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Geophysical assessment of potential hydrological units in hydrologically challenged geomaterials of Makurdi, Benue State, Nigeria

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A geo-electric survey employing the Vertical Electrical Sounding (VES) was carried out in order to access the distributions of electrical and hydraulic parameters of hydro-geologic units in some locations of Makurdi where groundwater resources are difficult to tap. A total of fifteen geo-electric soundings were acquired. The contour maps were generated using the results. From the bulk aquifer resistivity and water resistivity values, the formation factor was calculated and it ranges from 4.12 to 10.07. The porosity with a range of 24.58 to 39.36% and hydraulic conductivity with a range of 0.85 to 45.1 m/day were estimated. The porosity values confirm that hydro-geologic units in the study area consist mainly of sandstone. The high resistivity in the northern part of the study area is due to high water quality while the southern part has lower resistivity due to the presence of argillaceous materials. It is also observed that the areas with low resistivity have high porosity. The observed low resistivity zone with high porosity is believed to have poor interconnected pores, the condition for high total or absolute porosity in argillaceous materials. The analyses of the geophysical data constrained by geological and borehole information revealed that potable water can be extracted within the depth of 35 to 50 m in the study area.

Key words: Porosity, formation factor, hydraulic conductivity, aquifer resistivity, Makurdi, geo-electric survey.

INTRODUCTION

The increase in population and urbanization has led to an increase in the demand for groundwater by the populace in Makurdi. A greater percentage of the population depends on groundwater as the main supply of potable water. The study area located in the Benue trough has many challenges as regards to groundwater potential evaluation. The study area is located within the coastal sedimentary lowlands of the middle Benue trough. Markurdi Sandstone occurs where Sandstones dominate and Sandstones are usually believed to be the best aquifers in terms of groundwater yield. The discontinuous nature of the water bearing system makes detailed knowledge of the subsurface geology, its weathering depth and structural disposition through geologic and

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geophysical investigations difficult. According to Edet and Okereke (1997) and Olorunfemi and Fasuyi (1993), weathering is an important factor that determines the presence of porosity and permeability.

Some researchers have used different techniques to estimate the spatial distribution of aquifer parameters such as hydraulic conductivity, transmissivity and aquifer depth (Allen et al., 1997). The hydraulic characteristics of subsurface geo-materials are important properties for groundwater assessments and also for safe construction of civil engineering structures (Pantelis et al., 2007). Groundwater recharge is dependent on rainfall and high porosity and connectivity of pore space of the water bearing units and as such the amount of groundwater in a formation is a function of porosity. The number of pores and crevices in a soil and rock and how well they are connected determines how easily groundwater moves through the ground and how much groundwater comes from a particular layer. Because groundwater has to move between pores and crevices in soil and rock, it moves much more slowly than surface water. The aquifer's electrical resistivity is mainly influenced by porosity and fluid resistivity in pores and the geo-electrical data recorded on the subsurface contains useful information about the aquifer which can be interpreted by experienced geophysicists for hydro-geological studies (Niwas and Celik, 2012).

The problem of estimating rock fluid and hydraulic properties becomes more important as hydrologists are asked to solve problems related to groundwater flow in rock materials about which little is known (Jorgensen, 1989). Hydraulic and electric conductivities are dependent on each other since the mechanisms of fluid flow and electric current conduction through porous media are governed by the same physical parameters and lithological attributes (Salem, 1999). The poor knowledge of the geometry and nature of the aquifers have posed problem to groundwater exploitation as many boreholes have been drilled without any knowledge of the hydro-geophysical characteristics and distribution of aquifers in the Makurdi Formation.

Transmissivities, formation factors and hydraulic conductivity can be estimated in a porous media using empirical/semi-empirical correlation, often using simple linear relations (Kelly, 1977; Heigold et al., 1979; Schimschal, 1981; Urish, 1981; Chen et al., 2001). The physical condition controlling the electric current flow also controls the flow of water in a porous media. Groundwater flow in fractured aquifers is very complicated and accuracy in estimation of the hydraulic parameters depends on the hydraulic behavior in a particular fracture, which is site specific (Singh, 2005). The choice of Vertical Electrical Sounding (VES) for the study is based on the fact that the electrical resistivity of most rocks depends on the amount of water in their pores and the distribution of these pores and the salinity of the water in them (Todd, 2004). The variation of conductivity within the earth's subsurface layers affects the distribution of electric potential. The degree of this effect depends on the size, shape, location and bulk electrical resistivity of the subsurface layers. The bulk electrical resistivity depends on the mineralogy of the rock containing the fluids (Lowrie, 1997). This study is aimed at using the geo-electric attributes to define the aquifer geometry and to assess the variation of electric and hydraulic parameters in the study area in order to map out the area with high aquifer potential in the study area.

GEOLOGY AND HYDROGEOLOGY

The study area (Makurdi) is located along the Benue River bank. It lies between latitudes 7°40'N and 7°50'N of the Equator and between longitude 8°20'E and 8°40'E of the Greenwich Meridian, covering a total area of about 670 km². The town is drained by River Benue and its tributaries. The south bank has three flood plains namely: Wurukum, Wadata, and Idye. These areas are flooded in the rainy season and are highly populated. The Makurdi Formation comprises the Lower Makurdi Sandstone, the Upper Makurdi Sandstone and the Wadata limestone. Makurdi lies within the Guinea savannah vegetation zone with a few patches of forests. The annual rainfall ranges between 1,500 to 2,000 mm with its peak rainfall in the months of July and September. Temperatures in March and April are about 38 and 48°C respectively, while in December/January, the temperature is about 27°C (Benue State Water Supply and Sanitation Agency, 2008). The area is accessible through Nassarawa, Taraba, Obudu, Enugu, and Ankpa road. Also, a good road network exists within Makurdi metropolis and a railway line running through the town from Enugu to Jos and Kaduna. The area can also be accessible through the Benue River which flows through from the Cameroon Mountain to the Niger-Benue confluence at Lokoja. Makurdi, belongs to the Makurdi Formation which overlies the Albian Shale. It consists of thick current bedded coarse grained deposits. The Makurdi Sandstone has a thickness of about 900 m (Offodile, 1976). The southern part of the Benue valley is generally gently undulating and punctuated by a few low hills. But toward the northeast, the relief is exaggerated by hills like the Lammuder and Ligri hills, which rise up to 600m above sea level. Figure 1 shows the geological map of Benue State.

