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Research Article

Geophysical Modeling to Determine Hydraulic Characteristics in Parts of Mani Town, North-western Nigeria

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ABSTRACT

Keywords:

Aquifer characteristics, Hydraulic parameters, VES, Transmissivity

Electrical resistivity data acquired in twenty one (21) locations using vertical electrical sounding method of Schlumberger array have been used to evaluate the aquifer hydraulic properties of a coarse granite formation in parts of Mani area, Nigeria. The aim of the study was to estimate hydraulic parameters for community water supply. The data acquired were processed, analyzed and interpreted using the curve matching method with the IPI2Win software to generate sounding curves and different geo-electric layers, their resistivities, thicknesses, and depths. The aquifer units were found in the weathered and fractured layers. The result showed that 42.9% of VES locations were dominated by H ($\rho_1 > \rho_2 < \rho_3$) type, indicating potential water sites. The aquifer resistivity varied from 34.08 to 331 Ωm , aquifer thickness ranged from 4.37 m to 19.5 m, depth to the aquifer ranging from 30.2 - 54.8 m. The transverse resistance (R) of the study area varied from 274.07 to 5343 Ωm^2 . Hydraulic conductivity ranged from 1.724 – 14.371 m/day with an average value of 4.768 m/day. The transmissivity (Tr) showed a high value of 119.854 m^2/day and a low value of 9.972 m^2/day . Effective porosity (Φ) varied from 27.951 to 37.493 %, aquifer permeability (k_p) revealed semi-permeable formation, aquifer storativity indicates a confined aquifer. The results of transmissivity magnitude of this study indicate that the aquifer can yield water only for small community. VES 2,4,7,10 and 17 were recommended for borehole drilling in the area.

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INTRODUCTION

Groundwater is a crucial freshwater resource that supplies one-third of all freshwater abstractions and is regarded as the second most important freshwater reservoir globally (Arabameri, *et al.*, 2019; Mishra, 2023). It is an essential component of geological formations found beneath the surface (Uc Castillo, *et al.*, 2022), and its occurrence and availability are influenced by several climatic, geographic factors and other human activities (Hu, *et al.*, 2024) such as lithology, drainage pattern, precipitation, temperature (Dey, *et al.*, 2023). Groundwater is necessary for human survival and the sustainability of global socioeconomic growth (Akingboye, *et al.*, 2022). According to recent hydrogeological studies, in many arid to semi-arid regions across the world, groundwater depletion is the most prevalent issue influencing water resources (Lian, *et al.*, 2021). Indeed, because of variable or decreasing rainfall, rising water levels, flooding, extended drought, modifications to the water cycle, and other mechanisms that rely on it, climate change is making water scarce in many areas (Nouradine, *et al.*, 2024). These situations result in scarce and irregular surface runoff in different regions. Groundwater then becomes the main available water resource that can be exploited. Unfortunately, these water sources are often characterized by low turnover rates and are highly sensitive to climate change (Hamdi and Goita, 2023).

Water scarcity is a significant problem particularly in developing nations where there are insufficient exploration methods and inadequate water supply to meet the population demand (Shandu and Atif, 2023). To effectively manage scarce groundwater resources, it is necessary to characterize the hydraulic properties of the aquifer (Udosen, *et al.*, 2024). Aquifer properties such as resistivity, thickness, permeability, porosity and aquifer yield control groundwater movement, availability, quality and potential (George, 2020). The aquifer hydraulic parameters can be estimated from the measured field parameters. These parameters vary spatially due to heterogeneity of the geology of an area (Elemile, *et al.*, 2020). In hydro-geophysics, the relationship between hydraulic conductivity which characterises the ease with which water flows in the subsurface and electric resistivity is important (Teikeu,

et al. 2012). Estimating hydraulic conductivity using resistivity measurements helps in the evaluation of groundwater potential; understanding the hydraulic response of the subsurface aquifer and estimating other hydraulic parameters (Ibuot, *et al.*, 2023).

