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Estimation of Aquifer Hydraulic Parameters Using Electrical Resistivity Method: A Case Study for Damaturu, Northeast Nigeria.

Agada Livinus Emeka and Yakubu Mingyi Samuel

Department of Physics,
Yobe State University,
P.M.B, 1144,
Damaturu, Nigeria.

Federal Polytechnic Damaturu,
Yobe State.

Email: agadaman1908@gmail.com

Abstract
In this study we estimated the aquifer hydraulic parameters of Damaturu, Yobe State, Nigeria, using electrical resistivity method. Schlumberger configuration was adopted for the study. Five geologic layers, which are the Topsoil, Clay, Sand, Sandy-clay, and Sand were delineated in the study area. The results of the measured aquifer parameters revealed that the aquifer resistivity values in the study area ranged from 126 to 518 Ωm and the aquifer has an average resistivity of 328 Ωm. The aquifer thickness ranged from 39 to 71m with an average value of 59 m. The aquifer has hydraulic conductivity values which ranged from 1.138 to 4.231 m/day with an average value of 1.915 m/day. The transmissivity of the aquifer ranged from 62.7 to194.64 m^2 /day with an average transmissivity of 111 m^2 /day. The porosity of the aquifer ranged from 30.13 to 31.44 % with an average value of 30.6 %. The porosity values showed that the study area has an appreciable porosity for effective groundwater flow and storage. The results of the measured aquifer parameters also revealed that the study area has good groundwater potential. Therefore, the results of this study will assist in providing exquisite information for groundwater exploration, abstraction, development and pollution control in the study area.

Keywords: Groundwater, Damaturu, resistivity, aquifer, porosity.

INTRODUCTION
Proper understanding of aquifer parameters is essential for effective management of groundwater resources. The increasing demand for groundwater in recent times due to population growth, agricultural and industrial expansions requires explicit quantitative description of aquifer parameters in any given location in order to facilitate easy access and equitable provision of groundwater resources. The increasing trend of climate change has directly affected both the availability and the quality of groundwater resources (Agada and Yakubu, 2022). Climate change has contributed to water table fluctuation, groundwater pollution and poor groundwater rechargeability. These problems were exacerbated by the frequent occurrence of extreme weather events, such as heatwaves, drought and flood. The recent increase in both hydrological and hydrogeological problems can be adequately

**Author for Correspondence*

addressed with good understanding of aquifer parameters such as longitudinal conductance, transverse resistance, hydraulic conductivity, aquifer thickness and aquifer transmissivity.

Several researchers have used electrical resistivity method to delineate and evaluate aquifer properties in various locations around the world (Heigold *et al.*, 1979; Niwas and de lima, 2003; Abiola *et al*., 2009; Daniel *et al*., 2015; Adeeko *et al*., 2017; Emmanuel *et al*. 2021; Agada *et al*., 2021; Agada and Yakubu, 2022). Electrical resistivity method has proven to be a veritable tool for groundwater exploration over the years, and its efficiency depends on soil saturation, porosity, fluid dynamics, permeability, groundwater chemical composition and rock lithology. The selection of borehole drilling sites without adequate knowledge of the aquifer parameters has been identified as the major reason for borehole failure in Damaturu, Yobe State (Agada and Yakubu, 2022). Lack of consideration for aquifer parameters during borehole sitting could lead to dry borehole or borehole failure. In most developing countries such as Nigeria, groundwater resources data are relatively scarce and grossly inadequate, and this situation has led to great economic losses associated with borehole failures. The provision of adequate database for groundwater resources in any given location cannot be over-emphasized considering the enormous benefits associated with it. Many researchers have used electrical resistivity method to estimate aquifer hydraulic parameters ((Niwas and Singhal, 1981; Salem, 1999; Hubbard and Rubin, 2002; Khalil, 2006; Agada and Yakubu, 2022). In view of the importance of aquifer hydraulic parameters to effective and adequate groundwater resources management, the main objectives of this study are to delineate and estimate the aquifer hydraulic parameters in Damaturu and its environs. The results obtained from this study will greatly assist in providing useful information for groundwater exploration, abstraction, development and pollution control.

THEORY

Some established theories were used to carry out the estimation of the aquifer hydraulic parameters. There is an empirical relationship between hydraulic conductivity and the electrical resistivity of an aquifer. Heigold *et al.* (1979) established a relationship between hydraulic conductivity (K) and the resistivity of aquifer (R_{ϕ}) as,

$$K = 386.4(R_{\phi})^{-0.93283} \quad (1)$$

Rocks hydraulic conductivity can be characterized using Bouwer standards (Table 1).

