Communication in Physical Sciences, 2023, 9(3):325-335

Investigation of Aquifer Vulnerability in Damaturu Using Electrical Resistivity Method

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Received: 01 April 2023/Accepted 08 July 2023/Published 10 July 2023

Abstract: *The rapid growth in anthropogenic activities in both cities and rural areas has contributed immensely to aquifer vulnerability. Aquifer vulnerability has a significant impact on groundwater quality, groundwater recharge status and the vadose zone. Different geological environments may have diverse statuses of aquifer vulnerability. Therefore, to provide baseline information on aquifer vulnerability regarding Damaturu, the present study was designed to investigate the vulnerability of aquifers in Damaturu. The study area consisted of five geologic layers, which included the topsoil, clay, sand, sandy-clay and sand. Two aquifers were delineated in the study area. The first Aquifer was unconfined in some parts of the study area and it is also semi-confined in some parts of the study area. The first Aquifer is overlain by thin overburden units, which were not thick enough to protect it from invasion by infiltrating contaminants from the surface. The second Aquifer is confined by a thick sandy-clay formation with an appreciable thickness which enables it to possess quality groundwater. The longitudinal conductance of the first Aquifer in the study area ranged from 0.53 to 1.45 mΩ^{-1}, with an average value of 0.93 mΩ^{-1}. It is shallow and has an average depth of 50 m. The aquifer protective capacity was 93% good and 7% moderate. These results clearly showed that the first Aquifer in the study area is vulnerable to contamination by leachate and any other percolating fluids. The second Aquifer is overlain by a thick sandy-clay formation which protects it from pollution by leachate. It is the most appropriate for quality groundwater abstraction in the study area. Due to the proximity of the first Aquifer to the surface, there is a need for regular monitoring of the groundwater to protect it from pollution. A proper groundwater monitoring system is imperative in the study area to protect the population from the dangers of consumption of contaminated water.*

Keywords: *Groundwater, contaminations, vulnerability, infiltration, longitudinal conductance.*

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1.0 Introduction

Groundwater is the water which occurs beneath the ground surface in rocks such as sandstones, sand, gravel, fracture or weathered layers. About 30% of all fresh water in the world is groundwater. Water is one of the necessities of life and it has a direct bearing on human health. The rapid growth in the population of people in the cities and towns, as well as industrialization, has led to the reclamation of waste dumpsites for residential building development and the expansion of water facilities. Contaminants in groundwater pose serious health risks to humans, animals and plants. The increase in the demand for portable water and its importance to healthy life and sustainability requires that concerted efforts should be devoted to ensuring that groundwater is properly secured. The investigation of an aquifer vulnerability in any given location will help to reduce the uncertainty associated with groundwater quality.

An aquifer is a geologic formation such as sandstones, sand, gravel, fractured or weathered layers which store and transmit groundwater. An aquifer is vulnerable if it is not protected from the infiltration of contaminants such as leachate and inorganic substances from the Earth's surface. In the basement terrain, weathered and fractured rock layers are the main aquifers, while in the sedimentary environment, unconsolidated sediments with sufficient permeability, such as gravels, sand, sandstones and fractured limestones, are good aquifers. The electrical resistivity method has proven to be very effective and has been effectively used for groundwater and geotechnical investigations and also in environmental studies. Several studies have shown that most groundwater pollutants are anthropogenic. Aquifer vulnerability investigations contribute immensely to effective groundwater resources planning, design and quality monitoring.

Daniel *et al.* (2015) investigated the aquifer protective capacity of overburden units and soil corrosivity in Makurdi, Benue State, Nigeria, using the electrical resistivity method. The results of their study revealed that the longitudinal conductance of the study area is characterized by 36.6% weak, 10% poor, 40% moderate and 13.3% good. They concluded that the regions with moderate/good protective capacity are good sites for boreholes sitting. Aderemi and Bamiro, (2021) investigated the aquifer protective capacity in Ode-Ona in Elewe, Ibadan, Nigeria. The results of their study showed that the study area has good groundwater potential and the aquifer protective capacity range from poor to moderate. Aquifer protective capacity in Awka and its environs was investigated by Onyenweife *et al*. (2020) using the electrical resistivity method. The results they obtained revealed that the study area has good aquifer protective capacity with lenses of weak to poor protective capacity. The estimated values of the overburden longitudinal conductance of the Aquifer in the area ranged from 0.009 to 3.484 Ohm^{-1}.

