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Geoelectric characterisation of aquifer in Sabon-Gari, Bauchi, Northeastern Nigeria

***[1]Auwal A. Abdu, Othniel K. Likkason[1] and Mohammed M. Musa[2]**

[1]Department of Physics, Abubakar Tafawa Balewa University, Bauchi, Nigeria.
[2]Geo-pulse Solutions Ltd, Bauchi State, Nigeria.

*Corresponding Author's Email: mmmuhammed.ug@atbu.edu.ng

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Electrical Resistivity, Aquifer, Transmissivity, Groundwater Potential.

ABSTRACT

Electrical resistivity investigation using Schlumberger configuration was conducted in Sabon-Gari, Bauchi, Bauchi State Nigeria. The study area is situated between 10.399°N to 10.410°N and 009.815°E to 009.825°E within the Basement complex of Nigeria. Because of a good number of failed wells and boreholes in the area, there arises a need to carry out a geophysical study to characterise the underlying aquifer system. A total of twenty-five vertical electrical soundings (VES) were carried out with a maximum electrode spacing of 300 m (i.e. AB/2=150 m). Analysis of the acquired sounding data revealed a three-to-four geoelectric layer formations; topsoil, highly weathered, weathered, and fresh basement rocks as correlated with existing borehole data. Assessing the groundwater potential, thickness and resistivity of the unconsolidated overburden materials is the focus. The overburden thickness varies from 1.9 to 27.8 m where about 60% of it falls within the 1.9 m to 10 m bracket; thus indicating its thinness. The aquifer thickness varies within 1.5 to 25.4 m range. The aquifer resistivity varies from 7.5 to 373 Ωm, and this information was used to determine the aquifer's transmissivity, calculated to range from 18.2 to 275 m^2/day. The aquifer unit in the study area, therefore, shows a generally low to medium groundwater potential. The longitudinal conductance of the geoelectric topmost layer across the area was also used to assess the vulnerability of the underlying aquifer to near-surface contaminants. The aquifer is found to be of moderate to poor protective capacity rating. The general indication over the study area is that wells and boreholes fail because of its general low groundwater potential and poor borehole siting. This could be addressed by designing wells based on water flow and avoiding areas with low potential.

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INTRODUCTION

Groundwater exploration has become increasingly essential in both rural and urban areas of underdeveloped and developing countries for various purposes. Factors such as urbanization, industrialization, and population growth drive the need for exploring groundwater resources to meet domestic and industrial water demands (Dan Hassan and Adelike, 1991). Conducting groundwater exploration in basement terrains presents a significant challenge, as the groundwater is predominantly confined to weathered and fractured zones. In these settings, the potential for groundwater availability is largely influenced by the thickness of the weathered and fractured layer overlaying the basement (Eebo and Yusuf 2021). Addressing this challenge, geophysical surveys have gained widespread acceptance as a crucial preliminary step in the planning and execution of successful groundwater projects (Bello et al., 2022; Fawale et al., 2023).

The present study was carried out at Sabon-Gari area of Bauchi local government, Bauchi state. Its population growth and industrial expansion, supported by adequate electricity supply and a well-developed road network, have created challenges in accessing safe water for both domestic and industrial purposes. Numerous dug wells and boreholes sunk in the region have failed and been abandoned. The failures of boreholes can be attributed to various factors, such as incorrect point selection, insufficient data quality or knowledge of subsurface conditions, lack of technical expertise, and inadequate development of drilled hole, particularly prominent in the geologically complex Basement Complex terrains (Abiola et al., 2013). Therefore, this study aims to investigate and characterize the groundwater potential in the area by conducting vertical electrical soundings (VES) using Schlumberger array so as to identify and delineate productive aquifers suitable for the development of sustainable boreholes. This approach is crucial for mitigating the risks associated with drilling dry boreholes and ensuring reliable access to water resources for both domestic and industrial use.

Electrical resistivity method is highly effective for characterizing the geoelectric properties of subsurface formations, as it can elucidate the hydraulic conductivity and hydrogeological characteristics of the underlying rocks. This method offers simplicity in field procedures, cost-effectiveness, and the ability to provide precise information on groundwater potentials and aquifer attributes. In basement rocks, which typically exhibit low porosity and permeability unless extensively weathered, the development of good permeability occurs in areas with an interconnected network of joints, fractures, and weathering, creating favorable hydrogeological conditions. These zones are identifiable by their distinctive low electrical resistivity within the higher resistivity host rocks (Michael and Franklin, 2016), as evidenced in electrical resistivity data. Therefore, the relevance of employing the electrical resistivity survey method in the present study is justified for delineating such hydrogeological features and enhancing groundwater exploration efforts.

The study area is situated between 10.399°N to 10.410°N and 009.815°E to 009.825°E in Bauchi Local Government area of Bauchi State, NE Nigeria and lies within the basement complex of northern Nigeria (Fig. 1). The area is accessible principally by the Bauchi – Ningi road, as well as several minor paths and major paths linking villages, farms and settlements. The area has an average elevation of 600 m above mean sea level and falls within the semi-arid zone of Nigeria, characterised as Guinea Savannah. The climate of the study area is a characteristic of tropical climate with two demarcated seasons, the rainy and dry seasons. The dry season, usually between Novembers to February, is characterised by cold, dusty and harmattan wind while an average of 850 mm rain is received annually between March and October (Iloeje, 1981).

