmissivity T_c (188.9-2789.8 m^2/day) with $T_{c\ mean}$ of 1540.84 m^2/day; and field pumping transmissivity T (113.2 - 1436.6 m^2/day with T_{mean} of 634.96 m^2/day and derived hydraulic conductivity K_c values of 11.12-189.73 m/day, field pumping hydraulic conductivity K of 6.67-101.31 m/day with the $K_{c\ mean}$ of 115.34 m/day; K_{mean} of 36.22 m/day respectively. A linear fit relationship between the two datasets showed a correlation coefficient of 0.52861, standard deviation of 310.81. Higher values obtained from the geoelectric derived hydraulic parameters in few borehole sites in multiple of two or three suggested a limiting factor of the method. It may, therefore, be concluded that the limiting factor may have arisen from overestimation of the aquifer thickness occasioned by the degree of saturation and/or sand to clay ratio to which geoelectrical resistivity method might have responded. Hence, the method remained a tool on the choice of prospective high yielding borehole site selection from the consideration of the findings.

KEYWORDS: Aquifer, hydraulic, geoelectric, pumping, transmissivity, saturation

INTRODUCTION

Indirect estimation of hydrogeological/aquifer hydraulic properties from second order geoelectric sounding datasets other than the direct classical analytical Theis (1935) and Cooper and Jacob (1946) models to the pumping test data, plays a very important role in predicting aquifer hydraulic parameters of a given area. The method employs a concept called the Dar Zarrouk parameters (Maillet, 1947). This concept has gained a tremendous popularity not only because of its ability to extract hydrogeological information particularly where aquifer hydraulic characteristics such as transmissivity, hydraulic conductivity etc are desirable prior to drilling of wells, but also for extracting linear relationships among datasets. The possibility of using this method laid credence to the empirical equations of the earlier workers such as Maillet (1947), Niwas and Singhai (1981), Onuoha and Mbazi (1988), Mbonu *et al.* (1991), Dan Hassan and Olorunfemi (1999), Mohammed (2007), Mohammed *et al.* (2012).

The study area is part of River Jama'are floodplain in the West Chad Basin, West of Azare town in Katagum Local Government Area of Bauchi-State (Figure 1). The area is a transition zone of sedimentary/basement rock formations. It is underlain by Cretaceous-Tertiary Chad Formation and Recent alluvial Formation of Pleistocene age. The two formations directly rest on the basement rock. The alluvium deposits along the floodplain consists of silts, clays, and sands while the Chad Formation constitutes all Quaternary sediments of lacustrine origin (Carter et al, 1963). It is mainly argillaceous consisting of fine-medium-coarse grained clean/dirty sandy deposits or a variable lithologic sequence of interbedded clays, silts, and sands, grits and gravels (Ogilbe, 1965; GSN, 1978; BSADP 1988; Matheis, 1989 and Offodile, 2002, Mohammed, 2007).

The development of groundwater in the floodplain is beset with problems of failed (abortive) and/or poor groundwater yielding boreholes arising from poor knowledge of the hydrogeological characteristics of the area/porous media aquifers prior the drilling of well/boreholes. Low and unsatisfactory yields of between 0 and 5 litres/second are commonly observed from wells as against between 6.7 and 16.7 litres/second recorded in this floodplain area (BSADP, 1988).

This paper, therefore, presents the potential and the constraint of the geoelectrical method in estimating the aquifer transmissivity and hydraulic conductivity. The method is intended to serve as a tool to guide on the choice of prospective high yielding borehole site selection particularly in porous media aquifers of the Floodplain and others with similar geological settings. The results from this will provide the basis for which an alternative and cost effective approach to traditional pumping tests analysis may be sought in the evaluation of reliable values of aquifer hydraulic characteristics. The field parameters obtained from pumping test data

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would be related with the predictive estimable aquifer parameters obtained from the geoelectric sounding datasets to see if empirical relationships can be established from the datasets.

2. MATERIALS AND METHODS

One hundred and six (106) apparent resistivity Schlumberger sounding datasets with a maximum spread length of 450 m were processed and analysed (Figure 2). This involved plotting of the datasets on log-log transparent graph sheets followed by manual partial curve matching and computer aided/iteration techniques that gave the typical sounding curves and their corresponding layer models or geoelectric parameters (Figure 3). The parameters (layer resistivities and thicknesses) were later used to derive the second order geoelectric (Dar - Zarrouk) parameters (Maillet, 1947; Henriet, 1976; Odusanya and Amadi, 1990). Among these parameters include the Longitudinal Unit Conductance, S_i and Transverse Unit Resistance, R_i (Zohdy et al., 1974).

For n parallel layers of resistivities $\rho_i, \ldots \rho_n$, and thicknesses $h_i, \ldots, h_n$ as shown in a typical geoelectrical section with n-layers of infinite lateral extent (Figure 4);

The total longitudinal unit conductance,

$$S = \sum_{i=1}^{n} \frac{h_i}{\rho_i} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (1)$$

The total transverse unit resistance,

$$R = \sum_{i=1}^{n} h_i \rho_i \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (2)$$

The subscript i indicates the position of the layer in the section.

