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GEO-SPATIAL INTEGRATION OF DAR-ZARROUK GEOELECTRICAL PARAMETERS AND LAND SURFACE DYNAMICS FOR AQUIFER CHARACTERIZATION IN OHAFIA, SOUTHEASTERN NIGERIA

GEOPROSTORSKA INTEGRACIJA GEOELEKTRIČNIH PARAMETROV DAR-ZARROUKA IN DINAMIKE ZEMELJSKE POVRŠINE ZA OPREDELITEV LASTNOSTI VODONOSNIKA V OHAFII, V JUGOVZHODNI NIGERIJI

Charity Nkiru Nwokeabia[1], Okechukwu Ebuka Agbasi [*,2], Ojo Odunayo Tope[3]

[1]Department of Geophysics, Faculty of Physical Sciences, Nnamdi Azikiwe University, Awka, Nigeria.
[2]Department of Physics, School of Pure and Applied Science, Federal University of Technology Ikot Abasi, Nigeria.
[3]Department of Physical Sciences, Redeemer's University, Ede, Osun State, Nigeria.

Abstract

Sustainable groundwater management requires a deep understanding of subsurface aquifer characteristics and their interaction with surface environmental features. In southeastern Nigeria, where increasing population and land use changes threaten groundwater resources, such assessments are vital. This study aimed to evaluate the protective capacity and productivity of aquifers in Ohafia, Ohafia, southeastern Nigeria, using integrated geophysical and spatial analysis. A total of seven vertical electrical sounding (VES) points were investigated across Ohafia using a Schlumberger array to derive aquifer resistivity, thickness, and depth. Dar-Zarrouk parameters, including longitudinal conductance and transverse resistance, were computed. These subsurface metrics were integrated with drainage density, digital elevation models (DEM), and 2024 land use/land cover (LULC) data using GIS tools to analyze their spatial relationships and influence on groundwater potential. Aquifer resistivity values varied widely (99.4–1360 Ω·m), while longitudinal conductance ranged from 0.02 to 0.63 1/Ω. The highest transmissivity (40.40 m²/day) was recorded in rangeland-dominated Achị, suggesting productive aquifer conditions. Areas dominated by tree cover and rangelands demonstrated better aquifer protection and recharge potential than built-up regions like Elu and Abiriba. Drainage density and LULC patterns significantly influenced recharge dynamics. High drainage density zones correlated with poor recharge potential, except where offset by favorable subsurface lithology. Vegetated areas promoted infiltration, while impervious surfaces hindered it. This study demonstrates that combining Dar-Zarrouk parameters with surface geospatial data provides a robust framework for aquifer characterization. The novelty lies in the integrated assessment of geomorphological, anthropogenic, and geoelectrical indicators to prioritize groundwater development zones in a data-scarce tropical region.

Keywords: Dar-Zarrouk parameters, Vertical electrical sounding (VES), Groundwater recharge, Land use and drainage analysis, Ohafia.

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[*] Stik / *Correspondence*: agbasi.okechukwu@gmail.com