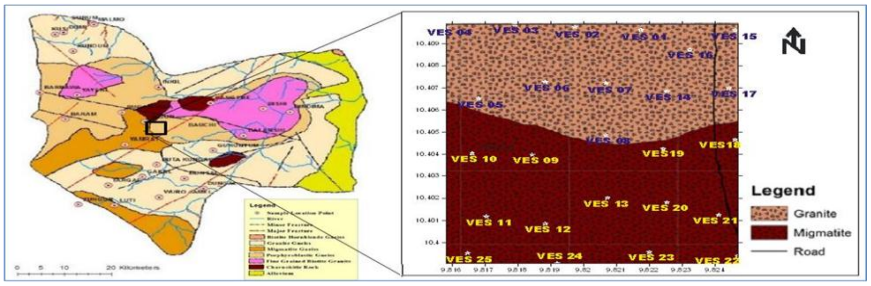


Fig. 1: Geologic map of Bauchi Local Government Area showing the study area

Figure 1: Geologic map of Bauchi Local Government Area showing the study area

The Nigeria's geological setup comprises, broadly, the sedimentary formations and crystalline rocks of the Basement complex type. The Basement complex rocks are thought to be Precambrian, mainly granitic in composition, and in different stages of metamorphism; either as gneisses, migmatite, schist, phyllites and/or quartzite (Offodile, 2014). The biotitic-granite, granite-gneiss, and migmatite-gneiss in the area are all

estimated to be Permian in age (McCurry, 1976) and are underlain by Older Granites. In the study area, migmatite is the predominant rock type, with minor occurrences of granites and rare schist. These rocks are well-exposed with mostly hilly outcrops and some flat-lying outcrops (Fig. 1). The rocks are primarily composed of metatexites and diatexites, coarse-grained biotites-granite and medium-grained granite with some east-west trending basaltic dykes (Muhammad et al, 2022).

The study area is underlain by crystalline basement complex of solid, dense rock. water-bearing zones in this hydrogeological unit occur either in fractures in poorly decomposed rock, intergranular permeability in moderately decomposed coarse grained igneous and metamorphic rock, and fractured pegmatite, aplite and quartz veins within highly and moderately decomposed gneisses and migmatite (BSADP, 1988). According to Shemang and Jiba (2005) the area is characterised by two aquiferous rock types: fractured crystalline rocks underlain by weathered crystalline rocks, and an overburden aquifer of decomposed rocks. The capacity of the crystalline rocks to store, transmit, and yield water depends mainly on the extent, size, and degree of openness of their fractures and also on the degree of their transmissivity.

Therefore, this study aims to investigate and characterise the groundwater potential in the area by conducting vertical electrical soundings (VES) using Schlumberger array so as to identify and delineate productive aquifers suitable for the development of sustainable boreholes.

MATERIALS AND METHODS

Electrical resistivity method was applied as it has been applied in areas of groundwater exploration due to its effectiveness in detecting geological structures such as faults, depth to bedrock, as well as in the search for geothermal reservoirs. Rock resistivity, in particular, is of special interest for hydrogeological investigations as it allows for the discrimination between water-bearing fractured rock and its solid host rock (Kirsch, 2004). This distinction is crucial for assessing water quality and availability in underground aquifers.

In resistivity surveying, an electric current is injected into the ground through a pair of current electrodes (A and B). The current flows along the path of least resistance between the electrodes. The potential difference is then measured using another pair of electrodes (M and N) connected to a voltmeter. From the current (I) and potential difference (ΔV) values, an apparent resistance (R) value is calculated. Resistivity meters normally give a resistance value, $R = \Delta V/I$, so in practice the apparent resistivity (ρ_a) value is calculated by:

$$\rho_a = kR. \qquad (1)$$

Where, k is the geometric factor which depends on the arrangement of the four electrodes and is calculated as:

$$k = 2\pi \cdot \left[\left(\frac{1}{AM} - \frac{1}{BM}\right) - \left(\frac{1}{AN} - \frac{1}{BN}\right)\right]^{-1} \qquad (2)$$

According to Reynolds (2011), a geoelectric unit is defined by two primary parameters: *layer resistivity* (ρ_i) and *layer thickness* (t_i). From these parameters, four additional parameters can be derived for each layer: longitudinal unit conductance (S_L), transverse unit resistance (T), longitudinal resistivity (ρ_L), and transverse resistivity (ρ_T). These parameters are collectively known as the Dar Zarrouk parameters, as termed by Maillet (1947). The longitudinal conductance function is given by:

$$S_L = \sum_{i=1}^{n}\left(\frac{h_i}{\rho_i}\right) = \frac{h_1}{\rho_1} + \frac{h_2}{\rho_2} + \frac{h_3}{\rho_3} + \cdots + \frac{h_n}{\rho_n} \qquad (3)$$

And the transverse resistance variable for a given layer is given by:

$$T = \sum_{i=1}^{n}(h_i \cdot \rho_i) = h_1\rho_1 + h_2\rho_2 + h_3\rho_3 + \cdots + h_n\rho_n \qquad (4)$$

Where h_i and ρ_i are the layer thicknesses and resistivities respectively.

