Aquifer Characterisation Using Vertical Electrical Sounding in Parts of Nasarawa State, Nigeria: Resistivity, Thickness and Overburden Mapping

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ABSTRACT

Groundwater in the Precambrian Basement Complex of Nasarawa State is governed by strong lithological and structural heterogeneity, so reliable aquifer characterisation is essential if groundwater development is to be sustainable. With that in mind, this study set out to evaluate the geo electrical characteristics of selected basement-complex locations in the state and consider what they imply for groundwater occurrence, using Vertical Electrical Sounding with the Schlumberger configuration. Four soundings were acquired at each site, three investigation points and one control station, with current-electrode half-spacing (AB/2) ranging from 1 to 150 m and potential-electrode half-spacing (MN/2) from 0.5 to 15 m. The interpreted resistivity data were then used to characterise the subsurface and to derive the Dar–Zarrouk parameters: longitudinal conductance (S), transverse resistance (T), longitudinal resistivity (ρL), transverse resistivity (ρT), and the coefficient of anisotropy (λ). The results reveal substantial spatial variability in subsurface electrical properties. Mean longitudinal conductance ranges from 0.182 to 0.344 S, with Angwa Adamu Kugbaru and Tudun Wada classified as having weak protective capacity, while Auta Balefi, Nasarawa-Toto, Keffi, Lafia Site 1, and Lafia Site 2 show moderate protective capacity. Mean transverse resistance varies markedly, from 2,801.25 Ωm² at Auta Balefi to 427,876.25 Ωm² at Lafia Site 2, reflecting pronounced differences in layer resistivity and thickness. The coefficient of anisotropy ranges from 1.188 at Auta Balefi to 11.918 at Lafia Site 2, indicating significant directional variability and subsurface heterogeneity at some locations. The exceptionally high anisotropy and transverse-resistance values at Keffi, Lafia Site 1, and Lafia Site 2 are treated cautiously, since they are strongly influenced by the very high resistivity assigned to deeper layers. In conclusion, the investigated basement terrain is highly heterogeneous, with weak-to-moderate groundwater protective capacity and substantial spatial variation in subsurface electrical structure. The study underscores the value of combining VES-derived Dar–Zarrouk parameters with lithological, structural, borehole, and hydrogeological information for reliable aquifer evaluation and sustainable groundwater development in basement-complex environments.

KEYWORDS

Aquifer characterisation; Basement Complex; Vertical Electrical Sounding; Schlumberger array; Dar–Zarrouk parameters; protective capacity; anisotropy; groundwater; Nasarawa State; hydro geophysics

I. INTRODUCTION

Groundwater is an essential component of water supply systems in many parts of Nigeria, particularly where surface-water resources are seasonal, inadequate, or vulnerable to contamination (Fashae et al., 2013). In crystalline basement terrains, however, groundwater exploration presents a particular challenge because the primary porosity of the un weathered crystalline rocks is generally limited (Fashae et al., 2013), while locating water-bearing units within these geologically complex rocks is inherently difficult owing to their great lithological and structural variability (Adeolu et al., 2024). Groundwater occurrence is therefore strongly influenced by secondary porosity developed through weathering, fracturing, jointing and faulting (Raji & Abdulkadir, 2020, p. 4), with the potential of crystalline basement aquifers governed largely by the extent of fracturing in the bedrock (Embaby et al., 2024). Consequently, successful groundwater development requires reliable information on the vertical and lateral distribution of subsurface materials, since the optimum potential of the aquifer network can only be realised through well-coordinated hydrogeological and geophysical investigation (Naiyeju et al., 2021), a point underscored by reports that more than 30% of boreholes drilled within the Nigerian Basement Complex have failed, largely where sites were selected without adequate geophysical investigation (Alao et al., 2024).

