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ORIGINAL RESEARCH ARTICLE

Characterization and Delineation of Aquifer Potential Zones in Basement Terrain in Parts of Mani Town, Katsina State, Nigeria

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ABSTRACT
Aquifer characteristics play a major role in the identification of potential zones. A geophysical investigation was carried out to characterize aquifer parameters and identify potential zones in Mani town of Katsina state utilizing Vertical Electrical Resistivity (VES) techniques. Aquifer parameters: aquifer resistivity, aquifer thickness, aquifer depth, transverse resistance, hydraulic conductivity, and transmissivity were evaluated in order to characterize and delineate aquifer potential zones for water supply. A total of 21 VES was carried out using the Schlumberger electrode array. Five model curve types were generated with the percentage distribution in the order of H > A > QH > HA > AK for the modeled curve types. The aquifer layer was identified mostly along the third layer with resistivity values ranging from 34.08 to 331 Ωm, and aquifer thickness ranged from 4.37 m to 19.5 m, with depth to the aquifer ranging from 30.2 to 54.8 m. The transverse resistance (R) of the study area ranged 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) value ranges from 9.972 – 119.854 m^2/day, with an average value of 46.574 m^2/day. The potentiality of the aquifer units of the study area indicated low to moderate potential zones. VES 2, 3, 4, 5, and 7 were recommended for groundwater exploration and management.

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Aquifer characteristics, Basement terrain, Hydraulic conductivity, Mani area, Transmissivity.

INTRODUCTION

The area around Mani has very little surface water readily accessible; thus, more groundwater must be extracted to fulfil the growing demand. Given its reputation as a consistent source of fresh water, groundwater will increasingly become more in demand in the years to come. Due to factors including population growth, unrestrained land use, intensive agricultural methods, industrial expansion, growing pumping facilities, and widespread domestic groundwater usage, this increased reliance on groundwater would have a significant effect on the aquifers (Baig *et al.,* 2023). Demand for groundwater will put more and more strain on the groundwater reservoirs due to the rapid climate change scenarios and the rising frequency of drought events (Lukac Reberski *et al.,* 2020). Accordingly, there could be significant effects of climate change on groundwater resources, potentially affecting several aspects of geography and hydrology (Sherif, *et al.,* 2023). Variations in surface runoff, for example, especially in semi-arid and arid regions, reduce recharging (Baig *et al.,* 2023).

The distribution of groundwater is ascribed to weathering-related fractures and faults, particularly in the basement complex rocks. In crystalline rocks, aquifers are contained in weathered layers or fractured layers. Sometimes, the best conditions for groundwater accumulation require a mix of weathered layers and fractured bedrock (Adagunodo *et al.,* 2017; Mogaji and Omobude, 2017; Musa *et al.,* 2023). Geologically, such fractured and weathered formations are known as aquifer formations (Ojoawo and Adagunodo, 2023). According to Satpathy and Kanungo (1976), Bala and Ike (2001), and Mogaji and Omobude (2017), such possible aquifer formations, which can either be unconfined or confined types in a complex geologic terrain, are often localized and discontinuous. The different physical characteristics of these previously stated aquifer types, such as transmissivity, permeability, and porosity, among others, greatly influenced an area's groundwater potential (Faleye and Olorunfemi, 2015).

In subsurface investigations, the potentials of the geophysical approach have proven extremely significant (Dong *et al.,* 2024; Idowu and Ojo, 2024). This might not be unrelated to its special non-invasive/non-destructive, less dangerous, and affordable qualities (Mogaji *et al.,* 2015; Olayanju *et al.,* 2017). Additionally, groundwater resource exploration has come to widely accept the use of geophysical techniques (Li *et al.,* 2024; Tyagi and Haritash,

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2024). For the effective investigation of groundwater, a number of geophysical techniques (including electromagnetic, magnetic, electrical resistivity, seismic refraction, magnetotelluric, and gravity) have been used, either singly or in conjunction with other approaches (Obasi *et al.,* 2021; Musa *et al.,* 2023). Among these aforementioned prospective geophysical methods, the direct-current electrical resistivity (ER) method is the most highly efficient in groundwater studies (Falowo, 2022; Falowo *et al.,* 2023). Because of its distinctiveness in the realm of hydrogeophysics, the ER approach can map both geological strata and identify the kind and makeup of underground formations that are not visible (Mogaji and Omobude (2017).

