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Hydraulic and Geoelectric relationships of Aquifers Using Vertical Electrical Sounding (VES) in parts of Obudu, Southern Nigeria

Thomas A. Harry[1], **Fidelis A. Ushie**[1] and **Okechukwu E. Agbasi**[2,*]

[1]Department of Geology, Akwa Ibom State University, Mkpat Enin, Nigeria

[2]Department of Physics, Michael Okpara University of Agriculture, Umudike, Nigeria

*E-mail address: ebukasean09@yahoo.com

ABSTRACT

Aquifer geoelectric (Formation factor and Porosity) and hydraulic parameters (Transmissivity and Hydraulic Conductivity) were estimated using VES in parts of Obudu, Southern Nigeria. Hydraulic parameters study would help in to reduce additional expenditures in carrying out pumping tests. Hydraulic parameters are used to estimate the groundwater supply potential, protective capacity rating, soil corrosivity and designation. Most of the estimated aquifers have poor protective capacity rating, low designation, smaller withdrawal for local water supply and slightly corrosive. The objectives of this study is to delineate relationship between geoelectric and hydraulic parameters in the study area, There is a strong correlation between hydraulic conductivity (K) with Porosity and Formation Factor respectively as 0.81 and 1.00, while a weak correlation exist between Transmissivity with Porosity and Formation Factor, respectively as 0.11 and 0.15. The regression equation of the hydraulic parameters and geoelectric parameters from the study area are; $T = -0.15\phi + 18.57$, $T = -0.10F + 3.90$, $K = 0.01\phi + 0.51$, $K = 0.01F + 0.69$, where K; Hydraulic Conductivity, T; Transmissivity, F; Formation Factor and ϕ; Porosity. The range of formation factor, porosity, transmissivity and hydraulic conductivity are 11.80 – 132.50, 8.69% - 29.11%, 1.32 – 19.64 and 0.52 – 0.67 respectively.

***Keywords*:** Hydraulic Conductivity, Transmissivity, Formation Factor, Porosity, Obudu

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1. INTRODUCTION

Water is generally accepted as the principal element of life. Ground water prospecting is part of geological problem and the geophysical approach is determined on the mode of the geological occurrence of water. Electrical resistivity methods have been extensively used for groundwater investigation by many workers (Yadav and Abelfazli, 1998) and is considered to be the most suitable method for groundwater investigation in most geological Terrains (Bhattacharya and Patra, 1968) due to its simplicity and low cost.

Research in groundwater geophysics reveals that a correlation exists between the hydraulic parameters and geoelectric properties of an aquifer and this can be used as a possible solution for this wildcat drilling, contamination, pump testing cost etc. (Laouini G. et al 2017; Urish 1981; Yadav and Abolfazli 1998). Application of surface resistivity survey and combining the results with those of pumping tests at the same site provide a helpful approach to extract and establish empirical relationships. This also creates a hydro geophysical model to show the fundamental factors which may govern the hydraulic behavior of any aquifer (Vereecken, et. al., 2006).

A large number of empirical and semi-empirical equations correlating geoelectrical results and hydraulic parameters of aquifers, under different geological conditions, have been proposed in the literature (Kelly 1977; Kosinski and Kelly 1981; Yadav and Abolfazli 1998). Both direct and inverse relations between aquifer resistivity and hydraulic conductivity are reported (Worthington 1993; Kelly 1977; Urish 1981; Mazac et al. 1985). Relationships between aquifer characteristics and electrical parameters of the geoelectrical layers have been studied and reviewed by many authors (Kelly, 1977; Niwas and Singhal, 1981; Onuoha and Mbazi, 1988; Mazac et al., 1985; Mbonu et al., 1991; Agbasi and Etuk 2016; Laouini et al., 2017; Huntley, 1986). Some researchers assume that both geology and ground water quality remain fairly constant within the area of interest and the relationships between aquifer and geophysical parameters deduced, are based on this assumption (Niwas and Singhal, 1981; Mbonu et al., 1991). Mazac et al. (1985) analyzed the correlation between aquifer and geoelectrical parameters in both the saturated and unsaturated zones of the aquifers. The analytical relationship between aquifer transmissivity and transverse resistance has also been developed by Niwas and Singhal (1981). Singhal and Niwas (1983) proposed a modification in the relationship (between transverse resistance and aquifer transmissivity) by multiplying the aquifer water resistivity by the ratio of actual average aquifer resistivity and aquifer water resistivity at a particular location. Sinha, Israil and Singhal et al., (2009) proposed hydro-geophysical model of the relationship between geoelectric and hydraulic parameters of an anisotropic aquifer.

A geological section consists of a sequence of layered rocks, with quite different textures making specific geologic boundaries. While the geoelectrical section constitutes of several zones of different resistivities and thicknesses with certain boundaries, which do not always coincide with those boundaries of the geological section. So the uniform electric layers can be combined into a single unit of geoelectrical section (Zohdy, 1974). For example, when salinity of groundwater in a given rock type varies with depth, so several geoelectrical layers may be distinguished within the same lithological rocks. In the opposite situation, layers of different lithologies or ages or both may have the same resistivity and thus form a single geoelectrical zone. Average geoelectrical properties of each unit in a layered section may be described with five parameters called Dar-Zarruok

Parameters (Maillet, 1947). They were created on the bases of resistivity and thickness of the geoelectrical unit.