Numerous researchers have utilized geophysical information in evaluating hydraulic parameters. Udosen, *et al.*, (2024) applied geo-electrical technique for estimating geo-hydraulic characteristics at a major coastal aquifer system in Uyo southern Nigeria. Ibuot, *et al.*, (2023) utilized resistivity data to evaluate hydraulic parameters of hydrogeological units in Uyo southern Nigeria. Other scholars combined pumping test with geophysical techniques such as Okamkpa, *et al.*, (2024) combined pumping test and geo-sounding data for determine aquifer geo-hydraulic properties and vulnerability characterization in south-eastern Nigeria. Musa, *et al.*, (2023) assessed groundwater potential and aquifer characteristics using inverted resistivity and pumping test data within Lokoja Area, North-Central Nigeria. Udeh, *et al.*, (2024) combined pumping test and geo-sounding data in Enugu and environs south-eastern Nigeria for estimating aquifer hydraulic characteristics. It is noteworthy that, despite the fact that numerous studies have been conducted in Nigeria, none have been conducted in the study area using any methodology. Therefore the adoption of electrical resistivity method in aquifer geohydraulic characteristics estimation is a novel idea since no research has done in the study area. The electrical resistivity approach has been shown to be effective in describing the pore characteristics of subsurface aquifers and the mechanism of electrical conduction across the subsurface (Ojo, *et al.*, 2024; Salami, *et al.*, 2024). The information generated by the electrical resistivity data helps to define the distribution and aquifer repositories (Ibuot and Obiora, 2021).

The growing demands for freshwater in both rural and urban areas necessitates exploring alternative sources of renewable groundwater resources (Benjmel, *et al.*, 2022; Echogdali, *et al.*, 2023). The Mani area in Katsina state is among the areas faced by water challenges as the demand is always increasing to satisfy the growing needs. The frequency of abundant boreholes and the scarcity of portable water in the study area is the motivation for this study.

About 40% borehole failure rate has been reported in the study area (Nova-Drill 2023, verbal communication). It is therefore important to understand the geological formation for proper groundwater management and supply. The aim of the study is to estimate the aquifer hydraulic properties from electrical resistivity data for sustainable groundwater management.

MATERIALS AND METHODS

Description of the Study Area

Mani town is situated in the northern part of Nigeria between latitude $12^{\circ}50'0''$ to $12^{\circ}52'0''$ and longitude $7^{\circ}52'0''$ to $7^{\circ}53'0''$. The study area has two distinct seasons, these two seasons cover rainy season (June – October)

and dry season (November – May) (Mukhtar, *et al.*, 2016). The study area receives an average annual rainfall of about 650 to 700 mm. Temperature of the area is high in almost all part of the year, with maximum temperature of about 41°C or higher recorded in the second quarter of the year and the minimum day temperature of about 22°C or lower in the late fourth quarter and the beginning of the first quarter of the year. The study area compose of Sudan Savannah vegetation belt, with scanty trees, shrubs and short grasses. As per Abdulkadir, *et al.*, (2023) the soil of the study area is ferruginous tropical soil (undifferentiated). The major land use in the area are residential and agricultural.

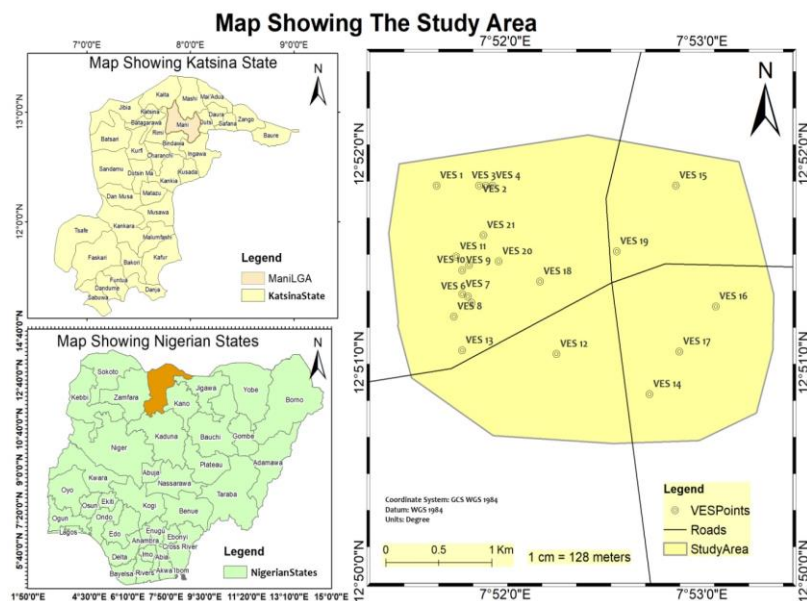


Figure 1: The study area map with VES locations.