Geologically, the Benue valley consists of a linear stretch of Sedimentary Basin running from about the present confluence of the Niger and the Benue rivers to the north east, and is bounded roughly by the Basement Complex areas in the north and south of the River (Figure 1).

MATERIALS AND METHODS

A direct current resistivity survey using the VES method was carried out in the study area. The VES is based on measuring the

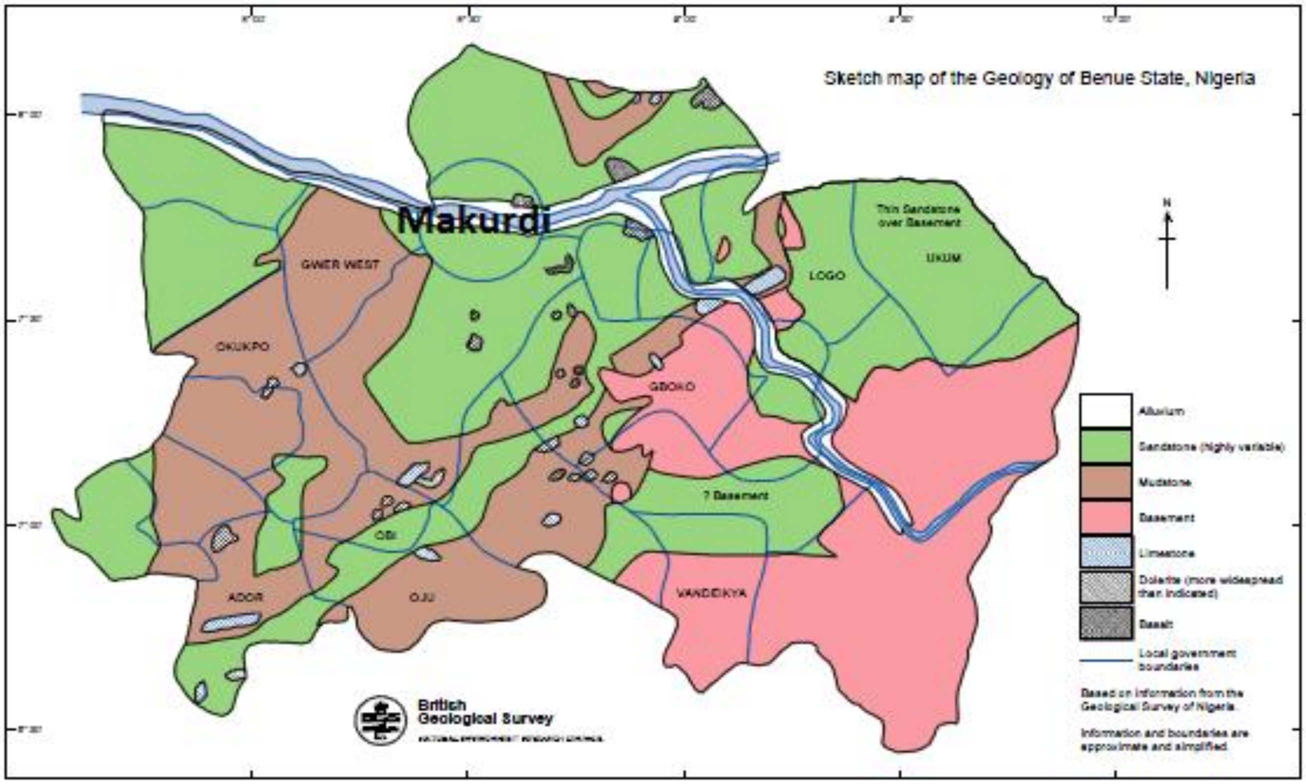

Figure 1. Geological Map of Benue State (British Geological survey 2001).

potentials between one electrode pair while transmitting direct current between another electrode pair. The Schlumberger array was chosen due to its better lateral resolution. The Schlumberger soundings were carried out with maximum half-current electrode spacing $\left(\frac{AB}{2}\right)$ of 100 m and potential electrode $\left(\frac{MN}{2}\right)$ of 15.0 m. The PZ-02 resistivity meter was used to acquire the resistivity data by moving two or four of the electrodes used between each measurement. The survey was completed with 15 soundings. The apparent resistivity (ρ_a) was calculated using:

$$\rho_a = \pi.\left[\frac{\left(\frac{AB}{2}\right)^2 - \left(\frac{MN}{2}\right)^2}{MN}\right].R_a \quad (1)$$

Where AB is the distance between the two current electrodes, MN is the distance between the potential electrodes, and R_a is the apparent electrical resistance measured from the equipment. The equation can be simplified to:

$$\rho_a = K.R_a \quad (2)$$

Where K is the geometric factor : $\pi.\left[\frac{\left(\frac{AB}{2}\right)^2 - \left(\frac{MN}{2}\right)^2}{MN}\right]$