2. STUDY AREA

The study area is part of Obudu Palteau in Cross Rivers State of Nigeria. It lies within the reactivated Precambian Basement of Nigeria, which forms a portion of the Pan-African Tectonothermal belt located between the West Africa Craton to the west and the Gabon-Congo Craton to the east. It is bounded by longitudes 9°15'E to 10°00'E and latitude 6°30'N to 6°45'N covering an area of about 75 km^2. The Obudu Plateau represents a terminal portion of the western Bamenda Massif of the Cameroons that wedges into eastern Nigeria (Umeji 1988, Ushie and Anike 2011).

Generally the geology of Obudu Plateau can be classified into four units

(a) Migmattie – gensis complex
(b) Schists
(c) Granitic, charnockitic and peridotitic intrusives
(d) Unmetamorphosed dolerite dykes and dioritic intrusive

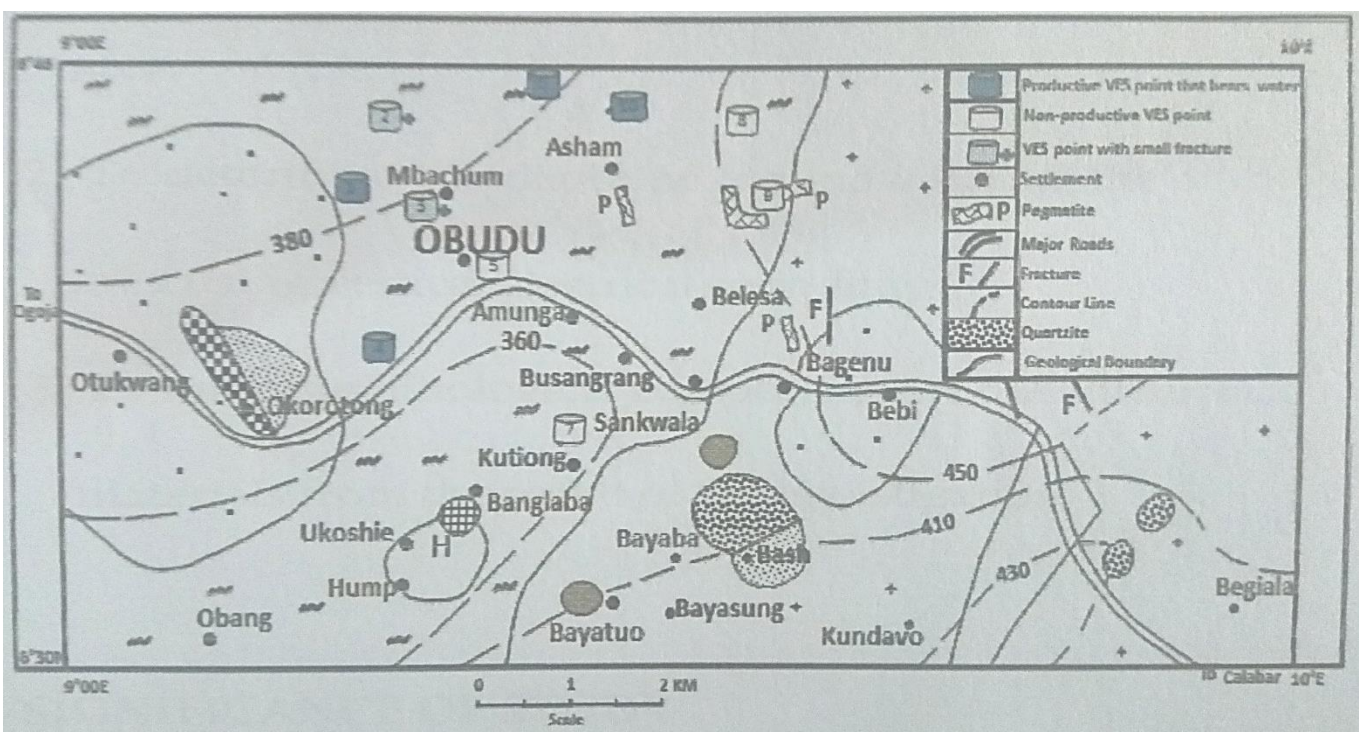


Figure 1. Map of the study area

The general elevation of the Obudu plateau is between 1,100 m to 1,750 m at the Cattle Ranch area while around other areas it grades down to about 226 m above sea level. Rock exposures exist from the high to low land. The highlands are generally made up of rocks of different types and therefore, it is not inhabited by any person. Much of the population of the area dwels on the lowland where different human activities can be carried out.

Different drainage patterns exist but the type peculiar to this area is dendritic drainage pattern. The river are controlled by seasonal changes in weather. During dry season, the rivers reduces in volume and little amount of water is taken to the sea. The river in this area flow into Cross River far South-East, via a single channel.