The longitudinal conductance (S_L) and transverse resistance (T) are crucial parameters in geoelectric surveys, as they indicate how current flows through the subsurface. Longitudinal conductance is essential when current flows parallel to the geoelectric borders, while transverse resistance (T) is vital when the current flows normal to bed boundaries (Telford *et al.*, 1976). The Dar-Zarrouk parameters offer significant advantages in assessing aquifer properties, including transmission, storage, and protection of groundwater (Kelly, 1977 and Dhakate and Singh, 2005). The Dar-Zarrouk parameters provide a practical solution for understanding aquifer behaviour, enabling the computation of surface potential and electrical resistivity graphs (Henriet 1976). Furthermore, aquifer resistivity obtained from the surface resistivity methods can estimate hydraulic conductivity and transmissivity, which are proportional to permeability (Chandra *et al.*, 2008; Kazakis *et al.*, 2016 and Heigold *et al.*, 1979). Mazac *et al.* (1985) developed a comprehensive hydrogeophysical model that relates hydraulic and electrical properties of aquifers. Calculated hydraulic conductivity K is expressed as:

$$K = 386.4R_{rw}{}^{-0.93283} \qquad (5)$$

Where, R_{rw} is the aquifer resistivity and K is expressed in m/day

Hydraulic conductivity values are used to determine the aquifer's transmissivity, which is the rate at which groundwater can flow through an aquifer section of unit width under a unit hydraulic gradient. Transmissivity represent the aquifer's ability to transmit groundwater, as described by Offodile (1983) using the equation:

$$T_a = Kb. \qquad (6)$$

Where, T_a is transmissivity (in m^2/day) and b is the aquifer thickness (m).

Reconnaissance was first carried out to study the physical geology of the area, determine the locations of existing wells and boreholes, and observe the geomorphic structures in the region. During this study, the static water levels of hand-dug wells were measured, and data on both functioning and abortive boreholes were collected. The geological and hydrogeological features of the area served as the basis for identifying possible sounding points. The possible VES (Vertical Electrical Sounding) points were located, marked, and investigated in this work.

The geophysical survey involved conducting Vertical Electrical Sounding (VES) traverses at selected locations within the study area. The Schlumberger electrode configuration was utilized, with the potential electrode separation at a constant distance while the current electrodes were symmetrically moved outward from the centre of the spread. A total of 25 VES points were surveyed across the entire area. Each point's measurement began with a potential electrode offset of 1 m and a current electrode spread of 3 m. During each VES operation, the distance between the current electrodes (AB) was varied between 3.0 to 300.0 m, and the distance between potential electrodes (MN) was adjusted between 1.0 to 16.0 m.

RESULTS AND DISCUSSION

Data processing began with the accurate recording of half the current electrode separation (AB/2), half potential electrode spacing (MN/2), and the measured resistance values (R) on the data sheet. The geometric factor (K) for the entire electrode spacings was calculated using equation (2), and the corresponding apparent resistivity values were subsequently calculated by multiplying the measured resistance values from the resistivity meter by their corresponding geometric factors (K) as per equation (1).

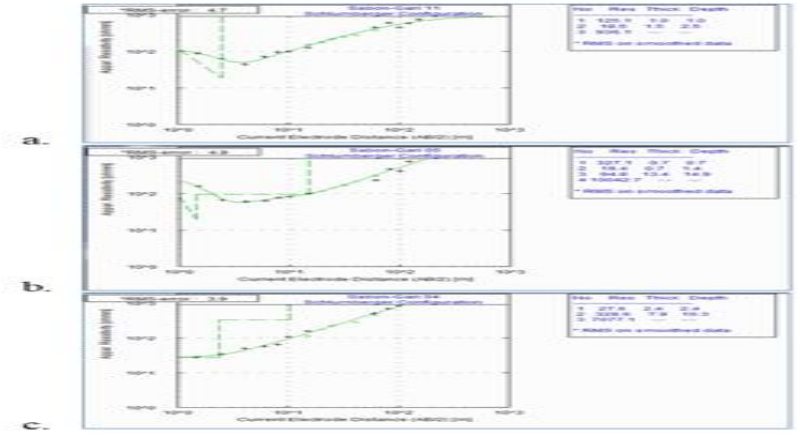


Figure 2: Curve-types encountered; (a) H-type, (b) HA-type and (c) A-type

Qualitative Interpretation of Field Curves

The raw field data were plotted and smoothed to produce curves of best fit on log-log graph. The apparent resistivity (ρ_a) was plotted against half the current electrode spacing (AB/2), generating an electrical resistivity sounding curves. The curves exhibit various char5acteristics, ranging from simple 3-layer H and A type curves to a 4-layer HA type curve (Fig. 2). The H-type curve, observed at 17 stations (VES 01,08-13, 15-18,20-23, and 25), represents a 3-layer model with two high-resistivity beds sandwiching a low resistivity layer (i.e. $\rho_1>\rho_2<\rho_3$). In contrast, the A-type curve, seen at VES 04, shows lower beds with higher resistivity than upper beds (i.e. $\rho_1<\rho_2<\rho_3$). Eight stations (VES 02, 03, 05-07, 14, 19 and 24) exhibit an HA-type curve, characterised by a sequence of four beds with varying resistivities ($\rho_1>\rho_2<\rho_3<\rho_4$).