Geology and Hyrogeology

Geologically, about 95% of the state is underlined by the Basement Complex which is characterized by nine geological formations consisting of biotite homeblend granite, coarse biotite homeblend granite, fine grained, granite gneiss, migmatite, porphyritic gneiss, rhyolite, sandstone and Solicted sheared rock. The area considered in this research, Mani town which is the headquarter of Mani Local Government area is underlain by coarse biotite homeblend granite and sandstone (Abdulkadir, *et al.*, 2023). The hydrological setting of the study area is typical of any basement complex terrain in the state and ground water in such terrain is usually found in the fractured zones and weathered basement. Occurrences of groundwater are rather shallow and its movement is controlled largely by topography.

At bedrock depressions in a typical basement complex just like in the study area in Nigeria are groundwater collecting centres. Consequently, the groundwater flows away from the crust of the basement ridges into bedrock depressions (Kasidi and Victor, 2019). The study area is drained by three rivers which include river Mailaba, river Aliyaba and River Hamceta and their tributaries. At the western part, river Aliyaba and its tributaries drained (flows) from south to north. However all the seasonal rivers systems that contain water in their channels only during the rainy season, with little or no water in the dry season.

Data collection, processing and analysis

Vertical electrical sounding (VES) was carried out using ABEM Terrameter SAS 4000 in twenty-four (24) locations within the study

area. The VES points were selected randomly based on the availability of space for spreading. Global Positioning System (GPS) was used to take the coordinate of each sounding point, Schlumberger electrode configuration was adopted with current electrode spacing (AB/2) ranging from 1m to 100 m while potential electrode spacing (MN/2) ranged from 0.5 m to 5 m. The values of resistance (R) were obtained directly from the resistivity meter, and the product of resistance (R) obtained and geometric factor (K) gives the apparent resistivity (ρ). The value of apparent resistivity (ρ) against half-

$$\rho_a = \pi \cdot \left(\frac{(AB/2)^2 - (MN/2)^2}{MN} \right) R_a \dots\dots\dots i$$

The transverse resistance R is given by:

$$R = \sum_{i=1}^n h\rho \dots\dots\dots ii$$

where h and ρ are respectively the thickness and resistivity of the ith layer in the section.

Hydraulic conductivity can be determined using:

$$K = 386.40 R_{rw}^{-.93283} \dots\dots\dots iii$$

where K = hydraulic conductivity and R_{rw} = aquifer resistivity.

The aquifer transmissivity (Tr) was estimated using the relation (Niwas and Singhal, 1981):

$$Tr = K\sigma T = KS/\sigma \dots\dots\dots iv$$

where r is the electrical conductivity (inverse of resistivity), S is the longitudinal conductance and T is the transverse resistance. Equations (iii) and (iv) were used in this study to determine the hydraulic conductivity and transmissivity of aquifers.

electrode spacing (AB/2) was first plotted manually on a logarithmic graph, and the graphs were interpreted using master curves and auxiliary charts (Orellana and Mooney 1966). Output from the quantitative manual interpretation was modelled using computer software. The IPI2Win version 1.0 interpretation software was used for the iteration and presentation of the curve in order to generate the geoelectric parameters. Equation i transformed the measured apparent resistance Ra to their corresponding apparent resistivity pa in the geological province.

The porosity ϕ is given as:

$$\phi = 25.5 + 4.5 \ln K \dots\dots\dots v$$

where K is the hydraulic conductivity.