Izvleček

Trajnostno upravljanje podtalnice zahteva poglobljeno razumevanje značilnosti podzemnih vodonosnikov in njihovega medsebojnega vpliva s površinskimi okoljskimi dejavniki. V jugovzhodni Nigeriji, kjer naraščanje prebivalstva in spremembe v rabi zemljišč vse bolj ogrožajo vodne vire, so tovrstne ocene ključnega pomena. Namen te študije je bil oceniti zaščitno sposobnost in produktivnost vodonosnikov v Ohafii v jugovzhodni Nigeriji z uporabo integrirane geofizikalne in prostorske analize. Skupno je bilo analiziranih sedem točk vertikalnega električnega sondiranja (VES) z uporabo Schlumbergerjeve razporeditve za določitev upornosti, debeline in globine vodonosnika. Izračunani so bili Dar-Zarroukovi parametri, vključno z vzdolžno prevodnostjo in prečno odpornostjo. Ti podzemni parametri so bili integrirani z gostoto rečne mreže, digitalnimi modeli višin (DEM) in podatki o rabi tal za leto 2024 (LULC) z uporabo orodij GIS za analizo prostorskih povezav in njihovega vpliva na potencial podzemne vode. Vrednosti upornosti vodonosnika so se gibale med 99,4 in 1360 Ω·m, medtem ko je vzdolžna prevodnost znašala od 0,02 do 0,63 1/Ω. Najvišja transmisivnost (40,40 m²/dan) je bila ugotovljena na območju Achị, kjer prevladujejo pašniki, kar kaže na ugodne pogoje za vodonosnik. Območja z večjim deležem drevesne vegetacije in pašnikov so izkazovala boljšo zaščito vodonosnika in večji potencial za obnovo podzemne vode kot pozidana območja, kot sta Elu in Abiriba. Gostota rečne mreže in vzorci rabe tal so pomembno vplivali na dinamiko ponikanja vode. Območja z visoko gostoto rečne mreže so bila povezana s slabšim potencialom ponikanja, razen kjer so bile prisotne ugodne litološke razmere. Območja z vegetacijo so spodbujala infiltracijo, medtem ko so neprepustne površine to ovirale. Študija kaže, da kombinacija Dar-Zarroukovih parametrov in površinskih geoinformacijskih podatkov zagotavlja zanesljiv okvir za karakterizacijo vodonosnika. Novost raziskave je v celostni obravnavi geomorfoloških, antropogenih in geoelektričnih kazalnikov za določanje prednostnih območij za izkoriščanje podtalnice v podatkovno omejenih tropskih regijah.

Ključne besede: parametri Dar-Zarrouk, vertikalno električno sondiranje (VES), obnavljanje podtalnice, analiza rabe zemljišč in odvodnjavanja, Ohafia.

1. Introduction

Groundwater is an indispensable resource in addressing water scarcity challenges, particularly in developing countries where urbanization and climatic variability exert pressure on available water sources (Ifeanyichukwu et al., 2021). In Nigeria, the demand for clean and sustainable water is rising, necessitating robust strategies for assessing groundwater potential and aquifer vulnerability (Akiang et al., 2024). Geophysical methods, especially vertical electrical sounding (VES), have proven highly effective in delineating subsurface lithology and determining aquifer parameters such as resistivity, longitudinal conductance, transverse resistance, hydraulic conductivity, and transmissivity (Agbasi et al., 2019; Akaolisa et al., 2022). These parameters, collectively referred to as Dar-Zarrouk parameters, offer valuable insights into aquifer protection and productivity (Aka et al., 2025; Okonkwo et al., 2025).

Beyond geoelectrical measurements, the integration of surface features such as land use/land cover (LULC), drainage density, and topography offers a holistic approach to groundwater studies. LULC changes driven by urban development, agriculture, and deforestation directly impact infiltration, recharge potential, and aquifer protectivity (Umoh et al., 2024). Similarly, drainage density, a measure of how dissected a surface is by river channels, affects surface runoff and recharge zones. The intersection of surface processes with subsurface parameters creates a dynamic system that must be thoroughly understood to facilitate sustainable groundwater exploration and management (Okoli et al., 2024).

This literature review synthesizes foundational and contemporary research on Dar-Zarrouk parameters, aquifer protectivity, groundwater potential assessments, and the influence of LULC and drainage density. It provides a conceptual and methodological framework for analyzing groundwater systems, particularly in data-scarce and environmentally stressed regions like Southeastern Nigeria.

The Dar-Zarrouk parameters, longitudinal conductance (S) and transverse resistance (T), are derived from VES data and are key to evaluating the protective capacity and transmissivity of aquifers. These parameters were first formalized by Maillet (1947) and later advanced by researchers such as Abdulrazzaq et al. (2020), who emphasized their relevance in groundwater potential and contamination vulnerability studies. Longitudinal conductance, computed as the ratio of layer thickness to resistivity, reflects the ability of the overburden material to protect underlying aquifers from surface contaminants. Higher conductance is typically associated with clayey or saturated zones that can absorb or delay the migration of pollutants (George et al., 2022). As such, areas with conductance values greater than 1 S are often classified as having excellent protective capacity, while those below 0.1 S are considered vulnerable (Joshua et al., 2023). Conversely, transverse resistance, calculated as the product of resistivity and layer thickness, is indicative of the aquifer's capacity to transmit water. High transverse resistance suggests thick, coarse-grained, and permeable formations such as sands and gravels (Ige et al., 2020). However, high resistance alone does not guarantee groundwater quality protection, as it may also correspond with unprotected or fractured formations susceptible to rapid contaminant transport.