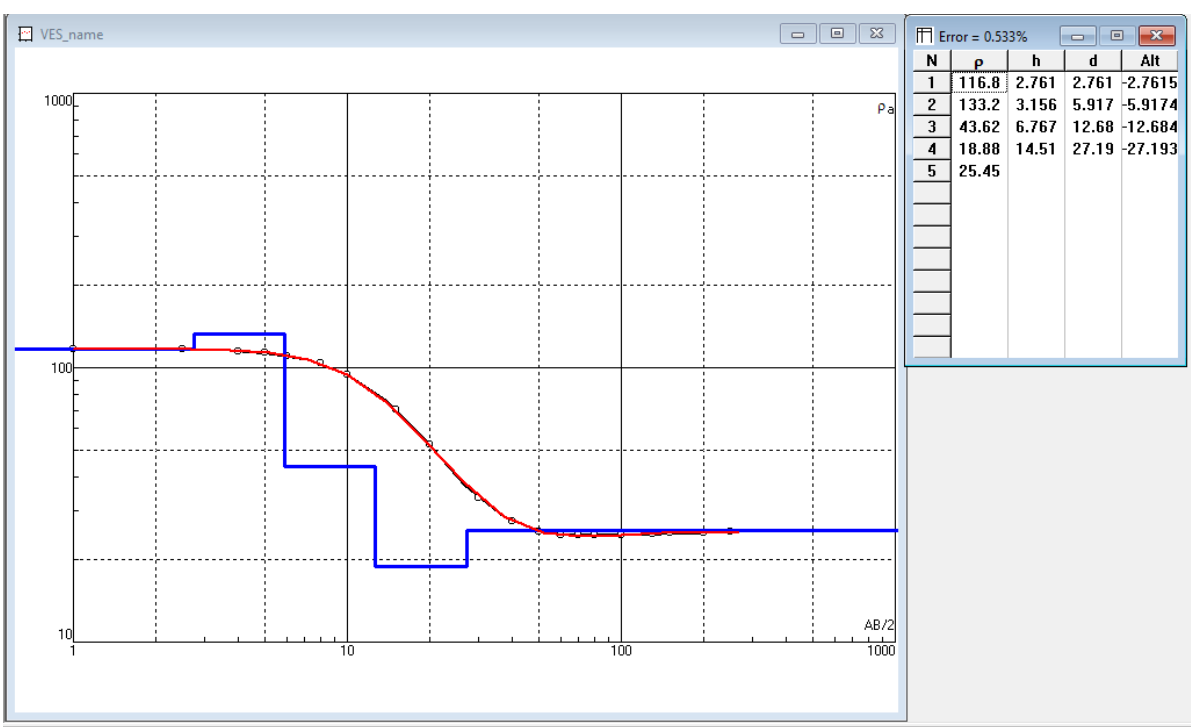
The Obudu plateau falls within the tropical environment. The pattern of the climate is reflected more in the rainfall pattern. In general the rainy season starts around March to October, during which the area experiences high precipitation (Orographic rainfall). The high precipitation and relatively high humidity promotes perennial vegetation growth and the area falls within the Savanna vegetation belt (Iloeje, 1977).

3. DATA ACQUISITION AND ANALYSIS

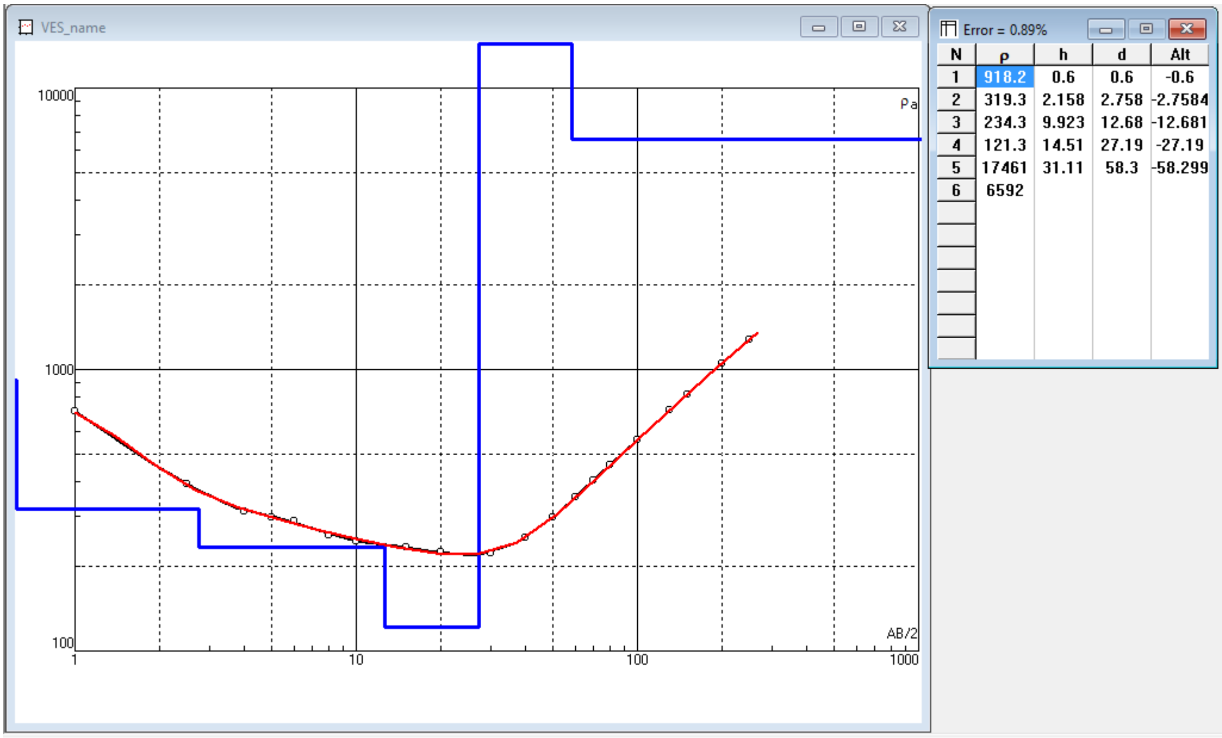
The study includes applying the Vertical Electric Sounding by using the symmetrical Schlumberger configuration in the area which located in Obudu, Cross Rivers State, Nigeria.