Permeability k_p is given as:

$$k_p = K \cdot \mu_d / \delta_w \cdot g \dots\dots\dots vi$$

where K is the hydraulic conductivity, μ_d is the dynamic water viscosity, which is given as 0.0014 kg/m according to Fetter (1994), δ_w is the density of water taken as 1,000 kg/m³ and g is the acceleration due to gravity taken as 10 m/s².

Aquifer storativity is estimated using equation:

$$S = 3 \times 10^{-6} h \dots\dots\dots vii$$

where S and h are the storativity and thickness (m) of the aquifer. For unconfined aquifers is usually used $S = 3 \times 10^{-3} h \dots\dots\dots viii$

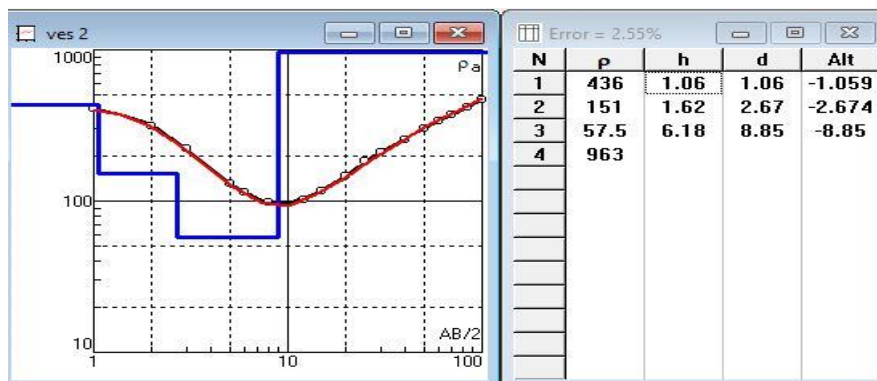


Figure 2: Resistivity curve of VES 3

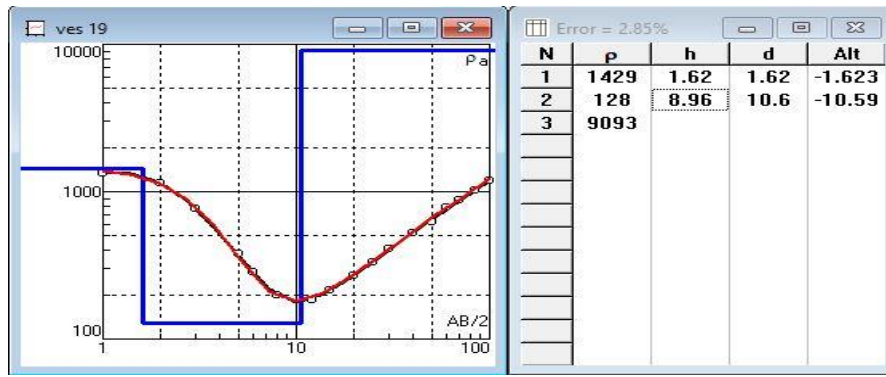


Figure 3: Resistivity curve of VES 19

RESULTS AND DISCUSSION

The obtained aquifer resistivity varied from 34.08 to 331 Ωm with the average value of 148.97 Ωm (Table 2). High aquifer resistivity value was recorded at VES 9 and lowest value was observed at VES 8. The variations in aquifers’ resistivity values may perhaps be attributed to the varying degrees of water–rock interaction, porosity, and permeability of the weathered soil materials (George, *et al.*, 2018; Akingboye, *et al.*, 2022). As far as groundwater is concerned, aquifer thickness is closely associated with the transmissivity and storativity of any terrain. It is seen from Table 3 that the thickest aquifer observed was at VES 13 with a thickness of 19.5 m, and lowest thickness at VES 1 with the value of 4.37 m. An average aquifer thickness of 10.617 m was

recorded in the study area. Depth to aquifer ranged from 8.09 to 26.9 m with the mean value of 14.76 m. The transverse resistance (R) of the study area ranged from 274.07 to 5343 Ωm² with the mean value of 1643.021 Ωm² (Table 2). The spatial distribution of the transverse resistance is shown in Fig. 4. Highest value of transverse resistance was observed around the extreme corner of southwestern part of the study area and lowest values were observed around the north, eastern area and some part of the central portion of the study area. This indicates that the western part of the study area has high thickness, and it can be assumed that these areas may likely have high transmissivity and high yield of aquifer units. This result is in agreement with the findings of Ankidawa, *et al.*, (2023).