From the above Dar Zarrouk parameters- the total transverse unit resistance (R) and total longitudinal unit conductance (S) in the equations 1 and 2 respectively was the relevant interpretational tools employed in this study.

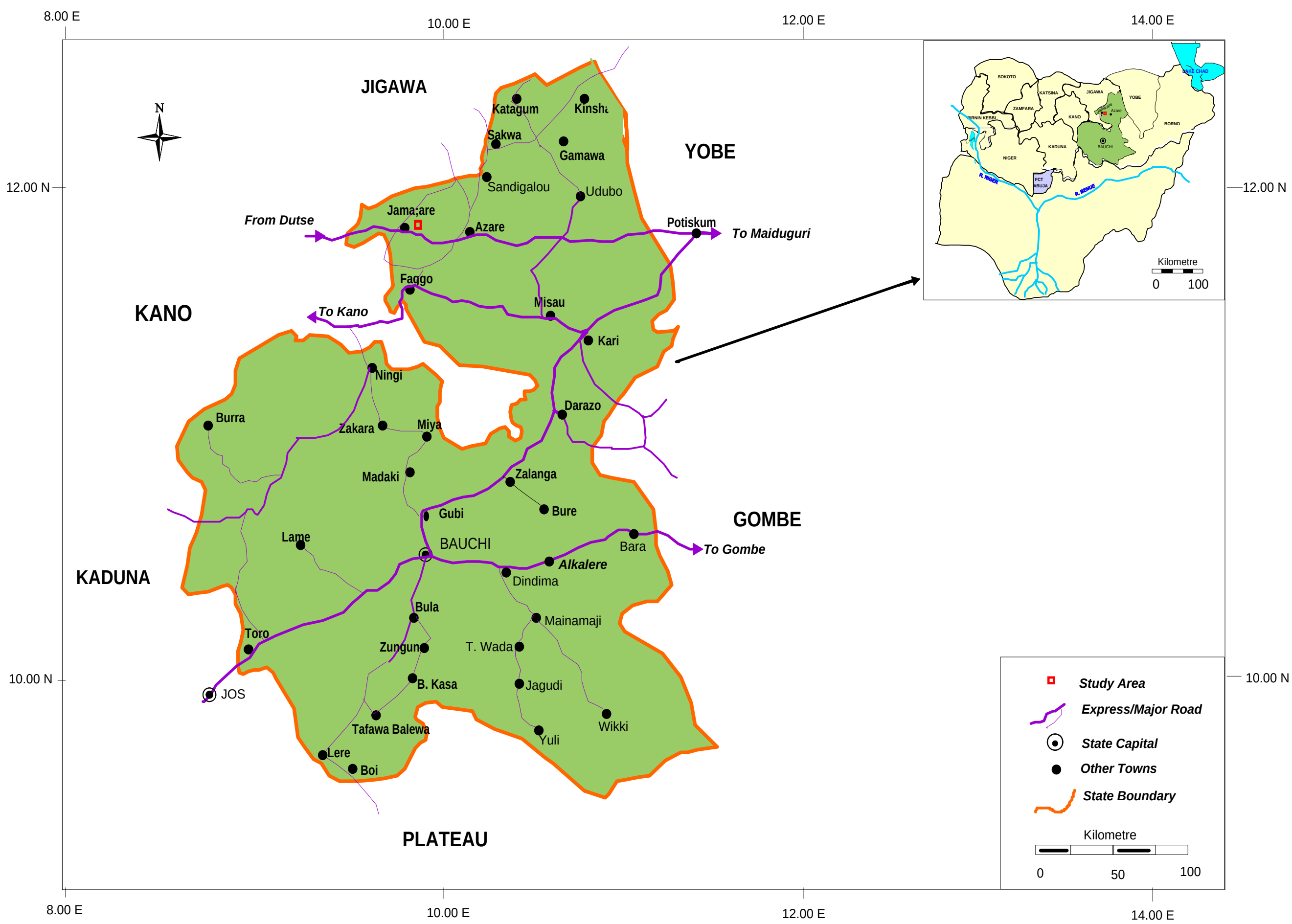