Table 1. Hydraulic conductivity values (Bouwers, 1978)

Rock type	Hydraulic conductivity range (m/day)
Clay soil (surface)	0.01-0.2
Deep clay beds	10^{-8} - 10^{-2}
Loam soil (surface)	0.1 - 1
Find sand	1 - 5
Medium sand	5 - 20
Coarse sand	20 -100
Gravel	100 - 1000
Sand and gravel mixture	5 - 100
Clay, sand and gravel mixture	0.01 - 0.1

Considering a sequence of horizontal, isotropic and homogeneous layers of resistivity ρ_i and thickness h_i, the Dar-Zarrouk parameters (longitudinal conductance S and transverse resistance T_r) are defined according to equations 2 and 3 respectively as,

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

$$T_r = \sum_{i}^{n} h_i \rho_i \quad (3)$$

The longitudinal conductance (S) is a measure of the impermeability of a rock layer while the transverse resistance is the product of the true layer resistivity and its thickness. The transmissivity of an aquifer is a measure of its ability to transmit water over its entire saturated thickness (Egbai and Iserhien, 2015). The higher the transmissivity the more productive the aquifer (Egbai and Iserhien, 2015). Niwas and Singhal (1981) conducted a study and they established an equation for estimating transmissivity values in a saturated aquifer.

$$T = KSR_{\emptyset} = \frac{KS}{\sigma} = Kh \quad (4)$$

R_{ϕ} is the aquifer resistivity, σ is aquifer electrical conductivity, h is the aquifer thickness, K is the hydraulic conductivity and S is the longitudinal conductance. However, Marotz (1968) in his experiment using sandstones established a relationship between hydraulic conductivity and effective porosity as;

$$\emptyset = 25.5 + 4.5 lnk \quad (5)$$

Formation factor (F) is a rock parameter which depends on porosity of the formation, tortuosity (pore geometry) lithology and degree of cementation. Winsauer *et al.* (1952) developed a relationship between formation factor and effective porosity, this relation is also known as Humble's equation. It is expressed as;

$$F = \frac{0.62}{\emptyset^{2.15}} \quad (6)$$

Where F is the formation factor. Tortuosity (τ) is an intrinsic property of porous material usually defined as the ratio of actual flow path length to the straight distance between the ends of the flow path (Bear, 1972). It can be estimated using the relation;

$$\mathrm{T} = (F\emptyset)^{1/2} \quad (7)$$

The Tortuosity will be used to characterize the structure of porous media and estimate their electrical and hydraulic conductivity.

The Study Area

Damaturu is located on Latitude 11.744° N and Longitude 11.961° E. It is within the Chad Basin in the semi-arid region of Nigeria (Figure 1). The study area experiences an annual rainfall of about 600 mm and evapotranspiration of about 2000 mm (Agada et al., 2011). There is scarcity of rivers and stream in the study area, its main source of domestic, industrial and irrigation water is the groundwater.