Interpreting VES data qualitatively is important as it provides an initial understanding of the expected model. However, relying solely on analysing simple curve shapes may not yield detailed information about the geoelectric parameters of the subsurface. Quantitative interpretation is essential for generating a more realistic earth model based on precise data analysis and calculation of geoelectric parameters.

Quantitative interpretation of field curves

The qualitative interpretation of the field data was conducted using the WINRESIST software (version 1.0), which implements the principles outlined by Zohdy (1989) for automatic iterative interpretation. This approach was used to determine the number of geoelectric layers (N), as well as the quantitative values of resistivity (ρ) and thickness (h) - key geoelectric parameters. Quantitatively, the iteration process yielded a maximum of four geoelectric layers, as indicated in Table 1.

Table 1: Quantitative Interpretation of the VES data

VES Name	No. of Layers	Resistivities (Ωm)				Thicknesses (m)			RMS error
		ρ_1	ρ_2	ρ_3	ρ_4	h_1	h_2	h_3	
VES 01	3	12.80	7.800	4225	-	0.800	3.900	-	08.2
VES 02	4	33.80	20.70	33.20	2937	0.100	1.400	18.70	08.6
VES 03	4	110.7	7.000	196.5	1106	0.700	1.200	16.40	07.3
VES 04	3	27.60	238.6	7077	-	2.400	7.900	-	03.9
VES 05	4	327.1	19.40	94.80	10043	0.700	0.700	13.40	04.8
VES 06	4	168.5	42.60	242.4	3364	0.700	3.300	10.80	04.5
VES 07	4	425.1	23.90	140.2	1181	0.600	0.700	10.10	06.6
VES 08	3	25.70	7.500	32463	-	0.500	1.400	-	12.1
VES 09	3	66.70	14.80	4953	-	0.900	2.200	-	06.0
VES 10	3	510.9	50.80	2746	-	0.800	2.200	-	05.1
VES 11	3	125.1	18.50	936.1	-	1.000	2.500	-	04.7
VES 12	3	115.7	59.10	8217	-	3.100	7.400	-	06.9
VES 13	3	170.8	35.10	1722	-	0.900	3.000	-	04.2
VES 14	4	263.0	74.80	373.0	8317	0.987	1.610	21.10	04.2
VES 15	4	76.40	33.20	2802	-	2.200	5.260	-	11.3
VES 16	3	64.50	13.10	1638	-	0.750	1.500	-	08.6
VES 17	3	56.50	45.90	3040	-	0.750	5.640	-	03.1
VES 18	3	140.0	54.30	6313	-	1.730	3.200	-	04.9
VES 19	4	151.0	48.80	271.0	5365	1.340	1.040	25.40	04.6
VES 20	3	33.00	15.80	1133	-	0.800	2.680	-	12.6
VES 21	3	234.0	131.0	1814	-	0.750	12.70	-	06.4
VES 22	3	120.0	83.40	3689	-	0.750	4.970	-	02.0
VES 23	3	85.60	51.70	8645	-	0.909	4.560	-	05.5
VES 24	4	51.20	16.40	55.7	1791	0.750	1.000	4.490	06.6
VES 25	3	103.0	48.60	1508	-	1.250	4.880	-	05.3

To determine the true lithologies of these geoelectric layers, the VES sections were correlated with borehole data obtained from Bauchi State Rural Water Supply and Sanitation Agency (RUWASSA). The borehole data provided valuable information on the lithologies encountered at various depths, allowing for a comprehensive analysis and interpretation of the VES sections. The information includes:

Borehole name: BH 01
Nothing: 10.96060°
Easting: 009.87928°
Depth: 27 m
Lithologies: 0 – 5 m
Topsoil 5 – 8 m
Highly weathered Basement 8 – 27 m
Weathered Basement
Fracture zones: 9-15, 16, 21, 24 & 27 m
Yield estimate: 0.44 L/s
Borehole design: 1/3
S→1B→1S→1B→2S→4B

Upon comparing the interpreted VES model sections with the borehole data, the identified geoelectric layers correspond to the Topsoil, Highly weathered, Weathered, and Fresh basement lithologies, as depicted in Figure 3. Table 2 provides information on the resistivity, thickness, and lithology of each individual layer. By integrating the resistivities and thicknesses of these layers, the distribution of layer parameters across the study area is achieved.

