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GROUNDWATER INVESTIGATION USING DAR ZARROUK PARAMETERS FOR HYDROGEOLOGICAL SUBSURFACE ASSESSMENT IN NIGER STATE POLYTECHNIC, ZUNGERU.

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Abstract
Groundwater constitutes the principal source of water for domestic and institutional use at Niger State Polytechnic, Zungeru, necessitating a detailed evaluation of its hydrogeological potential. This study employed Dar Zarrouk parameters derived from Vertical Electrical Sounding (VES) data to characterize the subsurface and assess aquifer properties within the Polytechnic environment. A total of forty (40) VES stations were acquired using the Schlumberger array, and data interpretation through curve matching and computer iteration delineated subsurface layers and aquifer characteristics. Results identified three to four lithological units: topsoil/lateritic cover, clay, sandy clay, clayey sand, weathered basement, and fresh basement. Dar Zarrouk parameters, such as longitudinal conductance, transverse resistance, hydraulic conductivity, transmissivity, reflection coefficient, and anisotropy, provided insights into aquifer protective capacity and groundwater potential. Aquifer resistivity ranged from 2-402 Ωm, with thicknesses of 0.6-19.6 m, while basement resistivity exceeded 1,000 Ωm, confirming a crystalline bedrock. High transmissivity and hydraulic conductivity at VES 1, 6, 11, 25, and 36 denote productive aquifers, whereas clayey zones showed poor recharge. Groundwater occurrence is predominantly associated with weathered and fractured basement zones, which constitute the main aquifers. It is recommended that borehole development target these zones to ensure a sustainable water supply for the Polytechnic and surrounding communities.
Keywords: *Groundwater Investigation, Dar Zarrouk Parameters, Vertical Electrical Sounding (VES), Hydrogeological Assessment.*

Introduction

Access to clean, sustainable water resources is a fundamental necessity for human survival and community development, especially in regions with limited water supply (Ejepu et al., 2024). Over many years, groundwater has proven to be a reliable source of water for domestic activities and industrial use worldwide, accounting for an estimated 85% of Nigeria's total water demand (Ejepu et al., 2024; Oguama et al., 2019). However, rapid population growth and urbanization in Nigeria, particularly at the Niger State Polytechnic, have led to rising water demand, exerting considerable pressure on available groundwater resources in the study area. This has highlighted the need to conduct groundwater investigations to support the sustainable development and management of groundwater systems at Niger State Polytechnic, Zungeru.

In groundwater investigations, geophysical methods offer non-invasive, cost-effective, and reliable options for subsurface characterization, delineation of geological formations, and evaluation of groundwater potential (Omolaiye et al., 2025; Eyankware & Aleke, 2021). Among these methods, the Electrical Resistivity method using the Vertical Electrical Sounding (VES) technique has proven to be one of the most efficient and widely used approaches for hydrogeological investigations (Babasola & Ifeanyi, 2025; Falade et al., 2025; Mahmud et al., 2022; Eyankware & Aleke, 2021). The VES method operates on the principle that different subsurface materials exhibit distinct electrical resistivity responses based on their lithology, porosity, and water saturation. In basement complex terrains, this method enables the delineation of aquifer zones, the measurement of overburden thickness, and the identification of groundwater-bearing formations with high accuracy, making it essential for groundwater resource evaluation and management (Omolaiye et al., 2025; Mahmud et al., 2022).

Moreover, Dar Zarrouk parameters such as Longitudinal Conductance (S), Transverse Resistance (Tr), Transmissivity (T), Hydraulic Conductivity (K), Reflection Coefficient and Coefficient of Anisotropy (λ), provide additional critical insight into groundwater occurrence,

flow dynamics, and aquifer vulnerability, serving as advanced quantitative tools for assessing geo-hydraulic properties of the subsurface (Pandey & Pratap, 2025; Ibuot et al., 2023; Eyankware & Aleke, 2021). The integration of these geo-hydraulic parameters enhances understanding of groundwater potential and helps evaluate the aquifer systems, facilitating better water resource planning and development.

This study focuses on groundwater investigation at Niger State Polytechnic, Zungeru, using Dar Zarrouk geoelectrical parameters derived from Vertical Electrical Sounding (VES) data to evaluate subsurface hydrogeological layers. The results are expected to provide essential information for effective groundwater exploration, inform future borehole development, and support sustainable groundwater management within Niger State Polytechnic and its surrounding areas.

Study Area

This study area is the Niger State Polytechnic, Zungeru, situated within Wushishi Local Government Area of Niger State, North-Central Nigeria. Geographically, it lies between latitudes 9°44′N and 9°46′N and longitudes 6°07′E and 6°09′E, covering land used for academic buildings and surrounding residential settlements. The VES locations are shown in Figure 1. The terrain has an average elevation of 95 to 130 m above sea level and features gently undulating topography, with low-lying plains and gentle slopes that affect surface runoff and drainage patterns. The climate is tropical continental, marked by two distinct seasons: a wet season from April to October and a dry season from November to March (Abdullahi et al., 2025). The area receives approximately 1,000-1,300 mm of rainfall annually, with peak precipitation between July and September. Temperatures range from about 24°C in the cooler months to over 37°C at the height of the dry season (Abdullahi et al., 2025). These climatic conditions significantly influence groundwater recharge, as intense and prolonged rainfall promotes infiltration through weathered and fractured zones, helping sustain aquifer systems and causing seasonal variations in groundwater availability. Additionally, drainage mainly comes from tributaries of the River Kaduna, which act as surface expressions of subsurface flow systems and play a key role in groundwater recharge during the rainy season. Geologically, Niger State Polytechnic, Zungeru is situated in North-Central of Nigeria forming part of the Precambrian Basement Complex with diverse lithological dominate rock units including metamorphic suite transitioning from granite to gneiss, granite gneiss, and granite, schist, and phyllite, which are predominantly composed of quartz, feldspar, biotite, and mica, exhibit medium to coarse grained textures (Adetona et al., 2025; Muhammad and Abbasi, 2025; Musa et al., 2025; Tsepav et al., 2023).