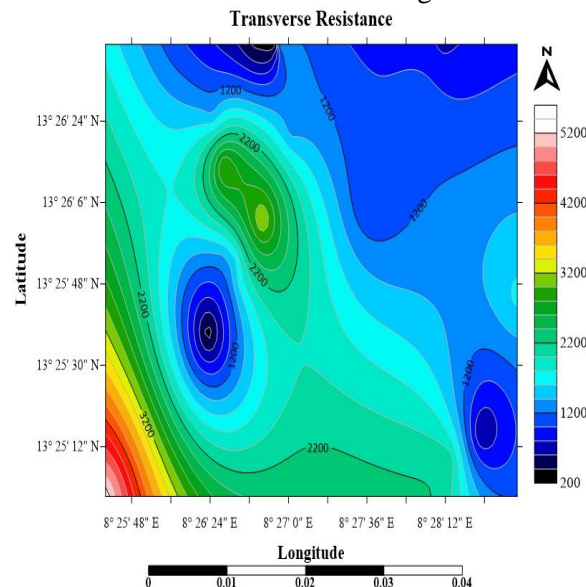


Fig. 4: Spatial distribution of transverse resistance

Hydrogeologic parameters, hydraulic conductivity (K) is a measure of the ease with which a fluid will pass through a medium

(Heigold, *et al.*, 1979). The aquifer hydraulic conductivity (K) ranges from 1.724 – 14.371 m/day (Table 2). The high range of hydraulic

conductivity of the aquifer may be due to the heterogeneity nature of the aquifer, a condition responsible for wide range in hydraulic conductivity (George *et al.*, 2015). The spatial distribution of hydraulic conductivity (Fig. 5) revealed low hydraulic conductivity values in the majority part of the area, indicates locations where fluid flow is slow and

complex. Low K values may be attributed to poor communication channels in the pore spaces and the variation in grain size. However, areas with high aquifer conductivity are usually associated with high hydropower flow values, thus indicating areas with high groundwater potential as observed by Akakuru, *et al.*, (2023).

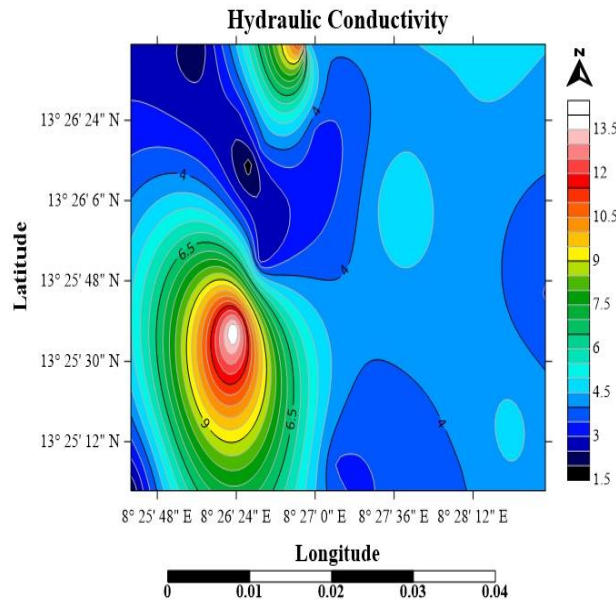


Fig. 5: Spatial distribution of hydraulic conductivity.

The transmissivity (Tr) value varied from 9.972 – 119.854 m²/day with an average value of 46.574 m²/day (Table 2), Area with high transmissivity values can be identified as area of high water bearing potential and aquifer materials are known to be relatively permeable to fluid flow. Based on transmissivity magnitude (Table 1) the surveyed area indicates that the aquifer can only provide

water for small community. The spatial distribution map of transmissivity was shown in Fig. 6. Low transmissivity values was observed at the extreme corner of northwestern part and higher values at the south-western part of the study area. The areas with high transmissivity can be attributed to having thick weathered basement thus, indicating that the area is of moderate groundwater potential.