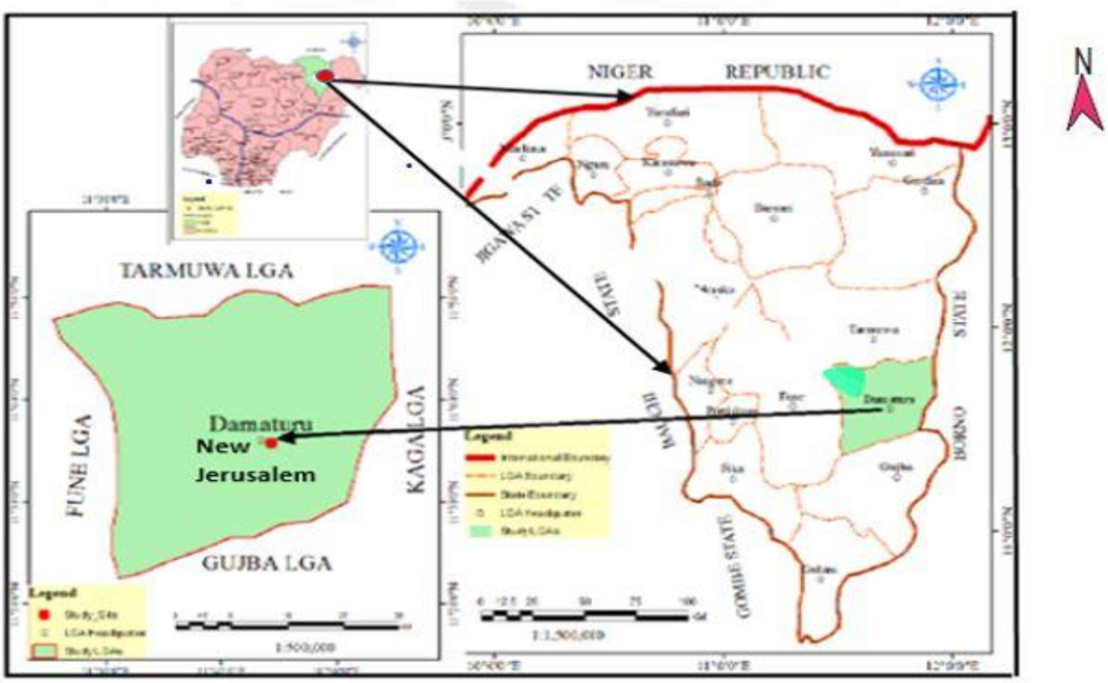

Figure 1: Map of Nigeria showing the study area in Yobe State.

The study area has a shot rainy season (June –September) and a long dry season (October – May), with high temperature of about 39 – 45oC (Agada et al., 2011). During the rainy season, the temperatures fall to 25oC (Agada et al., 2011).

Geology of Study Area

Damaturu is located within the Chad Basin. The Chad basin extends to five countries in Africa which includes Chad, Nigeria, Cameroon, Central Africa Republic and Niger. The Chad Basin covering parts of Borno, Yobe and Jigawa states. About ten percent of the Chad basin lies in the North-eastern part of Nigeria. The Chad Basin resulted from plate divergence along the West Africa continental margin (Oteze and Fayose, 1988). The various process which led to the plate divergence started with regional thermal doming, volcanism and rifting formation of sedimentation. Groundwater resources in Damaturu emanated from the aquifers in the Chad Basin. The Chad Basin consists of three aquifers which are the upper, middle and the lower zone aquifers. These aquifers are predominantly sandy formations separated by clay or sandy-clay formations. The Chad Basin aquifer has shown some considerable decline in water-table (Offodile, 1972; Oteze and Fayose, 1988; Goni et al., 2000; Agada and Yakubu, 2022). The aquifer consists of fine to coarse grained sands. The upper aquifer in some areas in Damaturu occurs under phreatic condition. The upper aquifer is recharged directly by the infiltration of surface rain run-off through the soil, fractures, fissures and clay cracks.

MATERIALS

The study was carried out using the following materials: Global Positioning System (GPS), ABEM SAS1000 digital Terrameter, personal computer, Electrodes, Reels of Cables and Jumpers, Hammers, Measuring tape, 12V Car Battery, pegs, ABEM SAS external Battery Adapter (EBA), Surfer 11 Software, OriginPro 2017 Software.

METHODOLOGY

A reconnaissance survey of the study area was carried out to identify the strategic Vertical Electrical Sounding (VES) points in the area. Electrical resistivity method involving Schlumberger array was adopted for this study. The field data acquisition was carried out by laying electrical cables along predefined profiles and the cables were linked to the ground using sets of electrodes and cable jumpers. An electrode test was performed to ensure that current was flowing through all the electrodes. The inner electrodes are the potential electrodes and the outer electrodes are the current electrodes. Twenty (20) Vertical Electrical Sounding (VES) were carried out in the study area with the aim of delineating the various subsurface layers, aquifer thicknesses, depth to groundwater and overburden thickness. ABEM Terrameter SAS100 was used to measure the resistance, voltage and current of the soil. The apparent resistivity values were obtained by multiplying the resistance by the geometric factor (*K*). The subsurface layer resistivities were modeled using Palacky 1988 true resistivity value Chart (Figure 2).

The apparent resistivity data were modeled using theoretical partial field curve matching method and the obtained results were used as input data for iteration, using WINRESIST version 1.0 Software to obtain the subsurface layers true resistivities. The geoelectric sections were developed using OriginPro 2017 Software and the various iso-resistivity contour maps were developed using Surfer 11 Software. The subsurface rock parameters obtained, such as layer resistivities and thicknesses were used to compute the hydraulic conductivity, porosity, transmissivity, aquifer resistivity, tortuosity, and formation factor. The aquifer transmissivity was modeled using Gheorghe, (1978) method (Figure 3). The resistivities and thicknesses of the first aquifer were used to compute the aquifer hydraulic conductivity, porosity, transmissivity, tortuosity, and the formation factor.