Using the conventional partial curve matching technique with two-layer master curves in conjunction with auxiliary point diagrams (Orellana and Mooney, 1966), the initial estimates of VES data was achieved. From this, estimates of layer resistivities and thicknesses were obtained which served as starting points for computer-assisted interpretation. The conventional curves and auxiliary point diagrams (theoretical curves) used in the interpretation helped in obtaining a good fit between the observed field curves and the theoretical curves during total and partial matching. The computer software program, WINRESIST version 1.0 (one of the geophysical software used to process electrical resistivity data) was used and the data sets obtained from the manual interpretation stage were keyed as inputs into the computer modeling software (WINRESIST) to generate data for the estimated model. Examples of typical modeled VES curves constrained by borehole information were obtained within the study area as shown in Figures 2 to 5. The estimate of geo-electric layers was obtained from the quantitative interpretations of vertical electrical sounding data whose fidelity was validated by the use of typical borehole information (Figure 6). From this, aquifer depth, thickness and curve frequency were identified. The hydraulic conductivity was estimated using the equation as given by Heigold et al. (1979):

$$K = 386.40R_{rw}^{-.93283} \quad (3)$$

Where *K* is the hydraulic conductivity, R_{rw} is the aquifer resistivity.

Rocks resistivity depends on the lithology and mineralization of water filling the pores. According to Archie's law 1942, the resistivity of aquifer (saturated rock) is directly proportional to the resistivity of water filling the pores:

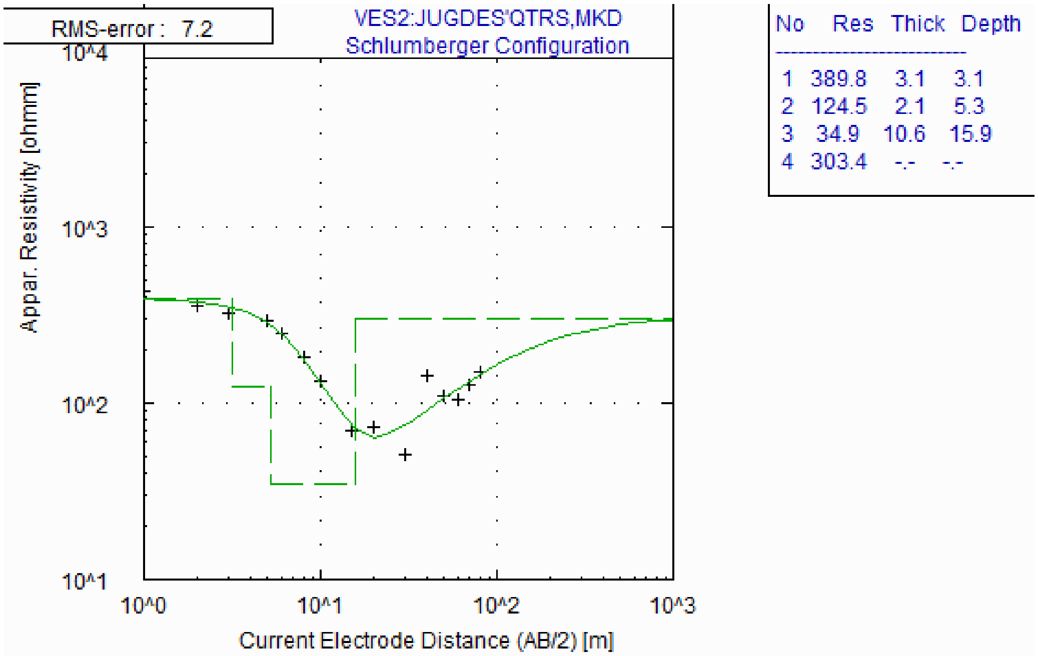

Figure 2. VES 1 Geoelectric curve.

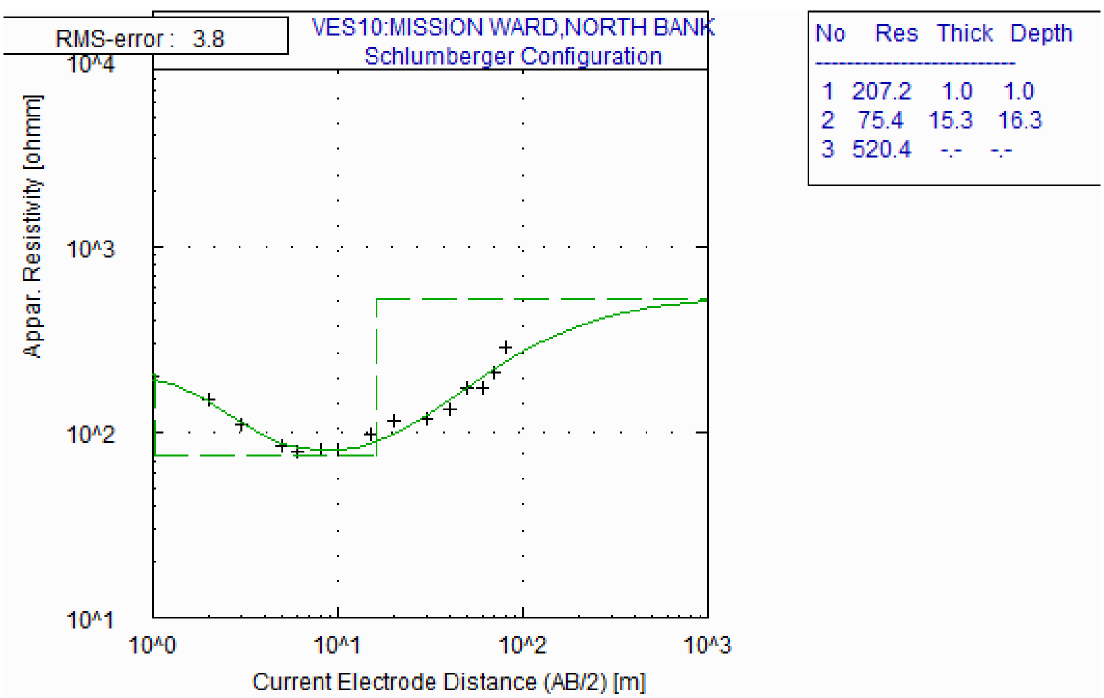

Figure 3. VES 5 Geoelectric curve.

$$\rho_a = F\rho_w \quad (4)$$

Where ρ_a is the aquifer resistivity, ρ_w is the water resistivity, F is the Formation factor.

