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GEOPHYSICAL INVESTIGATION OF AQUIFER POTENTIALS IN MASHI TOWN, KATSINA STATE NIGERIA: A VERTICAL RESISTIVITY APPROACH

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ABSTRACT
Groundwater is a vital natural resource concealed beneath the Earth's surface; it is the most undervalued component of global resources. It is a critical resource accounting for nearly one-third of the world's freshwater supplies, particularly in areas where surface water is limited or unpredictable. A geophysical survey using vertical electrical sounding (VES) was conducted to explore groundwater prospecting areas in Mashi town, Katsina state. A total of eighteen (18) VES survey points using Schlumberger array configuration were acquired, processed and interpreted. The results revealed aquifer resistivity ranges from 87.6 to 198 Ώm. In contrast, aquifer thickness ranges between 3.86 and 33.4 m, aquifer depth varies from 9.1 to 40.3 m, transverse resistance ranges between 206.124 and 4255 Ώm2, and the range of hydraulic conductivity is 2.734 to 5.955 m/day. The estimated transmissivity range is 13.634 to 126.047 m2/day. The results indicate that the southeastern part of the study area has the potential for groundwater development. Therefore, areas around VES 1 to 10 are suitable for borehole drilling, which could yield high-quality water, and a depth of 20-40 m should be targeted for groundwater development.

Keywords: Aquifers, Basement complex, Groundwater, Hydraulic conductivity.

INTRODUCTION

Groundwater is a critical natural resource, essential for human consumption and development, particularly in regions where surface water is limitedor unpredictable (Ali et al., 2024). The availability of potable groundwater is currently under increasing consideration as demand increases, with its availability controlled by geological factors that influence the occurrence, storage, and distribution of groundwater. Exploration and hydrostratigraphic analysis are reliable methods for determining the location and characteristics of an aquifer (Ostad-Ali-Askari & Shayannejad, 2021). It is essential to explore groundwater potential in the basement complex, given the nature of aquifers in this terrain (Obini et al., 2025). In the basement complex, aquifers are isolated and compartmentalised. In the undeformed state, these aquifers contain little or no porosity and permeability. As a result, groundwater occurrence depends on the development of secondary porosity and permeability in weathered rocks and fractured bedrock (Ojoawo & Adagunodo, 2023). Groundwater exploration is the study of subsurface formations to better understand the hydrologic cycle, assess groundwater quality, and characterise the nature, number, and type of aquifers (Udeh et al., 2024).

In numerous areas, especially in sub-Saharan Africa, groundwater serves as the principal source of freshwater, facilitating socioeconomic advancement (Odochi et al., 2024; Akidi et al., 2024). Semi-arid regions of the world, such as the Katsina state, rely on Groundwater resources are used to sustain numerous human activities. Groundwater resources in Katsina State predominantly lie in weathered and fractured crystalline basement aquifers, which occupy about 80% of the land area and provide water to millions of people in the state (Ohenhen et al., 2023). However, basement aquifers have a limited supply, and additional strain from global climate change limits potential recharge (Wu et al., 2020). Due to these constraints, basement aquifers are challenging to detect successfully using conventional drilling or wildcatting (Ohenhen et al., 2023). Additionally, basement groundwater sources are complex, posing challenges for aquifer characterisation (Wright, 1992; Ogundana & Falae, 2024).

The geoelectrical sounding, or vertical electrical sounding (VES), technique measures the distribution of electrical resistivity in the subsurface. This technique is widely used for aquifer delineation because it can penetrate more deeply into the subsurface (Akidi et al., 2024; Ibrahim et al., 2025). In addition, VES is a relatively non-destructive and cost-effective technique for locating aquifers compared to direct borehole drilling. However, more recently, geophysical techniques such as electrical resistivity (e.g. Oyeyemi et al. 2022; Salami et al., 2024; Ogundana & Falae, 2024). They are commonly utilised to site boreholes and to identify productive zones within basement aquifer systems. Electrical resistivity methods are generally sensitive to variations in lithology and moisture content and are widely used to identify fractures, regolith thickness, and potential water-bearing regions (Ohenhen et al., 2023).

Mashi Town, located in the Basement complex terrain of Katsina state, Nigeria, faces challenges in securing a sustainable water supply. To address this, the electrical resistivity method has emerged as a cost-effective and non-invasive geophysical technique for delineating subsurface layers and identifying potential aquifer zones. This application aims to use Vertical Electrical Sounding (VES) data to map the subsurface geology of Mashi Town, thereby identifying promising zones within the weathered and fractured basement layers for successful groundwater development and borehole placement.