The ability of the water supply to service many needs has been overworked, leading to scarcity. This can be explained by a number of factors, such as population growth, climate change, ecological degradation, poor and insufficient established capacity, and increasing rates of poverty in the country (Akaolisa *et al.,* 2022; Adewumi *et al.,* 2023). The limited water supply is under stress due to the rapid population development, making it challenging to meet growing needs. Mani town lacks pipe-borne water. As a result, there is no supply of fresh water from any source, and the area also lacks surface water. The area experiences borehole failures due to a lack of knowledge of the hydrogeological setting and insufficient investigation methods, despite the fact that some deep wells operate primarily by chance rather than scientific investigation methods. Research on electrical resistivity methods for exploring groundwater at Mani town remains very limited. Therefore, there is a need to explore groundwater prospecting zones using the vertical electrical sounding method in order to minimize the risk of borehole failures and meet water demand in the area. The study aimed to delineate aquifer potential zones using the electrical resistivity method in the area.

MATERIALS AND METHODS

Study Area and Geological Setting

Mani town is the study area, located in the northern region of Nigeria's crystalline basement terrain. It is found between latitude 12°50'0" to 12°52'0" and longitude 7°52'0" to 7°53'0". The landscape of the area is highly dominated by plain. It belongs to the tropical continental (wet and dry) climatic zone of northern Nigeria, characterized by short wet and long dry seasons, with a very high annual temperature range (Mukhtar *et al.,* 2016). The study area receives a few months of annual rainfall, normally between June and October, having an average of about 650 to 700 mm. The temperature of the area is high in almost all parts of the year because of its position in the tropical region, with a maximum temperature of about 41°C or higher recorded in the second quarter of the year and a 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 recorded lower relative humidity in April to May, ranging between 10-15%, that is when the atmosphere is most dry compared to its higher value of 70-80% in August/September when the highest amount of rainfall is received during the year (Inkani, 2015). The study area is composed of a 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 is residential.

Geologically, about 95% of the state is underlined by the Basement Complex, which is characterized by nine geological formations consisting of biotite hornblende granite, coarse biotite homeblend granite, fine-grained, granite gneiss, migmatite, porphyritic gneiss, rhyolite, sandstone and Solicited sheared rock. The area considered in this research, Mani town, which is the headquarters of the 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 groundwater 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. In the western part, river Aliyaba and its tributaries drained (flows) from South to north. However, all the seasonal river systems 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-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.