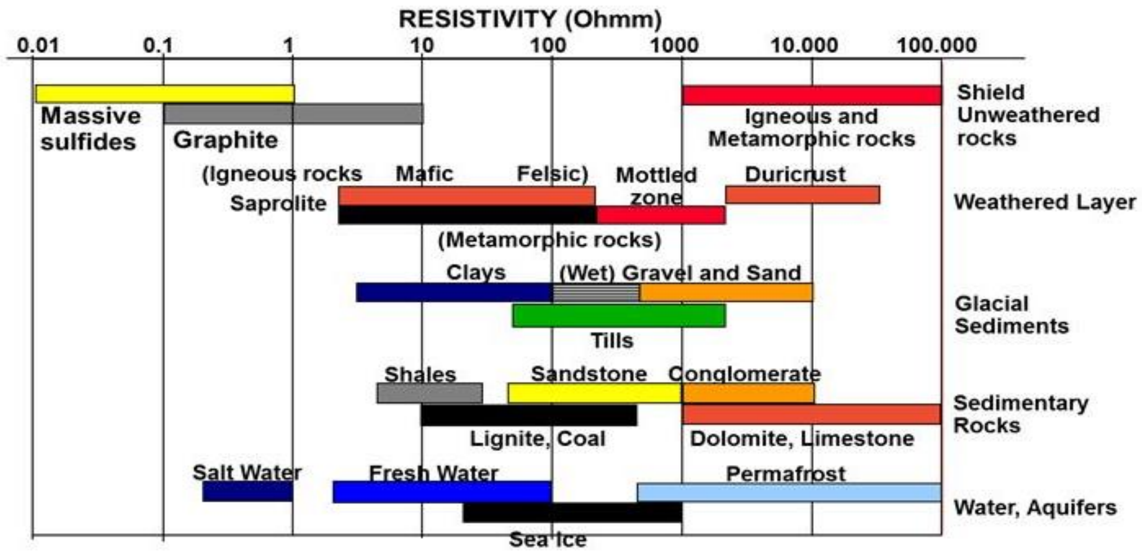

Figure 2: Rock true resistivity values (After Palacky, 1988).

Table 1. Aquifer Potential (After Gheorghe, 1978 and Oladapo, *et al*., 2004)

Aquifer Transmissivity (m^2/day)	Aquifer Potential
>500	High
50- 500	Moderate
5 – 50	Low
0.5 – 5	Very low
< 0.5	Negligible

RESULTS AND DISCUSSION

The results obtained from the study showed that the study area is composed of five geologic layers which are topsoil, clay, sand, sandy clay and sand (Figure 3). The resistivity characterization of the subsurface layers were done based on Palacky (1988) rock resistivity chart (Figure 2). The thickness of the first layer ranged from 0.7 m to 2.6 m, it is composed of a mixture of humus, clay and sand. The second layer which is clay has a thickness which varied from 4.5 m to 12.2 m. It is the layer overlying the third layer which is the first aquifer. This layer has high water retention capacity and its proximity to the surface is responsible for the flooding of some of the areas during the peak of the rainy season. The third layer has resistivity values which ranged from 126.4 Ωm to 516.7 Ωm, with an average of 327.7 Ωm. These resistivity values clearly indicate that the layer is a sandy formation. Its thickness ranged from 38.77 m to 71 m. It is the first aquifer in the study area with an average thickness of 59.1 m. The fourth layer is a sandy clay whose thickness ranged from 50.3m to 96.4 m. These results correlated well with existing borehole logs obtained from the study area. The thicknesses of the delineated subsurface layers showed that Damaturu is located within the fringe of the Chad Basin and the thickness of the subsurface layers increase as you move towards Maiduguri. The results of this study are in agreement with the results of Goni *et al*. 2000. The thickness of the second aquifer was not determine due to its depth. The third and the fifth layers were sandy formations and they constitute the aquifers in the study area. The first aquifer is semi-confined while the second aquifer is confined.