The apparent resistivity measured in nine (9) VES points in order to obtain a possible coverage of the studied area (Figure 1). The spreading of current electrodes (AB/2) reached a distance up to (250 m), and a distance of (100 m) was reached for the spreading of voltage electrodes (MN/2); thus, a depth penetration of (125 m) was obtained.

Field curves of VES points were interpreted quantitatively manually and automatically by Auxiliary point method and the computer software IPI2win (Figure 2) to find out the values of quantitative resistivity and thickness of the electrical zones.



(A)



(B)

Figure 2(A,B). VES Quantitative Interpretation from IPI2win

The amount of water that recharges an unconfined aquifer is determined by three factors:(1) the amount of precipitation that is not lost by evapotranspiration and runoff and is thus available for recharge; (2) the vertical hydraulic conductivity of surficial deposits and other strata in the recharge area of the aquifer, which determines the volume of recharged water capable of moving downward to the aquifer; and (3) the transmissivity of the aquifer and potentiometric gradient, which determine how much water can move away from the recharge area. Should an aquifer be transmitting the maximum volume of water, it is likely that some potential recharge is being rejected in the recharge area. This is often the case in humid areas. Should the water table below, indicating that the aquifer is not flowing at full capacity, there is probably either a lack of potential recharge or low vertical hydraulic conductivity in the recharge area, retarding downward movement. Aquifers in arid regions typically have deep water tables in the recharge areas, indicating a deficiency in the amount of potential recharge (Fetter Jr. 2014).

The relationship between the hydraulic conductivity (K) and geoelectrical resistivity (ρ) of an aquifer is strongly controlled by the nature of the aquifer substratum (Niwas and Singhal, 1985; Niwas K and de Lima, 2003). For a highly resistive substratum, both the current and the hydraulic flows are dominantly horizontal in a typical unit column of the aquifer, and the relationship between *K* and ρ, is inverse. If the substratum is highly conductive, the hydraulic flow will still be horizontal while the current flow in a characteristic unit column is dominantly vertical; thus, a direct relation exists between *K* and ρ.

If the aquifer material is cut in the form of a vertical prism of the unit cross-section from top to bottom, fluid flow and current flow in the aquifer material obeys Darcy's law and Ohm's law respectively. Thus, for current and fluid flows in a lateral direction, the Transmissivity of the aquifer is given as:

$$T = K\rho S \tag{1}$$

where: ρ is the bulk resistivity and

$$S = \frac{h}{\rho} \tag{2}$$

where: S is the longitudinal unit conductance of the aquifer material with thickness *h*.

Therefore

$$T = Kh \tag{3}$$

For a lateral hydraulic flow and current flowing transversely, the transmissivity of the aquifer becomes:

$$T = \left(\frac{K}{\rho}\right)R \tag{4}$$

where: ρ is the bulk resistivity and

$$R = h\rho \tag{5}$$

where: R is the transverse unit resistance of the aquifer material

Therefore

$$T = Kh \tag{6}$$

For hydraulic conductivity K, we have

$$K = 8\times10^{-6}e^{-0.0013\rho} \tag{7}$$

Then

$$T = \left(8\times10^{-6}e^{-0.0013\rho}\right)h \tag{8}$$

If the aquifer is saturated with water with uniform resistivity, then the product $K\rho$ or K/ρ would remain constant. Thus, the transmissivity of an aquifer is proportional to the longitudinal conductance for a highly resistive basement where electrical current tends to flow horizontally, and proportional to the transverse resistance for a highly conductive basement where electrical current tends to flow vertically (Sir Niwas et al., 2011). The above equations may therefore be written as:

$$\rho^2 = \frac{S}{R} \quad 9$$

From these relations, the model resistivity values obtained from the inversion process were used to estimate the longitudinal unit conductance and transverse unit resistance of the aquifer unit.

Since the electrical resistivity of most minerals is high (exception of saturated clay, metal ores, and graphite), the electrical current flows mainly through the pore water. According to Archie law (Archie 1942), the resistivity of water saturated clay-free material can be described as

$$F = \frac{\rho_0}{\rho_w} \quad 10$$

where: ρ_0 = specific resistivity of water saturated sand, ρ_w = specific resistivity of pore water, F = intrinsic formation factor.

The formation factor (F) combines all properties of the material influencing electrical current flow like porosity u, pore shape, and diagenetic cementation.

$$F = \frac{a}{\phi^m} \quad 11$$

$$\phi = \left(\frac{a}{F}\right)^{1/m} \quad 12$$

Different definitions for the material constant (m) are used like porosity exponent, shape factor, and cementation degree. Factors influencing (m) are, e.g., the geometry of pores, the compaction, the mineral composition, and the insolating properties of cementation. The constant (a) is associated with the medium and its value in many cases departs from the commonly assumed value of one. The quantities (a) and (m) have been reported to vary widely for different formations.