MATERIALS AND METHODS

Study Area Description

Mashi town is the study area, located in the northern Part of Katsina state. It lies between latitude 12º55'' and 13º20' North of the equator, and longitude 07º50 and 08º10' East of the Greenwich meridian (Figure 1). The landscape of the area is highly dominated by plain. The area is characterised by a tropical continental (wet and dry) climatic zone of northern Nigeria. It is characterised by short wet and long dry seasons, with a very high annual temperature range. The study area receives a few months of annual rainfall normally between June and October, with an annual average of about 650-700mm. (Hassan and Maiwada, 2021). The study area comprises the Sudan Savannah vegetation belt, characterised by sparse trees, shrubs, and short grasses. As per Abdulkadir et al. (2023), the soil of the study area is ferruginous tropical soil (undifferentiated).

Geological setting (Basement complex)

The underlying geology of Mashi Town is part of the Nigerian Basement Complex, which is composed primarily of crystalline Igneous and Metamorphic rocks (e.g. granites and gneisses). These fresh basement rocks are generally impermeable and have very low porosity. Consequently, the primary challenge in this terrain is that groundwater cannot be found uniformly across the area.

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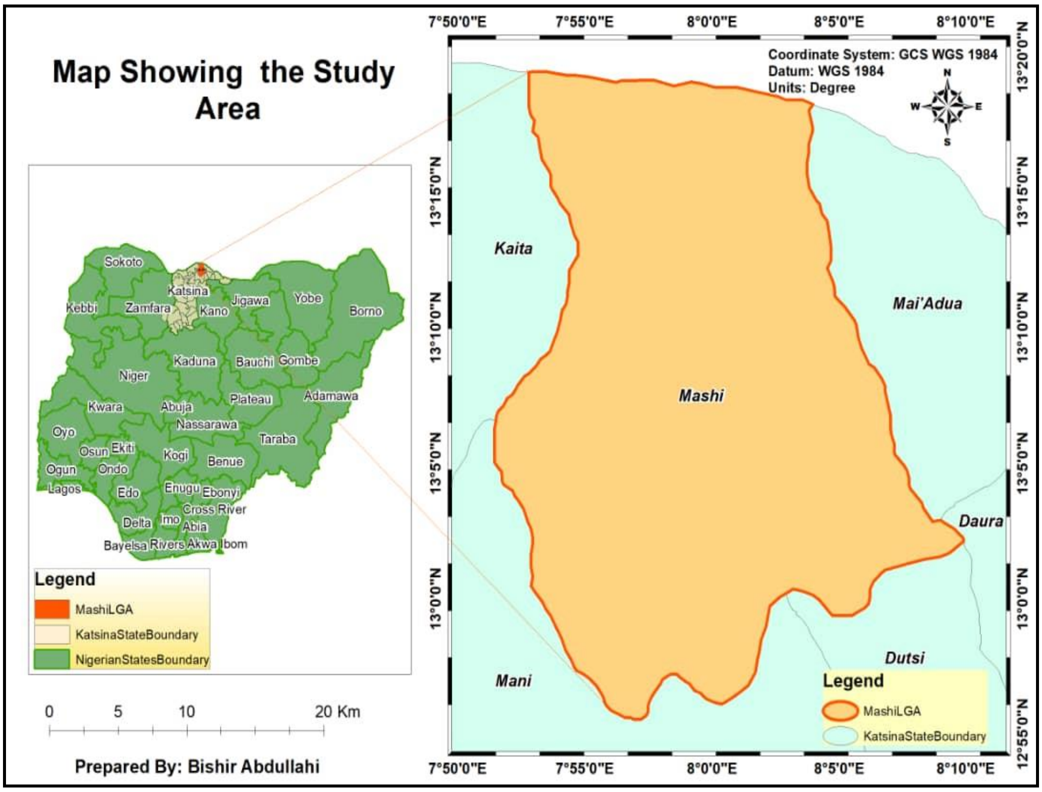

Figure 1: Map showing the study area.