Many researchers have used longitudinal conductance to evaluate the protective capacity of an aquifer (Oladapo *et al*., 2004; George *et al*., 2014; Adeniji *et al*., 2014; Obiora *et al*., 2015). Damaturu is the capital of Yobe State and its population is growing daily due to the influx of people from both far and nearby villages and towns into the city as a result of insurgency. The demand for potable water in the study area is increasing rapidly despite reports of water contamination in some parts of the study area (Umara *et al*., 2004; Emeka and Weltime, 2008; Waziri et al., 2009; Yakubu and Agada, 2022). An aquifer protective capacity is defined as the ability of an overburden unit to protect an aquifer from pollution by an infiltrating contaminant. It has also been defined by some researchers as a measure of the ability of the overburden unit to deter and filter percolating fluids (Olorunfemi *et al*., 1999; Adeniji *et al*., 2014; Aderemi and Bamiro, 2021). The investigation of aquifer vulnerability is important in ensuring effective groundwater management and protection. Domestic, agricultural and industrial wastes often contaminate groundwater when adequate measures are not taken to secure the groundwater.

A proper understanding of an aquifer's geological settings and characteristics will help in protecting the groundwater from contamination that can cause health hazards. Considering the groundwater situation in Damaturu, the high demand for potable water and the role of aquifer vulnerability in groundwater management and planning, this study investigated the aquifer protective capacity of the overburden units in Damaturu, Yobe State, Nigeria.

1.1 *The Study Area*

Damaturu is located within the Chad Basin in the semi-arid region of Nigeria. It is situated on latitude 11° '39'N and longitude 11° '54'E (Fig. 1). It is located in the Chad Basin, and it has a semi-arid climate characterized by a long dry season and a short rainy season. The duration for rainfall last for about three to four months, the annual rainfall ranges from 500-1000mm and the rainy season is from June to September (Agada *et al*., 2011). The Chad Basin is the largest area of inland drainage in Africa (Barber, 1960). The Basin is divided into three aquifer zones which are the upper, middle and lower. The Upper Aquifer is composed mainly of fine sand, clay and silts partly inter-stratified with fluvial sands.

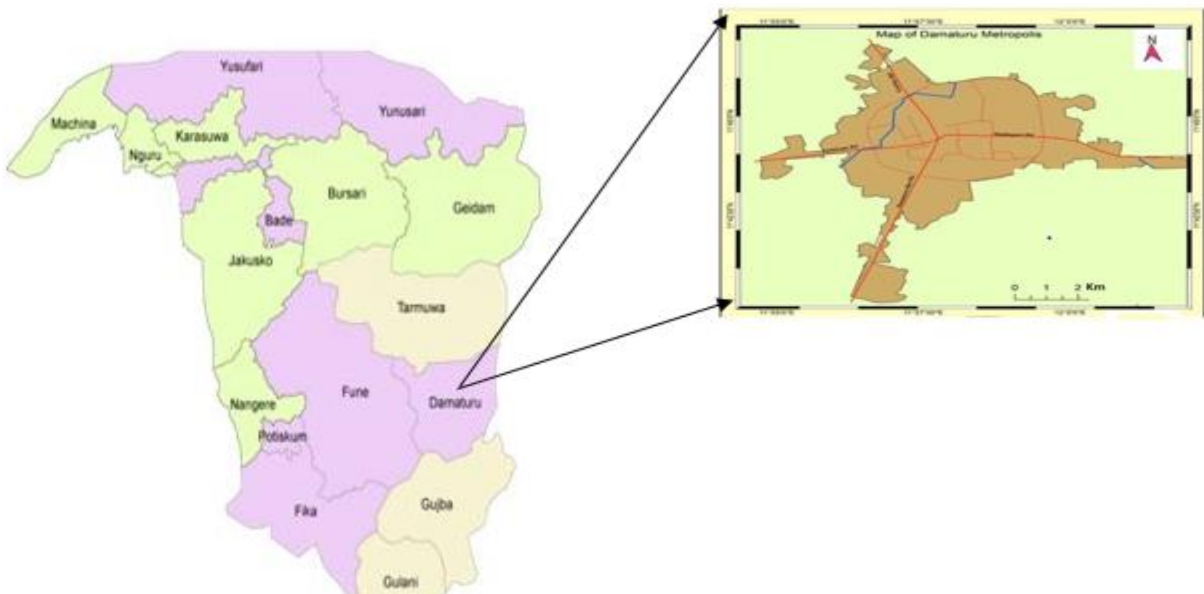

Fig. 1: Map of Yobe State showing the study area, Damaturu.

2.0 Materials and Methods

The materials used for this study are as follows: ABEM SAS 1000 Terrameter, four steel electrodes, four reels of wire cables, GPS, measuring tape, hammers, personal computer, 12V battery, pegs, and jumpers.