4. RESULTS AND DISCUSSION

Hydraulic and geoelectric parameters which include the following; Porosity (ϕ), Formation Factor (F), Transmissivity (T), Hydraulic Conductivity (K), Transverse Resistance (R) and Longitudinal Conductance (S), have been calculated for the aquifers identified in the study area using the Aquifer Thickness (h), Bulk Resistivity (ρ_0) and Apparent Resistivity (ρ_w), using equations 1 – 12, this are show in Table 1.

Table 1. Geoelectric and Hydraulic Parameters in the Study area.

VES	Hydraulic Conductivity K(m/day)	Transmissivity T(m2/day)	Transverse Resistance (R)	Longitudinal Conductance (S)	Formation Factor	Porosity (%)
VES 1	0.67	9.79	273.95	0.77	11.80	29.11
VES 2	0.55	17.11	5475.36	0.18	110.00	9.53
VES 3	0.52	3.57	1441.60	0.03	132.50	8.69
VES 4	0.61	19.64	3181.55	0.33	61.56	12.75
VES 5	0.67	1.32	49.25	0.08	15.63	25.30
VES 6	0.55	35.37	11008.00	0.37	107.50	9.64
VES 7	0.63	5.19	611.98	0.11	46.25	14.70
VES 8	0.60	3.79	681.48	0.06	67.50	12.17
VES 9	0.61	2.99	476.27	0.05	60.63	12.84

Table 2. Protective Capacity Rating, Designation, Groundwater Supply Potential and Soil Corrosivity for the Nine (9) VES station in the study area.

VES	Protective Capacity Rating	Designation	Groundwater Supply Potential	Soil Corrosivity
VES 1	Very good	Low	Smaller Withdrawal for local water supply	Moderately Corrosive
VES 2	Weak	Intermediate	Withdrawal of local water supply	Slightly Corrosive
VES 3	Poor	Low	Smaller Withdrawal for local water supply	Practically Noncorrosive
VES 4	Moderate	Intermediate	Withdrawal of local water supply	Slightly Corrosive
VES 5	Poor	Low	Smaller Withdrawal for local water supply	Moderately Corrosive
VES 6	Moderate	Intermediate	Withdrawal of local water supply	Slightly Corrosive
VES 7	Weak	Low	Smaller Withdrawal for local water supply	Slightly Corrosive
VES 8	Poor	Low	Smaller Withdrawal for local water supply	Slightly Corrosive
VES 9	Poor	Low	Smaller Withdrawal for local water supply	Slightly Corrosive

Geoelectric parameters estimated value are; apparent resistivity 18.88-212 Ω, Formation factor 11.80-132.50, Porosity 8.69-29.11%, while for hydraulic parameters estimated value are; longitudinal conductance 0.05-0.77 Ω^{-1}, Transverse resistance 49.25-11008.00 Ωm^2, hydraulic conductivity 0.52-0.67 m/day^2 and Transmissivity 1.32-19.64 m^2/day. Most of the possible aquifers identified in the study area have weak/poor protective capacity rating, low designation and smaller withdrawal for local groundwater supply potential and a slightly corrosive soil.

Figure 3 – 6, shows the relationship between Geoelectric parameters (Formation Factor and Porosity) with hydraulic parameters (Transmissivity and Hydraulic Conductivity). There is a strong correlation between hydraulic conductivity (K) with Porosity and Formation Factor respectively as 0.81 and 1.00, while a weak correlation exist between Transmissivity with Porosity and Formation Factor, respectively as 0.11 and 0.15. The regression equation of the hydraulic parameters and geoelectric parameters from the study area are given below;

$$T = -0.15\phi + 18.57 \quad (13)$$

$$T = -0.10F + 3.90 \quad (14)$$

$$K = 0.01\phi + 0.51 \quad (15)$$

$$K = 0.01F + 0.69 \quad (16)$$

where: K; Hydraulic Conductivity, T; Transmissivity, F; Formation Factor and ϕ; Porosity

Equations 13 – 16, can be used to estimate the protective capacity rating, groundwater supply potential, designation and soil corrosivity for the area that the survey did not cover.