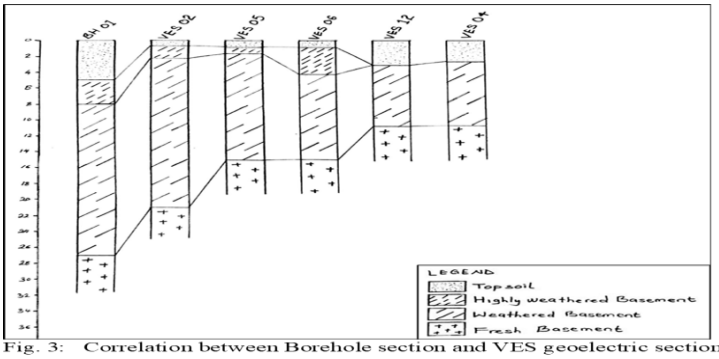


Fig. 3: Correlation between Borehole section and VES geoelectric sections

Figure 3: Correlation between Borehole section and VES geoelectric sections

Table 2: Interpreted Layer Resistivities and Thicknesses with Inferred Lithologies

VES Name	Layer No.	Apparent Resistivity (Ωm)	Thickness (m)	Depth (m)	Inferred Lithology from Borehole correlation
VES 01	1	12.8	0.8	0.8	Top soil
	2	7.8	3.9	4.7	Highly weathered Basement
	3	4225.4			Fresh Basement
VES 02	1	33.8	0.6	0.6	Top soil
	2	20.7	1.4	2.1	Highly weathered Basement
	3	33.2	18.7	20.8	Weathered Basement
	4	2937			Fresh Basement
VES 03	1	110.7	0.7	0.7	Top soil
	2	7.0	1.2	1.9	Highly weathered Basement
	3	196.5	16.4	18.3	Weathered Basement
	4	1106			Fresh Basement
VES 04	1	27.6	2.4	2.4	Top soil
	2	328.6	7.9	10.3	Weathered Basement
	3	7077			Fresh Basement
VES 05	1	327.1	0.7	0.7	Top soil
	2	19.4	0.7	1.4	Highly weathered Basement
	3	94.8	13.4	14.9	Weathered Basement
	4	10043			Fresh Basement
VES 06	1	165.8	0.7	0.7	Top soil
	2	42	3.3	4.0	Highly weathered Basement
	3	242.4	10.8	14.8	Weathered Basement
	4	3364			Fresh Basement
VES 07	1	425.1	0.6	0.6	Top soil
	2	23.9	0.7	1.3	Highly weathered Basement
	3	140.2	10.1	11.4	Weathered Basement
	4	1181			Fresh Basement
VES 08	1	25.7	0.5	0.5	Top soil
	2	7.5	1.4	1.9	Highly weathered Basement
	3	32464			Fresh Basement
VES 09	1	66.7	0.9	0.9	Top soil
	2	14.8	2.2	3.1	Highly weathered Basement
	3	4953			Fresh Basement
VES 10	1	510.9	0.8	0.8	Top soil
	2	50.8	2.2	3	Weathered Basement
	3	2746			Fresh Basement
VES 11	1	125.1	1.0	1.0	Top soil
	3	18.5	1.5	2.5	Highly weathered Basement
	2	936.1			Weathered Basement
VES 12	1	115.7	3.1	3.1	Top soil

	2	59.1	7.4	10.5	Weathered Basement
	3	8217			Fresh Basement
VES 13	1	170.8	0.9	0.9	Top soil
	2	35.1	3.1	4.0	Weathered Basement
	3	1722			Fresh Basement
VES 14	1	263	0.987	0.987	Top soil
	2	74.8	1.61	2.6	Highly weathered Basement
	3	373	21.1	23.7	Weathered Basement
	4	8317			Fresh Basement
VES 15	1	76.4	2.2	2.2	Top soil
	2	33.2	5.26	7.46	Highly weathered Basement
	3	2802			Weathered Basement
VES 16	1	64.5	0.75	0.75	Top soil
	2	13.1	1.5	2.25	Highly Weathered Basement
	3	1639			Fresh Basement
VES 17	1	56.5	0.75	0.75	Top soil
	2	45.9	5.64	6.39	Weathered Basement
	3	3041			Fresh Basement
VES 18	1	140	1.73	1.73	Top soil
	2	54.3	3.2	4.93	Weathered Basement
	3	6313			Fresh Basement
VES 19	1	151	1.34	1.34	Top soil
	2	48.8	1.04	2.38	Highly Weathered Basement
	3	271	25.4	27.8	Weathered Basement
	4	5365			Fresh Basement
VES 20	1	33	0.8	0.8	Top soil
	2	15.8	2.68	3.48	Highly Weathered Basement
	3	1133			Fresh Basement
VES 21	1	234	0.75	0.75	Top soil
	2	131	12.7	13.5	Weathered Basement
	3	1814			Fresh Basement
VES 22	1	120	0.75	0.75	Top soil
	2	83.8	4.97	5.72	Weathered Basement
	3	3689			Fresh Basement
VES 23	1	85.6	0.909	0.909	Top soil
	2	51.7	4.56	5.47	Weathered Basement
	3	8645			Fresh Basement
VES 24	1	51.2	0.75	0.75	Top soil
	2	16.4	1.0	1.75	Highly weathered Basement
	3	55.7	4.49	6.24	Weathered Basement
	4	1792			Fresh Basement
VES 25	1	103	1.25	1.25	Top soil
	2	48.6	4.88	6.13	Weathered Basement
	3	1505			Fresh Basement