Data collection, interpretation and analysis

Purposive sampling and convenience sampling techniques were used. At the beginning, purposive sampling was used to select the sample points for a geophysical survey using vertical electrical sounding (VES). This technique enabled us to locate the VES points along existing roads and paths, avoiding physical obstacles such as buildings and fences, as Chandra (2021) confirmed. The vertical electrical sounding technique was employed in this investigation. An ABEM Terrameter SAS 4000 was used to measure the earth resistance. Eighteen (18) electric soundings were carried out using the Schlumberger array. The selection of the Schlumberger electrode configuration is not only because it is faster and less likely to be influenced by lateral variation, but also because it requires fewer operators (Ige *et al.,* 2022). A 2-foot electrode, made of stainless steel, was driven into the ground at each end of the spread A and B. Both electrodes are then connected to the current sender at the centre via two-gauge cables. The electrodes M and N were also driven into the ground and connected to the voltage receiver at the centre by two coaxial cables, and the distance MN was kept equal.

At least five men were used for the fieldwork (see Plate 1). Two men were taping the distances, two men laid the cables, and two men moved and stood by the two current electrodes A and B. The final man, the observer, remains at the centre point; responsible for taking the measurement and for moving the electrodes M and N. Contact between the five men was established by 5-watt transceivers. Since the currents and voltages induced into the ground at A and B could be fatal, it is necessary to keep a man near each electrode to prevent someone from accidentally stepping over the electrode.

Plate 1: Researcher, along with field assistants, during the VES survey.

The current electrode spacing (AB/2) ranged from 1m to 100 m, while the 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*) and a 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 & Mooney, 1966). The output from the quantitative manual interpretation was modelled using computer software. The IPI2Win version 1.0 interpretation software was used to iterate and present the curve to generate the geoelectric parameters. Equally, Surfer software version 20 was used to generate the spatial distribution of the analysed parameters.

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

The transverse resistance R is given by:

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

where h and ρ are respectively the thickness and resistivity of the ith layer in the section.
Hydraulic conductivity can be determined using:

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

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

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

$$Tr = K\sigma T = KS/\sigma \quad ....iv$$

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.

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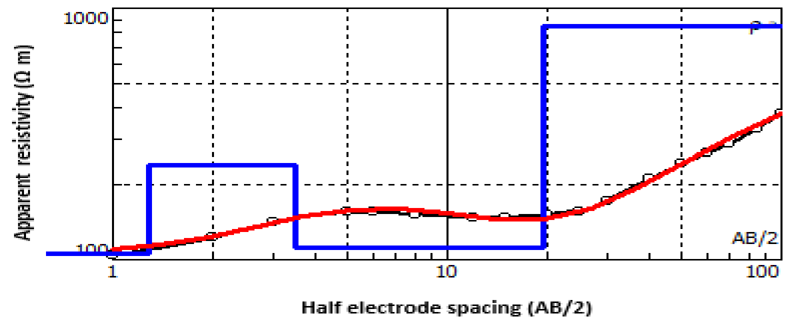
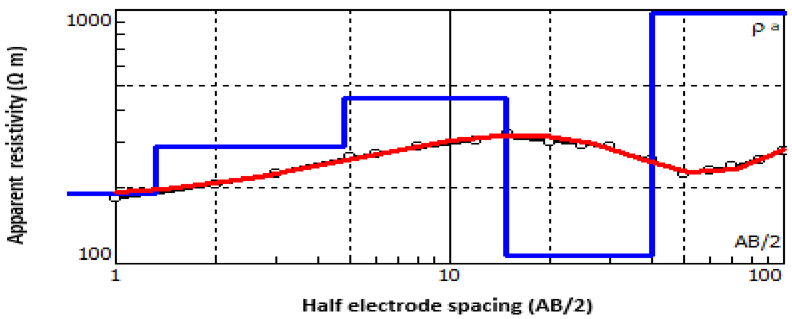


N	ρ	h	d
1	189	1.32	1.32
2	289	3.5	4.82
3	449	9.9	14.7
4	107	25.5	40.3
5	973		

Figure 2: Showing the VES 10 curve type



N	ρ	h	d
1	106	1.28	1.28
2	239	2.23	3.51
3	112	15.9	19.4
4	848		

Figure 3: Showing VES 18 curve type

RESULTS AND DISCUSSION

The resistivity of the aquiferous unit (Table 1) within the study area ranges from 87.6 to 198 Ωm, with an average of 143.12 Ωm. The spatial distribution map (Figure 4) revealed that the extreme northwest, northeast, southwest, and a small portion of the eastern part have the lowest resistivity values. In contrast, the southeastern part and parts of the central portion of the study area have the highest resistivity values. Consequently, the central portion, down to the north, south, west, and east, was dominated by moderate values. Low resistivity values indicate higher groundwater potential, and vice versa (Figure 4).