If a Formation factor is calculated from Equation (4), the apparent Formation factor is observed with increasing water resistivity. Formation factor (*F*) combines all the properties of the material influencing electrical current flow like porosity (Φ), pore shape, etc.

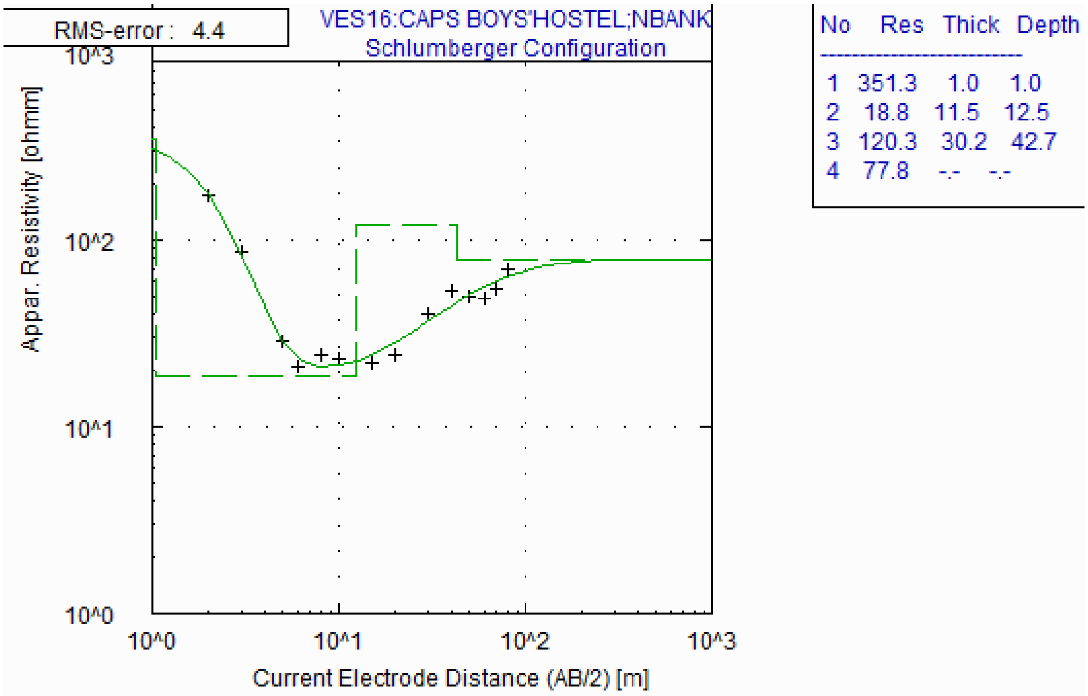

Figure 4. VES 8 Geoelectric curve.

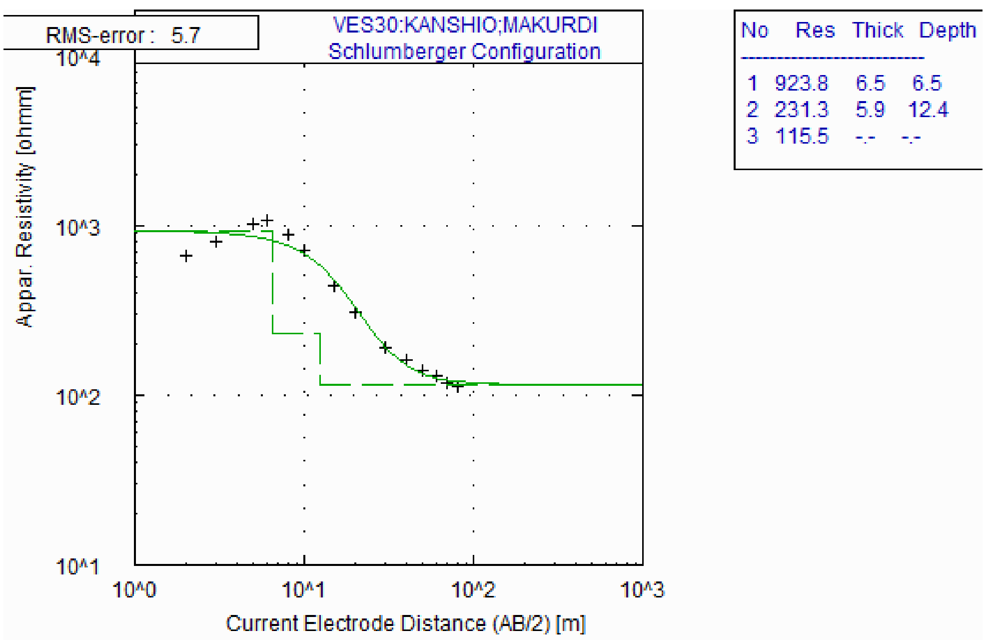

Figure 5. VES 15 Geoelectric curve.

$$F = a\phi^{-m} \quad (5)$$

Where *a* (0.7) is the average geometry factor and *m* (1.9) is the average cementation exponent for the study area being a sandstone region. From Equation (5), porosity is estimated.