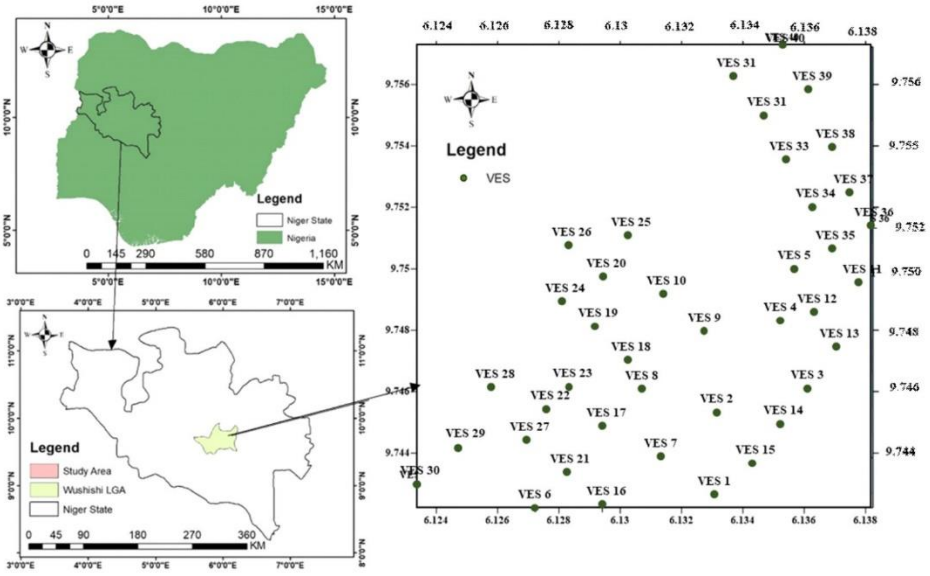

Fig. 1 *Basemap of the Study area showing the VES point locations*

Materials and Methodology

The primary materials used to acquire Vertical Electrical Sounding (VES) data within the study area are a Resistivity meter, Pairs of Electrodes, Cable Reels, Hammers, a Tape Meter, a Geographical Positioning System (GPS) reader, and Field Notes. A total of forty (40) VES points were investigated within the Niger State Polytechnic Area, with Schlumberger electrode configuration utilised with a maximum current electrode separation (AB/2) of 100m. In addition, the software used for processing and interpretation includes Microsoft Excel for data organisation, WinResist for plotting the Resistivity-Depth Curve, and Surfer for contour mapping of all parameters. The combination of these materials and software tools ensures high data precision of hydro-geophysical interpretation.

The Vertical Electrical Sounding (VES) technique is one of the geophysical electrical resistivity methods used for investigating subsurface lithological properties of the Earth, which involves measuring the electrical resistivity of the subsurface at various depths in order to delineate different geological formations and structures (Babasola and Ifeanyi, 2025; Adeniji et al., 2022). The theoretical foundation of this method is Ohm's law, which states that the voltage across a conductor is directly proportional to the current, provided that all physical conditions and temperature remain constant, as shown in equations 1 and 2.

$$\boldsymbol{V = IR} \qquad \textbf{Eqn. 1}$$

$$\boldsymbol{R = \frac{V}{I}} \qquad \textbf{Eqn. 2}$$

Where V is Voltage, I is Current, and R is the Resistance.

This method applies this principle to identify differences in resistance among various subsurface materials, where the level of resistance to the passage of electrical current is measured as the material's resistivity, in ohm-meters; resistivity is the inverse of the material's conductivity (Adeniji et al., 2022). The resistance of a medium (R) is proportional to its length and inversely proportional to its cross-sectional area (A), as shown in equations 3 and 4.

$$\boldsymbol{R = \frac{\rho L}{A}} \qquad \textbf{Eqn. 3}$$

$$\boldsymbol{\rho = \frac{RA}{L} = \frac{VA}{IL}} \qquad \textbf{Eqn. 4}$$

Where R is Resistance, L is Length, A is the Cross-sectional Area, and $\boldsymbol{\rho}$ is the Resistivity of the material.

The Vertical Electrical Sounding technique uses the Schlumberger electrode configuration for subsurface characterization due to its sensitivity to vertical resistivity variations and its established reliability in groundwater exploration in crystalline basement terrains (Pandey and Pratap, 2025). In this study, the current electrodes (A and B) were progressively expanded by about a fixed center from 1 to 100 m. In contrast, the potential electrodes (M and N) remained relatively close, ensuring adequate sensitivity for potential measurement. Apparent resistivity values were computed from field resistance readings using the appropriate geometric factor (K) as shown in equations 5 and 6 (Pandey and Pratap, 2025).

$$\boldsymbol{\rho_A = \rho * G} \qquad \textbf{Eqn. 5}$$

$$\boldsymbol{G = \pi \frac{(AB/2)^2 - (MN/2)^2}{MN}} \qquad \textbf{Eqn. 6}$$

Where $\boldsymbol{\rho_A}$ is the apparent resistivity, $\boldsymbol{\rho}$ is the resistance value, and G is the Schlumberger electrode configuration.

The obtained apparent resistivity data were plotted on log–log paper to generate preliminary curve types and subsequently processed using WinResist for computer-aided inversion, yielding true resistivity and thickness values for individual subsurface layers. These parameters formed the basis for the computation of Dar Zarrouk parameters, which provided hydrogeological insights into aquifer characteristics, protective capacity, and transmissivity potential of the study area (Pandey and Pratap, 2025).

Longitudinal Conductance (S)

Longitudinal Conductance (S) is the summation of the ratio of layer thickness to resistivity across overburden units, representing the capacity of the overlying materials to conduct electrical current vertically and is inversely related to resistivity calculated using equation 7 (Adewoye and Agbaje, 2025; Aladeboyeje et al., 2024; Eyankware and Aleke, 2021). High values indicate thick, conductive (often clayey) layers that provide strong protection against the infiltration of contaminants from the surface, whereas low values denote thin or resistive overburden, leaving underlying aquifers more vulnerable to pollution (Adewoye and Agbaje, 2025; Sekar et al., 2021).

$$\boldsymbol{S = \frac{h_1}{\rho_1} + \frac{h_2}{\rho_2} + \frac{h_3}{\rho_3} + \ ... + \frac{h_n}{\rho_n} = \sum_{i=1}^{n} \frac{h_i}{\rho_i}} \qquad \textbf{Eqn. 7}$$

Where $h_i$represent the thickness of each geological layer and ρ_i represent the resistivity of each layer.

Transverse Resistance (Tr)

Transverse Resistance (Tr) is a geoelectrical parameter defined as the product of resistivity and thickness of a subsurface layer, which measures the conductive strength of a layer in the horizontal direction and is directly proportional to aquifer transmissivity as presented mathematically in equation 8 (Aladeboyeje et al., 2024; Fatoye et al., 2024; Eyankware and Aleke, 2021). High transverse resistance values suggest thick, permeable aquifer formations capable of transmitting large volumes of groundwater, while low values indicate thin or clay-rich layers with low permeability (Adewoye and Agbaje, 2025).

$$\boldsymbol{Tr = \rho_1 h_1 + \rho_2 h_2 + \rho_3 h_3 + \cdots + \rho_n h_n = \sum_i^n \rho_i h_i} \qquad \textbf{Eqn. 8}$$

Where $h_i$represent the thickness of each geological layer and ρ_i represent the resistivity of each layer.