Electrical resistivity methods have become important tools in groundwater investigations because subsurface materials exhibit measurable contrasts in their ability to conduct electrical current (Ayantola & Amigun, 2023). The Vertical Electrical Sounding technique is particularly useful for investigating vertical changes in electrical resistivity and has been widely applied in basement-complex terrains in Nigeria (Bayewu et al., 2017; Raji & Abdulkadir, 2020). Previous Nigerian studies have demonstrated that VES can be used to distinguish topsoil, lateritic materials, weathered zones, fractured basement and fresh basement where adequate inversion and geological control are available (Bayewu et al., 2017; Coker, 2012; Taiwo et al., 2016).

The hydrogeological importance of VES arises from the relationship between electrical resistivity and subsurface properties such as lithology, porosity, saturation, clay content and groundwater mineralisation, since the resistivity of a deposit is controlled mainly by the salinity of its pore water and its clay content (Høyer et al., 2018). However, resistivity is not uniquely diagnostic of lithology or groundwater. A low-resistivity layer may represent clay-rich material, conductive groundwater, or both; brackish water, for instance, exhibits resistivities similar to those of low-permeability clay and silt deposits (Donno & Cercato, 2023), and both clayey sediments and contaminated pore water depress resistivity to comparable values (Høyer et al., 2018). In basement-complex settings specifically, the aquifer units and hydrogeological parameters vary both laterally and vertically, which distorts VES curves and introduces genuine ambiguities into interpretation (Olorunfemi et al., 2020). Conversely, high resistivity may reflect dry or competent material, coarse-grained sediments, or relatively fresh basement: electrically resistive earth materials include undersaturated sand and gravel, till and competent bedrock, while saturated clay, till and gravel all register as conductive bodies (Huntley et al., 2020). Consequently, resistivity interpretation requires geological and hydrogeological constraints; the integration of resistivity models with borehole data is indispensable for resolving these ambiguities and validating inversion outcomes (Foged et al., 2014; Lejzerowicz et al., 2026).

II. GEOLOGICAL AND HYDROGEOLOGICAL SETTING

Nasarawa State, located in north-central Nigeria, is underlain by two geologically contrasting terrains: The Precambrian Basement Complex in the north and the Cretaceous–Tertiary sedimentary succession of the Middle Benue Trough in the south (Ifediegwu, 2021). The basement is dominated by the migmatite–gneiss complex of Neo-Proterozoic to Meso-Archean age, which alone covers approximately 358.95 km² (69.54%) of the Lafia district, alongside minor Pan-African basaltic rocks (2.21 km², 0.10%) (Ifediegwu, 2021). The crystalline lithologies comprise schist, gneiss, migmatite and granite (Kana et al., 2014), locally represented by medium-grained biotite granite, biotite gneiss, phyllite and muscovite schist, which exhibit structural features such as joints, veins, foliation, faults and xenoliths (Okeke et al., 2022). The southern part of the state forms part of the Middle Benue Trough, an intracratonic Cretaceous rift system trending NE–SW, whose evolution is linked to the breakup of Gondwanaland and the opening of the South Atlantic Ocean (Moshood et al., 2026). The trough succession, in ascending order, comprises the Yolde Formation, the Ezeaku Formation, the Lafia–Wukari Sandstone and alluvium (Ifediegwu, 2021). The Yolde Formation consists of feldspathic sandstone, calcareous sandstone and shelly limestone (7.09 km², 2.01%), while the Ezeaku Formation is composed mainly of calcareous shales, micaceous fine-to-medium friable sandstones and beds of limestone (17.23 km², 3.84%; 12.39 km², 2.38%) (Ifediegwu, 2021).

Hydrogeologically, the crystalline basement is regarded as a poor aquifer because its metamorphic and igneous rocks possess low primary porosity and permeability, such that groundwater occurrence depends on secondary porosity developed through weathering and fracturing (Naiyeju et al., 2021). Two principal aquifer types have been identified in the Nasarawa basement: the weathered (unconfined) aquifer and the fractured (confined) aquifer (Oluyede, 2021). In the area south of Zakum Bello, yields from the weathered aquifer reach 0.63 L/s, exceeding the 0.28 L/s obtained from the fractured aquifer, with fractures developed mainly in the gneiss at thicknesses of 5–10 m within depths of 15–40 m (Oluyede, 2021). Depth to basement across parts of Karu Local Government Area ranges from 20 to 90 m, with geo-electric sections revealing four to seven lithologic sequences comprising topsoil, laterite, clay and weathered/fractured basement (Okeke et al., 2022). Fracture trends exert a strong control on groundwater movement: structures trending NNE–SSW and N–S influence both groundwater and surface-water flow directions in the Nasarawa town area (Kana et al., 2014), while NW–SE structural trends characterise the Karu area (Okeke et al., 2022).