RESULTS AND DISCUSSION

The summary of the VES results of fifteen geo-electrical soundings and the calculated hydraulic parameters of the aquifer layer is shown in Table 1. The interpreted curve

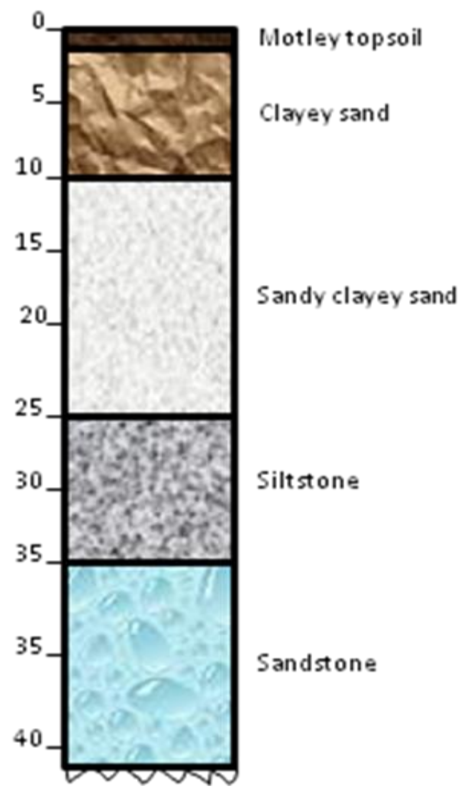

Figure 6. Typical borehole in the study area.

Table 1. Summary of results of geo-electric and hydraulic parameters.

VES station	Location name	Long. (deg)	Lat. (deg)	Aquifer resistivity (ρ_a) (Ωm)	Water resistivity (ρ_w) (Ωm)	Formation factor (F)	Porosity (φ)(%)	Hydraulic conductivity (K) (mday^{-1})	VES curve types
1	Judges Qtrs	7.7123	8.5780	82	16.3	5.03	35.42	6.34	QH
2	Owner,s occupier	7.6964	8.5486	135	21.3	6.34	31.36	3.98	KQ
3	Nyiman layout	7.6963	8.5448	72	15.6	4.62	37.06	7.15	KQ
4	Nyiman layout	7.7053	8.5153	273	28.2	9.68	25.09	2.06	KQ
5	High level	7.7184	8.5225	131	19.5	6.72	30.42	4.09	AA
6	Industrial Estate	7.7020	8.4901	10	2.4	4.12	39.36	45.1	H
7	UniAgric road	7.7631	8.5753	31	5.7	5.44	33.99	15.7	HK
8	CAPS Staff Qtrs	7.7726	8.5958	39	6.4	6.09	32.02	8.75	A
9	Shamija village	7.7623	8.6181	304	32.9	9.24	25.72	1.87	KQ
10	Uchonu village	7.7706	8.5510	271	27.6	9.82	24.91	2.08	KQ
11	Wadata	7.7444	8.5155	39	6.9	5.65	33.31	12.67	QH
12	Ankpa Qtrs	7.7096	8.5040	46	7.8	5.90	32.57	10.44	Q
13	New GRA	7.6872	8.5388	702	69.7	10.07	24.58	0.85	K
14	Kanshio	7.6834	8.5367	150	24.6	6.01	32.01	3.61	QH
15	Lower Staff Qtrs	7.6606	8.5592	160	25.8	6.20	31.72	3.4	HK
	Average			163.0	20.71	6.73	31.30	8.54	

types show that the study area is characterized by seven sounding curve types; QH, KQ, AA, H, HK, A, Q, and KQ-curve types. Geo-electric curve type is the use of letters H, K, A and Q to describe the relation between layer

Table 2. Ranges of porosity in typical earth materials (Driscoll, 1986; Freeze and Cherry, 1979; Roscoe Moss, 1990).

Consolidated rock	Porosity (%)
Sandstone	5 - 35
Limestone/Dolomite	< 1 - 20
Shale	< 1 - 10
Crystalline rock (fractured)	< 1 - 5
Vesicular basalt	5 - 10

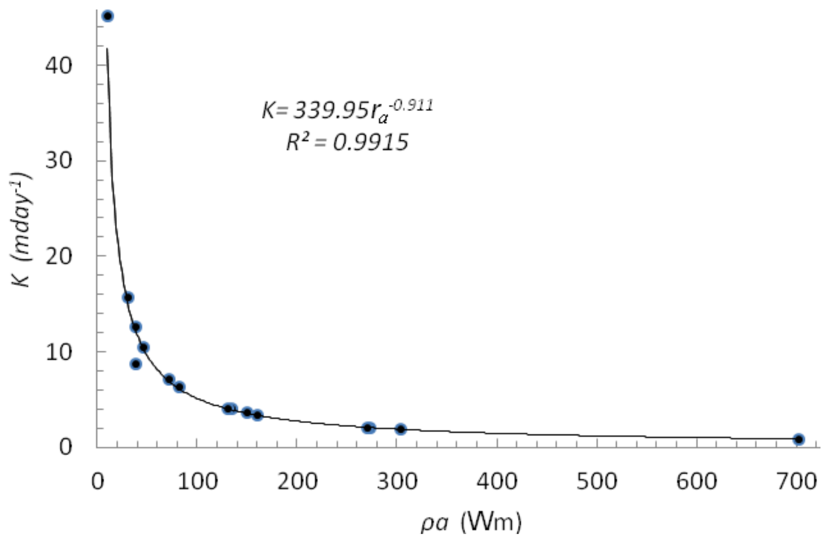

Figure 7. A graph of hydraulic conductivity against aquifer bulk resistivity.

resistivities in a geo-electric section. It indicates that electrical sounding curve is obtained over a geoelectric section in which the layer resistivities varies (Zohdy et al., 1990). The bulk aquifer resistivity (ρ_a) with an average of 163 Ωm ranges from 10 to 702 Ωm. The water resistivity ranges from 2.4 to 69.7 Ωm with an average value of 20.71 Ωm. The aquifer formation factor (F) calculated from the bulk aquifer resistivity and water resistivity ranges from 4.12 to 10.07 and its average value calculated as 6.73. The aquifer porosity was estimated to range from 24.58 to 39.36% with an average of 31.35%. This shows that the aquifer in the study area is dominated by sandstone (Table 2). The hydraulic conductivity is highly variable and is observed to decrease as resistivity increases. The hydraulic conductivity ranges from 0.85 to 45.1 m/day and its average value is 8.54 m/day.