Hydraulic Conductivity (K)

Hydraulic Conductivity refers to the ease with which water flows through porous media and describes the medium's water-transmitting property (Nzemeka et al., 2025). The hydraulic conductivity of geological formation depends on various physical factors, including porosity, particle size and distribution and other factors, which are estimated to evaluate the movement and yield potential of groundwater within the identified aquifer zones, and it is mathematically expressed by equation 7 below (Pandey and Pratap, 2025; Fatoye et al., 2024; Seli et al., 2021).

$$\boldsymbol{K = 386.4 * R^{-0.93283}_{rw}} \qquad \textbf{Eqn. 7}$$

Where R_{rw} is the aquifer layer resistivity

Aquifer Transmissivity (T)

The Aquifer Transmissivity defines the ability of the entire saturated thickness to transmit water, which defines the amount of water that can be transmitted horizontally through an aquifer unit by the full saturated thickness of the aquifer under a hydraulic gradient of 1 (Babasola and Ifeanyi, 2025; Fatoye et al., 2024).

$$\boldsymbol{T = K * h} \qquad \textbf{Eqn. 8}$$

Where **K** is Hydraulic Conductivity and **h** is the thickness of the aquifer.

Reflection Coefficient (Rc)

This is expressed as the contrast in resistivity between the weathered or fractured layer and the underlying fresh basement (Pandey and Pratap, 2025). Rc values approaching zero indicate minimal contrast and suggest a good hydraulic connection between the layers, favorable for groundwater accumulation. On the other hand, high Rc values denote a sharp resistivity contrast, indicating compact, impermeable bedrock with limited water transmission. Therefore, the reflection coefficient helps identify zones of fractured development and aquifer potential.

$$\boldsymbol{R_c = \frac{\rho_n - \rho_{(n-1)}}{\rho_n + \rho_{(n-1)}}} \qquad \textbf{Eqn. 9}$$

Where ρ_n and $\rho_{(n-1)}$ represent the resistivity of the nth layer and the resistivity of the layer immediately above the nth layer, respectively.

Coefficient of Anisotropy

Coefficient of Anisotropy (λ) expresses the degree of directional variation in subsurface resistivity, providing insight into the anisotropic nature of the geological formation, which values closer to 1 indicate isotropic conditions revealing uniform resistivity in all directions, while higher values suggest anisotropy arising from fractures, as shown using equation 10 (Eyankware and Aleke, 2021; Sekar et al., 2021).

$$\boldsymbol{\lambda_a = \sqrt{\frac{\rho_t}{\rho_L}}} \qquad \textbf{Eqn. 10}$$

Where ρ_t is the transverse resistivity and ρ_L is the longitudinal resistivity

Results

The results of the geoelectrical investigation conducted within Niger State Polytechnic, Zungeru, revealed notable subsurface lithological variations across the study area. The interpretation of the Vertical Electrical Sounding (VES) data identified three to four distinct geoelectric layers: topsoil or lateritic topsoil, clay, sandy clay, clayey sand, fractured basement, and fresh basement. These layers demonstrate the heterogeneity of subsurface materials and their distinct hydrogeological significance for groundwater occurrence and movement. The curve types obtained from the VES data include H, A, QH, HA, and KH, indicating diverse

subsurface resistivity distributions that suggest differences in lithological composition, degree of weathering, and groundwater potential. Figure 2 shows a sample of the Winresist Plot within the study area. The predominance of H and HA curve types across most VES points suggests a weathered or fractured basement aquifer system, which is typical of basement complex terrains and favorable for groundwater accumulation and exploration. Table 1 shows the summarized values of all the Dar Zarrouk parameters for all the VES stations.

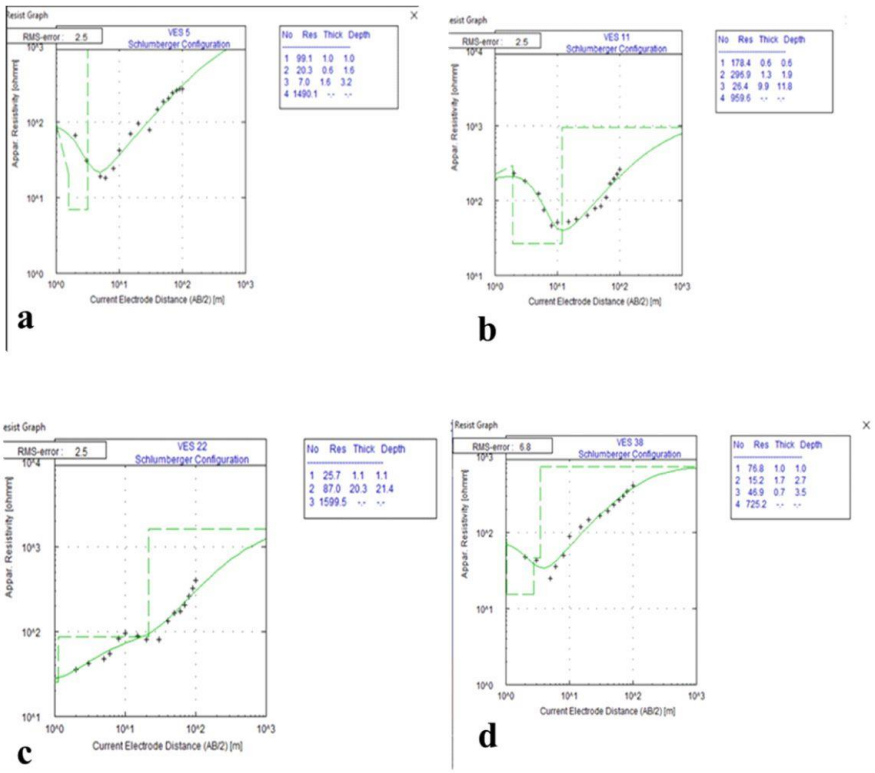

Fig. 2 *WinResist Curve plot at (a) VES 5, (b) VES 11, (c) VES 22 and (d) VES 38*

Table 1 Summarized Values of all the Dar Zarrouk Parameters within the VES stations