At the regional scale, the crystalline–sedimentary transition supports prolific aquifer systems, with boreholes commonly drilled to depths of ≥50 m, drawdowns of ≤5 m and transmissivities of ≥100 m²/day (Ukpai, 2021). In the Nasarawa town basin, static water resources of the dam drainage basin are estimated at 1,814 × 10^6 m³, and groundwater is considered sufficient to supplement surface water in meeting both the current demand of 4.0 × 10^6 m³/a and the ultimate demand of 22.5 × 10^6 m³/a (Kana et al., 2014). This dual geological framework; weathered and fractured basement aquifers to the north, and Cretaceous sedimentary aquifers of the Middle Benue Trough to the south, underpins the heterogeneous aquifer behaviour across the state that the present geophysical investigations seek to characterise.

III. MATERIALS AND METHODS

The investigation employed the Schlumberger electrode configuration. Four soundings were recorded at each investigation site, comprising VES 1, VES 2, VES 3 and a control sounding (seven sites in all) making 28 VES altogether. The field data of apparent resistivity together with current-electrode half-spacing (AB/2), potential-electrode half-spacing (MN/2), and geometric factor (K) were recorded.

The AB/2 spacing ranges from 1 to 150 m, while MN/2 ranges from 0.5 to 15 m. This progressively increasing current-electrode separation allows investigation of progressively greater subsurface volumes. The apparent resistivity was obtained from the measured resistance and the geometric factor according to:

$$\rho_a = KR \quad (1)$$

Where:

- (ρ_a) = apparent resistivity (Ωm);
- (K) = geometric factor (m);
- (R) represents the measured ground resistance in ohms.

The Dar-Zarrouk Parameters

The Dar–Zarrouk parameters are a set of geo electrical indices which are obtained from the resistivity and the thickness of the separate layers beneath the surface and thus give an integrated expression of the electrical properties of a stratified earth model (Sendrós et al., 2023; Zohdy, 1974). They offer a quantitative basis for evaluating features of an aquifer, the groundwater potential, transmissivity, protective capacity and subsurface heterogeneity by means of data from electrical resistivity surveys (Adeniji et al., 2013; Mohammed et al., 2023; Nemer et al., 2023; Olumurewa et al., 2023).

Longitudinal Conductance (S)

$$S = \sum \frac{h_i}{\rho_i} \quad (2)$$

Where (hi) = thickness of layer (i) and (ρi) = resistivity of layer (i)

Transverse Resistance (T)

$$T = \sum h_i \rho_i \quad (3)$$

Longitudinal Resistivity (ρL)

$$\rho L = \frac{H}{S} \quad (4)$$

where:

$$H = \sum h_i \quad (5)$$

Transverse Resistivity (ρT)

$$\rho T = \frac{T}{H} \quad (6)$$

Coefficient of Anisotropy (λ)

$$\lambda = \sqrt{\frac{\rho T}{\rho L}} \quad (7)$$

It indicates the degree of heterogeneity and fracturing. High values often suggest enhanced groundwater potential.

Hydraulic Conductivity (K)

Common empirical relation:

$$K = a \times \rho^{-b} \quad (8)$$

Where (a) and (b) are empirical constants.

Alternatively, the relation of Heigold et al. (1979) is often used:

$$K = 386.4 \times \rho^{-0.9328} \quad (9)$$

It measures ease of groundwater movement.