Table 1: Classification of transmissivity magnitude (after Krasny, 1993).

T (m ² /day)	Aquifer potential	Groundwater supply potential
> 1000	Very high	Regional importance
100 – 1000	High	Lesser regional importance
10 – 100	Intermediate	Local supply for a small community
1– 10	Low	Private consumption
0.1 – 1	Very low	Limited consumption
< 0.1	Negligible	Impermeable sources for difficult groundwater supply

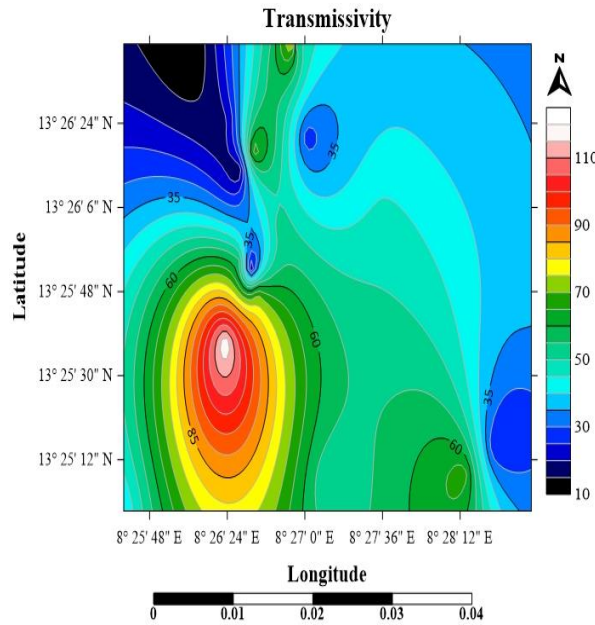


Fig. 6: Spatial distribution map of transmissivity.

The estimated value of effective porosity for aquifer in the study area ranged from about 27.951 – 37.493 % with the mean value of 31.856 % (Table 2). The measured range of values for the porosity depicts the presence of earth materials, such as clayey, sandy, and lateritic strata. The spatial distributions of porosity (Fig. 7) have a good correlation with hydraulic conductivity and transmissivity (Fig. 5 and 6). High porosity values were observed around extreme north central and

southwestern part of the study area and lower values were found around extreme northwest and southwest portion. Majority of the study area was dominated by moderate porosity. The high and low values correlate well with the presented sections of high and low K and T values recorded above. Therefore, aquifers with high K, T, ϕ , and k_p are suggestive of moderate to high yield, especially the southwestern and north western portion of the study area with higher overburden thickness.

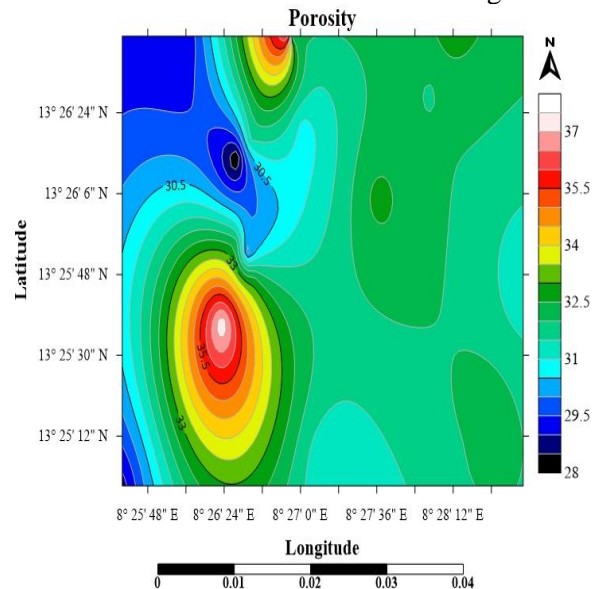


Fig. 7: Spatial distribution map of effective porosity

Permeability (k_p) values ranged from 1.2351e7 to 6.9804e7 μm^2 with the average value of 4.5763e7 μm^2 (Table 2). Spatial distribution

map revealed higher values at the central, northeastern and southeastern part of the study area while low values were observed at the

southwestern and northern part (Fig. 8). The obtained k_p values revealed that the geological formation of the study area is semi-permeable constitutes of sands and jointed crystalline rocks. The low permeability will affect the groundwater flow and vice versa. Singh (2005), observed that the k_p of the weathered

aquifer in hard rock and the alluvium aquifer increases exponentially with an increasing resistivity, but their T values decrease exponentially. However, in the case of fractured and sandwiched aquifers, transmissivity increases exponentially with increasing resistivity.