VES	Long.	Lat.	S	Tr	K	T	Rc	λ
1	9.742694	6.133028	21.08	114.27	43.88	223.77	-0.253	7.1
2	9.745306	6.133139	246.21	206.3	22.88	59.49	-0.042	64.4
3	9.746039	6.136077	14.81	769.6	18.17	118.11	-0.158	7.7
4	9.748333	6.135167	19.96	236.84	13.58	78.79	0.06	9.7
5	9.749950	6.135667	195.29	351.36	62.91	100.65	-0.009	25.9
6	9.742222	6.127222	17.67	239.79	19.48	163.61	0.003	6.6
7	9.743805	6.131242	25.52	56.88	26.76	56.20	0.003	8.3
8	9.746065	6.130733	188.99	167.61	12.43	17.41	0.005	46.8
9	9.748027	6.132745	24.68	141.58	16.19	42.08	0.001	12.3
10	9.749170	6.131475	98	109.99	12.73	12.73	0.046	27.3
11	9.749537	6.137795	538.39	754.37	18.24	180.54	-0.274	53.5
12	9.748635	6.136327	79.78	990.42	9.18	93.64	-0.186	22.49
13	9.747427	6.136996	64.43	864.78	8.34	115.04	0.034	16.28
14	9.744832	6.135234	124.31	996.92	8.45	102.27	-0.033	25.9
15	9.743638	6.134277	1755.8	1372.58	27.95	103.43	-0.051	258.7
16	9.742222	6.129416	36.92	476.52	11.14	106.90	0.004	12.28
17	9.744809	6.129422	191.38	142.96	46.85	112.45	-0.178	53.4
18	9.747011	6.130220	19.22	49.62	37.47	134.88	0.002	7.4

19	9.748105	6.129174	19.46	177.99	24.54	93.26	-0.002	8.9
20	9.749750	6.129441	195.29	351.36	15.42	148.03	-0.03	25.9
21	9.743372	6.128242	168.08	248.3	12.92	32.30	-0.157	58.4
22	9.745385	6.127639	27.65	1794.37	6.0	121.70	0.036	23
23	9.746138	6.128305	146.52	2907.66	1.54	11.07	0.065	75
24	9.748908	6.128115	1148.22	2754.4	1.40	8.39	-0.037	273.6
25	9.751061	6.130303	27.72	972.68	12.86	221.14	-0.055	8
26	9.750750	6.128250	107.46	584.02	8.56	77.02	-0.009	25.8
27	9.744438	6.126979	119.6	237.26	14.48	36.21	-0.171	45.5
28	9.746111	6.125833	249.73	223.04	5.42	5.96	0.015	71.5
29	9.744222	6.124750	41.51	467.23	12.04	62.61	0.004	11.8
30	9.742972	6.123361	251.9	347.68	15.07	15.07	0.003	29.3
31	9.7563	6.13369	53.85	201.94	23.85	50.08	-0.053	33.6
32	9.754961	6.134693	70.47	186.68	19.48	52.59	-0.042	28
33	9.753516	6.135396	130.01	266.39	16.44	65.77	-0.042	35.79
34	9.752011	6.136235	161.34	235.19	15.38	41.51	-0.017	52.65
35	9.750641	6.136899	195.72	321.54	10.69	60.93	0.017	35.83
36	9.751315	6.138236	32.27	10.05	202.41	242.89	-0.005	11.26
37	9.7525	6.1375	293.43	949.84	3.62	2.17	-0.013	103.52
38	9.573888	6.136844	152.74	135.47	10.67	7.47	0.041	41.1
39	9.755833	6.136111	32.33	403.82	10.18	81.47	0.002	13.3
40	9.757222	6.135277	55.49	91.35	21.17	50.80	-0.002	21.6

Resistivity and Thickness of the Topsoil Layer

As shown in Figure 3, the resistivity distribution of the topsoil across the study area exhibits considerable variation, ranging from 9 Ωm to 859 Ωm, which reflects distinct lithological compositions and hydrogeological characteristics. Low resistivity values below 59 Ωm observed at VES 4, 6, 7, 9, 10, 16, 18, 19, 39, and 40 indicate a clay-rich topsoil with high moisture retention and low permeability, providing excellent protective capacity but limited recharge potential. Conversely, high resistivity values exceeding 459 Ωm noted at VES 15 and 24 correspond to lateritic topsoil with compact material, which provides strong aquifer protection but poor infiltration. Most of the area exhibits intermediate resistivity values between 109 Ωm and 359 Ωm, characteristic of sandy or sandy-lateritic materials that facilitate infiltration and recharge while offering moderate protection.

In addition, the topsoil thickness varies considerably as illustrated in Figure 4, ranging from less than 1 m to about 8 m. Thin overburden, less than 1 m found at VES 2, 5, 7, 8, 10, 11, 13, 15, 17, 18, 20, and 24-40 suggests high aquifer vulnerability due to minimal protective cover. Conversely, thicker overburden greater than 1.5 m observed at VES 3, 9, 12, 14, 19, 25, 29, and 37 provides enhanced protection against contamination but may reduce recharge rates. Moderately thick layers between 1 m and 1.5 m dominate most parts of the area, indicating a balance between recharge and protection. Therefore, the spatial variation in resistivity and thickness highlights the dual hydrogeological role of the topsoil in controlling groundwater recharge and aquifer vulnerability within the study area.