Transmissivity (Tr)

$$Tr = K \times h \quad (10)$$

Where (K) = hydraulic conductivity and (h) = aquifer thickness

IV. RESULTS

The calculated Dar–Zarrouk parameters show a great deal of variation when looked at for each individual VES location. Keffi VES 3 had the highest longitudinal conductance (S), being 0.479 S, while the lowest value of 0.103 S was measured at the Lafia Site 2 control station. With regard to transverse resistance (T), the highest value of 440,685 Ωm² was found at the Lafia Site 2 control station, this showing a strong transverse electrical response in the interpreted section. The coefficient of anisotropy (λ) also showed substantial variation between the different stations, the highest value of 14.99 occurring at Lafia Site 1 VES 1 and the lowest value of 1.01 being recorded at the Auta Balefi control station. This degree of variation illustrates the considerable spatial heterogeneity of the subsurface electrical properties at the sites studied.

Table 1 gives the average Dar-Zarrouk parameters for all seven locations, four VES in each location.

Table 1: Dar–Zarrouk Parameters for All the Seven VES Locations

Site	Mean S (S)	Mean T (Ωm²)	Mean ρL (Ωm)	Mean ρT (Ωm)	Mean λ	Protective Capacity
Angwa Adamu Kugbaru	0.183	7986.250	141.720	319.450	1.499	Weak
Auta Balefi	0.318	2801.250	79.220	112.050	1.188	Moderate
Tudun Wada	0.182	11246.250	143.450	449.850	1.776	Weak

Keffi	0.337	106106.250	86.780	4244.250	4.930	Moderate
Nasarawa-Toto	0.344	4943.750	79.410	197.750	1.620	Moderate
Lafia Site 1	0.328	108955.000	95.930	4358.200	4.894	Moderate
Lafia Site 2	0.214	427876.250	135.430	17115.050	11.918	Moderate

A. Interpretation and Analysis of Dar–Zarrouk Parameters

The average Dar–Zarrouk values show a great deal of spatial variability in the geo-electrical properties of the subsurface at the six sites. The differences in longitudinal conductance (S), transverse resistance (T), longitudinal resistivity (ρL), transverse resistivity (ρT), and the coefficient of anisotropy (λ) indicate variations in the electrical properties, thickness, and likely heterogeneity of the overburden materials. Generally, the findings show that the subsurface conditions are not the same throughout the study area and that the hydro geophysical characteristics differ greatly from one location to another.

B. Longitudinal Conductance

The average longitudinal conductance varies from 0.182 S at Tudun Wada to 0.344 S at Nasarawa-Toto; Angwa Adamu Kugbaru and Tudun Wada have the lowest average values, 0.183 S and 0.182 S respectively, and are therefore regarded as having a weak protective capacity. This indicates that the materials lying above these sites provide only a relatively small degree of electrical conductance and, according to the classification used in the study, afford comparatively little protection to the underlying groundwater-bearing rock formations. The low level of conductance may be due to combinations of thinner conductive layers and/or a relatively resistive overburden.

On the other hand, Auta Balefi, Keffi, Nasarawa-Toto, Lafia Site 1, and Lafia Site 2 have mean longitudinal conductance values of 0.318, 0.337, 0.344, 0.328 and 0.214 S respectively and are considered to have a moderate protective capacity. Of these sites, Nasarawa-Toto has the highest mean S value at 0.344 S, then comes Keffi with 0.337 S and Lafia Site 1 with 0.328 S. The findings show that the overburden makes a relatively greater conductive contribution than it does at Angwa Adamu Kugbaru and Tudun Wada. The relatively low S values at all six sites, especially in comparison with those of the higher protective-capacity classes, indicate that the overburden studied as a whole does not offer very strong protection against the downward migration of contaminants originating on the surface. This finding is especially important in areas where groundwater occurs beneath zones that are exposed to possible sources of contamination.