Recent studies across Nigeria have successfully applied Dar-Zarrouk parameters to assess groundwater potential in crystalline basement terrains and sedimentary basins. For instance, Alabi et al. (2021) found that areas with moderate to high transverse resistance but low longitudinal conductance in southwestern Nigeria were prone to poor aquifer protection despite their yield potential. Similarly, Ojo et al. (2024) applied these parameters in Delta State to identify regions suitable for borehole development.

Evaluating groundwater potential requires the consideration of aquifer geometry, hydraulic characteristics, and recharge mechanisms. VES techniques provide estimates of aquifer depth, thickness, and resistivity, which are used to compute transmissivity and hydraulic conductivity (Jimoh et al., 2023). Transmissivity (T) is critical for estimating aquifer yield, while hydraulic conductivity (K) reflects the ease with which water moves through porous media (Ibuot et al., 2022). Together, these parameters form the basis for estimating groundwater availability and informing drilling depth. Hydrogeological studies in Nigeria have consistently demonstrated that combining resistivity-based methods with GIS-based spatial analysis enhances groundwater exploration outcomes. Akinluyi et al. (2021) used VES and GIS overlay models to delineate favorable groundwater zones in Ondo State, while Mgbolu et al. (2024) emphasized the role of apparent resistivity in modeling aquifer performance in the Niger Delta.

Protectivity refers to the capacity of overburden materials to shield aquifers from contamination. As highlighted earlier, longitudinal conductance serves as a proxy for evaluating this protective function (Falade et al., 2023). Several studies have classified protective capacity based on conductance thresholds: >1 1/Ω (excellent), 0.7–1 1/Ω (very good), 0.5–0.7 1/Ω (good), 0.2–0.5 1/Ω (moderate), and <0.1 1/Ω (poor) (Adewumi et al., 2023). In regions with intense agricultural or industrial activities, protectivity mapping becomes crucial. In a study by Olabanji et al. (2024) in Osun State, low-conductance zones coincided with areas of shallow aquifers and high nitrate concentrations, indicating poor filtration and high vulnerability. Similarly, studies in urban areas of Ibadan and Abuja have revealed that unprotected aquifers are more susceptible to contaminants from surface runoff and effluents. This phenomenon, known as urban hydrological transformation, has been well documented in hydrology literature (Pang et al., 2022; Kimbi et al., 2024).

LULC is a primary determinant of surface infiltration and recharge. Forests and grasslands enhance infiltration by reducing runoff and promoting soil moisture retention, while built-up areas with impervious surfaces significantly hinder groundwater recharge. Croplands exhibit moderate recharge potential, depending on soil type, tillage practices, and irrigation methods (Aragaw & Kura, 2024). In a GIS-based study in northeast Nigeria, Ejepu et al. (2017) found a direct relationship between forest cover and recharge potential. In contrast, urban centers such as Maiduguri and Kano showed minimal recharge due to sealed surfaces. A similar observation was made by Khalil et al. (2021) in the Nile Delta, where changes in LULC significantly impacted aquifer recharge patterns over three decades.

Drainage density (Dd), defined as the total length of streams per unit area, is a hydrological index that reflects terrain permeability and runoff characteristics. High drainage density is often linked to impervious or steep terrains with rapid runoff and minimal recharge, while low drainage density areas exhibit higher infiltration and recharge rates (Dongare et al., 2022). In groundwater studies, integrating drainage density with aquifer parameters enhances recharge modeling. For instance, Doke et al. (2020) established that areas with low Dd values are more conducive to groundwater development due to the higher residence time of surface water. Modern studies utilizing DEM-derived drainage networks support this assertion.

The integration of geoelectrical surveys with GIS tools marks a significant advancement in hydrogeological studies. GIS enables the spatial overlay of VES data, LULC maps, drainage density layers, and elevation models, facilitating multi-criteria decision analysis (MCDA) for groundwater development (George et al., 2022). Numerous Nigerian studies have successfully adopted this integrated approach. Ilevbare and Imasuen (2020) applied VES and GIS to map aquifer potential in the Anambra Basin, while Olaseeni et al. (2020) used MCDA in Lagos to rank zones based on groundwater productivity and risk exposure.