Figure 1: Map of Bauchi State showing the study area

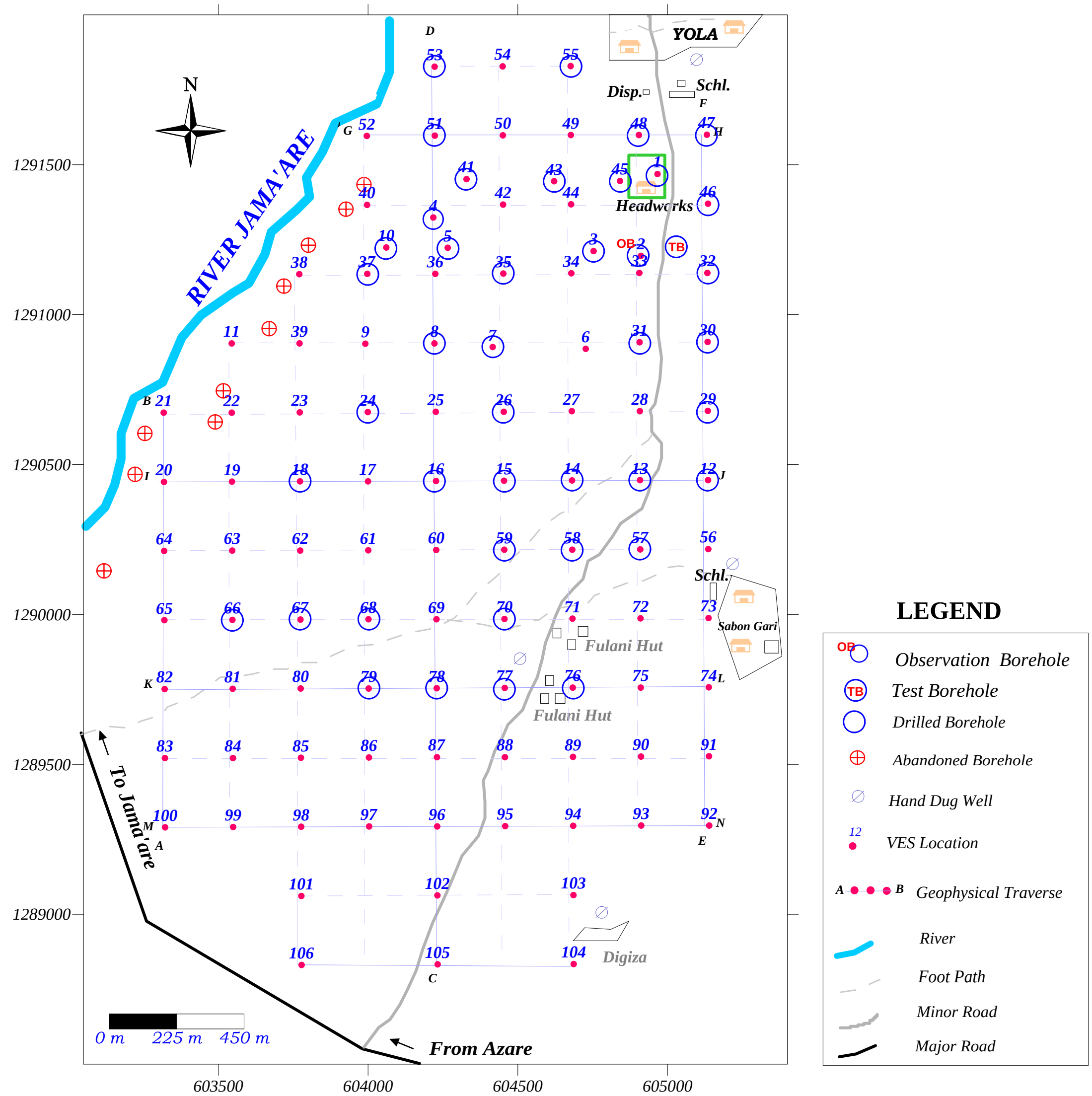
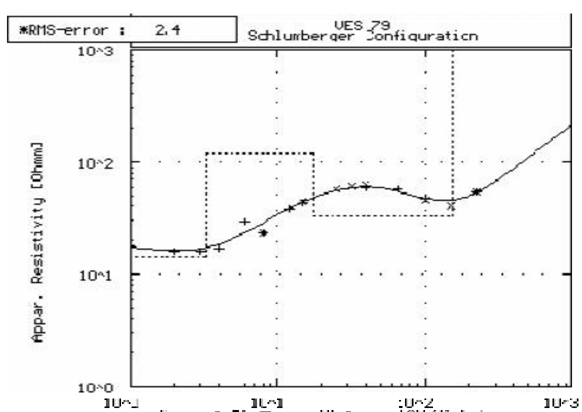


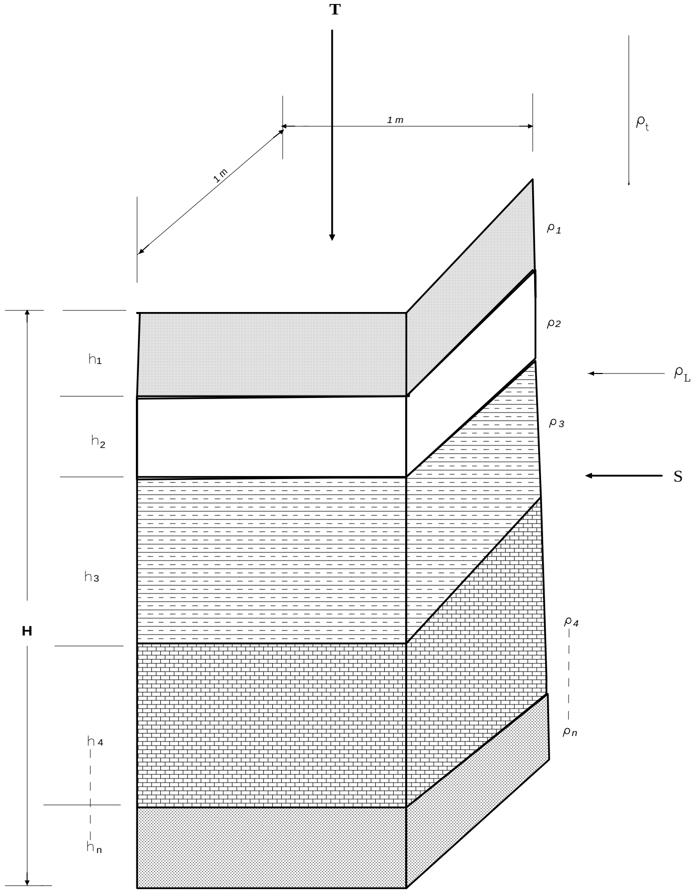
Figure 2: Data acquisition map showing sounding stations and Location of boreholes