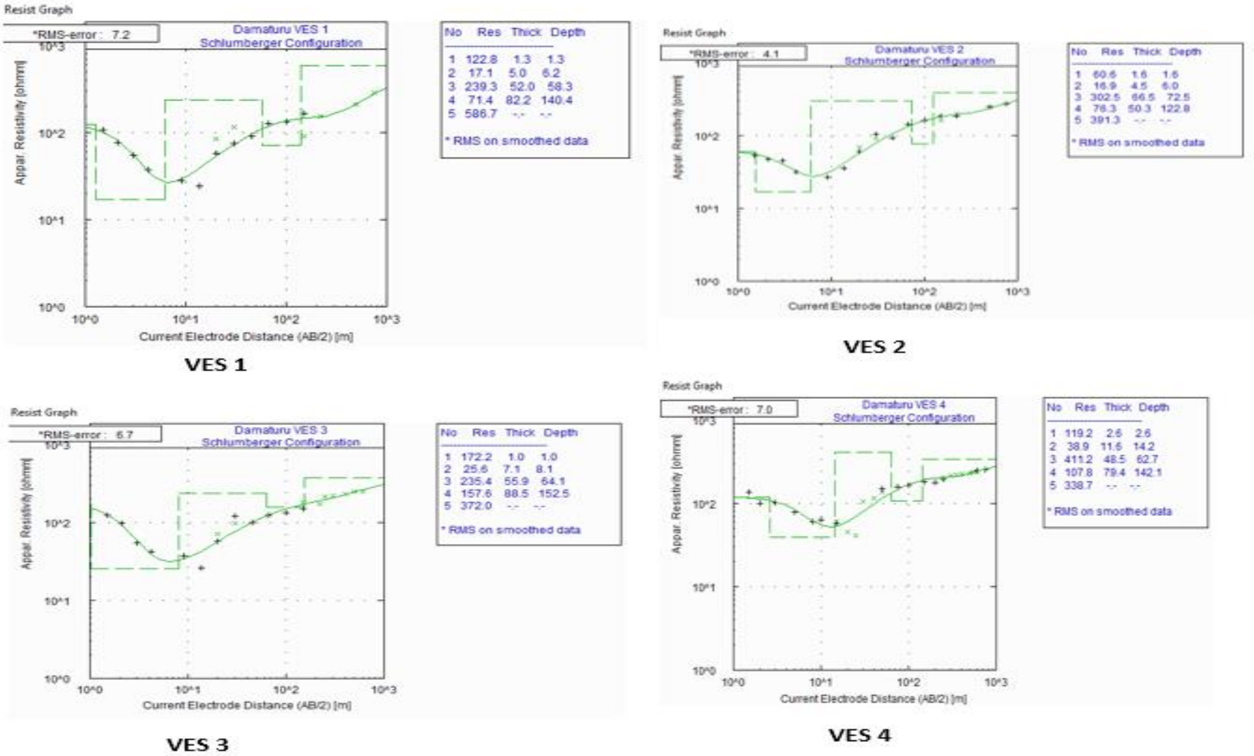

Figure 3: Typical resistivity curves obtained from the study area and the number of geologic layers.

The magnitude of the aquifer hydraulic parameters (transmissivity, hydraulic conductivity, porosity, tortuosity, and formation factor) were estimated using the established models in the literature (Winsauer *et al.*, 1952; Marotz, 1968; Bear, 1972; Heigold *et al.*, 1979; Niwas and Singhal, 1981). The various aquifer parameters delineated in the study area are shown in Table 3. The porosity of an aquifer is the ratio of the volume of void spaces to the total volume. The aquifer porosity in the study area ranged from 30.13 to 31.44 %, with an average value of 30.6 % (Table 5). The aquifer porosity is almost uniform due its stratification (Figure 4). It is a little higher towards the southwestern part of the study area (Figure 4). The aquifer transmissivity which is a measure of the groundwater flow through the aquifer has a magnitude which ranged from 62.7 to 194.6 m^2/day with an average value of 111 m^2/day (Table 4). A comparison of the average aquifer transmissivity value obtained in the study area with the results of Gheorghe, 1978 and Oladapo**,** *et al*. 2004 (Table 2), indicates that the aquifer potential in study area is moderate. The aquifer transmissivity contour map showed that the transmissivity is higher towards the southwestern part of the study area (Figure 5). The magnitude of the average transmissivity showed that higher porosity is associated with high transmissivity (Table 4)

Table 3: Delineated Aquifer Parameters in the study area.

VES No.	Aquifer Resistivity (Ωm)	Aquifer Thickness (m)	Hydraulic Conductivity (m/d)	Transmissivity (m^2/day)	Porosity (%)	Formation factor	Tortuosity	Latitude (°N)	Longitude (°E)
1	239.3	52.0	2.332856	121.308	30.84709	0.111631	1.855664	11.73136	11.97754
2	302.5	66.5	1.874744	124.670	30.62847	0.112029	1.852368	11.72919	11.96958
3	235.4	55.9	2.368893	132.421	30.86242	0.111603	1.855895	11.73426	11.96183
4	411.2	48.5	1.407894	68.2828	30.34209	0.112556	1.848022	11.72577	11.97331
5	516.7	60.2	1.137752	68.4356	30.12905	0.112953	1.84477	11.72779	11.96726
6	354.4	38.3	1.617223	62.6997	30.48071	0.112312	1.850129	11.72901	11.98116
7	126.4	46.0	4.231208	194.635	31.44249	0.110569	1.864554	11.73094	11.96103
8	264.7	52.1	2.123343	110.626	30.75299	0.111802	1.854247	11.73275	11.96914
9	455.8	58.4	1.278947	74.6905	30.24604	0.112735	1.846558	11.73497	11.96569
10	301.7	56.1	1.879381	105.508	30.63094	0.112024	1.852405	11.73317	11.97183
11	267.0	67.2	2.106273	141.541	30.74492	0.111816	1.854126	11.73175	11.96659
12	470.8	65.8	1.240846	81.6104	30.21579	0.112791	1.846096	11.72734	11.96202
13	264.0	54.9	2.128592	116.838	30.75546	0.111797	1.854285	11.72496	11.96387
14	516.0	70.6	1.139192	80.3812	30.13032	0.112951	1.844789	11.73033	11.96991
15	334.2	65.0	1.708554	111.065	30.53565	0.112199	1.850963	11.73745	11.97615
16	240.0	62.0	2.326509	144.243	30.84437	0.111636	1.855623	11.72991	11.96547
17	394.1	71.0	1.464763	103.998	30.38169	0.112483	1.848625	11.75162	11.98946
18	267.3	67.5	2.103774	142.004	30.74373	0.111818	1.854108	11.74944	11.99156
19	312.1	5.26	1.820896	102.243	30.59933	0.112082	1.851927	11.73561	11.96344
20	280.9	67.2	2.008883	135.017	30.69758	0.111902	1.853412	11.74944	11.99156