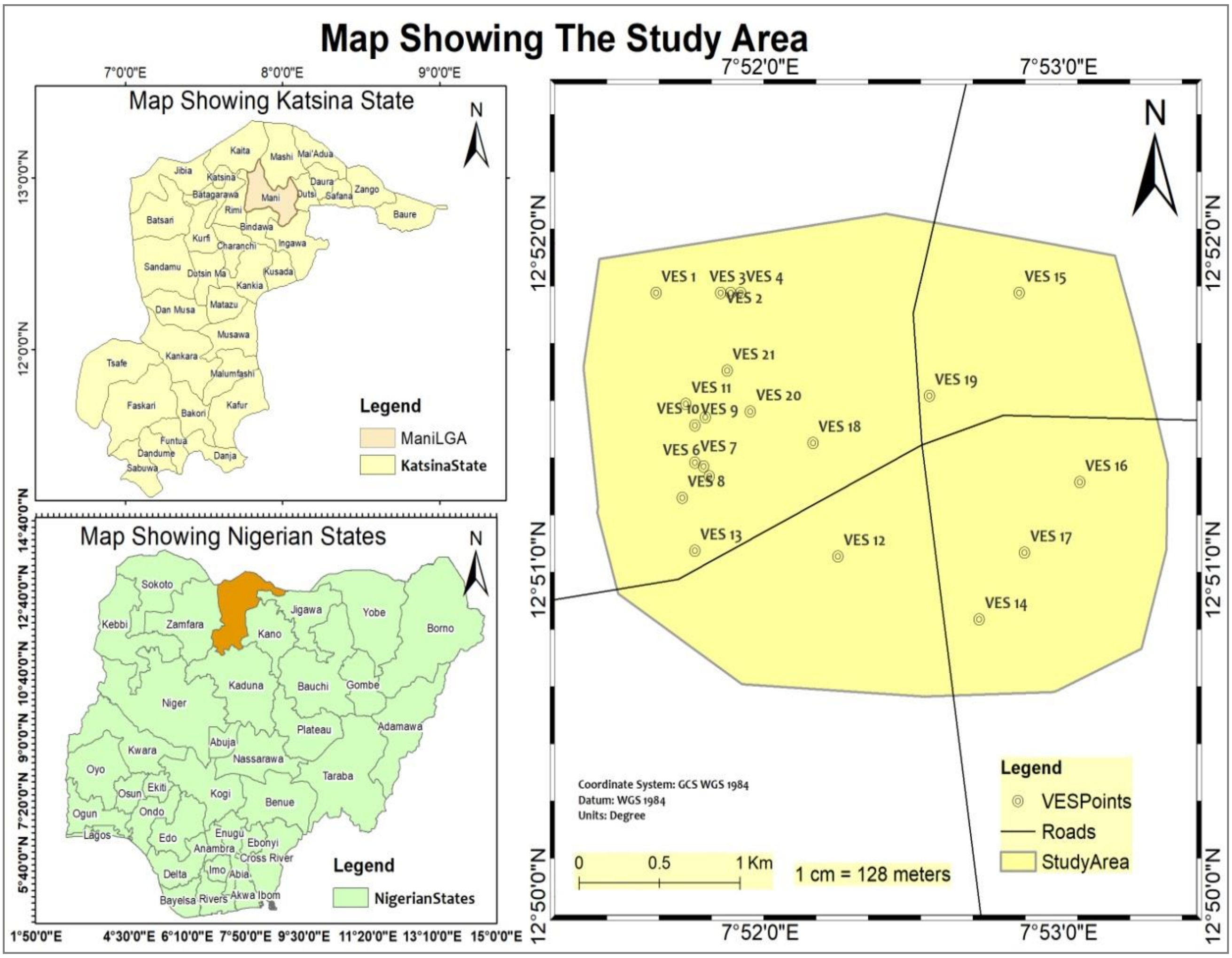


Figure 1. The study area map.

$$\rho a=\pi.\left(\frac{\left(\frac{AB}{2}\right)^{2}-\left(\frac{AB}{2}\right)^{2}}{MN}\right)R \quad \dots\dots\dots\dots\dots\dots i$$

The transverse resistance R is given by:

$$R = \sum_{i=1}^{n} hp \quad \dots\dots\dots ii$$

The longitudinal conductance S can be estimated using equation vi.

$$S = \sum_{i=1}^{n} h/p \quad \dots\dots\dots iii$$

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

Hydraulic conductivity can be determined using:

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

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

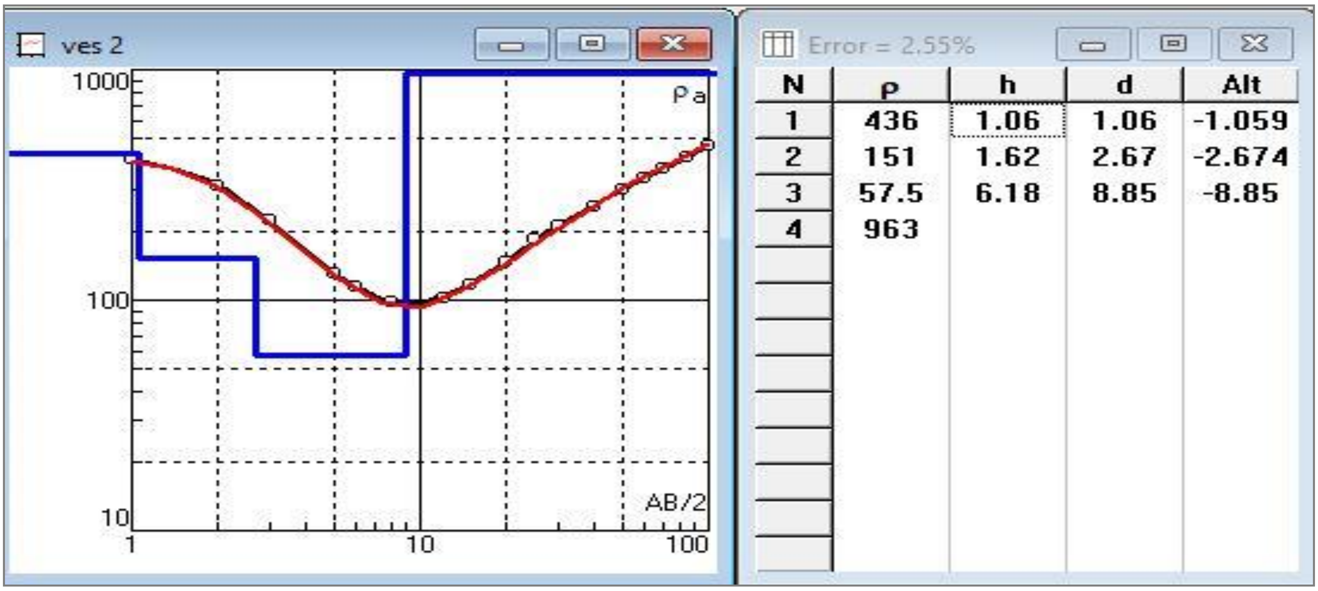
The aquifer transmissivity (Tr) was estimated using the relation (Niwas and Singhal, 1981):