No	Res	Thick	Depth
1	19.0	0.6	0.6
2	14.0	2.7	3.3
3	120.0	14.1	17.4
4	33.0	138.9	156.3
5	10000.0	-.-	-.-

* RMS on smoothed data

Figure 3: Typical sounding curve and geoelectric parameters



n = Number of layer
h_n = Layer thickness
S = Total longitudinal conductance
ρ_L = Average longitudinal resistivity
ρ_n = Layer resistivity
H = Total depth
T = Total transverse resistance
ρ_t = Average transverse resistivity

Figure 4: A typical Geoelectrical Section for Nth Layered Model

However, the determination of aquifer hydraulic parameters (transmissivity and hydraulic conductivity) from direct classical analytical Cooper – Jacob (1946) model is expressed as:

Transmissivity, $$T = \frac{2.3Q}{4\pi\Delta s} \quad \ldots\ldots\ldots\ldots \quad (3)$$

or $$T = \frac{0.183Q}{\Delta s} \quad \ldots\ldots\ldots\ldots \quad (4)$$

Where,
T = Coefficient of transmissivity in m^2/day
Q = Flow discharge/Pumping rate in m^3/day
Δs = Change in drawdown between two log cycles or change in drawdown between 10 and 100 minutes after the start of the pumping test (i.e. $S_{w100} - S_{w10}$) in metre
Hence, the transmissivity, T, of an aquifer is related to the field hydraulic conductivity, K, and screen length, b, by the equation:

T = Kb ………………………………………. (5)

Where b = average saturated thickness/screen length in metre, and K = hydraulic conductivity in m^2/day.
According to Niwas and Singhai (1981), estimates of transmissivity may further be expressed from the combination of Darcy law,

Q=KIA .... (6)

and Ohms law, **J=Eρ** ………………………… (7)

as $$T_C = KR\rho^{-1} = KS\rho \quad \ldots\ldots\ldots \quad (8)$$

Thus eq. 8 is transmissivity expression from the Dar - Zarrouk or geoelectric parameters

Where T_c = Calculated transmissivity (m^2/day) from geoelectric parameters.
R = Total transverse resistance (ohm-metre^2)
S = Total longitudinal conductance (ohm^{-1}) and
ρ = Resistivity of the aquiferous zone (ohm-metre)
I = Hydraulic gradient

A = Cross-sectional area perpendicular to the direction of flow
J = Current density

Equation 8 above is analogous to Equation 5 (i.e. T = KSρ = Kb)

Furthermore, the Hydraulic conductivity (K) is expressed as flow rate in m^2/day through a cross-section of the aquifer under a hydraulic gradient of one.

$$K \; Z \; \frac{T}{b} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (9)$$

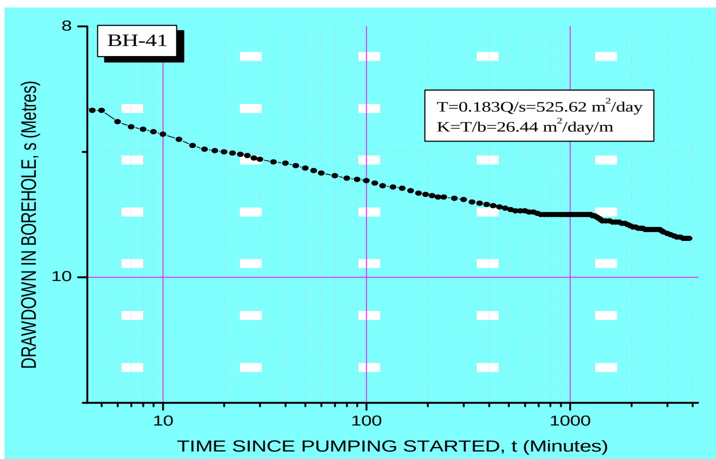
Hydraulic conductivity varies widely for unconsolidated porous materials, being high for sands and gravels and low for silts and clays with low effective porosity. It has also been shown by Niwas and Singhai (1981) that in areas of similar geologic setting and water quality the product Kσ remains fairly constant.