The calculated hydraulic conductivity (K) was plotted against aquifer resistivity (ρ_a), where an inverse relationship was obtained between the two variables (Figure 7). The relationship between aquifer resistivity and water resistivity is shown in Figure 8. A linear relationship between the two variables is obtained which shows that aquifer resistivity increases in direct proportional to water resistivity with a strong correlation coefficient:

$$\rho_a = 10.41\rho_w - 52.80 \quad (6)$$

From the results in Table 1, contour maps were generated. The aquifer contour map (Figure 9) shows the distribution of aquifer resistivity in the study area. It can be seen that conductivity (inverse of resistivity) is high at the southern part of the study area and it increases gradually towards the northeastern part with low conductivity observed in the extreme north through northwest down to part of the southwest, thus resistivity increases towards the northern part of the study area. This means that the geo-materials in the northern part are highly resistive (low conductive minerals) and the aquifer is saturated and thus a high groundwater quality. VES 13 (New GRA) has the highest resistivity value of 702 Ωm while the least 10 Ωm is observed in VES 6 (Industrial Estate) indicating shale/clay signatures. From the average value of 163 Ωm, it can be inferred that the study area is more of Sandstone intercalated with clay.

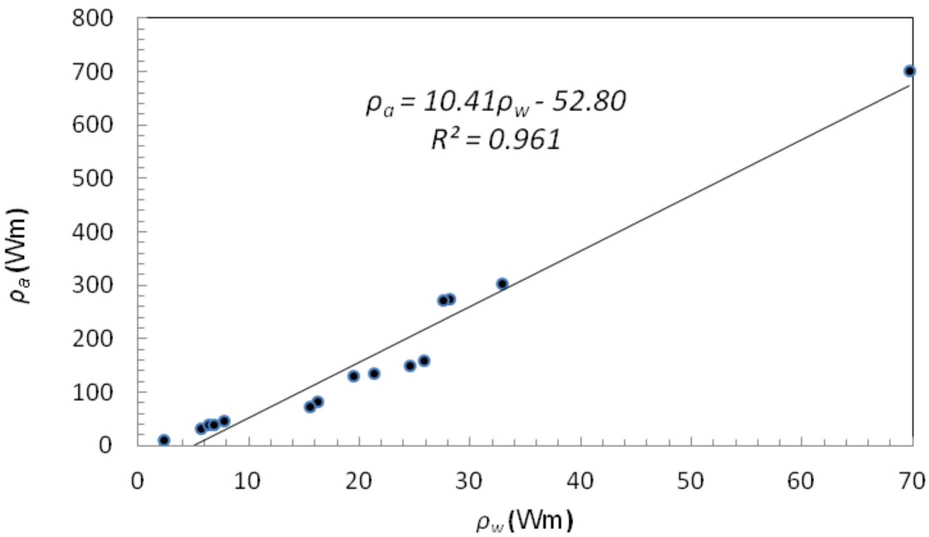

Figure 8. A graph of aquifer bulk resistivity against water resistivity.

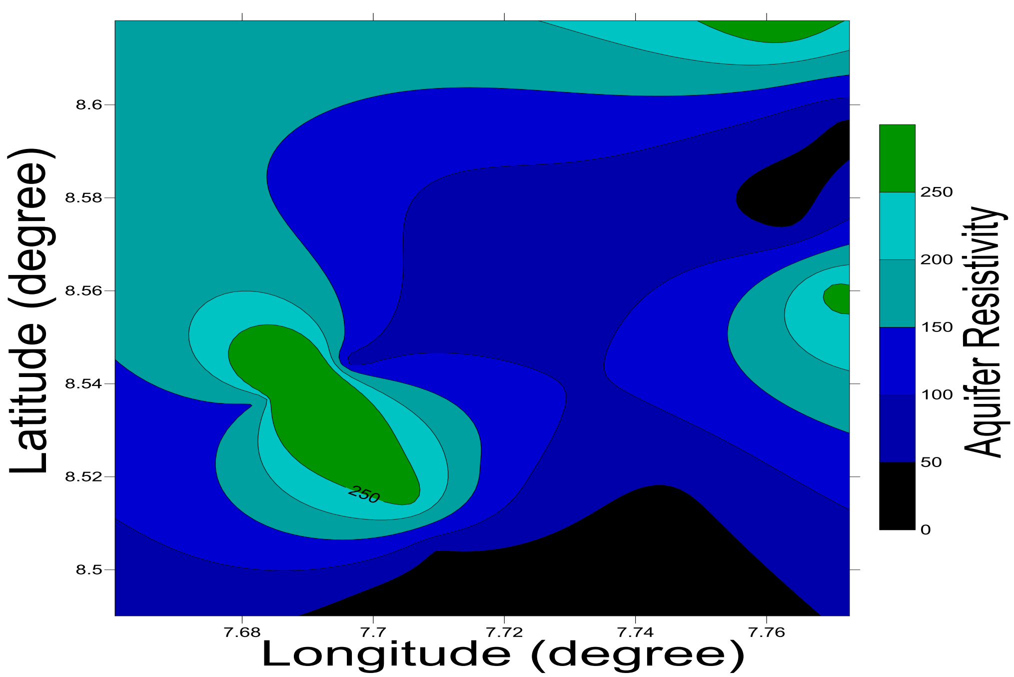

Figure 9. Contour map showing the distribution of aquifer resistivity in the study area.