C. Transverse Resistance

The mean transverse resistance shows a great deal more spatial variation than longitudinal conductance, going from 2,801.25 Ωm² at Auta Balefi to 427,876.25 Ωm² at Lafia Site 2. The lowest value is found at Auta Balefi, then comes Nasarawa-Toto with 4,943.75 Ωm² and Angwa Adamu Kugbaru with 7,986.25 Ωm². Tudun Wada has a higher value of 11,246.25 Ωm², and exceptionally high values are recorded at Keffi (106,106.25 Ωm²), Lafia Site 1 (108,955.00 Ωm²), and especially at Lafia Site 2 (427,876.25 Ωm²).

The high transverse resistance values at Keffi, Lafia Site 1, and Lafia Site 2 indicate pronounced transverse electrical resistance within the interpreted 0–25 m section. These values are primarily associated with the very high resistivity assigned to some of the deeper interpreted layers. Consequently, the unusually high values should be interpreted with caution and in conjunction with the underlying inversion results, rather than as direct measures of groundwater productivity.

The markedly higher T values at Lafia Site 2 compared with Auta Balefi indicate substantial spatial variation in the electrical structure of the subsurface. This contrast suggests that the geological and hydro geophysical conditions controlling resistivity and layer thickness differ significantly between the two sites.

D. Longitudinal and Transverse Resistivity

The Mean longitudinal resistivity varies from 79.22 Ωm at Auta Balefi to 143.45 Ωm at Tudun Wada, while the mean transverse resistivity ranges much more widely, from 112.05 Ωm at Auta Balefi to 17,115.05 Ωm at Lafia Site 2.

Auta Balefi has the lowest values for both parameters, with mean ρL and ρT of 79.22 Ωm and 112.05 Ωm, respectively. This relatively narrow difference between the two resistivity measures is reflected in its low coefficient of anisotropy. In contrast, Lafia Site 2 has a mean ρL of 135.43 Ωm but an exceptionally high mean ρT of 17,115.05 Ωm. The large disparity between the two values indicates strong directional variation in the electrical response of the subsurface. Angwa Adamu Kugbaru and Tudun Wada show relatively similar mean longitudinal resistivity (141.72 and 143.45 Ωm, respectively), despite differences in their transverse resistivity (319.45 and 449.85 Ωm). This indicates that the two locations have broadly comparable longitudinal electrical characteristics but differ in their transverse response.

E. Coefficient of Anisotropy

The coefficient of anisotropy (λ) provides an indication of the degree of directional variation in the electrical properties of the subsurface. The mean λ values range from 1.188 at Auta Balefi to 11.918 at Lafia Site 2. Auta Balefi exhibits the lowest Mean anisotropy (λ = 1.188), indicating relatively limited directional variation between the longitudinal and transverse electrical responses. Angwa Adamu Kugbaru (λ = 1.499) and Nasarawa-Toto (λ = 1.620) also exhibit relatively low anisotropy, while Tudun Wada records a somewhat higher value of 1.776.

A pronounced increase in anisotropy occurs at Keffi and Lafia Site 1, with mean λ values of 4.930 and 4.894, respectively. The highest anisotropy is observed at Lafia Site 2 (λ = 11.918). This very high value indicates a substantial difference between the longitudinal and transverse resistivity characteristics of the interpreted subsurface. Such a response may reflect strong geological heterogeneity, layering, structural effects, or pronounced resistivity contrasts within the interpreted units. Importantly, anisotropy should not be interpreted in isolation as direct evidence of fracturing or groundwater productivity. Its geological significance depends on the underlying layer model and should ideally be supported by geological, structural, borehole, or hydrogeological information.

F. Comparative Hydro geo-physical Assessment

Taken collectively, the Dar–Zarrouk parameters reveal three broad groups of behaviour. Angwa Adamu Kugbaru and Tudun Wada are characterised by relatively low longitudinal conductance and weak protective capacity, together with moderate transverse resistance and comparatively low anisotropy. Auta Balefi and Nasarawa-Toto exhibit moderate protective capacity, relatively low-to-moderate transverse resistance, and relatively low anisotropy, suggesting comparatively uniform electrical behaviour within the interpreted section. Keffi, Lafia Site 1, and Lafia Site 2, on the other hand, are distinguished by exceptionally high transverse resistance and anisotropy, indicating pronounced electrical heterogeneity.