The field hydraulic conductivity can further be estimated from geoelectric results using the equation:

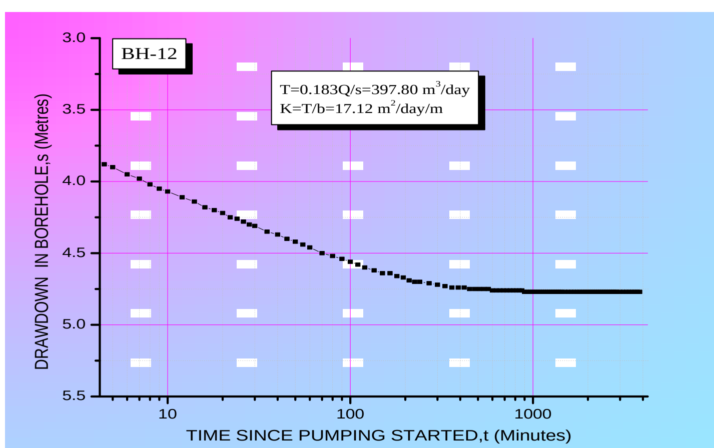
$$K_C \; Z \; T_C b^{J1} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (10)$$

Where K_c = Calculated hydraulic conductivity (m^2/day/m) from geoelectric.

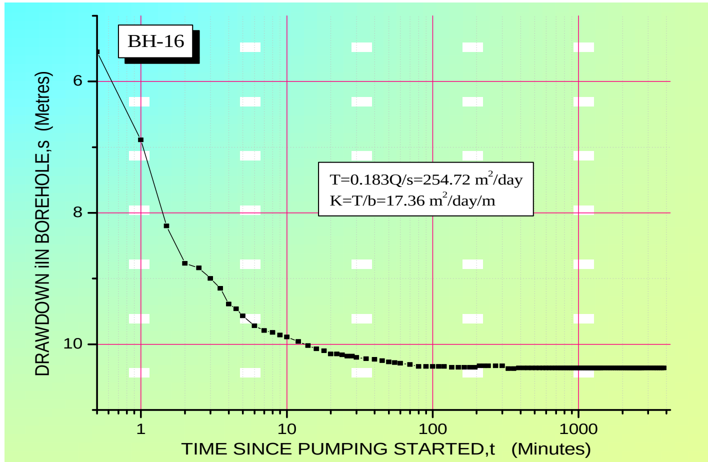
However, the aquifer hydraulic values were compared with those derived from traditional pumping test datasets. The aquifer parameters which include the transmissivity, hydraulic conductivity etc in Table 1 were obtained from the slopes (Δs) of the first legs of the time drawdown curves in (Figure 5).



(a)



(b)



(c)

Figure 5: Typical constant-discharge rate drawdown curves showing pumped wells under (a) Jacob's model response (b) recharge condition (c) casing storage/steepening effect

Table 1: Hydraulic parameters of aquifers of the production boreholes

Borehole	Borehole	Aquifer	Aquifer		Aquifer	Aquifer
Borehole Code Yield		Screen	T_c	T	K_c	K
(m³/day)	Length (m)	(m²/day)		(m²/day)	(m/day)	(m/day)
BH-12	20.02	1709.57	397.8	74.67	17.12	1065.31
BH-13	19.97	461.02	354.9	23.09	17.17	1086.05
BH-14	16.95	1077.99	893.33	63.60	25.70	1073.95
BH-15	14.16	1042.67	374.82	73.64	26.47	1044.58
BH-16	14.15	408.49	254.72	28.87	17.36	1141.34
BH-18	14.25	647.03	380.91	45.41	26.73	1144.8
BH-26	14.16	2134.41	552.08	150.73	38.99	1086.05
BH-29	14.16	2789.79	1046.04	197.02	73.87	1086.05
BH-30	14.16	101.52	375.59	70.73	26.52	1087.73
BH-41	19.88	2530.88	525.62	127.27	26.44	1062.72
BH-43	19.88	2320.47	958.01	116.72	48.19	1151.71
BH-45	14.27	2707.48	781.62	189.73	54.77	982.37
BH-57	16.98	188.88	113.24	11.12	6.67	1144.8
BH-58	14.8	2229.31	1436.56	157.21	101.31	1099.01
BH-59	14.13	7179.46	810.63	508.10	57.37	1151.71
BH-68	14.15	1371.27	585.94	96.91	41.41	1088.64
BH-79	14.08	365.77	142.62	25.98	10.13	779.33

Note: T_c = Transmissivity from Geoelectric Datasets, K_c = Hydraulic Conductivity from Geoelectric Datasets, T = Transmissivity from Pumping test datasets, K = Hydraulic Conductivity from Pumping test datasets

4. RESULTS AND DISCUSSION

Generally, four distinct subsurface geologic layers were identified from the geoelectric sequences aided by borehole lithological logs (Figures 6 a & b). These include the topsoil of variable moisture, the alluvium, the clay/sandy clay/clayey weathered column and the bedrock. The peculiarity of the succession here as against the three basic geoelectric succession commonly encountered in tropical and sub-tropical area underlain by basement complex rocks is the detection of a thick clayey Chad Formation column sandwiched between the alluvium (second layer) and the resistive fresh bedrock/basement (Mohammed, 2007; Mohammed and Olorunfemi, 2012)