Table 4. Summary of Hydraulic Parameters

	Aquifer Resistivity (Ωm)	Aquifer Thickness (m)	Hydraulic Conductivity (m/d)	Transmissivity (m^2/day)	Porosity (%)	Formation Factor	Tortuosity
Minimum	126.4	38.77	1.138	62.700	30.13	0.1105	1.84
Maximum	516.7	71.00	4.231	194.636	31.44	0.1129	1.86
Mean	327.7	59.09	1.915	111.111	30.60	0.1121	1.85

An aquifer hydraulic conductivity is a measure of how easily groundwater flow through the aquifer. The aquifer hydraulic conductivity in the study area ranged from 1.138 to 4.231 m/day (Figure 6). The average hydraulic conductivity is 1.915 m/day and this value indicates that the aquifer hydraulic conductivity in the study area is good. The values of the aquifer hydraulic conductivity showed that the aquifer in the area is fine grained sand (Table 3). The groundwater movement varied from place to place and depends on the hydraulic gradient. This finding is in agreement with the report of Consulints, (1976). The aquifer resistivity is higher towards the southwestern part of the study area. It is moderate in the eastern part and lower towards the northern part of the study area (Figure 7). The aquifer resistivity ranged from 126.4 to 516.7 Ωm and it has an average resistivity of 327.7 Ωm.

The variation of the aquifer resistivity is a reflection the subsurface stratigraphy.

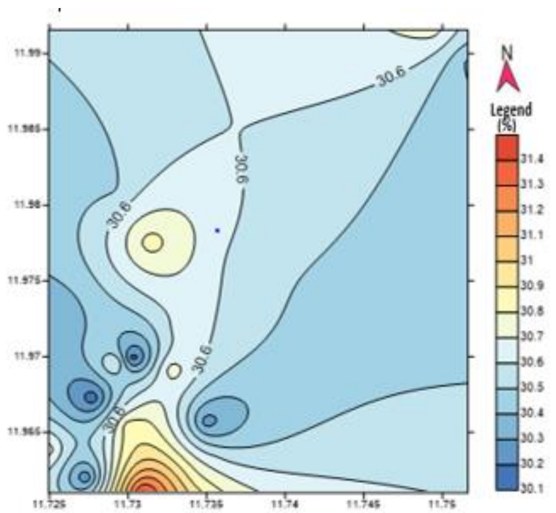

Figure 4. **Porosity contour map of the study area. The aquifer porosity is higher towards the southern part of the study area.**

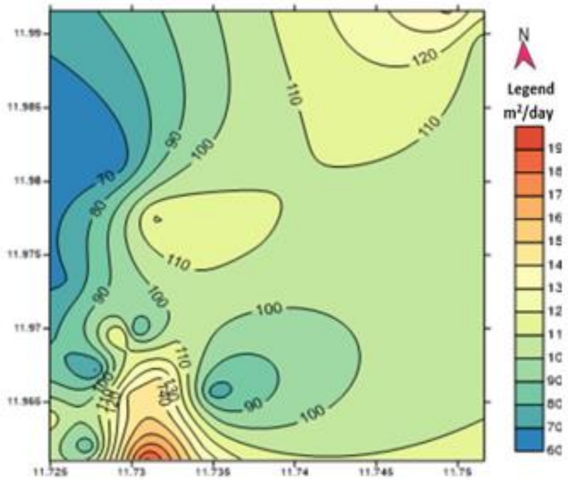

Figure 5. Aquifer transmissivity contour map of the study area. The transmissivity is higher towards the southwestern part of the study area, lower towards the eastern part and moderate in other parts of the study area.