$$Tr = K\sigma T = KS/\sigma \quad \dots\dots\dots v$$

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.

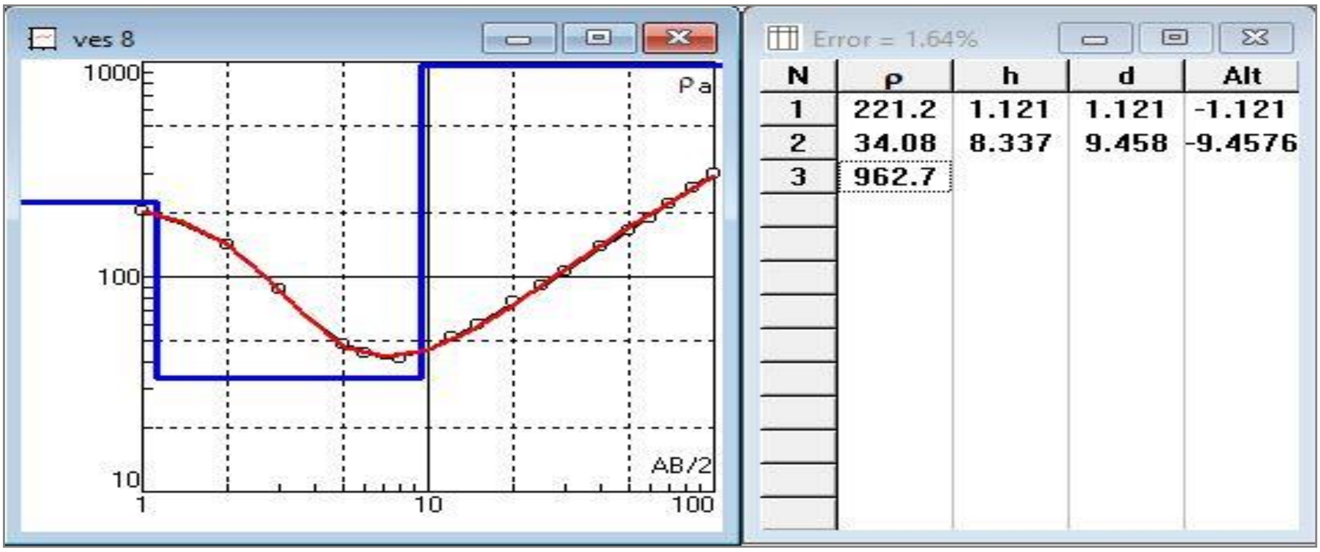
Table 1. Transmissivity/aquifer potential scale (after Gheorghe, 1978).

S/no	Range	Potential	Remark	% of VES
1	> 500 m²/day	High potential	None	0%
2	50 – 500 m²/day	Moderate potential	VES 2, 3, 4, 5, 7, 8, 10, 17, 21	42.9%
3	5 – 50 m²/day	Low potential	VES 1, 6, 9, 11, 12, 13, 14, 15, 16, 18, 19 & VES 20	57.1%
4	0.5 – 5 m²/day	Very low potential	None	0%
5	<0.5 m²/day	Negligible potential	None	0%