Overburden Thickness

The overburden thickness, representing the depth to bedrock, encompasses the combined thicknesses of materials above the fresh basement. This thickness range varies from 1.9 to 27.8 m. Analysis from the map (Fig. 4) indicates that the northern section of the study area features the thickest overburden, ranging from 10 to 27.8 m, with this trend continuing towards the central part extending eastward. The remaining southern part of the area has overburden thicknesses below 5 m, with the exception of VES 12 point where it reaches 10.5 m. According to Zohdy *et. al.* (1974), regions with thicker overburden often indicate high groundwater potential in Basement Complex terrains.

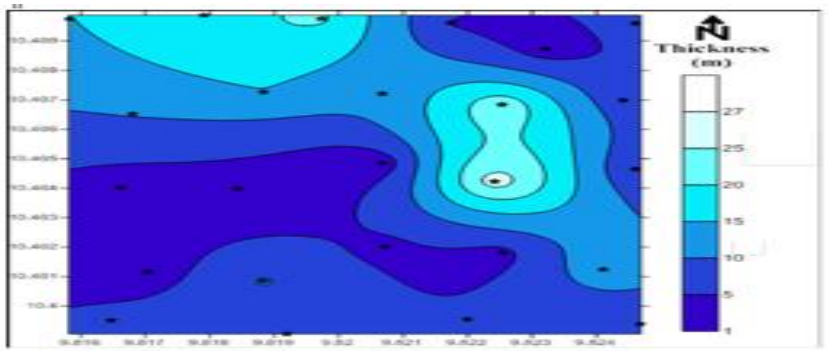


Figure 4: Overburden thickness

Aquifer thickness

The weathered bedrock serves as the aquiferous unit in the study area. Figure 5 displays the range of aquifer thickness across the study area, with measurements ranging from 1.5 to 25.4 m. The maximum thickness is observed at VES 19. In the southern region, the aquifer tends to be thinner, typically measuring less than 10 m. Moving towards the northern part, the thickness ranges from 10 to 20 m, with certain areas reaching beyond 20 m. A correlation is noticed between the thickness of the aquifer and the overburden in this region, suggesting that groundwater yield is anticipated to be high in these areas.

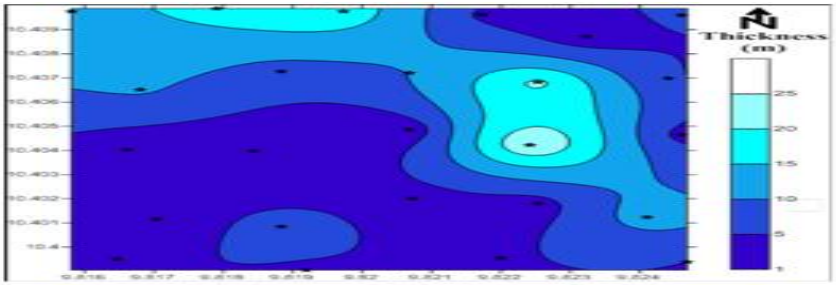


Figure 5: Aquifer thickness

Aquifer Resistivity

The aquifer resistivity ranges from 7.5 to 373 Ωm, as plotted and shown in Figure 6. From the map, the study area has been divided into two distinct regions, the northern and southern zones, based on resistivity range. In the southern part, the prevalence of low resistivity levels between 10 to 100 Ωm signifies optimum weathering and good groundwater potential, with the exception of VES 21, which shows a resistivity of 131 Ωm. In contrast, the northwestern part displays limited weathering and poor potential, with resistivity values falling between 150 to 300 Ωm. The northeastern part exhibits resistivity in the range of 7.8 to 100 Ωm towards the upper boundary, indicating high potential. The lower boundary, characterised by resistivity values of 150 to 300 Ωm, suggests low weathering capacity and poor water potentials. Across the central to north part of the area, an intermediate resistivity range of 100 to 150 Ωm is observed extending from the central area to the northwestern part, with VES 21 marking a significant point at the boundary between the northern and southern sections, constituting the main aquifer unit of the study area.

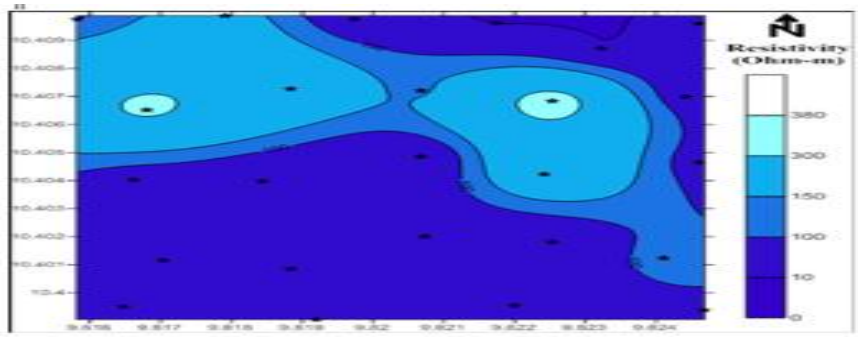


Figure 6: Aquifer resistivity map

Aquifer Transmissivity

The study area exhibits a transmissivity range of 18.2 to 275 m^2/day. Notably, the northeastern region boasts transmissivity values exceeding 100 m^2/day, while the remaining areas have values below 100 m^2/day (Fig. 7). Based on Krasny's (1993) criteria, areas with transmissivity values between 10 to 100 m^2/day are considered to have intermediate potential for private consumption, while those with values greater than 100 m^2/day are expected to have high potential for community consumption.