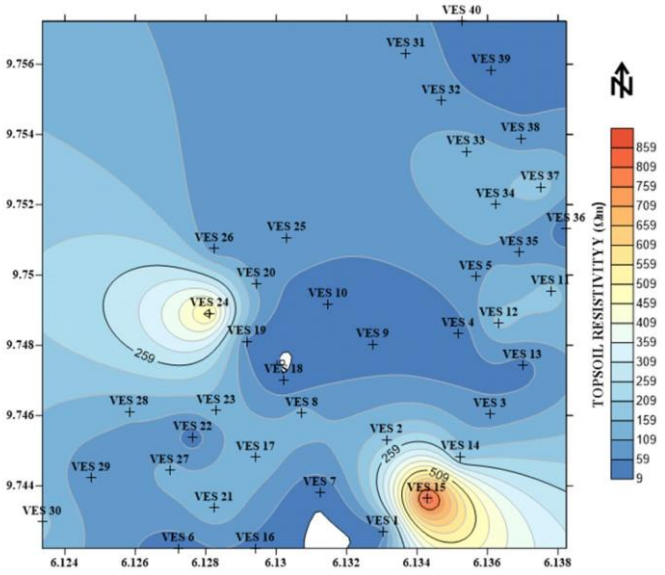

Fig. 3 Topsoil Resistivity map of the Study Area

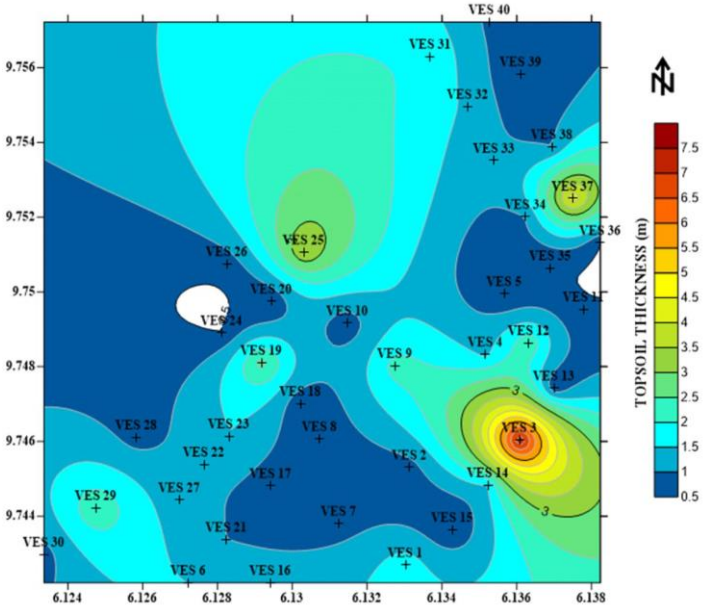

Fig. 4 *Topsoil Thickness map of the Study Area*

Resistivity and Thickness of Aquifer Layer

As shown in Figure 5, the aquifer resistivity values across the study area range from 2 Ωm to 402 Ωm, reflecting notable spatial variation linked to differences in lithology, porosity, and groundwater quality. Moderate resistivity values between 50 Ωm and 100 Ωm are associated with saturated sandy clay formations, suggesting low-yield aquifers with limited permeability. Higher resistivity values exceeding 150 Ωm, observed at VES 23, 24, and 37, correspond to weathered formations with improved pore connectivity and groundwater potential. In contrast, very low resistivity values below 20 Ωm, found at VES 1, 2, 5, 7, 15, 18-19, 31, and 36, indicate clay-rich zones with poor permeability and minimal water-bearing capacity. This variability illustrates the influence of lithological composition and groundwater quality on aquifer performance and underscores the importance of integrating geoelectrical data with hydrogeological interpretations for groundwater evaluation.

Moreover, the aquifer thickness varies from less than 0.6 m to over 19.6 m across the area, revealing significant differences in groundwater storage and productivity as shown in Figure 6. Thin aquifers less than 2.6 m identified at VES 2, 5, 7-10, 17, 18, 28, 30-32, 34, and 36-38 represent low storage zones with limited yields, while thick aquifers greater than 8 m, found at VES 6, 11-14, 16, 20, 22, 23, 25, and 26, indicate highly productive units suitable for sustainable water supply development. Moderately thick aquifers between 2.6 m to 8 m dominate much of the area, suggesting balanced conditions between storage and yield potential. Generally, aquifer thickness correlates positively with transmissivity, indicating that thicker aquifer units support both higher groundwater storage and flow efficiency, making them ideal targets for groundwater development in the study area.

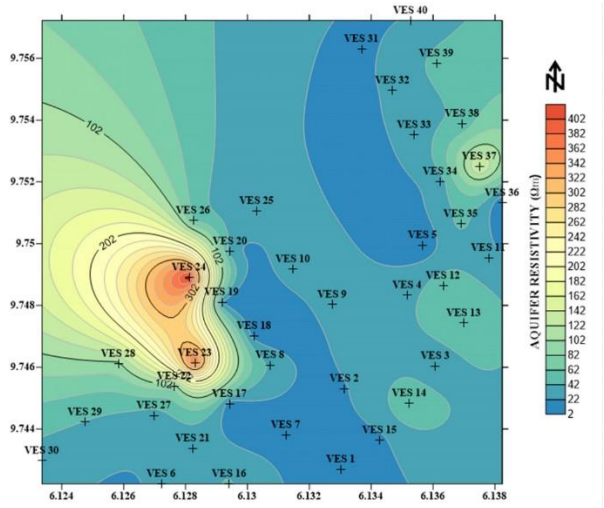

Fig. 5 *Aquifer Resistivity of the Study Area*

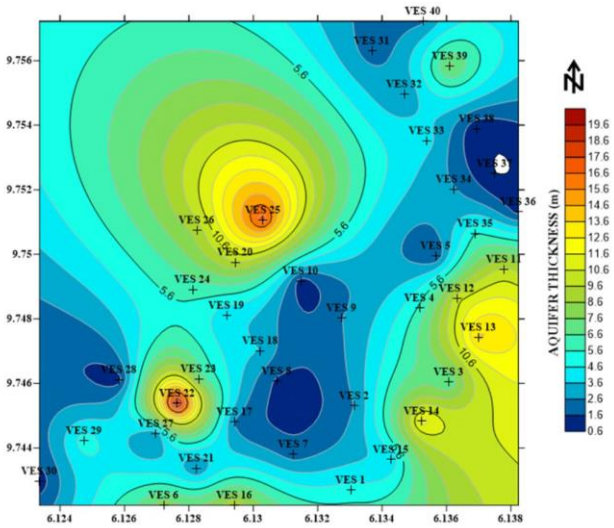

Fig. 6 Aquifer Thickness of the Study Area

Resistivity and Depth of Basement Layer

The basement resistivity across the study area as shown in Figure 7, ranges from slightly above 1,000 Ωm to about 20,000 Ωm, reflecting the heterogeneous nature of the crystalline basement complex. Extremely high resistivity values greater than 1,000 Ωm recorded at VES 2, 8, 15, 19, 28-30, 34, and 39-40 are characteristic of fresh, compact, and unfractured basement rocks with negligible porosity and permeability, indicating poor groundwater potential. These fresh

basement zones act as aquicludes, restricting groundwater storage and movement. Conversely, lower basement resistivity values less than 1,000 Ωm observed in most other locations suggest weathered or fractured basement materials, which are more hydro-geologically favorable. Such zones promote groundwater accumulation and flow within the fractured network, making them more suitable for groundwater development. Therefore, the spatial variation in basement resistivity effectively differentiates between unproductive fresh basement and prospective weathered or fractured zones.

Furthermore, Figure 8 shows that the depth to the basement within the study area varies from 1 m to approximately 21 m, revealing differences in overburden thickness and aquifer potential. Shallow basement depths of less than 5 m identified at VES 2, 5, 7-10, 17, 18, 21, 27, 28, 31-34, 36-38, and 40 indicate thin overburden that limits aquifer storage and makes groundwater occurrence less reliable. In contrast, deeper basement levels greater than 10 m recorded at VES 3, 11-14, 25, and 29-30 correspond to thicker overburden, offering enhanced potential for groundwater accumulation within weathered or fractured zones above the bedrock. The majority of the area exhibits moderate basement depths between 5 m and 9 m, suggesting sufficient overburden thickness to support localized aquifer systems. Generally, a greater depth to the basement correlates with higher groundwater storage and yield, while shallow basement zones tend to be less productive for sustainable groundwater development.