Maillet (1947) highlighted the equivalence problem in electrical sounding interpretation, whereby different layered earth models may produce similar apparent resistivity responses. In practical hydrogeophysical applications, Dar-Zarrouk parameters are therefore not used to replace detailed lithological interpretation but to derive equivalent hydrogeoelectrical parameters representing the integrated behavior of aquifer and overburden units (Mohammed et al., 2022; Mohammed et al., 2023). In this study, the parameters are computed from inverted layer resistivity and thickness values corresponding specifically to interpreted aquifer horizons, rather than from generalized equivalent layer reduction.

This study in Ohafia similarly utilizes a composite framework of Dar-Zarrouk parameters, LULC, and drainage metrics to delineate areas with high, moderate, and low groundwater potential. Such integrative models enhance the accuracy of aquifer evaluation and ensure sustainable water resource planning, particularly in regions experiencing land use transformation and climatic stress.

2. Research area description and geology

The study area, as depicted in Figure 1, is located within the Ohafia Local Government Area (LGA) of Abia State, situated in southeastern Nigeria. Ohafia lies between latitudes 5°30′N and 5°45′N, and longitudes 7°40′E and 7°50′E, forming part of the humid tropical rainforest belt. The regional overview (Figure 1a) shows the national context with Abia State highlighted, while Figure 1b zooms into Abia, showing Ohafia's boundary in relation to adjacent LGAs such as Bende, Isuikwuato, and Arochukwu.

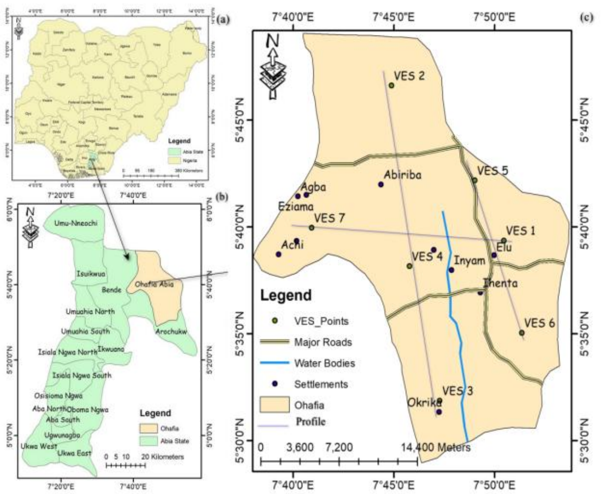

Figure 1: *Location map of the study area showing VES points, settlements, road networks, and water bodies in Ohafia, southeastern Nigeria.*

Slika 1: *Lokacija raziskovalnega območja, na katerem so prikazane točke VES, naselja, cestna omrežja in vodna telesa v Ohafii, JV Nigerija.*

Figure 1c presents the detailed study map, showing the distribution of seven VES points labeled VES 1 through VES 7. These points are strategically positioned to represent various hydrogeological and physiographic conditions across Ohafia. Settlements such as Abiriba, Elu, Inyam, and Agba are prominently marked, aiding spatial orientation and supporting socio-environmental relevance. The map includes major road networks crisscrossing the region, enhancing access to the VES locations and providing insight into potential development corridors. A prominent river system runs from north to south through the central region, intersecting near VES 4 and VES 3, which may play a role in groundwater recharge and local aquifer dynamics.

In Figure 2, the topography of the study area is visualized using a Digital Elevation Model (DEM), overlaid with contour lines at consistent intervals and VES points. Elevation in the region varies significantly, ranging from 19 meters to 228 meters above sea level. High-elevation areas, marked in darker shades, dominate the central and northeastern portions (e.g., near VES 2 and VES 5), while lower elevations are concentrated in the southwest (e.g., VES 3 and VES 6). These variations are crucial for understanding surface runoff, groundwater infiltration, and aquifer vulnerability. The 65 m and 130 m contour lines indicate potential watershed boundaries that may influence groundwater recharge.

The integrated interpretation of Figures 1 and 2 supports a multi-scalar analysis of Ohafia's hydrogeophysical setting, providing critical spatial context for evaluating groundwater vulnerability. The distribution of VES points in relation to topographic gradients, surface water bodies, and settlements offers insights for sustainable water resource planning and land-use decisions.