Among the six sites, Lafia Site 2 is the most distinctive, with the highest mean transverse resistance (427,876.25 Ωm^2), highest mean transverse resistivity (17,115.05 Ωm), and highest coefficient of anisotropy (11.918). However, its Mean longitudinal conductance is only 0.214 S, placing it within the moderate protective-capacity class. This combination demonstrates that a site may exhibit a very strong transverse electrical response while simultaneously having only moderate overburden protective capacity. Keffi and Lafia Site 1 show comparable behaviour, with mean transverse resistance values exceeding 100,000 Ωm^2 and anisotropy coefficients close to 4.9. Their moderate protective-capacity classification indicates that the high transverse resistance should not be interpreted as equivalent to strong protection against contamination.

The Dar–Zarrouk analysis demonstrates pronounced spatial and directional variability in the electrical properties of the subsurface across the investigated locations. Longitudinal conductance indicates that protective capacity ranges from weak to moderate, with no site falling within the higher protective-capacity classes represented in the adopted classification. This suggests that groundwater resources within the investigated area may be susceptible to surface-derived contamination where permeable or poorly protective overburden is present. The transverse-resistance and anisotropy results, particularly at Keffi, Lafia Site 1, and Lafia Site 2, reveal strong electrical contrasts within the interpreted subsurface. These contrasts may have important implications for aquifer geometry and subsurface heterogeneity, but their hydrogeological significance should be established by integrating them with true layer resistivities, thicknesses, lithological information, geological structures, and borehole data.

A particularly important observation is that Dar–Zarrouk parameters should be interpreted collectively rather than individually. Longitudinal conductance provides information relevant to protective capacity; transverse resistance reflects the combined influence of resistivity and thickness; and the coefficient of anisotropy expresses the relationship between the longitudinal and transverse electrical responses. Their integration therefore provides a more robust representation of subsurface heterogeneity than any single parameter. Generally, the results identify Lafia Site 2 as the most electrically anisotropic and transversely resistive location, Keffi and Lafia Site 1 as similarly heterogeneous zones, and Auta Balefi as the least anisotropic site. Angwa Adamu Kugbaru and Tudun Wada exhibit comparatively weak protective capacity. These variations provide important constraints for subsequent aquifer evaluation and groundwater exploration, but the Dar–Zarrouk results should be validated against geological and hydrogeological evidence before being used for definitive borehole-siting decisions.

V. DISCUSSION

A. Longitudinal conductance and protective capacity

The Dar–Zarrouk parameters are secondary geoelectric attributes derived from the primary layer resistivities and thicknesses obtained through VES inversion, longitudinal conductance (S), transverse resistance (T), and the coefficient of anisotropy (λ); first introduced by Maillet (Akanbi, 2018). S and T are computed as h/ρ and hρ, respectively (Ibuot et al., 2017), and they carry a clear physical meaning: transverse resistance represents the resistance offered to current flowing perpendicular to the strata, while longitudinal conductance represents the conductance to current flowing parallel to them (Utom et al., 2012).

Because S integrates the thickness and resistivity of the entire overburden column, it has become the standard index of aquifer protective capacity, which is considered proportional to the longitudinal unit conductance of the overburden (Agyemang, 2021). Impervious materials yield high conductance values by virtue of their low resistivity, whereas permeable overburden yields low conductance values (Agyemang, 2021); the ability of the earth medium to act as a natural filter that retards percolating surface pollutants is likewise a direct measure of its protective capacity (Alabi et al., 2021). On the classification adopted here (S < 0.1 S poor; 0.1–0.19 S weak; 0.2–0.69 S moderate) (Chinyem et al., 2024), Angwa Adamu Kugbaru (0.183 S) and Tudun Wada (0.182 S) fall within the weak class, while Auta Balefi (0.318 S), Nasarawa-Toto (0.344 S), Keffi (0.337 S), Lafia Site 1 (0.328 S) and Lafia Site 2 (0.214 S) fall within the moderate class. Low conductance values of this order indicate loose, porous overburden materials with a reduced capacity to protect underlying aquifers, which are thereby vulnerable to infiltration (M. et al., 2013); by contrast, regions of high longitudinal conductance are known to carry good aquifer protective capacity and low susceptibility to surficial pollutants (Uzochi et al., 2024). The fact that none of the six locations attains the good or excellent classes is therefore significant, since zones of weak-to-moderate protection have consistently been adjudged to be at elevated risk of groundwater contamination (Ekanem et al., 2024); a concern that applies wherever groundwater occurs beneath areas exposed to contaminant sources.