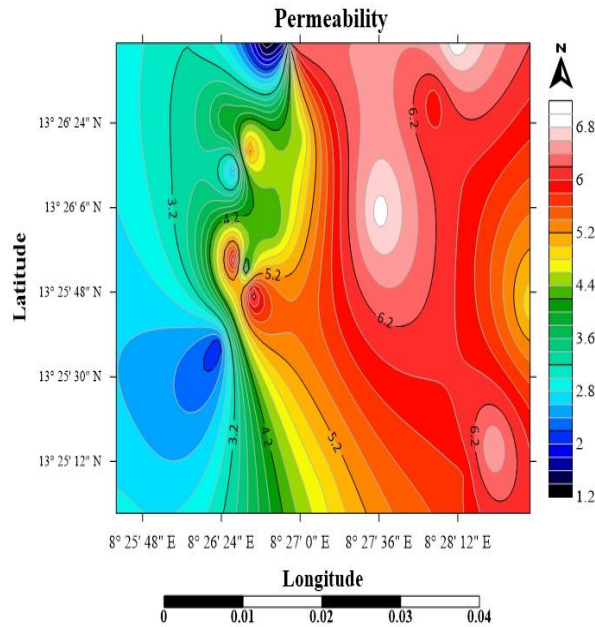


Fig. 8: Spatial distribution map of permeability

Table 3: Summary of aquifer geo-hydraulic parameters of the study area.

VES No.	Long. (°E)	Lat. (°N)	ρ (Ω m)	h (m)	d (m)	R (Ω m ²)	K (m/day)	Tr (m ² /day)	Φ (%)	Kp (μ m ²)	S (3×10^{-6})
1	7°86'08"	12°86'41"	245	4.37	8.1	1070.65	2.282	9.972	29.213	3.1948 e7	0.00001311
2	7°86'44"	12°86'41"	57.5	6.18	8.85	355.35	8.822	54.52	35.298	1.23508 e7	0.00001854
3	7°86'50"	12°86'41"	42.1	6.51	8.09	274.071	11.799	76.811	36.606	1.65186 e7	0.00001953
4	7°86'56"	12°86'41"	115.8	11.6	13.61	1343.28	4.591	53.256	32.358	6.4274 e7	0.0000348
5	7°86'38"	12°85'48"	115	14.8	16.23	1702	4.621	68.391	32.392	6.475 e7	0.0000444
6	7°86'35"	12°85'53"	213	7.13	10.42	1518.69	2.600	18.538	29.8	3.64 e7	0.00002139
7	7°86'30"	12°85'55"	119	12.1	14.52	1439.9	4.476	54.16	32.244	6.2664 e7	0.0000363
8	7°86'23"	12°85'37"	34.08	8.34	9.46	284.227	14.371	119.854	37.493	2.0119 e7	0.00002502
9	7°86'30"	12°85'74"	331	9.23	15.27	3055.13	1.724	15.913	27.951	2.4136 e7	0.00002769
10	7°86'36"	12°85'78"	141	18	21.4	2538	3.821	68.778	31.532	5.3494 e7	0.000054
11	7°86'25"	12°85'85"	192	7.44	10.9	1428.48	2.865	21.316	30.237	4.011 e7	0.00002232
12	7°87'10"	12°85'07"	158	14.5	15.4	2291	3.436	49.822	31.054	4.8104 e7	0.0000435
13	7°85'36"	12°85'01"	274	19.5	24.6	5343	2.056	40.092	28.743	2.8784 e7	0.00001585
14	7°87'88"	12°84'75"	112	5.18	9.82	580.16	4.737	24.538	32.499	6.6318 e7	0.00001554
15	7°88'11"	12°86'41"	106	7.04	8.12	746.24	4.986	35.101	32.73	6.9804 e7	0.00002112
16	7°88'45"	12°85'45"	157	10.6	16.31	1664.2	3.456	36.634	31.081	4.8384 e7	0.00003118
17	7°88'14"	12°85'09"	130	16.4	23.7	2132	4.122	67.601	31.874	5.7708 e7	0.0000492
18	7°86'96"	12°85'65"	107	9.4	24.7	1005.8	4.943	46.464	32.691	6.9202 e7	0.0000282
19	7°87'61"	12°85'89"	128	8.96	10.6	1146.88	4.182	37.471	31.939	5.8548 e7	0.00002688
20	7°86'61"	12°85'81"	167	8.17	12.96	1364.39	3.263	26.659	30.822	4.5682 e7	0.00002451
21	7°86'48"	12°86'02"	184	17.5	26.9	3220	2.981	52.168	30.415	4.1734 e7	0.0000525
Min			34.08	4.37	8.09	274.07	1.724	9.972	27.951	1.2351e7	0.0000131
Max			331	19.5	26.9	5343	14.371	119.854	37.493	6.9804e7	0.0000540
Mean			148.97	10.617	14.76	1643.021	4.768	46.574	31.856	4.5763e7	0.00002979