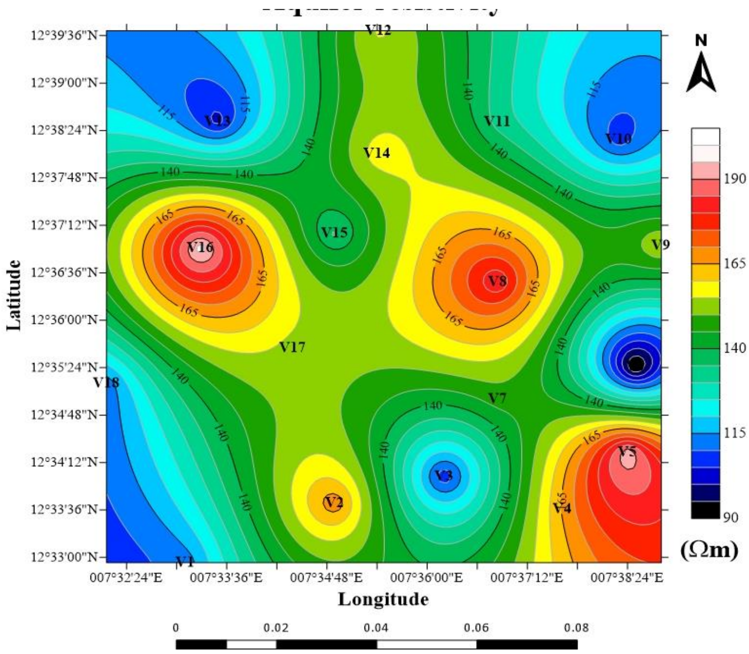


Figure 4: Spatial distribution of aquifer resistivity.

Table 1: Locations and analysed aquifer parameters of the study area

VES No.	Latitude	Longitude	ρ (Ωm)	h (m)	d (m)	R (Ωm^2)	K (m/day)	Tc (m^2/day)
1	12º54'89	7º55'17	112	18.1	16.4	2027.2	4.734	85.73
2	12º56'14	7º58'16	168.8	33.4	35.6	2297.92	3.23	107.92
3	12º56'70	7º60'34	106	23.4	25	2480.4	4.99	116.67
4	12º56'01	7º62'70	165.67	22.3	24.8	3694.44	3.29	73.3
5	12º57'21	7º64'00	194	21.34	23.2	4139.96	2.84	60.54
6	12º59'02	7º64'15	87.63	14.11	17.8	1236.46	5.96	84.03
7	12º58'34	7º61'41	147.5	16.8	17.4	2478	3.66	61.56
8	12º60'81	7º61'41	185	23	24.5	4255	2.97	68.22
9	12º61'57	7º64'67	155.4	16.8	18	2610.72	3.49	58.63
10	12º63'80	7º63'82	107	25.5	40.3	2728.5	4.94	126.05
11	12º64'17	7º61'41	133	8.22	10.3	1093.26	4.04	33.17
12	12º66'10	7º59'03	156	13.2	16.7	2059.2	3.48	45.90
13	12º64'18	7º55'82	103	16.53	18.6	672.59	5.12	84.67
14	12º63'51	7º59'00	158	12.86	14.5	2031.88	3.44	44.19
15	12º61'83	7º58'15	133.8	8.06	9.09	1078.43	4.01	32.35
16	12º61'52	7º55'47	198	7.8	10.2	1544.4	2.73	21.72
17	12º59'41	7º57'31	153.4	3.86	14.35	206.124	3.53	13.63
18	12º58'67	7º53'60	112	15.9	19.4	1780.8	4.74	75.32
Minimum			87.6	3.86	9.1	206.124	2.73	13.63
Maximum			198	33.4	40.3	4255	5.96	126.05
Mean			143.22	16.732	19.786	2134.183	3.96	66.31

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

The aquifer thickness (h) (Table 1) ranges from 3.86 to 33.4 m with a mean value of 16.73 m. The majority of the study area has a higher aquifer thickness (≥ 5 m), indicating moderate aquifer thickness, which could support water volume. Figure 5 displayed the spatial distribution of aquifer thickness. Higher values were observed in the southern and slightly eastern parts, while lower values were found in the central and northern parts. Greater thicknesses in the south and east suggest a possible increase in groundwater storage capacity, increasing the likelihood of groundwater extraction in the area. These results have important ramifications for managing groundwater resources since thicker aquifers may provide more conducive circumstances for environmentally friendly extraction methods.