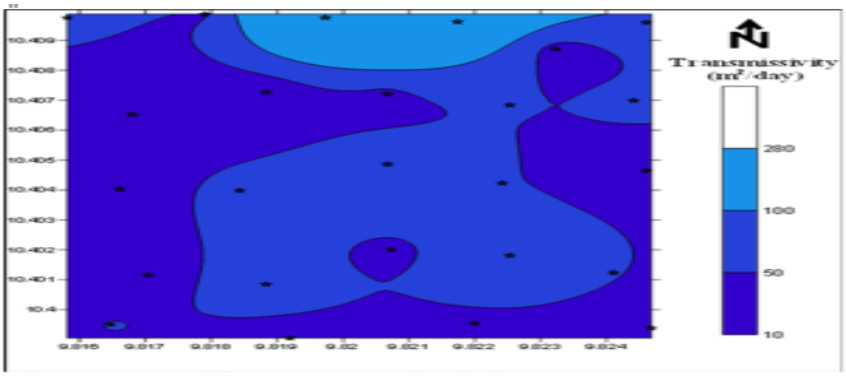


Figure 7: Aquifer Transmissivity map

Aquifer Protective Capacity

The aquifer protective capacity, as defined by Olorunfemi and Fasuyi (1993) and Adeniji *et al.,* (2014), refers to the ability of the overburden unit to impede and filter percolating ground surface liquids, thereby protecting the aquiferous unit from pollution. This capacity is a measure of the earth medium's ability to retard and filter percolating fluids. The clay material in the overburden acts as a protective covering for aquifer formations (Abiola *et al.,* 2013 and Henriet, 1976). The overburden's longitudinal conductance is directly proportional to its protective capacity (Tsepav *et al.,* 2015), which is a measure of the permeability of a confining clay layer with low hydraulic conductivity and low resistivity. The longitudinal conductance ranges from 0.04 to 0.9 m/day, and Table 3 outlines the characterisation of aquifer protective capacity based on longitudinal conductance (Henriet 1976).

Table 3: Aquifer Protective Capacity Rating (After Henriet 1976)

Longitudinal Conductance	Protective Capacity Rating
>10	Excellent
5 – 10	Very good
0.7 - 4.9	Good
0.2 - 0.69	Moderate
0.1 - 0.19	Weak
<0.1	Poor

Figure 8 dsplays the map llustrating the aquifers protective capacity across the study area. Specifically, certan sections of northern boundary, corresponding to VES 01, 02 & 03 and VES 13 & 20, exhibit a moderate protective capacity overbudden. This sggests that the aquifer in these areas is less vulnerable to pollution

through infiltration. In contrast, the study area predominantly shows a weak to poor protective capacity overbudden, indicating that it is unprotected and vulnerable to contaminants from near surface infiltration.

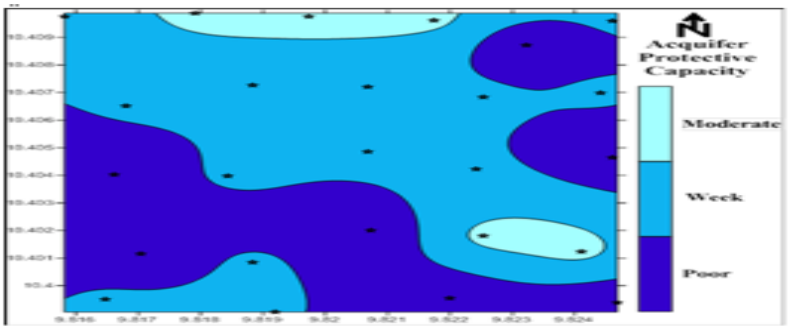


Figure 8: Aquifer Protective capacity Map

Groundwater Potential Assessment

Groundwater potential in a basement terrain is significantly influenced, to a certain extent, by the thickness and resistivity of the overburden. A thicker overburden with relatively low resistivity indicates a favourable groundwater prospect, as it allows for greater water infiltration and storage. The primary aquifer unit in the area is the weathered bed rock, whose degree of weathering is reflected in its moderate resistivity, which is a function of its water saturation. Furthermore, transmissivity values play a crucial role in evaluating the groundwater potentiality of the study area, as higher values indicate areas with greater groundwater potential. These key parameters were utilized to assess the groundwater potentials of the study area, as outlined in Table 4.