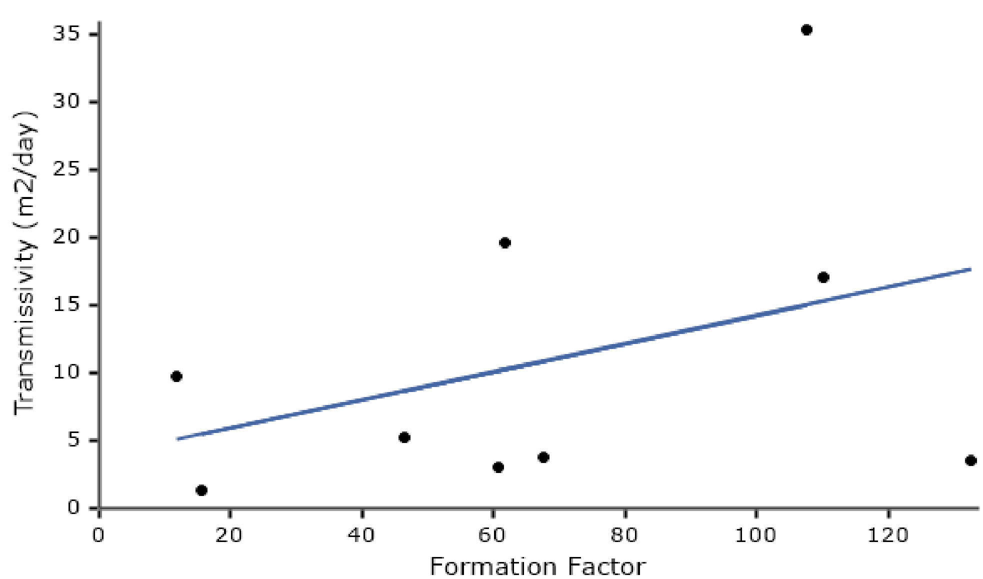


Figure 3. Linear relationship between Transmissivity and Formation Factor

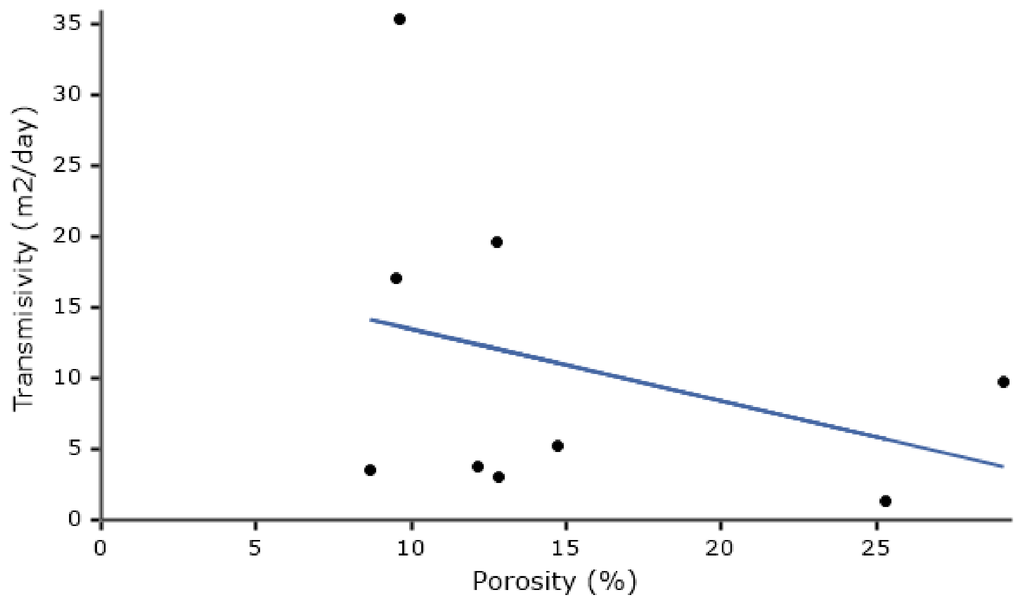


Figure 4. Linear relationship between Transmissivity and Porosity

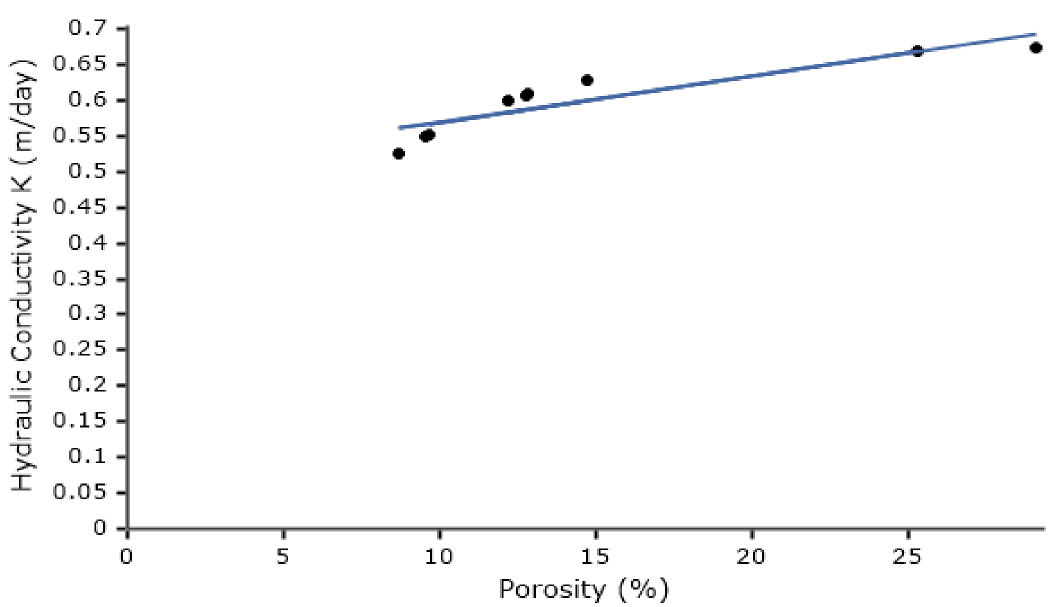


Figure 5. Linear relationship between Hydraulic Conductivity and Porosity