The thickness of the alluvium generally varies from 1.6 to 32.2 m with the most frequently occurring thickness being in the 0 - 16 m range (Figures 6 and 7). The mean thickness is 10.6 ± 7.1 m with a coefficient of variation of 66.7%. The average thickness of 10.6 m recorded suggests a fairly thick column of alluvium. This is in good agreement with 10.0 m average earlier suggested by BSADP (1988). The groundwater level distribution shows an easterly groundwater flow direction (Figure 8). The electrical resistivity characteristics of this layer are controlled by its degree of water saturation (Odusanya and Amadi, 1990). Zones characterized by relatively thick, sandy and permeable alluvium have high groundwater transmission and storage capabilities and are priority sites for groundwater. The thickness pattern is generally non-uniform. The thickness of the clay/clayey weathered layer varies from 15.9-168.6 m with most frequent occurring thickness of between 20-80 m (Figures 6 and 7). The wide spectrum of thicknesses observed is due to the uneven topography of the basement bedrock.

The time drawdown curves obtained from traditional pumping test data for well performance under the different hydrogeological conditions show characteristic Jacob's Models' Response, recharge effects, aquifer or casing storage/steepening effects. Seasonal variations in the amount of available recharge and topographic elevation/depth of water table may have led to these effects. The field pumping transmissivity (T) values range between 113.2 and 1436.6 m^2/day with T_{mean} of 634.96 m^2/day. The field pumping hydraulic conductivity (K) values range from 6.67-101.31 m/day with the mean of 36.22 m/day. The geoelectric derived transmissivity (T_c) values range between 188.9 and 2789.8 m^2/day with the mean of the transmissivity $T_{c\ mean}$ of 1540.84 m^2/day;, while the hydraulic conductivity (K_c) values are between 11.12 and 189.73 m/day with a mean value of 115.34 m/day for the entire saturated thickness of the aquifer. The observation is in agreement with the range of known values of hydraulic conductivity of 2 - 295 gpd/$ft^{2,}$ (8.3 x 10^{-4} - 1.22 x 10^{-3} m/day) and transmissivity of between 12.4 and 12400 m^3/day for unconsolidated sediments as earlier observed by Driscol (1986). The transmissivity values (T_c) calculated from the geoelectric parameters/VES results are higher than the range of values obtained from the field pumping test data in few places by factor of 2 – 3 multiple. The calculated values are higher because the whole length of the saturation thickness was considered as alluvium or aquifer thickness 'b' used in the analysis. However, linear fit relationship between pumping test – based and geoelectric – based aquifer parameters (Figure 9) indicates a fairly good fit of datasets though with correlation coefficient 'R' of 0.53, standard deviation 'SD' of 310. This indicates a high degree of dispersion and therefore may be explained by the wide textural/compositional variation in the alluvium.

In conclusion, the resistivity response of the subsurface geologic units in the area may have depended on the sand to clay ratio and the degree of saturation. The alluvium unit with about 70 % quartz may have enhanced the resistivity values and perhaps hydraulic conductivity and transmissivity better than its immediate underlying clay Chad Formation/weathered unit. Where alluvial sand materials predominate, is characterized by good hydraulic properties as obtained from the two datasets. Higher values obtained from the geoelectric derived hydraulic parameters in few borehole sites in multiple of two or three suggested a limiting factor of the method. The limiting factor may have arisen from overestimation of the aquifer thickness used in the analysis of the derived hydraulic parameters.