The variation of aquifer water resistivity is directly proportional to that of aquifer bulk resistivity. Figure 10 shows a gradual increase in water resistivity from south towards the northern part of the study area. This indicates that the southern part of the study area will have highly conductive ions. Areas with low aquifer formation factor correspond to areas with low aquifer bulk resistivity. The distribution of formation factor (ratio of bulk aquifer resistivity to water resistivity) is shown in Figure 11. A decrease of the formation factor is observed with increasing aquifer bulk and water resistivity. The range of porosity in the study area revealed that the study area is dominated with Sandstone with the mean value being 31.3%. Variation of porosity is shown in Figure 12. The highest porosity value is observed in VES 6 (Industrial Estate) with a value of 39.36%. It can thus be inferred that high porosities are associated with aquifers of relatively low aquifer resistivity values and also it suggests high storativity of the aquifer in the area. From the contour map (Figure 12), porosity is high at the

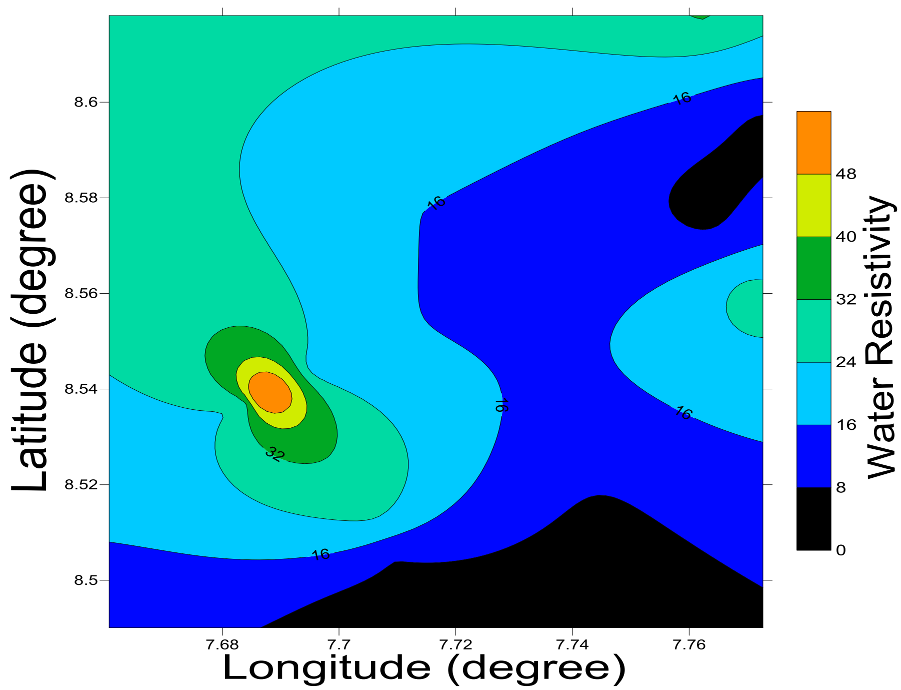

Figure 10. Contour map of showing distribution of water resistivity.

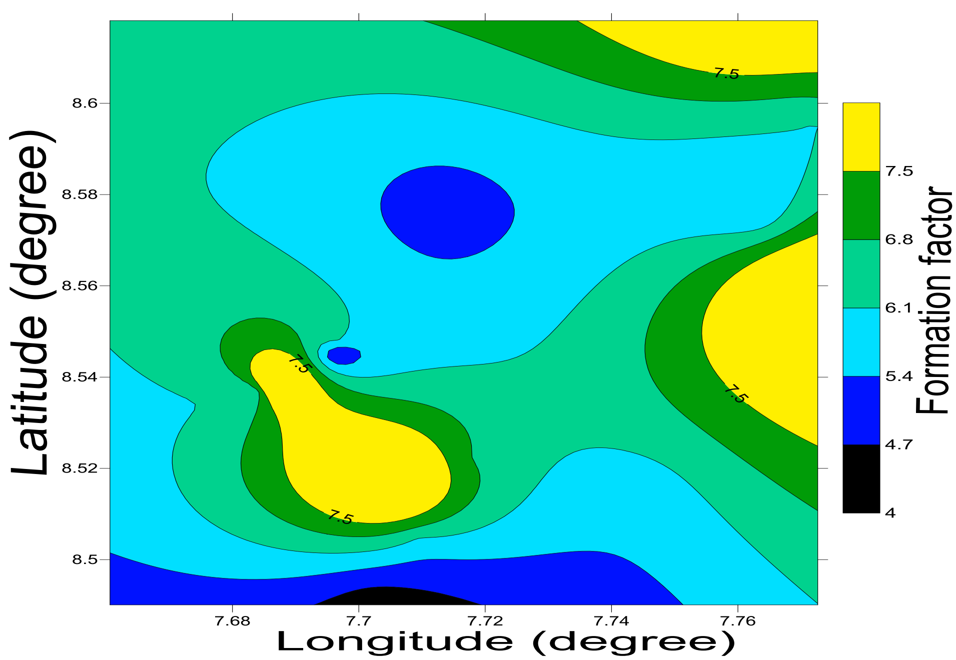

Figure 11. Contour map showing the distribution of Formation factor.