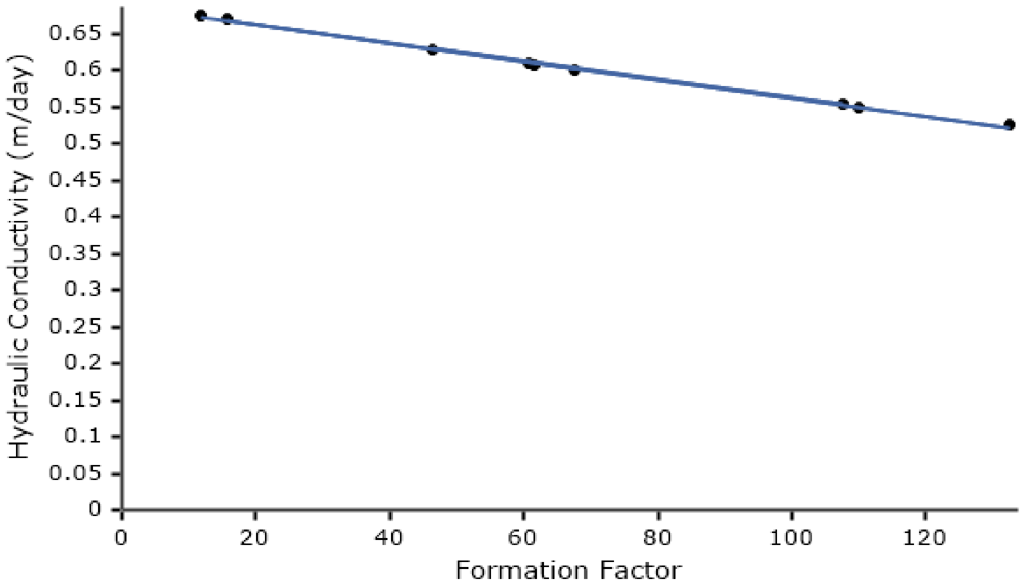


Figure 6. Linear relationship between Hydraulic Conductivity and Formation Factor

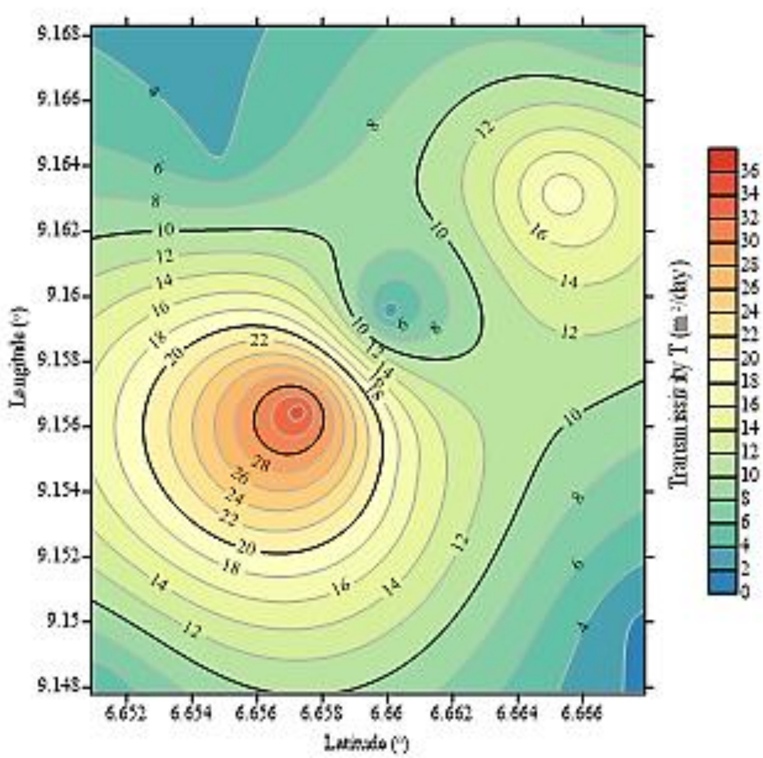


Fig. 7A

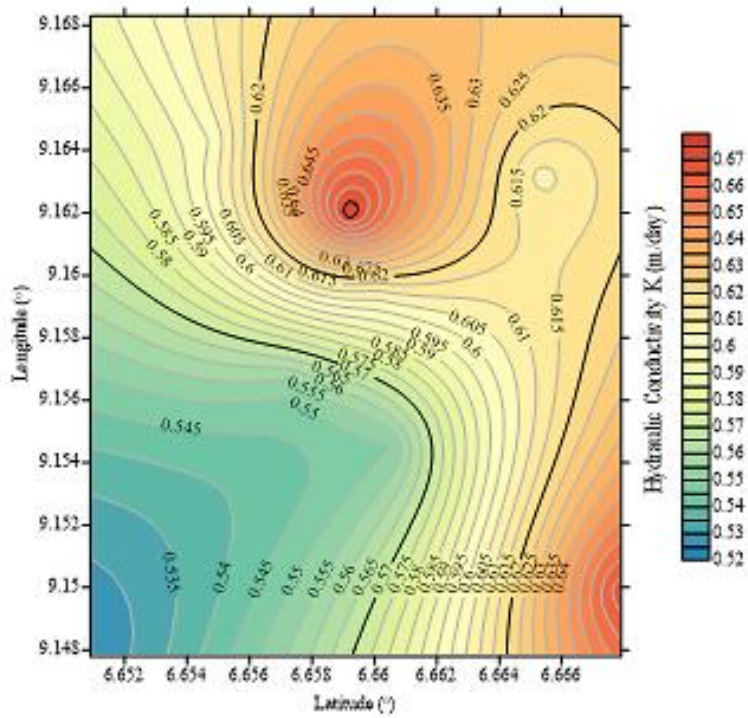


Fig. 7B

Figure 7(A,B). 2D contour map for hydraulic parameters (Transmissivity and Hydraulic Conductivity) of the study area