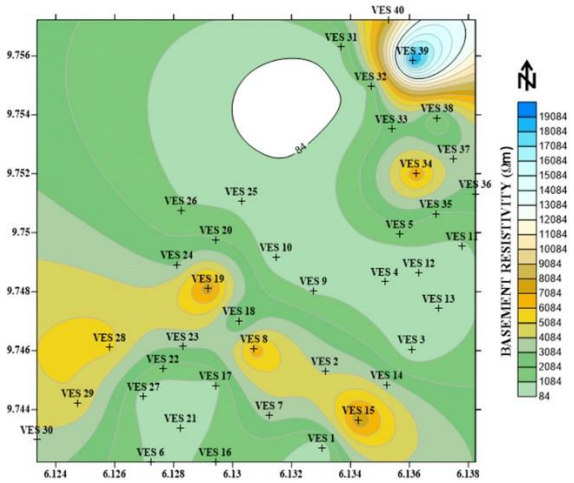

Fig. 7 Basement Resistivity of the Study Area

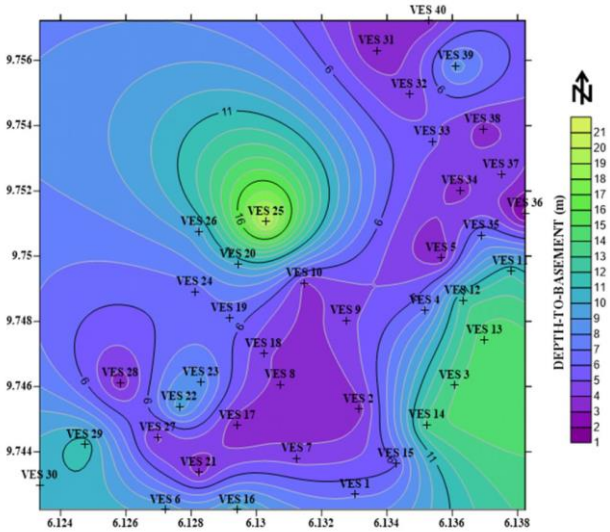

Fig. 8 *Depth to Basement of the Study Area*

Longitudinal Conductance and Transverse Resistance

As shown in Figure 9, the total longitudinal conductance across the study area ranges from 14 to 1,714 Ω^{-1}, indicating generally high protective capacity of the overburden materials. Elevated conductance values are typically associated with clay-rich or fine-grained sediments, which act as effective barriers to contaminant infiltration into underlying aquifers. The predominance of high conductance (>10 Ω^{-1}) throughout the study area suggests that the aquifers are well protected from surface pollution, reducing their vulnerability to contamination. However, while high conductance indicates strong protection, it may also reflect reduced permeability and slower recharge. Therefore, the spatial distribution of longitudinal conductance highlights the hydrogeological balance between aquifer protection and recharge dynamics, making it a vital indicator in groundwater vulnerability assessment.

Furthermore, Figure 10 shows the total transverse resistance values ranging from 10 to 2,810 Ωm^2, indicating considerable spatial variability in aquifer potential. High transverse resistance values are associated with thick, resistive, water-saturated formations, often sandy or fractured basement units, which indicate zones with enhanced groundwater storage and transmission capacity. The widespread presence of high transverse resistance across many VES stations suggests the existence of productive aquifer systems with good yield potential. In contrast, lower transverse resistance values represent thinner or less permeable layers with limited storage capacity. Thus, areas with high transverse resistance are more suitable for groundwater development, whereas lower values suggest marginal aquifer conditions. The combined analysis of longitudinal conductance and transverse resistance offers an integrated understanding of aquifer protective capacity and productivity within the study area.

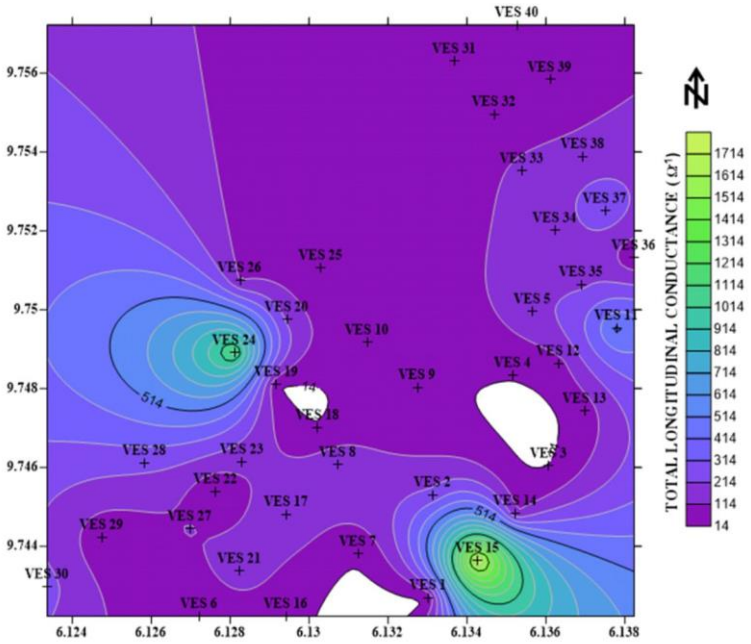

Fig. 9 *Total Longitudinal Conductance of the Study Area*

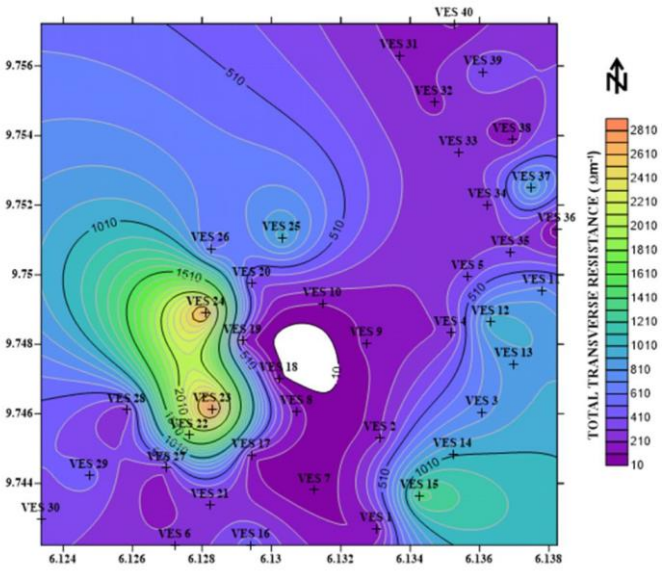

Fig. 10 *Total Transverse Resistance of the Study Area*

Hydraulic Conductivity and Transmissivity

The hydraulic conductivity distribution across the study area mainly varies between 1 and 40 m/day, with some notable higher values (Figure 11). Elevated hydraulic conductivity readings at VES 1, 5, 17, and 18, and a peak of 243 m/day at VES 36, point to highly permeable zones made up of sandy or fractured formations that allow quick groundwater infiltration and flow. Conversely, most VES sites with conductivity below 40 m/day are associated with clayey or fine-grained formations, which hinder groundwater movement and lower recharge potential. These differences emphasize the role of lithological composition in groundwater mobility and pinpoint localized zones of high groundwater potential within the study area.