ρ = aquifer resistivity, h = aquifer thickness, d = aquifer depth, R = transverse resistance, K = hydraulic conductivity, Tr = transmissivity, Φ = effective porosity, Kp = permeability, S = storativity.

The estimated values of aquifer storativity revealed the ranged of 0.0000131 to 0.0000540 with the mean value of 0.00002979. The spatial distribution map (Figure 9) shows highest values at the central and southern part while lowest values were

observed at the extreme northwest and southwestern portion. This is consistent with the typical storativity range of 5×10^{-5} to 5×10^{-3} for a confined aquifer (Todd 1980). These findings is contrary to the previous studies done by Akakuru, *et al.* (2023).

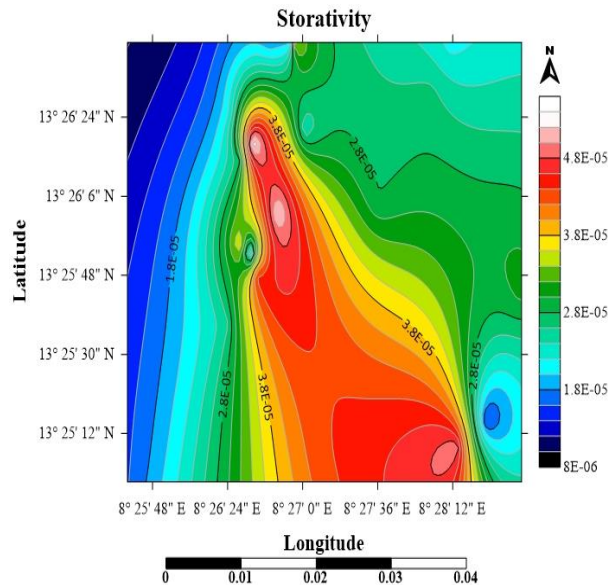


Fig. 9: Spatial distribution map of storativity

CONCLUSION

Hydraulic characteristics of aquifer system in parts of Mani town, Katsina state north-western Nigeria using electrical resistivity method have been studied. The survey results demonstrate the importance of electrical resistivity surveys for the quantitative estimation of aquifer hydraulic parameters. The aquifer units were found in the weathered and fractured layers. The result revealed the domination of H-curve type, indicating potential water sites. The aquifer resistivity, thickness and depth varied from 34.08 to 331 Ω m, 4.37 m to 19.5 m and 30.2 to 54.8 m respectively. Aquifer permeability (k_p) revealed semi-permeable formation, aquifer storativity indicates a confined aquifer. Hydraulic conductivity indicated slow and complex fluid flow. The transmissivity of the study area indicates the aquifer can only supply water for small community. It is recommended that VES 2,4,7,10 and 17 should be considered for borehole drilling in the area.

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