extreme south and the central parts of the study area. Increase or decrease in porosity leads to a corresponding increase or decrease in hydraulic conductivity (K). Figure 13 shows the variation of hydraulic conductivity in the study area which is revealed to be highly variable (0.85 to 45.1 m/day). Hydraulic conductivity increases in the north-south direction as shown on the contour map. The hydraulic conductivity controls the behavior of groundwater flow within an aquifer. It is observed from this study that, increase in resistivity lowers the hydraulic

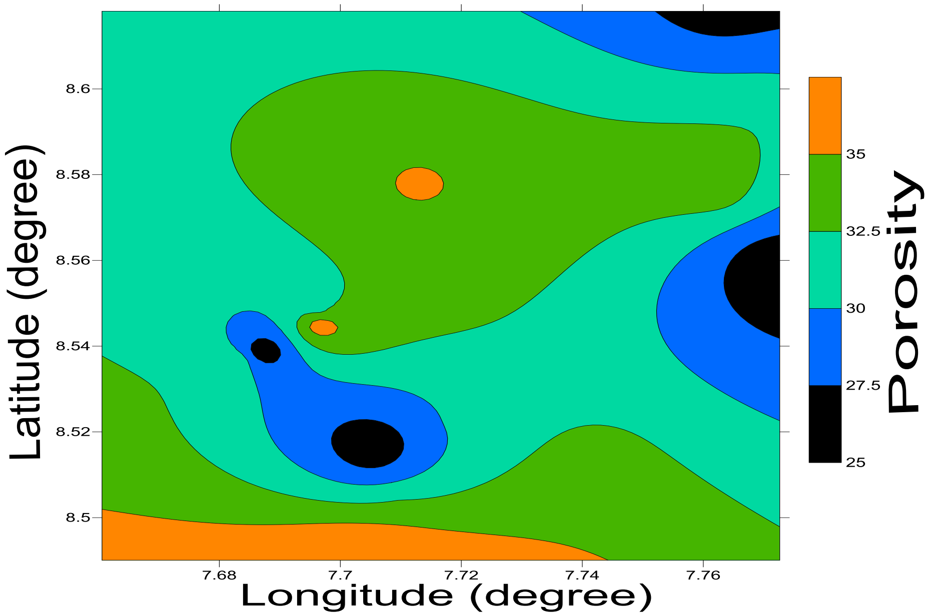

Figure 12. Contour map of the study area showing the variation of porosity.

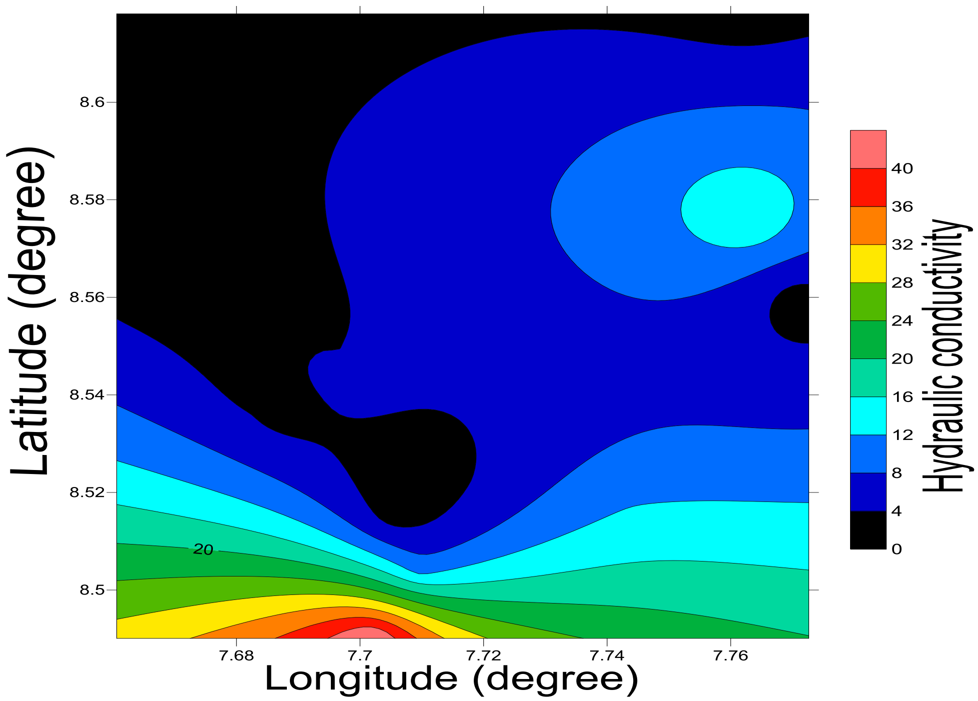

Figure 13. Contour map showing variation of hydraulic conductivity.

conductivity of the aquifer geo-materials.

Conclusion

Fifteen VES were used for this study to evaluate the geo-electric and hydraulic conditions of the study area. There is a good correlation existing between aquifer bulk resistivity and water resistivity. The results indicate the presence of aquifer consisting mainly of Sandstone. The contour maps show increase in both bulk aquifer and water resistivities towards the north. The study revealed that areas with relatively low aquifer resistivity have high porosity values, which indicates high storativity. The porosity is high in the southern and central parts of the study area. It is also observed that hydraulic conductivity decreases as resistivity increases in the area. The area characterized by high porosity but low resistivity is believed to have poor communicating pores and there could not be regarded as potential aquifers. The low resistivity with high absolute porosity zone indicates the presence of argillaceous materials. The use of vertical electrical sounding technique provides geo-electrical and geo-hydraulic information that can be used in resolving the existing challenge in the extraction of groundwater in Makurdi Formation. The estimated contour distributions and simulated models can improve the extraction of potable subsurface water in the study area.

Conflict of Interest

The authors have not declared any conflict of interest.

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