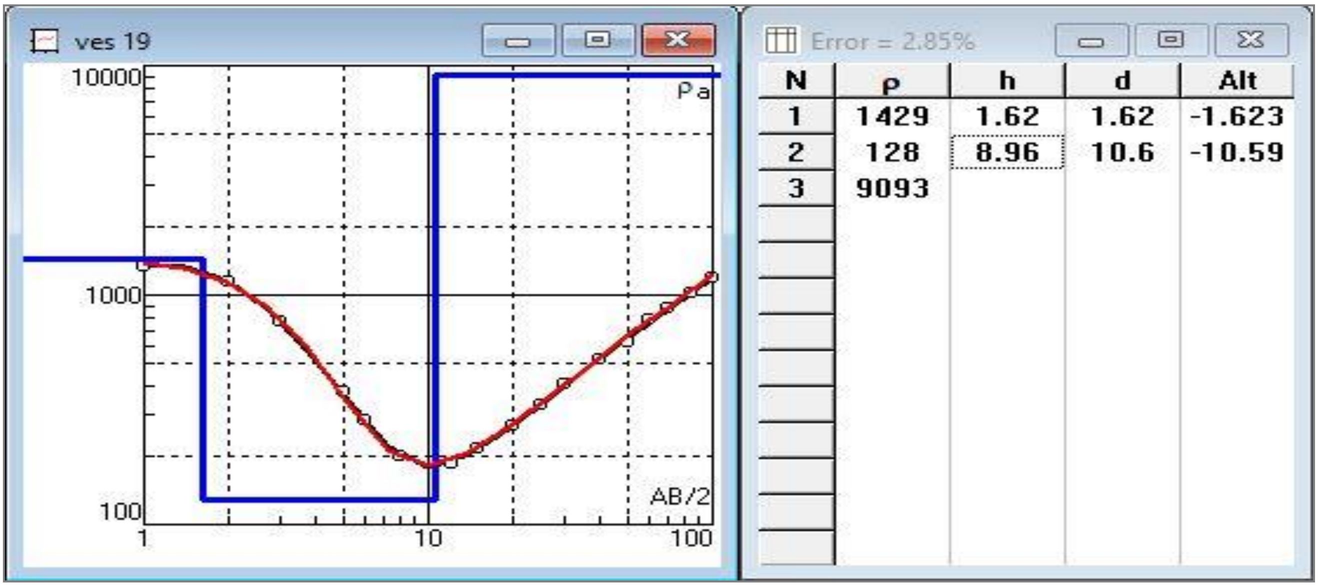
N	ρ	h	d	Alt
1	436	1.06	1.06	-1.059
2	151	1.62	2.67	-2.674
3	57.5	6.18	8.85	-8.85
4	963			

Figure 2: Resistivity curve of VES 3



N	ρ	h	d	Alt
1	221.2	1.121	1.121	-1.121
2	34.08	8.337	9.458	-9.4576
3	962.7			

Figure 3: Resistivity curve of VES 8



N	ρ	h	d	Alt
1	1429	1.62	1.62	-1.623
2	128	8.96	10.6	-10.59
3	9093			

Figure 4: Resistivity curve of VES 19

RESULTS AND DISCUSSIONS

The resistivity curve model results are summarized and presented in Table 2. Five VES models were generated in this study: H, A, QH, HA, and AK. Table 2 revealed the interpretation of VES curve types. The H curve type has the highest frequency of 9 VES station points, constituting 42.9% of the estimated frequency. The AK type has the least with the frequency of 1 VES point, constituting 4.8%.

In contrast, the curve types of A, QH, and HA, respectively, constitute about 28.6%, 14.3%, and 9.5% (Table 2 and Figure 2). Hence, the percentage distribution indicated the order H > A > QH > HA > AK for the modeled curve types. These H curve types are prolific aquifer units and can accommodate a borehole for water supply in the study area. Its domination indicates potential water sites, however, A type signifying complex rock with poor terrain for groundwater storage. The geo-electric sounding data revealed three to five geo-electric layers with varying intrafacies and interfacies changes (Table 4). The third and fourth layers have the majority of the aquiferous zones.

Table 2. Curve distribution and model resistivity.

Curve type	Frequency	VES points	Model resistivity
H	9 (42.9%)	2, 3, 4, 5, 7, 8, 10, 17, 21	$\rho_1 > \rho_2 < \rho_3$
A	6 (28.6%)	1, 9, 11, 14, 19, 20	$\rho_1 > \rho_2 < \rho_3$
QH	3 (14.3%)	12, 13, 18	$\rho_1 > \rho_2 > \rho_3 < \rho_4$
HA	2 (9.5%)	15, 16	$\rho_1 > \rho_2 < \rho_3 < \rho_4$
AK	1 (4.8%)	6	$\rho_1 < \rho_2 < \rho_3 > \rho_4$

Source: Fieldwork (2024).