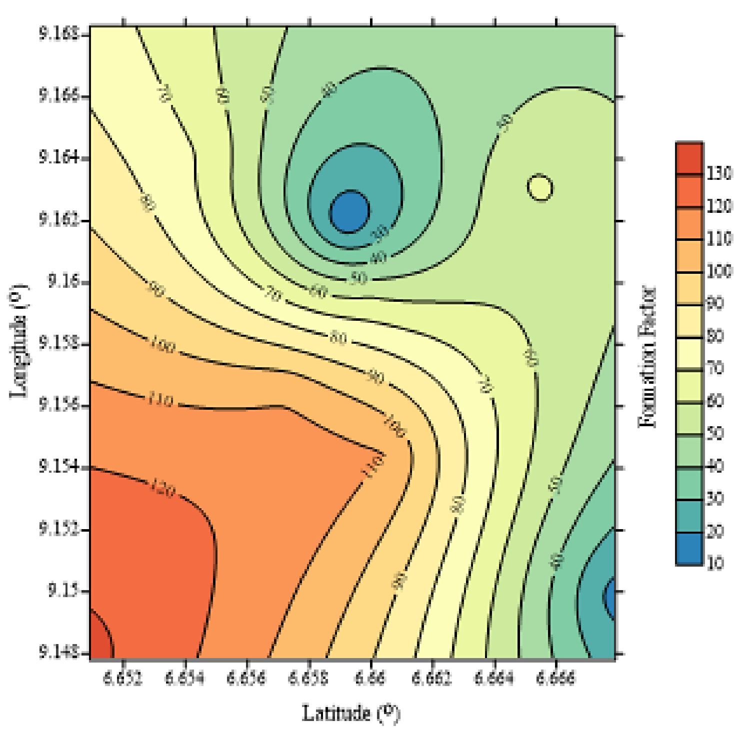


Fig. 8A

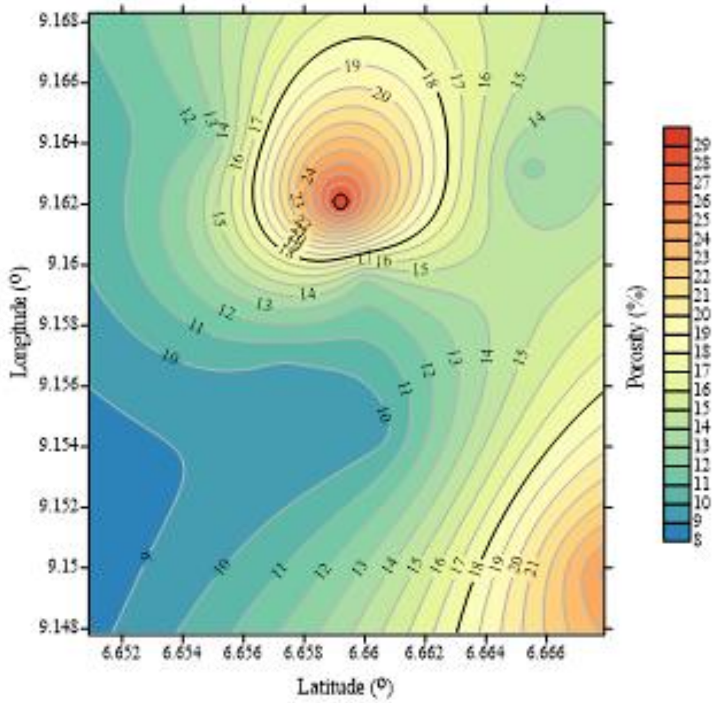


Fig. 8A

Figure 8(A,B). 2D contour map for geoelectic parameters (Formation Factor and Porosity) of the study area

Figure 7 and 8 shows the 2D contour maps of the study area for Porosity, Formation Factor, Transmissivity and Hydraulic Conductivity. The highest Porosity and Hydraulic Conductivty are found at the Northern part of the study area an it decreases towards the south western part of the study area, while for the 2D contour map for formation factor and transmissivity increases from the Northern part of the study area, with the highest values around the south western parts of the study area.

5. CONCLUSION

The study successfully revealed the subsurface lithology of the study area. Subsurface resistivity, thickness and depth values were obtained from the computer modelling. The varying electrical properties shows the following curve types: QKH, KH Q AND H. Vertical Electrical Sounding survey was carried out in the study area to delineate aquifer's geoelectric and hydraulic parameters, including a correlation between some of the geoelectric and hydraulic parameters of the aquifer, the result shows a weak to strong correlation between the parameters. Aquifers in the study area are slightly corrosive, low designation and have a poor protective capacity. The formation factor of the aquifers in the study area range from 11.80 to 132.50, the aquifers are found to be very porous, porosity range from 8.69% to 29.11%. Hydraulic parameters help reduce the additional expenditures of carrying out pumping tests and offers an alternative approach for estimating the hydraulic parameters, as it would give pre-drilling estimation of the yield of a prospective borehole in the area, which we have identified that the groundwater supply potential is between withdrawal of lesser regional importance and withdrawal of local water supply.

This study emphasizes the applicability of geophysical methods in the determination and distribution of aquifer repositories, it helps provides a database for water sourcing, assessment and management.

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