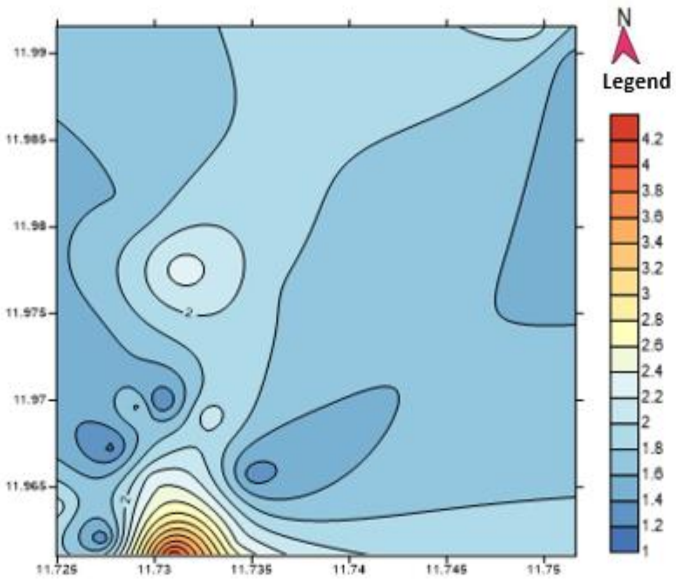

Figure 6. Aquifer hydraulic conductivity contour map of the study area. The hydraulic conductivity is higher towards the southwestern part of the study area.

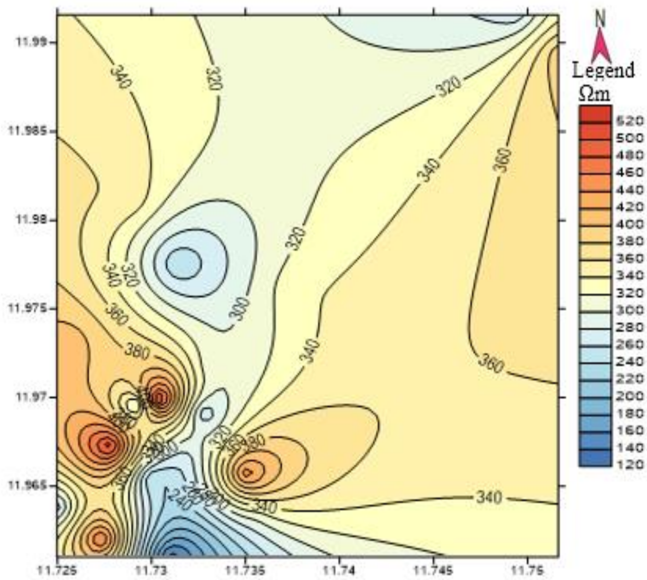

Figure 7. Aquifer resistivity contour map of the study area. The resistivity of the aquifer is higher towards the southwestern part and moderate in the eastern part of the study area.

The aquifer thickness of the study area increases from the western part of the study area to the eastern part, and it indicates that the thickness increases towards the centre of the Chad Basin (Figure 8). This result confirms the reports of Barbar and Jones (1960), and Goni *et al.*, (2000). The aquifer thickness ranged from 38.77 to 71.00 m. It has an average thickness of 59.09 m and its thickness shows that the study area has good groundwater potential.

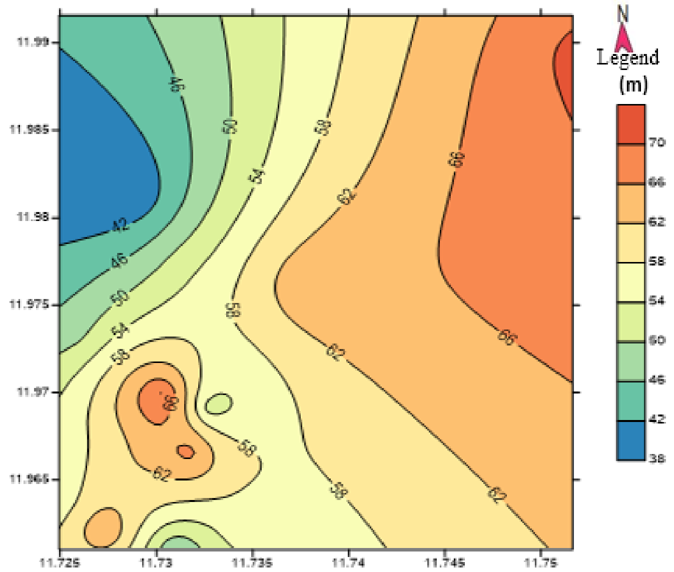

Figure 8. Aquifer thickness contour map. The aquifer thickness increases towards the eastern part of the study area.