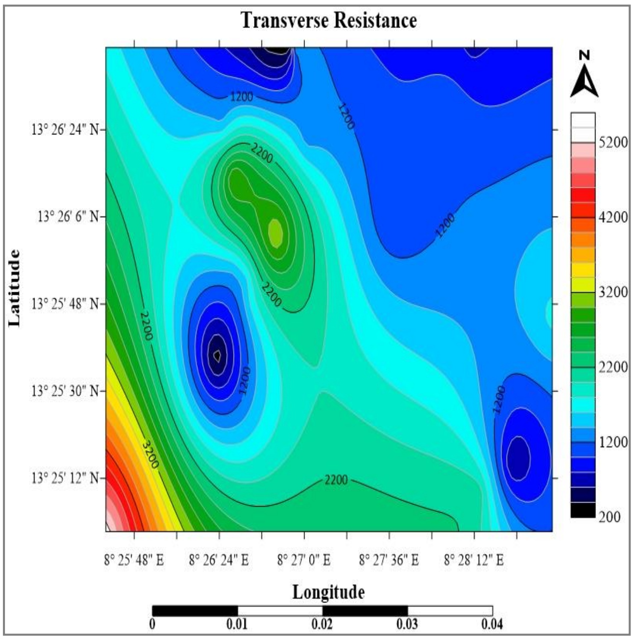


Figure 5: Spatial distribution of transverse resistance

The obtained aquifer resistivity varied from 34.08 to 331 Ωm with an average value of 148.97 Ωm. A high aquifer resistivity value was recorded at VES 9, and the 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 (Stober and Bucher, 2015; 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. The thickest aquifer observed was at VES 13 with a thickness of 19.5 m, and the lowest thickness was at VES 1 with a value of 4.37 m. An average aquifer thickness of 10.617 m was observed in the study area (Table 3). Depth to aquifer ranged from 8.09 to 26.9 m with a mean value of 14.76 m.

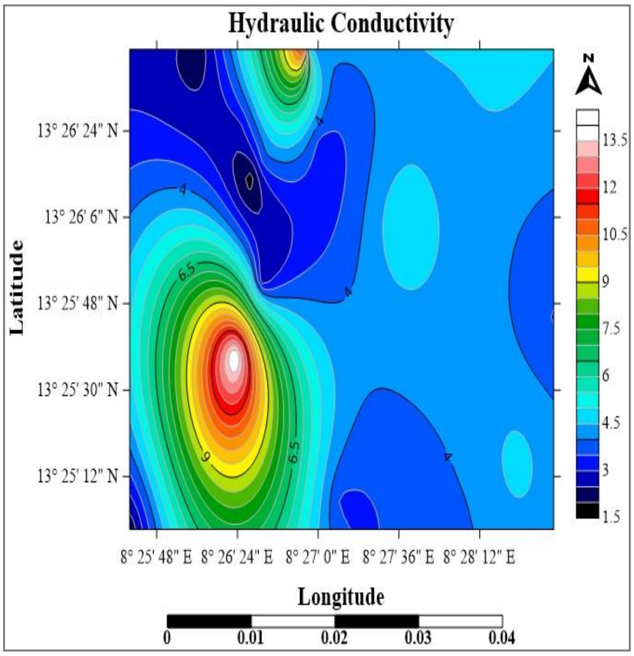


Figure 6: Spatial distribution of hydraulic conductivity

The transverse resistance (R) of the study area ranged from 274.07 to 5343 Ωm^2 with a mean value of 1643.021 Ωm^2. The spatial distribution of the transverse resistance is shown in Figure 5. The Highest value of transverse resistance was observed around the extreme corner of the southwestern part of the study area, and the 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 a 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 line with the findings of Ankidawa *et al.* (2023).