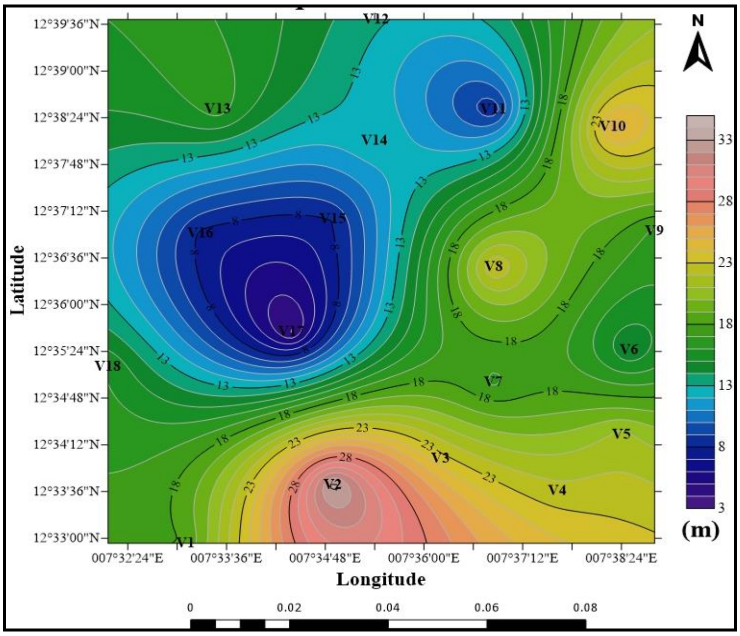


Figure 5: Spatial distribution of aquifer thickness

Aquifer depth represents the vertical distance between the saturation zone and the overlying zones of aeration, situated above the water table (Ejepu *et al.,* 2024). The observed depth to the aquifer (Table 1) ranged from 9.1 to 40.3 m, with a mean of 19.79 m. A higher aquifer depth was observed in the southern and extreme northeastern parts, while the lowest values were found in the central and northern portions of the study area, as shown in Figure 6. These variations in aquifer depth highlighted the heterogeneity of subsurface conditions and the complex interaction between hydrological processes and geological formations (George *et al.,* 2020). Therefore, approximately 20-40 m should be targeted for borehole siting in these areas for groundwater development.