Figure 12 illustrates that Transmissivity values range from 2 to 242 m²/day, reflecting both aquifer thickness and hydraulic conductivity. High transmissivity values above 142 m²/day observed at VES 1, 6, 11, 25, and 36 indicate productive aquifer zones capable of supporting boreholes with substantial yields. Conversely, low transmissivity values below 32 m²/day at VES 8, 10, 23, 24, 28, 30, 37, and 38 suggest thin or low-permeability aquifers with limited storage and poor yield potential. This spatial variability highlights the heterogeneous nature of the subsurface, where high transmissivity zones are suitable for groundwater extraction, while low transmissivity regions are less favorable for large-scale abstraction. Generally, transmissivity values above 100 m²/day denote highly productive aquifers, whereas those below 20 m²/day indicate marginal zones. Therefore, the combined analysis of hydraulic conductivity and transmissivity offers vital insights into aquifer storage and transmission capacity, guiding sustainable groundwater exploration and management within the study area.

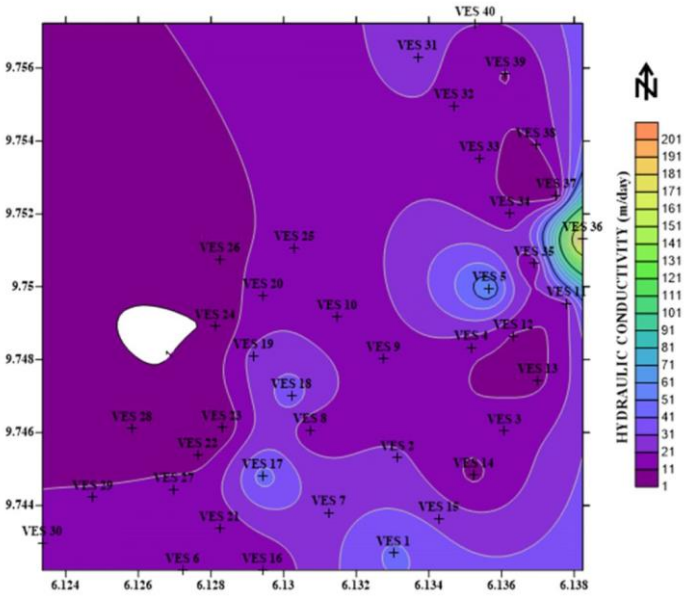

Fig. 11 *Hydraulic Conductivity of the Study Area*

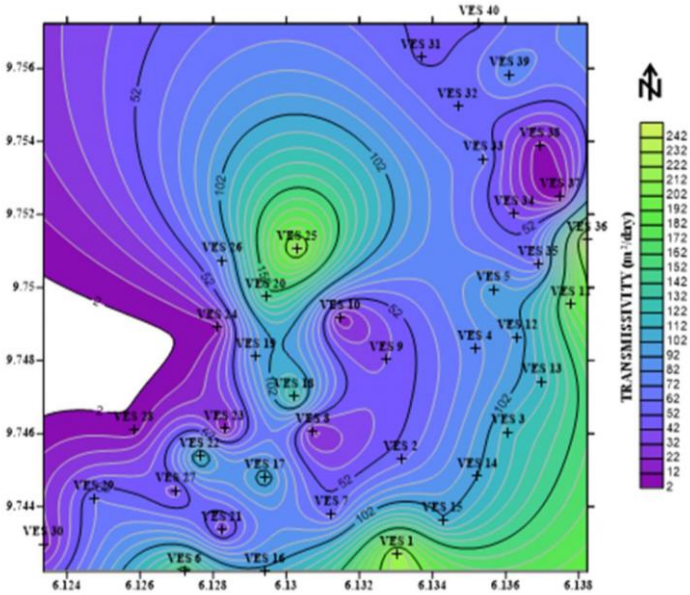

Fig. 12 Transmissivity of the Study Area

Reflection Coefficient and Coefficient of Anisotropy

As shown in Figure 13, the reflection coefficient across the study area ranges from –0.28 to 0.08, with most VES locations displaying very low values, indicating weak resistivity contrasts between layers. This suggests gradual lithological transitions and limited protective cover above aquifers, making them more vulnerable to contamination. However, a few points, such as VES 4, 10, 13, 22, 23, and 38, record moderately higher values between 0.06 and 0.08, indicating sharper layer boundaries and stronger aquifer confinement. Overall, the reflection coefficient pattern reveals that most aquifers are semi-confined to unconfined, with varying levels of groundwater protection across the study area.

Furthermore, the coefficient of anisotropy depicted in Figure 14 ranges from 7 to 267, with most values above 1, indicating significant subsurface heterogeneity. High anisotropy indicates alternating lithological layers, fractures, and variations in grain size, which affect

groundwater flow and storage. Although such conditions promote groundwater occurrence, they also create complex flow paths that require careful management. Areas with values closer to 1 denote more uniform and isotropic aquifer zones with consistent groundwater flow.