2.1 Methodology

An electrical resistivity survey using Schlumberger configuration was used to carry out the study. An electric current was injected into the subsurface through the two current electrodes and the corresponding voltage was measured through the two voltage electrodes. The current and voltage electrode spacing was varied for several distances to obtain several resistivity values for the various subsurface geologic layers. Fifteen (15) Vertical Electrical Sounding (VES) were carried out during the study to delineate the depth of the groundwater, aquifer resistivity and thickness. The progressive increase in the distance between the current electrodes and the distance between the voltage electrodes causes the current lines to penetrate deep into the subsurface. The apparent resistivity values were obtained by multiplying the resistance by the geometric factor (K). The subsurface layer resistivities were characterized using Palacky 1988 true resistivity value Chart shown in Fig. 2.

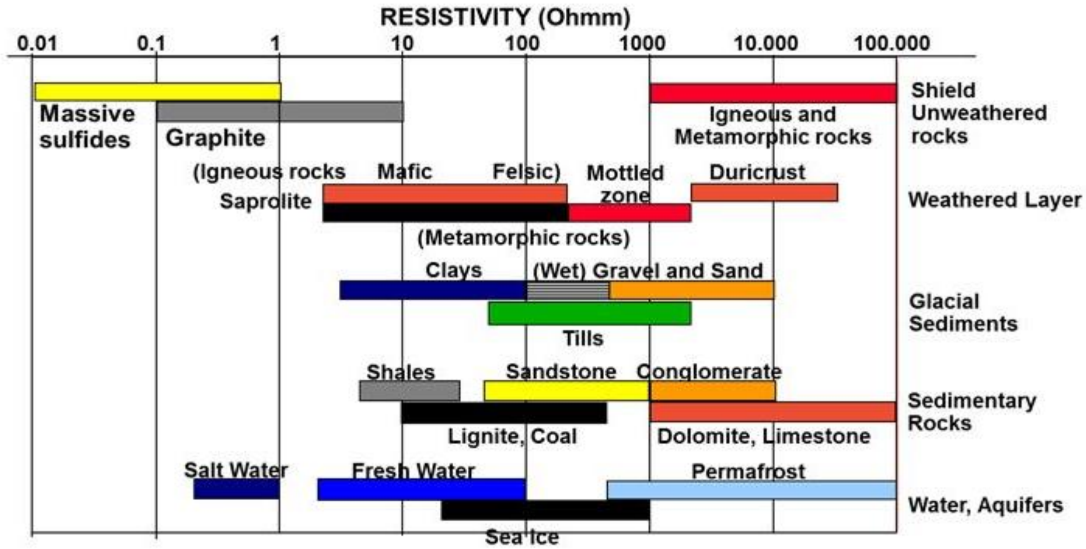

Fig. 2: Rock true resistivity values (After Palacky, 1988).

2.2 Dar Zarrouk parameters

The Dar-Zarrouk parameters, such as the longitudinal conductance (S_i) and the Transverse resistance (Tr), were computed using the results of the Vertical Electrical Sounding (VES) obtained from the field data. The computed Dar Zarrouk parameters were used to evaluate the aquifer protective capacity of the study area and the aquifer groundwater potential following the study conducted by Oladapo *et al*., 2004 (Table 1). The longitudinal conductance, S_i of the study area was calculated using the equation,

$$S_i = \sum_{i=0}^{n} \frac{h_i}{\rho_i} = \frac{h_1}{\rho_1} + \frac{h_2}{\rho_2} + \frac{h_3}{\rho_3} + ... + \frac{h_n}{\rho_n} \quad (1)$$

where ρ_i is the layer resistivity, and h_i represents the layer thickness for i^{th} layer. Impervious materials such as clay and shale are characterized by high longitudinal conductance values, while porous materials such as sand and gravel have low longitudinal conductance values. The rating was categorized as poor, weak, moderate, good, very good and excellent, depending on the magnitude of the total longitudinal conductance value (Table 1).

Transverse resistance is the product of a ' 'layer's true resistivity and thickness. The total transverse resistance of the study area was calculated using the equation,

$$Tr = \sum h_i \, p_i, \quad (2)$$

where h_i is ith layer thickness and p_i denotes the corresponding true resistivity of the ith layer.

Table 1. Aquifer Protective Capacity Rating (Oladapo *et al*., 2004)

Longitudinal conductance (mho)	Protective capacity rating
< 0.10	Poor
0.10 – 0.19	Weak
0.20 -0.69	Moderate
0.70-0.49	Good
5.0-10.00	Very Good
>10.00	Excellent

The magnitude of the total Transverse resistance (Tr) was used to characterize the groundwater potential in the study area following the studies of Henriet, (1976) and Oladapo *et al*. (2004).