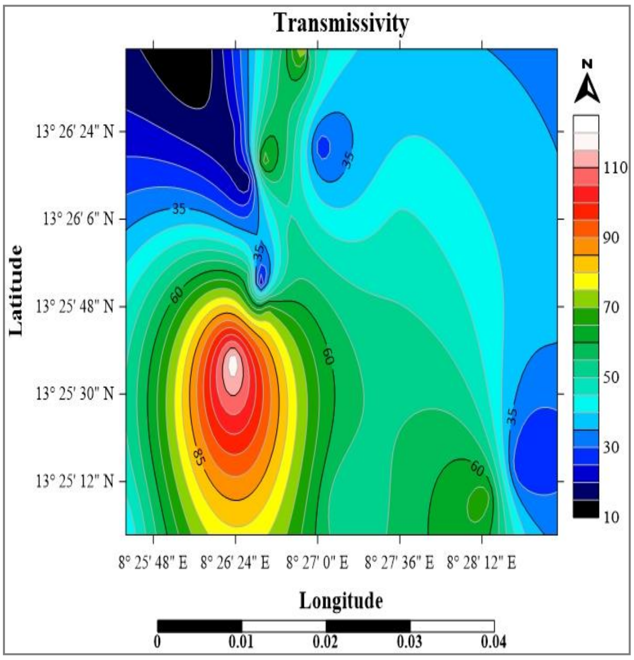


Figure 7: Spatial distribution map of transmissivity

Hydrogeologic parameters, hydraulic conductivity (K), and transmissivity (T) are critical to estimating the groundwater potential of weathered/fractured aquifers. Hydraulic conductivity is a measure of the ease with which a fluid will pass through a medium (Heigold *et al.,* 1979). The hydraulic conductivity of the study area is shown in Figure 6. The aquifer hydraulic conductivity (K) ranges from 1.724 – 14.371 m/day (Table 3). The high range of hydraulic conductivity of the aquifer may be due to the heterogeneous nature of the aquifer, a condition responsible for a wide range of hydraulic conductivity (George *et al.,* 2018). The spatial distribution of hydraulic conductivity (Figure 3) revealed low hydraulic conductivity values in the majority part of the area, suggesting that the limited aquifers' geologic restrictions make groundwater flow in the area complex rather than simple. Higher values were observed in the southwestern part, corresponding with the high transmissivity contour map. 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).

The transmissivity (Tr) value ranges from 9.972 – 119.854 m^2/day, with an average value of 46.574 m^2/day (Table 3). Areas with high transmissivity values can be identified as areas of high water-bearing potential, and aquifer materials are known to be relatively permeable to fluid flow. The spatial distribution map of transmissivity is shown in Figure 7. Low transmissivity values were observed at the extreme corner of the northwestern part and higher values at the southwestern part of the study area. The areas with high transmissivity can be attributed to having a thick, weathered basement, thus indicating that the area has moderate groundwater potential.

Table 3: Summary of aquifer parameters of the study area

VES No.	ρ (Ωm)	h (m)	d (m)	R = hρ	K = (m/d)	Tr = Kh (m^2/d)	Aquifer Potentials
1	245	4.37	8.1	1070.65	2.282	9.972	Low
2	57.5	6.18	8.85	355.35	8.822	54.520	Moderate
3	42.1	6.51	8.09	274.071	11.799	76.811	Moderate
4	115.8	11.6	13.61	1518.69	4.591	53.256	Moderate
5	115	14.8	16.23	1439.9	4.621	68.391	Moderate
6	213	7.13	10.42	660.18	2.600	18.538	Low
7	119	12.1	14.52	3055.13	4.476	54.160	Moderate
8	34.08	8.34	9.46	284.227	14.371	119.854	Moderate
9	331	9.23	15.27	3055.13	1.724	15.913	Low
10	141	18	21.4	2538	3.821	68.778	Moderate
11	192	7.44	10.9	1428.48	2.865	21.316	Low
12	158	14.5	15.4	2291	3.436	49.822	Low
13	274	19.5	24.6	5343	2.056	40.092	Low
14	112	5.18	9.82	580.16	4.737	24.538	Low
15	106	7.04	8.12	746.24	4.986	35.101	Low
16	157	10.06	16.31	1664.2	3.456	36.634	Low
17	130	16.4	23.7	2132	4.122	67.601	Moderate
18	107	9.4	24.7	1005.8	4.943	46.464	Low
19	128	8.96	10.6	1146.88	4.182	37.471	Low
20	167	8.17	12.96	1364.39	3.263	26.659	Low
21	184	17.5	26.9	3220	2.981	52.168	Moderate
Average	148.98	10.62	14.76	1643.02	4.768	46.574	

ρ = Aquifer resistivity, h = Aquifer thickness, d = depth, R = Transverse resistance, K = Hydraulic conductivity, Tr = Transmissivity.

Table 4: Summary of the result of interpreted parameters.