B. Transverse resistance and resistivity

The mean transverse resistance exhibits far stronger spatial variability, rising from 2,801.25 Ωm² at Auta Balefi through Nasarawa-Toto (4,943.75 Ωm²), Angwa Adamu Kugbaru (7,986.25 Ωm²) and Tudun Wada (11,246.25 Ωm²) to Keffi (106,106.25 Ωm²), Lafia Site 1 (108,955.00 Ωm²) and, exceptionally, Lafia Site 2 (427,876.25 Ωm²). Transverse resistance is analytically related to aquifer transmissivity through the Niwas–Singhal relationship ($T = K\sigma \cdot TR$), which is why it has proved useful in evaluating hydraulic conductivity and transmissivity from surface measurements (Guevara et al., 2017; Ige et al., 2018). However, because T = hρ, a large value can arise either from thick layers or from very high resistivity. Here, the elevated values at Keffi, Lafia Site 1, and Lafia Site 2 are dominated by the very high resistivity associated with deeper layers within the interpreted 0–25 m section, and thick high-resistivity layers are known to complicate resistivity interpretation (Lejzerowicz et al., 2026). The values should therefore be read cautiously and in conjunction with the layer-model inversion results rather than as direct measures of groundwater productivity; a caution reinforced by the two-order-of-magnitude contrast between Lafia Site and Auta Balefi, which signals fundamentally different subsurface electrical structure rather than proportionate differences in productivity.

C. Coefficient of anisotropy

The coefficient of anisotropy, $\lambda = \sqrt{(\rho T/\rho L)}$ (Adeolu et al., 2024), expresses the degree of directional variation in the electrical response and is widely used in basement-complex terrains to gauge subsurface fracturing and inhomogeneity, since permeability in such settings is enhanced by faults, fractures, joints and shear zones (Bayode et al., 2024). Regions of low anisotropy are commonly associated with considerable porosity and permeability, along with some degree of fracturing, whereas high anisotropy values indicate low porosity and permeability, and hence low hydrogeological viability (Adeolu et al., 2024). The results follow a striking progression: Auta Balefi ($\lambda = 1.188$), Angwa Adamu Kugbaru (1.499), Nasarawa-Toto (1.620) and Tudun Wada (1.776) fall within the ranges associated with thick weathered overburden, fractured bedrock and basement depressions of high groundwater potential (typically 1.3–1.6), while the mean longitudinal and transverse resistivities at these sites (79.22–143.45 Ωm and 112.05–449.85 Ωm) remain comparatively close, consistent with limited directional contrast (Olayinka & Oyedele, 2019). In contrast, Keffi (4.930), Lafia Site 1 (4.894) and Lafia Site 2 (11.918) record values far beyond the ranges ordinarily reported for basement aquifers, commonly 0.97–1.11 (Ayuk et al., 2013), 1.23–1.44 (Ben & Onwuemesi, 2009), or at most 1.8–2.8 in low-potential ridge settings (Olayinka & Oyedele, 2019); with Lafia Site 2's mean ρL of 135.43 Ωm against a ρT of 17,115.05 Ωm producing the extreme λ of 11.918. Such magnitudes most plausibly reflect the strong resistivity contrasts embedded in the layered model, notably the very high-resistivity deeper units, rather than genuine fracture-induced anisotropy, and they should not be interpreted in isolation as direct evidence of fracturing or productivity; the geological significance of λ depends on the underlying layer model (Adeolu et al., 2024).