3.0 Results and Discussion

The results of the Vertical Electrical Sounding (VES) data were interpreted with the aid of nearby borehole logs and the various subsurface layers in the study area were classified using the Palacky (1988) rock resistivity chart (Fig. 2). The study area is composed of five geologic layers (Fig. 3). The subsurface condition is a typical sedimentary terrain in nature (Fig. 4). The resistivity of the first layer ranged from 15 to 232 Ωm with an average value of 153 Ωm (Table 2). This layer is the topsoil which is made up of a mixture of clay, sand and some plant remains. It has an average thickness of 0.9 m. Table 2 also reveals that the second layer has resistivity values which ranged from 25 to 98 Ωm with an average of 55 Ωm (Table 2). It has a mean thickness of 9.0 m. The resistivity range indicates that the second layer is a clay formation (Fig. 2).

The third layer has resistivity values which range from 156 to 832 Ωm with an average resistivity of 309 Ωm (Fig. 4). The resistivity characteristic of the third layer indicates that it is a sand formation (Palacky, 1988), with an average thickness of 50 m. It is the first Aquifer in the study area and it is semi-confined in some parts of the study area. The depth of some of the hand-dug wells in the study area ends in the first Aquifer. The fourth layer has resistivity values which range from 38 to 127 Ωm with an average value of 107 Ωm (Table 2). It has an average thickness of 65 m. The resistivity characteristic of the fourth layer showed that it is a sandy-clay formation (Fig. 5). It is overlying the fifth layer, whose resistivity ranged from 158 to 460 Ωm (Table 2).

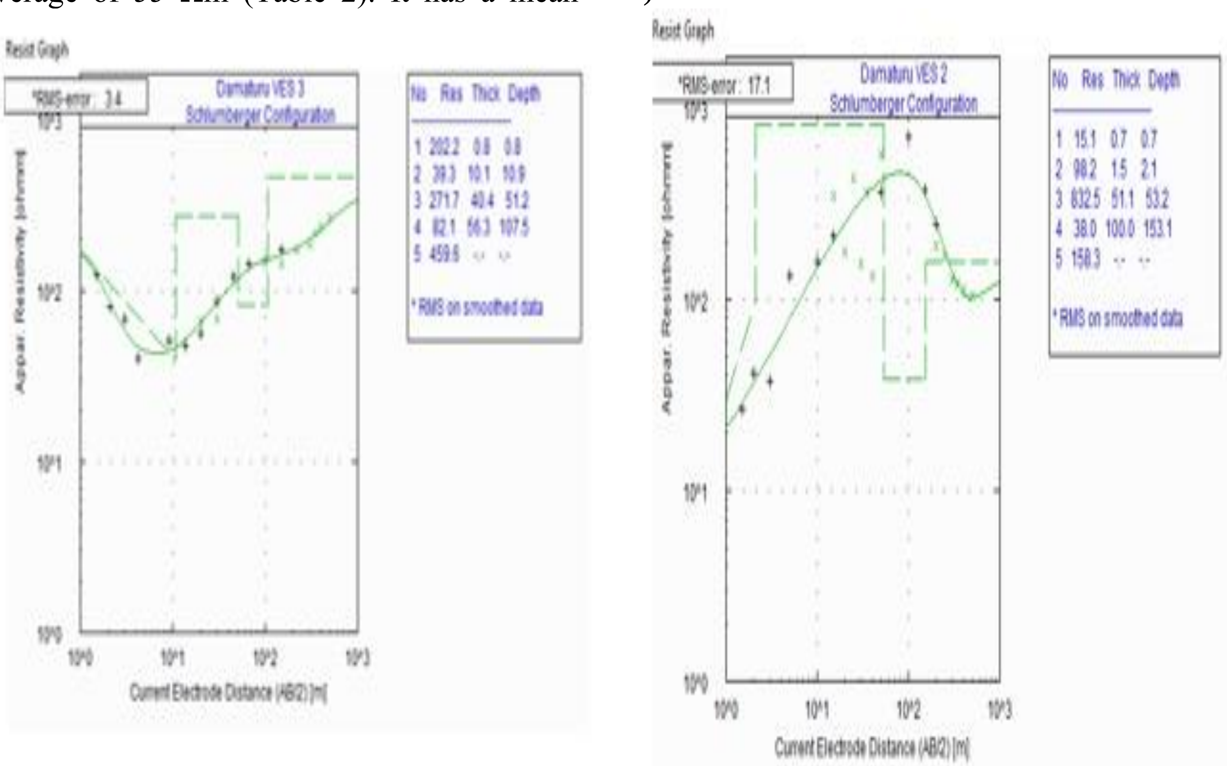

Fig. 3: Typical Curves obtained from the study area.
(The model curves showed that the study area is composed of five geologic layers)