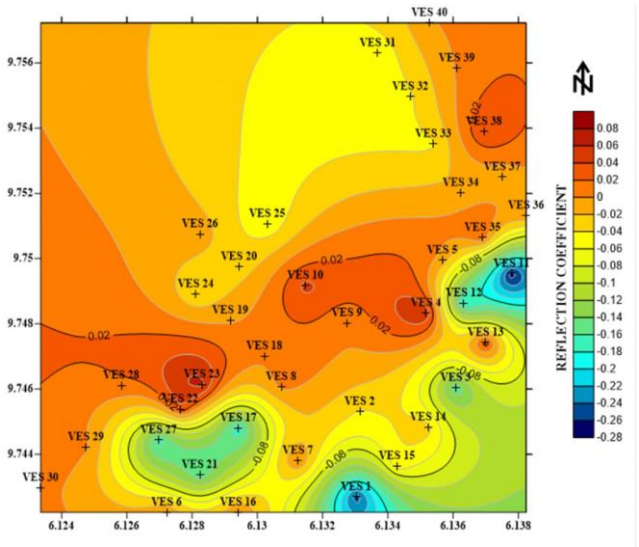

Fig. 13 *Reflection Coefficient of the Study Area*

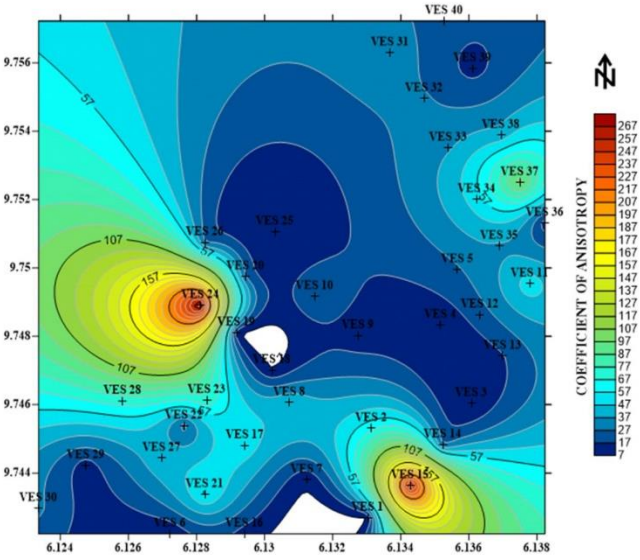

Fig. 14 *Coefficient of Anisotropy of the Study Area*

Discussion

The integrated analysis of geo-electrical parameters offers a thorough understanding of the hydrogeological conditions and groundwater investigation within Niger State Polytechnic, Zungeru. Variations in resistivity and thickness in the topsoil layer indicate a heterogeneous near-surface environment mainly composed of lateritic topsoil, clay, and sandy clay materials. Areas with low resistivity and thicker topsoil suggest moisture-retentive and permeable soils that facilitate infiltration and groundwater recharge. Conversely, regions with high resistivity and thin topsoil point to compacted lateritic materials with limited infiltration capacity. The aquifer layer displays a wide range of resistivity and thickness values, indicating the presence of both weathered and fractured basement aquifers. Low-to-moderate resistivity readings correspond to water-bearing formations, while higher resistivity values denote semi-saturated or less productive zones. Additionally, basement resistivity ranging from about 1,000 to over

20,000 Ωm reflects transitions from weathered or fractured zones conducive to groundwater storage to fresh, compact, and impermeable crystalline bedrock. The basement depth varies from 1 to 21m, with deeper zones showing greater groundwater potential due to thicker overburden and more extensive weathered layers.

Furthermore, derived Dar Zarrouk parameters enhance the interpretation of aquifer characteristics and protective capacities for groundwater investigation within the study area. Longitudinal conductance values range from 14 to 1,714 Ω^{-1}, indicating a generally high overburden protective capacity, suggesting that the aquifers are well shielded from surface contamination by clay-rich materials. Meanwhile, transverse resistance values from 10 to 2,810 Ωm^2 reflect the aquifer's transmissive strength, with higher values corresponding to thick, resistive, and saturated zones capable of significant groundwater storage and yield. Similarly, hydraulic conductivity values ranging from 1 to 243 m/day, along with transmissivity values between 2 and 242 m^2/day, highlight the spatial variability in aquifer performance. High hydraulic and transmissivity values observed at VES 1, 6, 11, 25, and 36 indicate highly productive zones, likely associated with sandy or fractured formations. In contrast, low values indicate fine-grained or clayey formations that restrict groundwater movement and recharge.

Moreover, the reflection coefficient and the coefficient of anisotropy provide additional insights into the subsurface structure and aquifer vulnerability. Reflection coefficient values ranging from -0.28 to 0.08 indicate that most aquifers are semi-confined to unconfined, with weak resistivity contrasts suggesting gradual lithological transitions and moderate protective capacity. However, localized higher values of 0.06 to 0.08 points to distinct lithological boundaries and better aquifer confinement. Furthermore, coefficient of anisotropy values between 7 and 267 reveal a highly heterogeneous subsurface environment dominated by structural discontinuities, variable grain sizes, and fractured zones that influence groundwater flow and storage. Areas with higher anisotropies suggest anisotropic flow behaviour and enhanced groundwater occurrence, while zones approaching isotropy reflect more uniform and predictable aquifer conditions.

In general, combining resistivity, layer thickness, and Dar Zarrouk parameters shows that the study area has diverse but mostly suitable hydrogeological conditions, with productive weathered and fractured basement aquifers capable of supporting sustainable groundwater development and management.

Conclusion

This study effectively utilized Dar Zarrouk's geo-electrical parameters for groundwater investigation at Niger State Polytechnic, Zungeru. The interpretation of resistivity and thickness data revealed a complex structure comprising clay, sandy clay, clayey sand, weathered/fractured basement, and fresh basement units. These layers collectively influence aquifer distribution, groundwater storage, and recharge characteristics. The Dar Zarrouk parameters, such as longitudinal conductance, transverse resistance, hydraulic conductivity, transmissivity, reflection coefficient, and coefficient of anisotropy, proved essential in delineating groundwater-bearing formations and assessing aquifer productivity within the study area. Results identified VES 1, 6, 11, 25, and 36 locations as highly productive groundwater zones characterized by high transmissivity and hydraulic conductivity, suitable for sustainable groundwater abstraction. In contrast, VES 8, 10, 23, 24, 28, 30, 37, and 38 reflect low transmissivity and limited recharge potential due to the dominance of clayey formations. Overall, the integration of resistivity interpretation and analysis of Dar Zarrouk geo-electrical parameters provides a reliable and comprehensive understanding of

groundwater occurrence and the protective strength of subsurface formations within Niger State Polytechnic, Zungeru.

Based on the findings, this study recommends that groundwater development within Niger State Polytechnic, Zungeru, should concentrate on high-yielding VES points such as VES 1, 6, 11, 25, and 36, where transmissivity and hydraulic conductivity values indicate favorable aquifer conditions. These locations are ideal for installing productive boreholes and groundwater infrastructure. Conversely, low-yielding points like VES 8, 10, 23, 24, 28, 30, 37, and 38 should be avoided for major abstraction projects but could be used for small-scale or domestic water supply. Continuous groundwater monitoring is advised in areas with shallow overburden, such as VES 2, 5, 7-10, 17, 18, 31-34, 36-38, and 40, to evaluate contamination risks and seasonal recharge variations. Future investigations should combine borehole lithology, pumping tests, and hydro-chemical analyses with geoelectrical interpretations to improve aquifer assessment. Sustainable management practices, such as controlled abstraction and proper waste disposal, are vital to protecting aquifer systems and ensuring long-term groundwater security for the institution and its surrounding areas.

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