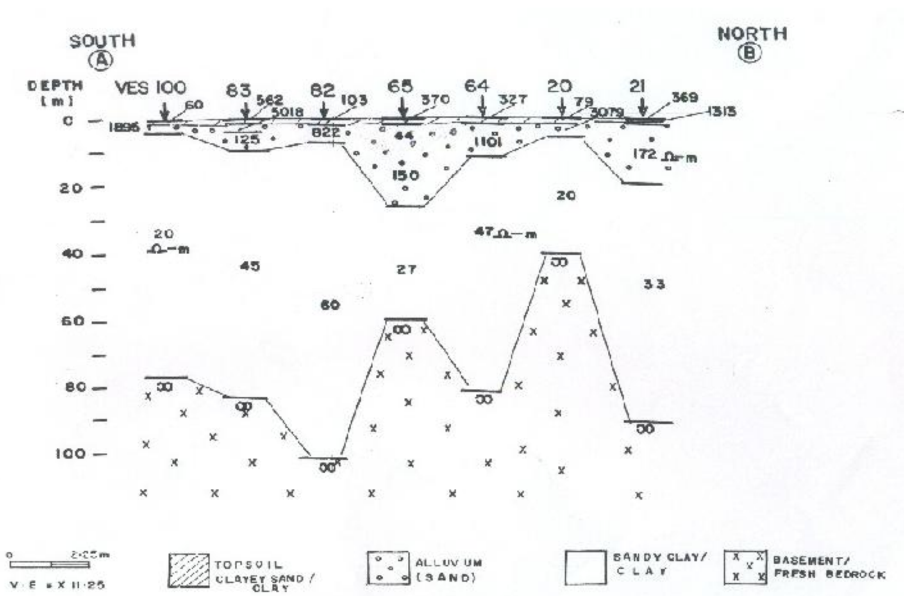


Figure 6 a: Geoelectric section across N-S traverse

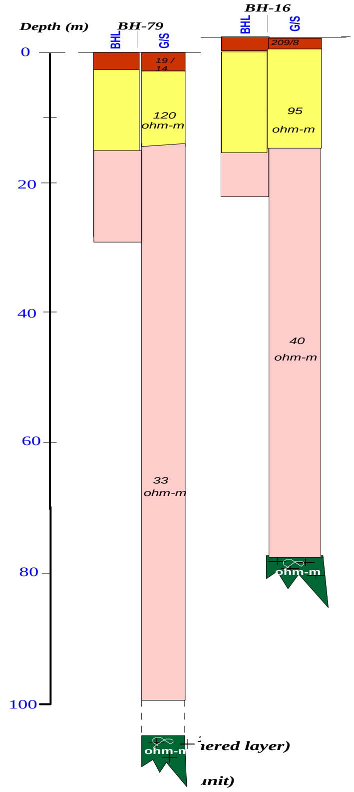


Figure 6 b: Geoelectric parameters and lithological logs of boreholes BH 16 and BH 79