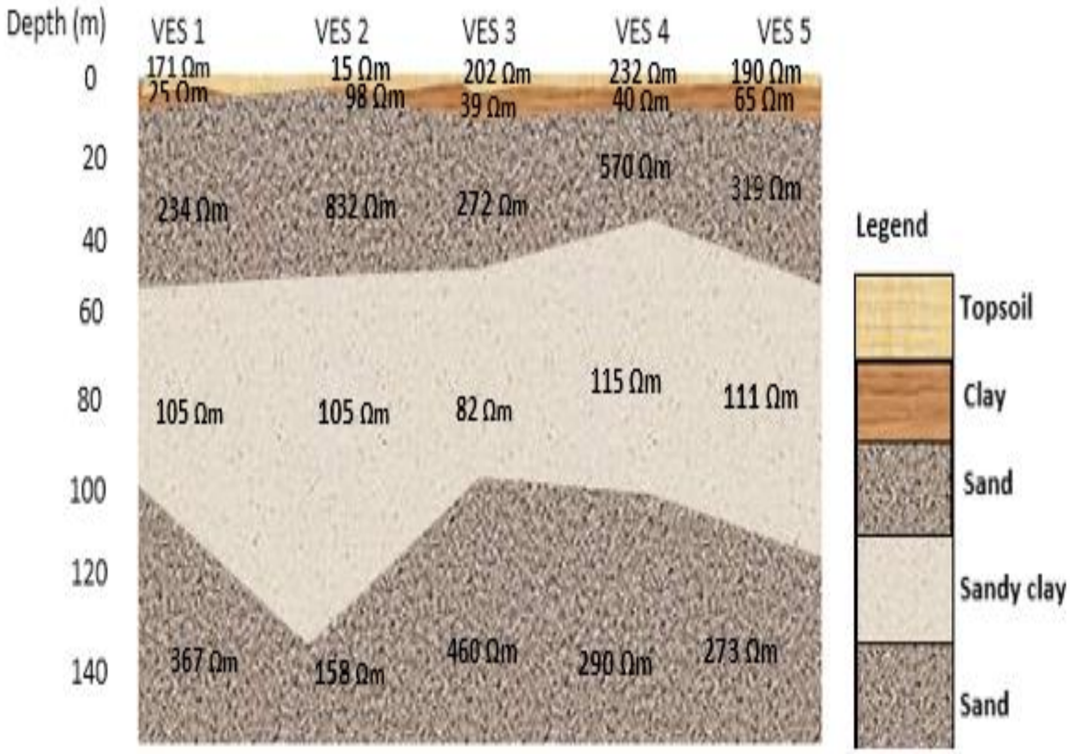

Fig. 4. Geoelectric Section of Profile 1
(The overburden thickness unit above the first Aquifer is relatively small along profile 1 and it accounts for the vulnerability of the Aquifer to contamination in the study area)

Table 2. Vertical electrical sounding results

VES	Layer Resistivity (Ωm)					Layer Thickness (m)				Depth (m)			
	$\rho 1$	$\rho 2$	$\rho 3$	$\rho 4$	$\rho 5$	$h1$	$h2$	$h3$	$h4$	$d1$	$d2$	$d3$	$d4$
1	171.2	25.3	234.5	105.5	368.8	1.0	7.0	48.8	53.4	1.0	8.0	56.8	110.2
2	15.1	98.2	832.5	38.0	158.3	0.7	1.5	51.1	100	0.7	2.1	53.2	153.1
3	202.2	39.3	271.7	82.1	459.6	0.8	10.1	40.4	56.3	0.8	10.9	51.2	107.5
4	232.0	39.9	570.0	115.0	290.0	0.9	6.4	30.8	74.2	0.9	7.3	38.1	112.3
5	190.0	65.3	319.0	110.6	273.2	0.8	10.6	44.0	74.8	0.8	11.4	55.4	130.2
6	117.5	84.0	208.0	118.5	247.7	0.9	12.6	67.7	80.4	0.9	13.5	80.5	160.9
7	154.0	55.2	213.4	106.2	200.8	1.1	11.5	40.0	56.3	1.1	12.6	52.6	108.9
8	125.4	76.0	190.3	119.7	301.4	0.7	12.0	61.2	50.6	0.7	12.7	73.9	124.5
9	114.1	25.4	156.0	101.5	282.1	0.9	10.6	56.6	67.4	0.9	10.6	67.2	134.6
10	219.0	75.4	195.5	120.2	340.3	1.3	6.2	48.3	49.8	1.3	7.5	55.8	105.6
11	176.2	47.8	432.5	114.5	304.0	1.1	8.2	53.1	68.2	1.1	9.3	62.4	130.6
12	146.1	50.6	240.0	127.1	289.5	1.2	8.5	62.0	55.8	1.2	9.7	71.7	127.5
13	109.5	29.0	285.2	115.0	213.8	0.8	6.9	44.7	58.7	0.8	7.7	52.4	111.1
14	130.0	31.5	214.3	120.0	281.9	1.0	9.5	52.0	65.2	1.0	10.5	62.5	127.7
15	199.7	81.6	274.0	117.3	203.3	0.8	11.4	46.9	62.3	0.8	12.2	59.1	124.4