Table 4: Groundwater potential assessment

VES Name	Location		Overb.*[1] Thick. (m)	Aquif.*[2] Thick. (m)	Aquif.*[3] Resist. (Ωm)	Aquif.*[4] Trans. (m^2/day)	Aquif.*[5] PC Rating	GW*[6] Potential Rating
	Nothing	Easting						
VES 01	9.821742	10.40962	4.70	3.90	7.80	223	Moderate	Medium
VES 02	9.819733	10.40976	20.8	18.7	33.2	275	Moderate	Medium
VES 03	9.817911	10.40988	18.3	16.4	197	46.0	Moderate	Low
VES 04	9.818835	10.40727	14.8	7.90	242	18.2	Weak	Low
VES 05	9.815818	10.40976	14.9	13.4	94.8	74.1	Weak	Medium
VES 06	9.816803	10.40652	10.3	10.8	329	18.7	Weak	Low
VES 07	9.820679	10.40721	11.4	10.1	140	38.8	Weak	Medium
VES 08	9.820679	10.40486	1.90	1.50	7.50	82.6	Moderate	Low
VES 09	9.818434	10.40398	3.10	2.20	14.8	68.8	Weak	Medium
VES 10	9.816614	10.40403	3.00	2.20	50.8	21.8	Poor	Low
VES 11	9.817039	10.40116	2.50	1.50	18.5	38.1	Poor	Low
VES 12	9.818835	10.40085	10.5	7.40	59.1	63.6	Weak	Medium
VES 13	9.820729	10.40201	4.00	3.00	35.1	41.9	Poor	Low
VES 14	9.822534	10.40684	2.25	1.40	13.1	52.6	Weak	Medium
VES 15	9.824606	10.40960	7.94	6.74	38.9	85.6	Weak	Low
VES 16	9.823225	10.40872	23.7	21.1	373	32.5	Poor	Medium
VES 17	9.824414	10.40699	6.39	5.64	45.9	61.4	Weak	Medium
VES 18	9.824606	10.40465	4.93	3.20	54.3	29.8	Poor	Low
VES 19	9.822419	10.40423	27.8	25.4	271	52.8	Weak	Medium
VES 20	9.822534	10.40181	3.48	2.68	15.8	78.9	Weak	Medium
VES 21	9.824107	10.40124	13.5	12.7	131	52.0	Good	Medium

VES 22	9.824683	10.39939	5.72	4.97	83.8	30.9	Poor	Low
VES 23	9.821996	10.39955	5.47	4.56	51.7	44.4	Poor	Low
VES 24	9.819195	10.39905	6.24	4.49	55.7	40.1	Weak	Low
VES 25	9.816470	10.39951	6.13	4.88	48.1	50.9	Weak	Medium

[1]Overburden thickness[2]Aquifer Thickness*[3]Aquifer Resistivity
[4]Aquifer Transmissivity[5]Aquifer Protective Capacity Rating*[6]Groundwater Potential Rating

The approach of Abdulrahman *et al*. (2016), Anudu *et al.* (2012) and Krasny (1993) has been adopted and applied to assess the groundwater potential of the study area utilizing data from individual VES point. Table 4 outline the groundwater potential as a function of overburden thickness, weathered bedrock resistivity and transmissivity, highlighting their significance in the assessment process.

Table 5: Aquifer Potential Assessment (Modified from Abdulrahman et al. (2016), Anudu *et al.* (2012) and Krasny (1993))

Influencing factor	Category based on all the VES points	Aquifer characteristics
Overburden Thickness (m)		
	< 10	Negligible potential
	10 – 20	Low potential
	20 – 30	Medium potential
	> 30	High potential
Aquifer Thickness (m)		
	< 10	Negligible potential
	10 – 20	Low potential
	20 – 30	Medium potential
	> 30	High potential
Aquifer Resistivity (Ωm)		
	< 10	Clays with limited potential
	10 – 100	Optimum weathering and good groundwater potential
	100 – 150	Medium conditions and potential
	150 – 300	Little weathering and poor potential
	> 300	Negligible potential
Aquifer Transmissivity (m^2/day)		
	< 10	Low potential
	10 – 100	Intermediate potential; for private consumption
	>100	High potential; for community consumption

CONCLUSION

The study highlighted the importance of resistivity methods in effective geoelectric characterisation of subsurface aquifer of Sabon-Gari Bauchi, of Bauchi State Nigeria. Geoelectric soundings around the study area revealed subsurface sequence composing topsoil with weak protective capacity, a thin highly weathered basement, a weathered layer (aquifer unit), and a fresh basement. The overburden thickness ranges between 1.9 – 27.8 m, the aquifer thickness ranges from 1.5 – 25.4 m, the aquifer resistivity ranges from 7.5 - 373 Ωm, and the aquifer transmissivity ranges from 18.2 – 275 m^2/day. The integrated analysis of these geoelectric layers and aquifer parameters assesses the underlying aquifer's groundwater potential and protective capacity, indicating a low to medium rating. This explains the prevalent borehole failures in the area. Table 6 can therefore assist in identifying areas characterized by high transmissivity, water potential, and protective capacity for borehole siting.

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