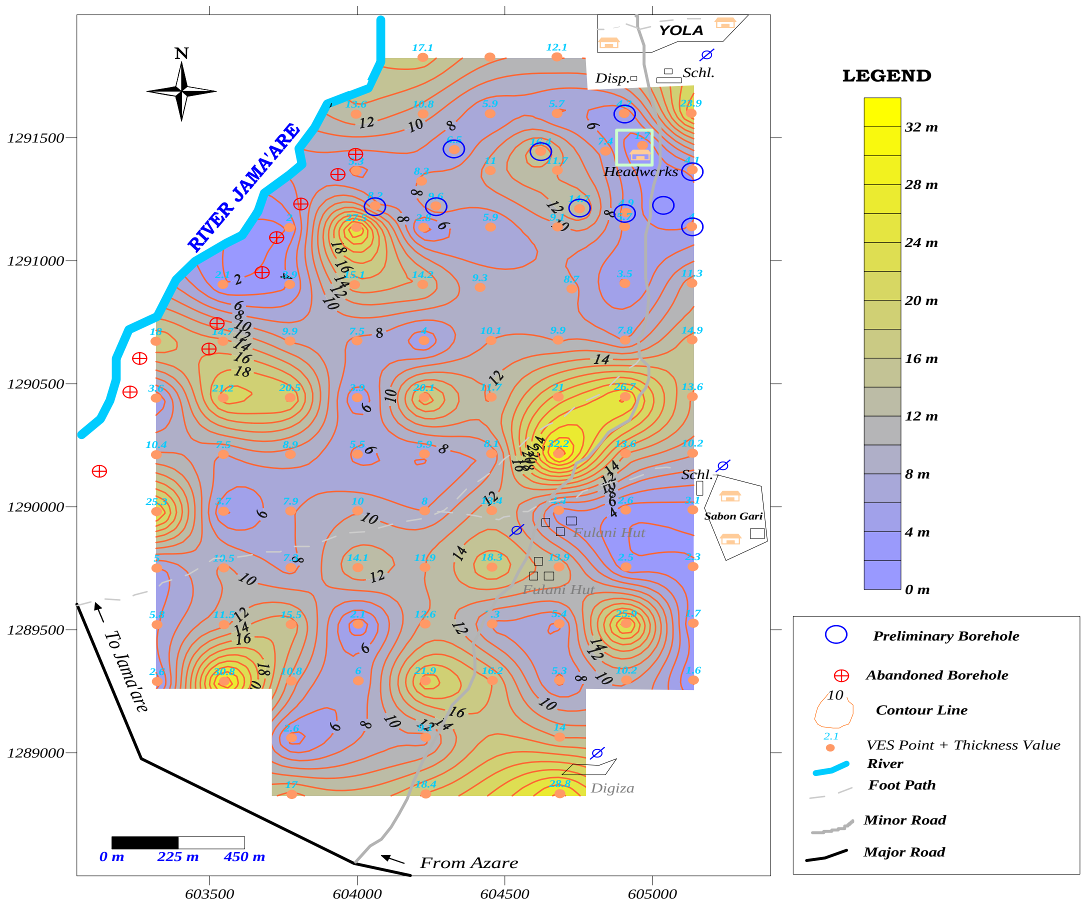


Figure 7: Map of alluvium layer thickness

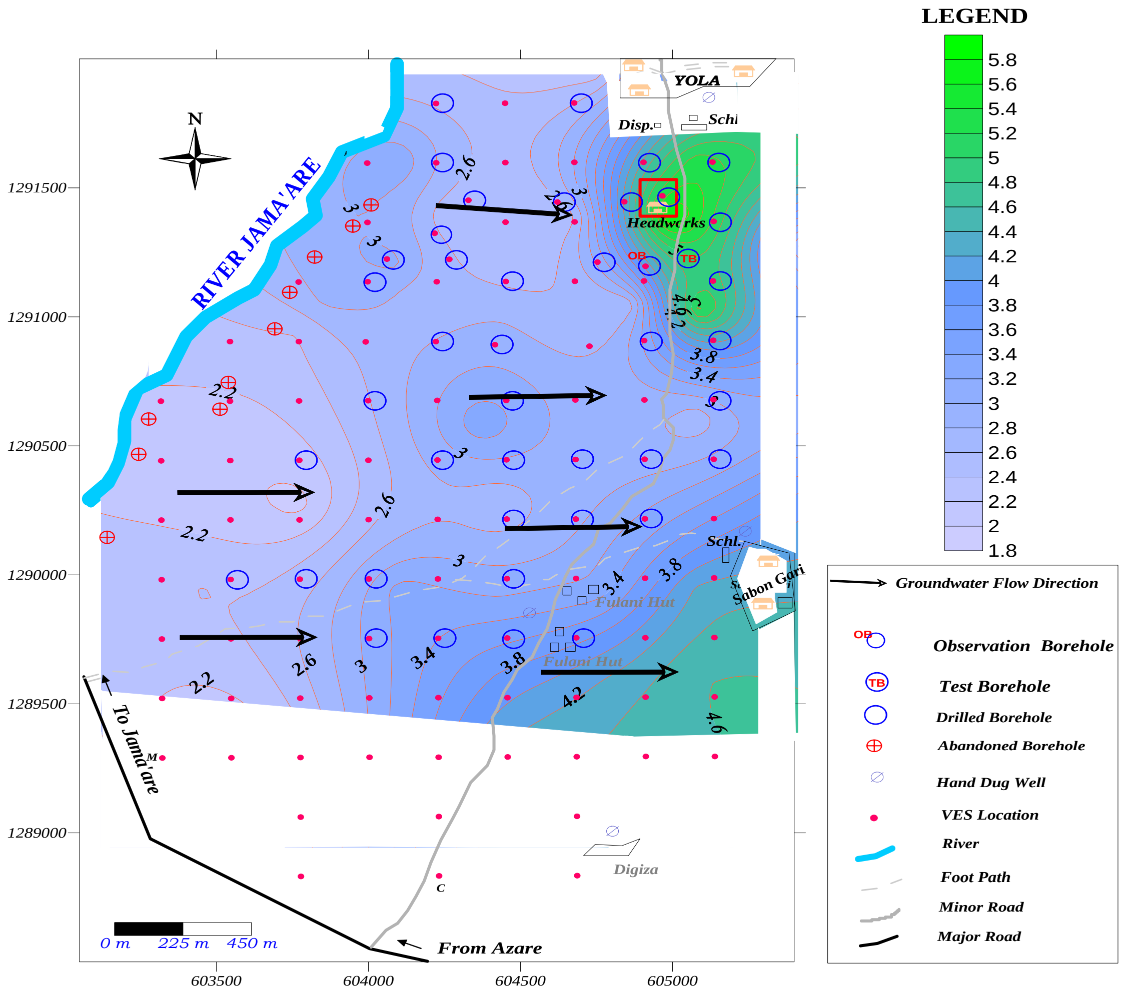


Figure 8: Map of the groundwater head showing the flow distribution patterns in the study area

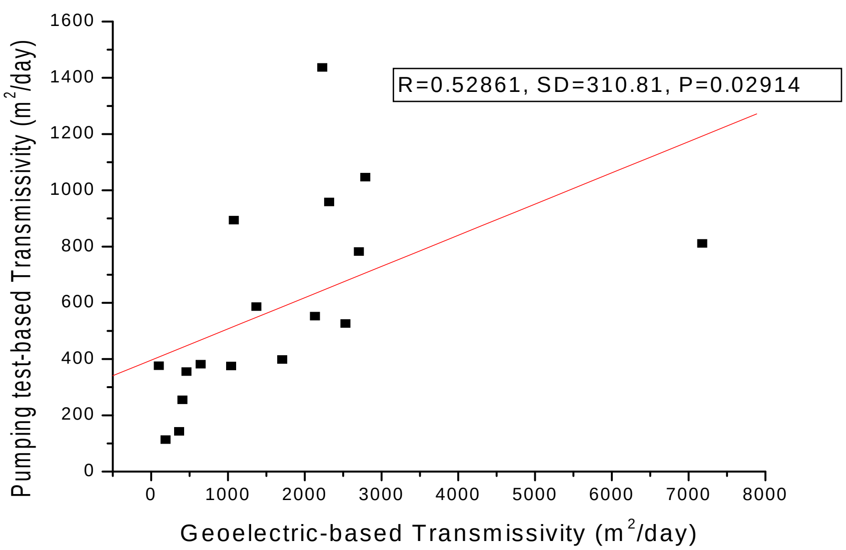


Figure 9: Linear fit relationship between the two datasets

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