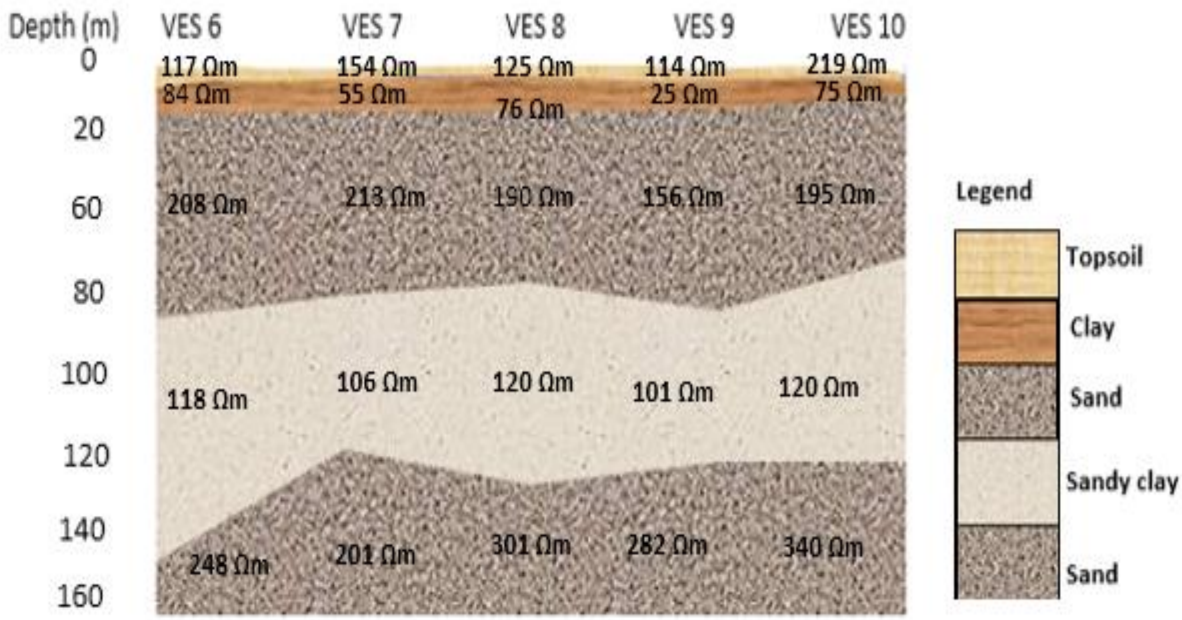

Fig. 5: Geoelectric Section of Profile 2.
(The geoelectric section of profile 2 showed that there is an increase in the overburden thickness overlying the Aquifer in some parts of the study area (vicinity of VES 7 to VES 10). In these areas, the first Aquifer is semi-confined and it is vulnerable to contamination)

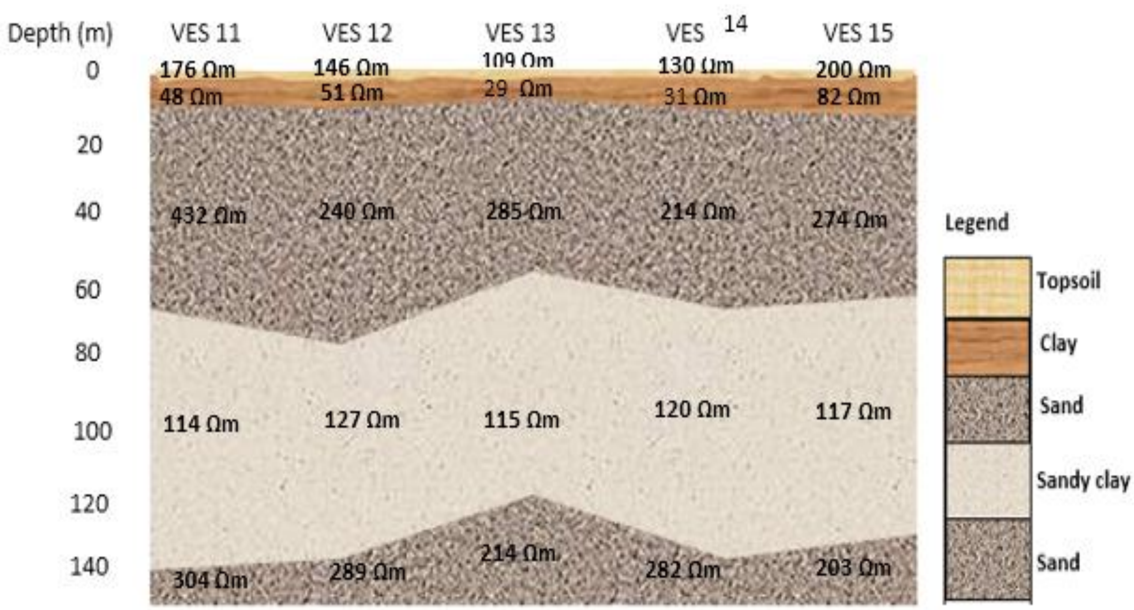

Fig. 6: Geoelectric Section of Profile 3
(The second Aquifer is confined by a very thick sandy clay formation. It is the most appropriate Aquifer for quality groundwater abstraction in the study area)