Ves No.	Coordinates	Layer Resistivity (ohm-m)					Layer thickness (m)				Lithological description	Error %	Curve Type
		p_1	$P2$	$P3$	$P4$	$P5$	h_1	h_2	h_3	h_4			
1	12°86'41"; 07°86'08"	446	46	245	2235	∞	1.14	3.11	4.37	∞	TLS, SC, WS, FB	2.7	A
2	12°86'41"; 07°86'44"	436	151	57.5	963	∞	1.06	1.62	6.18	∞	TLS, SC, WS, FB	2.55	H
3	12°86'41"; 07°86'50"	381	42.1	963	∞	∞	1.58	6.51	∞	∞	TS, WB, FB	2.22	H
4	12°86'41"; 07°86'56"	596.2	35	115.8	638	∞	1.02	4.96	11.6	∞	TLS, SC, WS, FB	1.21	H
5	12°85'48"; 07°86'38"	492	91	315	870	∞	1.25	2.03	14.8	∞	TLS, SC, WS, FB	2.94	H
6	12°85'53"; 07°86'35"	837	547	213	1274	∞	0.96	1.3	7.13	∞	TLS, DS, WB, FB	3.71	AK
7	12°85'55"; 07°86'30"	823	409	119	607	∞	1.72	3.741	12.1	∞	TLS, SC, WS, FB	4.63	H
8	12°85'37"; 07°86'23"	221.2	34.0	962.7	∞	∞	1.121	8.337	∞	∞	TS, WB, FB	1.64	H
9	12°85'74"; 07°86'30"	1148	61.1	331	2492	∞	1.388	2.12	9.23	∞	TLS, SC, WSS, WB	3.5	A
10	12°85'78"; 07°86'36"	985	97.1	141	781	∞	1.33	4.73	18	∞	TLS, SC, WS, FB	2.46	H
11	12°85'85"; 07°86'25"	639	464	192	705	∞	2.12	4.4	7.44	∞	TLS, DS, WB, FB	2.10	A
12	12°85'07"; 07°87'10"	901	435	158	483	2976	0.95	5.39	14.5	20.2	TS, DS, WB, PWL, FB	1.62	QH
13	12°85'01"; 07°85'36"	693	96.0	754	274	905	1.51	1.32	4.43	19.5	TS, SC, LS, WL, FB	2.27	QH
14	12°84'75"; 07°87'88"	755	316	112	872	67	1.55	2.6	5.18	7.87	TL, DS, WL, FB, FRB	2.89	A
15	12°86'41"; 07°88'11"	739	421	106	3106	∞	1.03	2.32	7.04	∞	TS, LS, WB, FB	3.01	AH
16	12°85'45"; 07°88'45"	618	157	809	∞	∞	1.1	10.6	∞	∞	TS, WB, FB	2.84	H
17	12°85'09"; 07°88'14"	1104	74	361	130	812	1.04	2.87	9.7	16.4	TL, SC, WL, FRB, FB	2.1	QH
18	12°85'65"; 07°86'96"	941	561	412	107	963	1.316	2.6	4.52	9.4	TS, LS, PWB, WL, FB	2.67	A
19	12°85'89"; 07°87'61"	1429	128	9093	∞	∞	1.62	8.96	∞	∞	TS, WB, FB	2.85	A
20	12°85'81"; 07°86'61"	638	468	167	759	∞	1.06	3.21	8.17	∞	TS, LS, WB, FB	2.01	H
21	12°86'02"; 07°86'48"	805	479	399	184	852	1.34	1.01	4.7	17.5	TS, LS, PWB, WL, FB	2.51	H

KEY: TLS: Top laterite soil; SC: sandy clayey; WS: weathered basement; FB: fresh basement; TS: topsoil; DS: Dry Sand; WSS: weathered sandstone; PWL: partially weathered layer; LS: lateritic soil; WL: weathered layer; TL: Top laterite; FRB: fractured basement

Source: Researcher fieldwork, (2024)

CONCLUSION

The geo-electrical sounding method was used in this study to characterize and evaluate the aquifer potential zones. The results provide information on aquifer parameters, which included the aquifer resistivity, aquifer thickness, transverse resistance, hydraulic conductivity, and transmissivity. These parameters were used to generate different contour maps. The result revealed that some areas with high transverse resistance values may give high aquifer yield; it also shows that the aquifers are characterized by low hydraulic conductivity, indicating the complexity of groundwater flow in the area, and transmissivity revealed the area is of low to moderate groundwater potential. It can be concluded that groundwater development can be undertaken within areas that have the highest transmissivity values, suggesting that the aquifer can transmit high-yielding capacity and sustain the needs of the area.

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