D. Comparative Synthesis

Taken collectively, the Dar–Zarrouk results separate the sites into three behavioural groups: Angwa Adamu Kugbaru and Tudun Wada (weak protective capacity, moderate transverse resistance, low anisotropy), Auta Balefi and Nasarawa-Toto (moderate protective capacity, low-to-moderate transverse resistance, low anisotropy indicating comparatively uniform electrical behaviour), and Keffi, Lafia Site 1 and Lafia Site 2 (exceptionally high transverse resistance and anisotropy). Because no single parameter is diagnostic, the collective interpretation of S, T and λ provides a more robust representation of subsurface heterogeneity and reduces the non-uniqueness inherent in surface resistivity interpretation (Abam et al., 2021; Utom et al., 2012). Nevertheless, the hydrogeological significance of these contrasts should be established through integration with true layer resistivity and thicknesses, lithology, geological structure and borehole data (Akanbi, 2018), since geophysical estimates of aquifer properties gain validity only when checked against pumping-test and well-inventory information (Ige et al., 2018; Lekone et al., 2024). Pending such validation, the Dar–Zarrouk results provide valuable constraints for aquifer evaluation but should not, on their own, form the basis for definitive borehole-siting decisions.

VI. CONCLUSION

Vertical Electrical Sounding proved an effective framework for characterising heterogeneous subsurface conditions controlling groundwater occurrence in Nasarawa State. The surveys revealed marked spatial variability in electrical properties, consistent with the complex lithology of Precambrian Basement Complex terrains, where groundwater occurs chiefly in secondary porosity from weathering, fracturing, jointing, and faulting; therefore, interpretation must weigh both electrical and geological contexts. Mean longitudinal conductance ranged from 0.182 S to 0.344 S. Angwa Adamu Kugbaru and Tudun Wada fell into the weak protective-capacity class; the other five were moderate. With no site in the higher classes, the overburden offers only limited to moderate shielding against downward contaminant movement; a concern where groundwater lies beneath urbanisation, agriculture or waste disposal.

Transverse resistance varied far more widely, from 2,801.25 Ωm² at Auta Balefi to 427,876.25 Ωm² at Lafia Site 2, with Keffi (106,106.25 Ωm²) and Lafia Site 1 (108,955.00 Ωm²) also exceptional. Such values signal strong contrasts, not productivity: transverse resistance depends jointly on layer resistivity and thickness, driven by the very high resistivities assigned to deeper units. The coefficient of anisotropy corroborates the terrain's heterogeneity: mean values ranged from 1.188 at Auta Balefi to 11.918 at Lafia Site 2, with Keffi and the two Lafia sites far higher. Its extreme anisotropy stems from the gap between its longitudinal (135.43 Ωm) and transverse (17,115.05 Ωm) resistivities; better read as strong electrical layering than as fracturing or enhanced yield. Three behaviours emerge: Angwa Adamu Kugbaru and Tudun Wada combine weak protective capacity with moderate transverse resistance; Auta Balefi and Nasarawa-Toto show moderate capacity and low anisotropy; Keffi, Lafia Site 1 and Lafia Site 2 display very high transverse resistance and anisotropy. Lafia Site 2 is the most distinctive geo-electrical environment; Auta Balefi the least.

No single Dar–Zarrouk parameter defines aquifer quality: longitudinal conductance assesses protective capacity, transverse resistance reflects the combined effects of layer resistivity and thickness, and anisotropy reveals directional variability. Resistivity is not uniquely diagnostic; low values may indicate clay-rich material or conductive groundwater, while high values may indicate competent basement or dry ground. Results must therefore be checked against borehole logs, water-level data, geological structure, and pumping tests.

In conclusion, the investigated area is geo-electrically and hydro geologically heterogeneous, with protective capacity ranging from weak to moderate. The Dar–Zarrouk parameters are valuable for identifying contrasting subsurface conditions but constitute a geophysical framework rather than a standalone basis for borehole siting. Future development should integrate them with geological mapping, structural analysis, borehole control and hydraulic testing to reduce uncertainty.

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