The fifth layer showed an average resistivity of 281 Ωm which indicates that it is a sandy formation (Fig. 2). It is the second Aquifer in the study area, which is confined by the overlying sandy-clay (Fig. 6). Although its thickness was not estimated due to its depth. From existing literature, it is the most reliable Aquifer for quality groundwater supply in the study area (Agada and Yakubu, 2022). The results of the vertical electrical sounding survey and the existing borehole logs in the study area also showed a significant correlation.

Dar Zarrouk parameters such as longitudinal resistance, longitudinal conductance, transverse resistivity and the coefficient of anisotropy (Table 3) were used to assess the nature of the materials overlying the mapped aquifers in the study area. The aquifer protective capacity was evaluated according to the standards used by Oladapo et al. (2004) and Henriet (1976). The results of the study showed that the aquifers in the study area were 93% good and 7% moderate (Table 3).

Table 3: Measured Dar Zarrouk Parameters for the study area

VES No.	Coordinates		Longitudinal Conductance, S_i (mΩ^{-1})	Protective Capacity Rating	Transverse Resistance (Ωm^2)	Aquifer Thickness (m)	Longitudinal Resistivity $\ell_L = \frac{h}{s}$ (Ωm)	Transverse Resistivity $\ell_t = \frac{T}{h}$ (Ωm)	Coefficient of anisotropy $\lambda = \sqrt{\frac{\ell_t}{\ell_L}}$
	Latitude (°N)	Longitude (°E)							
1	11.72734	11.97199	0.996784	Good	13319	56.8	56.98	234.5	2.029
2	11.72577	11.97331	0.754726	Good	44289	53.2	70.49	832.5	3.437
3	11.72844	11.97403	0.532145	Moderate	13911	51.2	96.21	271.7	1.680
4	11.72585	11.96227	0.863533	Good	21717	38.1	44.12	570.0	3.595
5	11.73335	11.97392	0.980780	Good	17673	55.4	56.48	319.0	2.376
6	11.73293	11.97510	1.161621	Good	16744	80.5	69.30	208.0	1.732
7	11.73274	11.97647	0.933049	Good	11204	52.6	56.37	213.0	1.944
8	11.73516	11.96974	0.907798	Good	14041	73.9	81.41	190.0	1.523
9	11.74613	11.98872	1. 452071	Good	10483	67.2	46.28	156.0	1.836
10	11.74726	11.98979	0.749532	Good	10909	55.8	74.45	195.5	1.620
11	11.74795	11.99094	0.896199	Good	26988	62.4	69.63	432.5	2.492
12	11.74778	11.98795	0.873555	Good	17208	71.7	82.08	240.0	1.710
13	11.76724	11.96846	0.912404	Good	14944	52.4	57.43	285.2	2.228
14	11.77396	11.97309	1.095263	Good	13394	62.5	57.06	214.3	1.938
15	11.76 892	11.97664	0.845997	Good	16193	59.1	69.84	274.0	1.980

The proximity of the first Aquifer to the surface in some parts of the study area is responsible for its susceptibility to contamination (Fig. 4). The contamination of groundwater, in most cases, starts from the ground surface. The contaminants, through the process of advection, diffusion and dispersion, migrate through the vadose zone to the Aquifer and thereby pollute the groundwater. The thickness of clay formation which is the second layer varies from one point to another in the study area. Contaminants from the surface mostly penetrate through cracks, fissures and joints into the aquifers, especially in areas where the thickness of the geologic material overlying the Aquifer is small. According to Oladapo *et al*. (2004), the geologic materials overlying an aquifer are natural filtering mechanism which helps to prevent percolating contaminants such as leachate and other toxic plumes from reaching the Aquifer. But in the absence of sufficient overburden, filtering materials such as clay or sandy clay, the Aquifer becomes much more vulnerable to pollution. The first Aquifer in the study area is less protected, considering the thickness of the overlying materials (Fig. 4).