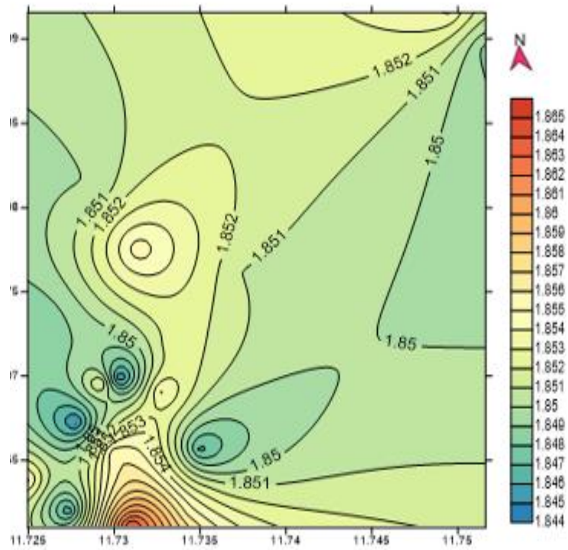

Figure 9. Aquifer tortuosity map of the study area. The tortuosity is higher in the southern part of the study area.

Groundwater flows from area of high hydraulic head to the area of low hydraulic head. The quantification of groundwater tortuosity is very important as it helps to improve the understanding of groundwater and contaminant migration through the aquifer. The aquifer tortuosity in the study area ranged from 1.84 to 1.86 (Figure 9), and its average in the study area was 1.85. It is higher in the southern part of the study area (Figure 9). The aquifer tortuosity ranged from 0.1105 to 0.1129 (Figure 10), and it has an average value of 0.1121.

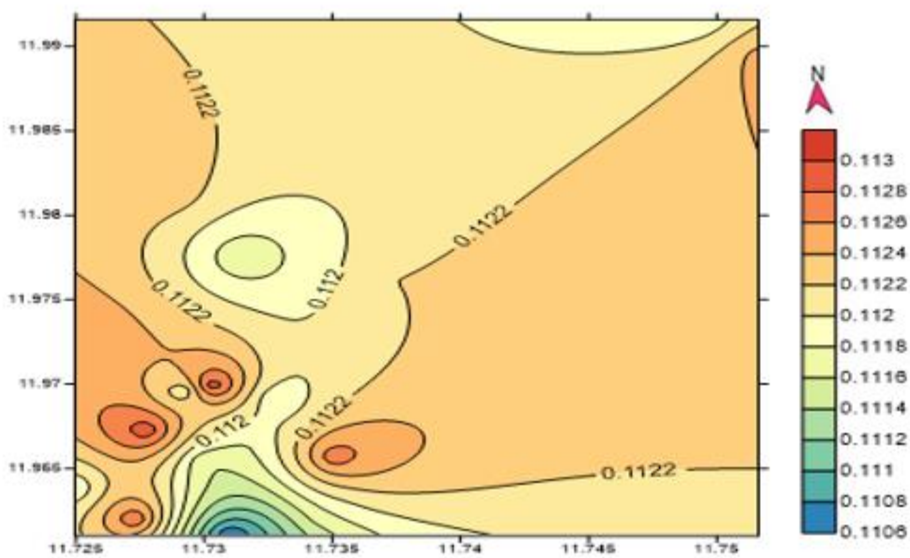

Figure 10. Aquifer formation factor contour map. The formation factor is almost uniform across the study area considering its range (0.1105-0.1129).

The results of the assessed hydraulic parameters of the aquifer have revealed that the aquifer in the study area has good groundwater potential and it also has appreciable porosity for effective groundwater flow and storage. These evaluated aquifer parameters will help to provide the basis for groundwater exploration, abstraction, development and protection.

CONCLUSION

This study was devoted to estimating the aquifer parameters in Damaturu, northeastern Nigeria, using electrical resistivity method. In this study, Vertical Electrical Sounding (VES) which involved Schlumberger configuration, were used to characterize the aquifer parameters. The results showed that the study area has good groundwater potential and it is susceptible to pollution due to the porous nature of the study area. The proximity of the first aquifer to the surface requires an enhanced protection to secure it from contamination. The results obtained in this study will serve as good basis for effective groundwater development and protection. Significantly, the results will be used to control environmental pollution leading to groundwater contamination in the area.

CONFLICT OF INTEREST

The authurs declared that there were no competing interest.

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