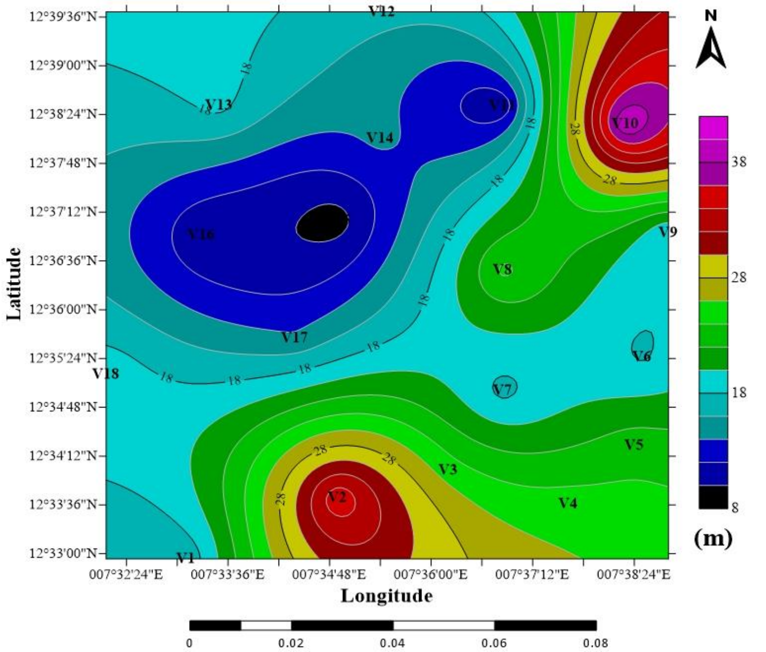


Figure 6: Spatial distribution of aquifer depth

Transverse resistance plays a crucial role in characterising the resistance encountered by groundwater as it flows laterally within the aquifer. It provides insights into the level of hindrance faced by groundwater moving perpendicular to the hydraulic gradient (George, 2020). The estimated transverse resistance (R) of the study area ranged from 206.124 to 4255 Ωm^2, with a mean of 2134.183 Ωm^2. Relatively high transverse unit resistance values characterise the areas around the southeastern and some parts of the central portion, while low values were observed around the significant part of the central area and the northwestern part, as shown in Figure 6. Zones with high transverse unit resistance values are likely characterised by high recharge capability and thus are the best groundwater exploitation targets in the area. The spatial distribution map (Figure 7) revealed that moderate-to-low values dominate the area. For analysing groundwater flow dynamics, identifying potential groundwater recharge or discharge locations, and determining the aquifer's susceptibility to contamination, an understanding of aquifer transverse resistance is vital (Ejepu *et al.,* 2024).

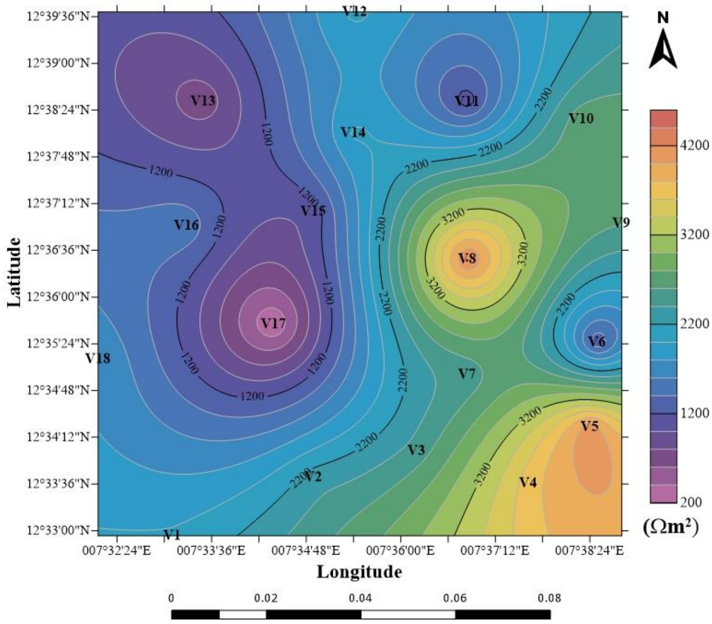


Figure 7: Spatial distribution of transverse resistance

Hydraulic conductivity is a measure of the ease with which a fluid passes through a medium (Heigold *et al.,* 1979). The hydraulic conductivity of the study area is shown in Figure 7. The aquifer hydraulic conductivity (K) ranges from 2.734 to 5.955 m/day, with the average value of 3.955 m/day (Table 1). The spatial distribution of hydraulic conductivity (Figure 8) revealed low values around the northern, central and extreme southeastern parts of the area. In contrast, higher values were observed around the eastern, southern, extreme northwest, and extreme southwest parts. High values indicate the presence of conductive materials; as such, these stations would optimally enhance appreciable recharge from rainwater and contribute significantly to the borehole yield when explored. This study contrasts with the findings of Obini et al. (2025).