The first Aquifer, which is both unconfined and semi-confined in some parts of the study area, is prone to pollution. The spatial distribution of the longitudinal conductance in the study area showed that the magnitude of the longitudinal conductance is higher towards the western part of the study area and it is lower towards the southern part (Fig. 7). The longitudinal conductance of the study area ranged from 0.53 to 1.45 mΩ^{-1}, with an average of 0.93 mΩ^{-1} (Table 3).

Some reports on the contamination of the groundwater in the study area gave credence to the results of this study that areas with moderate and good aquifer protective capacities are vulnerable to groundwater pollution (Emeka and Weltime, 2008; Kwaya *et al*., 2017; Agada and Yakubu, 2002). The transverse resistance in the study area ranged from 10483 Ωm^2 to 44289 Ωm^2 with an average of 17534 Ωm^2 (Table 3). These values indicate that the study area has good groundwater potential. The resistivity coefficient of anisotropy in the study area ranged from 1.5 to 3.6, with an average value of 2 (Fig. 8).

The values evaluated for the longitudinal resistivity ranged from 44 to 96 Ωm with an average of 66 Ωm. The transverse resistivity values of the study areas ranged from 156 to 832 Ωm, with an average value of 309 Ωm in the study area. The longitudinal resistivity and the transverse resistivity values were used to evaluate the coefficient of anisotropy of the study area (Table 3).

The values of the coefficient of anisotropy obtained in the study area reflected the nature of the subsurface of the study area. The range of the values of the coefficient of anisotropy of the subsurface indicates that the rocks in the study area were deposited in layers and they are stratified. (Fig. 8).

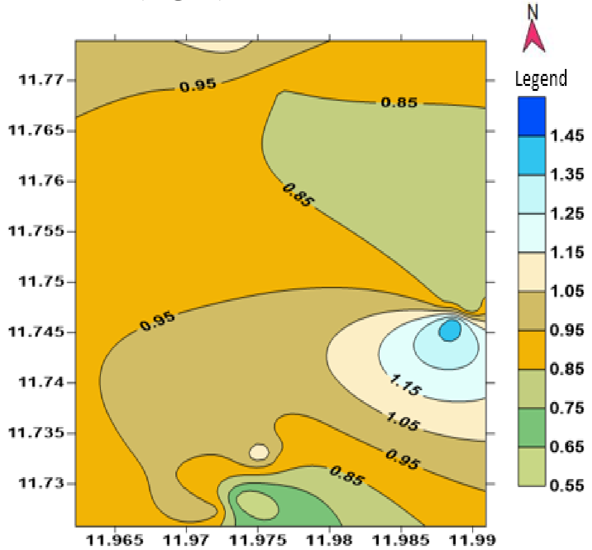

Fig. 7: Longitudinal conductance spatial distribution in the study area.

The iso-resistivity coefficient of the anisotropy contour map of the study area indicates that the area is a semi-flat terrain (Fig. 8). The coefficient of anisotropy in the study area increases towards the southwestern part.

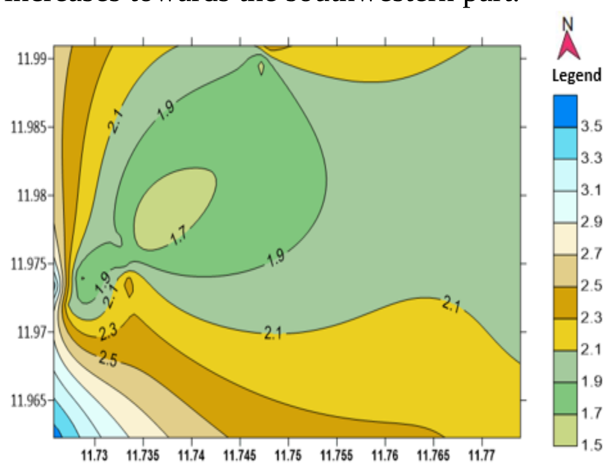

Fig. 8: Resistivity coefficient of anisotropy for the study area.

4.0 Conclusion

In this study, we investigated the aquifer vulnerability in Damaturu, Yobe State, Nigeria, using the electrical resistivity method. The results of the study showed that the first

Aquifer is vulnerable to pollution due to the thin size nature of the overburden unit. The second layer, which is overlying the first Aquifer in the study area, is relatively small in size and it could not provide enough protection for the underlying Aquifer. Therefore, the results of this study showed that most of the reported cases on the pollution status of groundwater in Damaturu and its environs may be true and are connected with the percolation of contaminants into the first Aquifer, which is the major source of water for domestic and cottage industrial purposes in the study area. Therefore, it is recommended that a detailed environmental impact assessment should be conducted on the study area.

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Consent for publication

Not Applicable

Availability of data and materials

The publisher has the right to make the data Public

Competing interests

The authors declared no conflict of interest.

Funding

There is no source of external funding.

Authors' contributions

The two authors contributed equally to the success of the study**.**