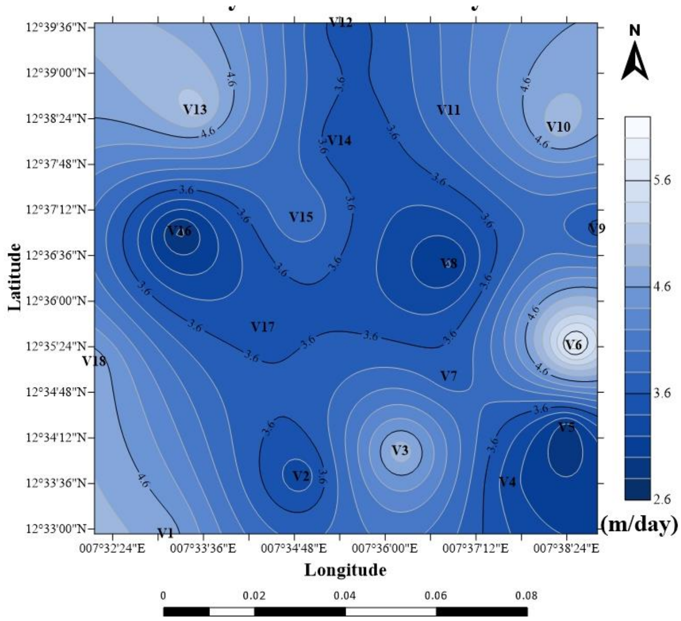


Figure 8: Spatial distribution of hydraulic conductivity

Transmissivity is a crucial parameter that quantifies an aquifer's ability to transmit groundwater across its saturated thickness. It represents the volume of water that can flow through a unit width of the aquifer under specified hydraulic-gradient conditions. The transmissivity (Tr) value ranges from 13.634 to 126.047 m^2/day, with an average of 66.309 m2/day (Table 1). Figure 9 displays the spatial distribution of transmissivity. High values were observed around the southern part, extreme northeast and northwest, while low values dominated the central part towards the northern and western parts. Areas with high transmissivity values can be identified as areas of high water-bearing potential, and aquifer materials are relatively permeable to fluid flow, potentially yielding higher yields. Conversely, lower transmissivity values indicate areas with reduced porosity and permeability, thereby limiting the potential for groundwater flow.

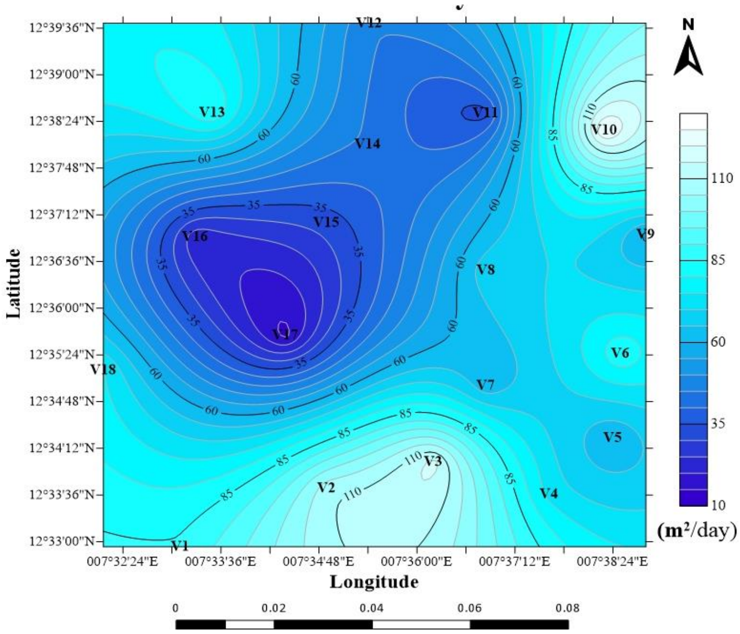


Figure 9: Spatial distribution of transmissivity

Table 2 presents the transmissivity rating scale for the study site. It shows that about 66.67% of the area falls under moderate potential, while 33.33% falls under low potential. This indicates that the aquifer system in the area is moderately potential to supply water for domestic uses

Table 2: Transmissivity/aquifer potential scale

S/no	Range	Potential	Remark	% of VES
1	> 500 m^2/day	High potential	None	0%
2	50 – 500 m^2/day	Moderate potential	VES 1 - 10, 13, 18	66.67 %
3	5 – 50 m^2/day	Low potential	VES 11, 12, 14 - 17.	33.33 %
4	0.5 – 5 m^2/day	Very low potential	None	0%
5	<0.5 m^2/day	Negligible potential	None	0%

Source: (after Gheorghe, 1978).

CONCLUSION AND RECOMMENDATIONS

Based on the results, the aquifer resistivity ranged from 87.6 to 198 Ώm. In contrast, aquifer thickness ranges from 3.86 to 33.4 m, aquifer depth varies from 9.1 to 40.3 m, transverse resistance ranges from 206.124 to 4255 Ώm2, and hydraulic conductivity ranges from 2.734 to 5.955 m/day. The estimated transmissivity range is 13.634 to 126.047 m2/day. The study observed that areas around the southeastern part have higher transmissivity values, indicating greater potential. This information aids in optimising well placement and designing sustainable extraction strategies, considering the varying transmissivity characteristics across the study area. Groundwater is a significant natural resource that is often undervalued despite accounting for a substantial portion of the world's freshwater. Geophysical surveys using vertical electrical sounding (VES) in Mashi town, Katsina State, Nigeria, identified potential groundwater development in the south-eastern part of the study region, with suitable borehole sites recommended at depths of 20-40 meters.

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