The study area is located within the Afikpo Basin in southeastern Nigeria, forming part of the southern Benue Trough sedimentary sequence. The geology is dominated by the Ajali Sandstone and associated formations, consisting of alternating sandstone, sandy shale, and clay units (Okoro et al., 2020). These lithological sequences form a multi-layered aquifer system in which permeable sandstone horizons serve as aquifers, while shale and clay layers act as confining or semi-confining units (Okoro & Igwe, 2018). Groundwater occurrence and electrical resistivity variations in the area are therefore strongly controlled by the lithological heterogeneity and vertical stratification of sedimentary units.

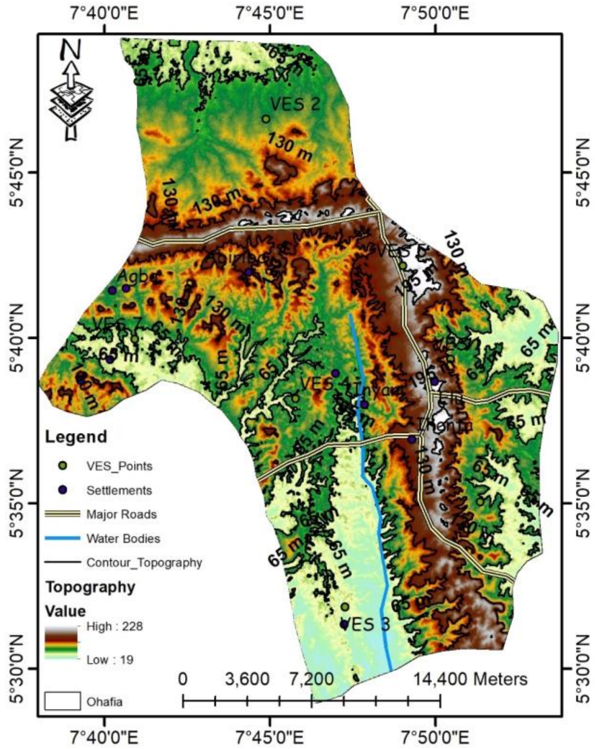

***Figure 2:** Topographic map of Ohafia LGA showing elevation ranges.*

***Slika 2:** Topografska karta Ohafie, na kateri so prikazani višinski razponi.*

3. Methodology

3.1 Data acquisition

The geophysical investigation was conducted using the VES method with the ABEM Terrameter SAS1000 Signal Averaging System. The Schlumberger electrode configuration was employed throughout the survey due to its efficiency in resolving subsurface layers at varying depths. A maximum current electrode spread of 800 meters was utilized, facilitating deeper current penetration and broader subsurface coverage. The current electrodes were symmetrically extended, 400 meters to the right and 400 meters to the left of the central point, to maintain balance and optimize the depth of investigation (George et al., 2024).

Seven VES stations were strategically located across the study area, arranged in an approximate grid to ensure comprehensive spatial coverage. However, the initial layout was adjusted in some cases due to natural and man-made obstructions, including valleys, gullies, and densely built-up zones, which made direct access to specific locations impractical. These adjustments ensured that high-quality data could still be collected while preserving spatial representation. All field operations were carried out under stable weather conditions to minimize environmental interference and enhance data reliability (Abdulrazzaq et al., 2022).

The depth of current penetration, also referred to as the depth of investigation, increases proportionally with the spacing between the current electrodes (AB). Consequently, wider electrode spacing enables the exploration of deeper subsurface features, making the method useful for identifying aquifer-bearing zones (Aladeboyeje et al., 2024). The Schlumberger array's flexibility in electrode adjustment makes it particularly effective in delineating resistivity contrasts at multiple depths, offering both the resolution and penetration essential for accurate subsurface characterization.

The apparent resistivity ($\rho_{a(s)}$) at each station was calculated based on the electrode geometry and measured potential differences. This method allowed for the accurate interpretation of subsurface lithological variations.

$$\rho_{a(s)} = R\pi\left(\frac{a^2}{b} - \frac{b}{4}\right) \tag{1}$$

Two fundamental variables, a and b, are defined based on the electrode configuration used in a resistivity survey. The variable a represents half the distance between the current electrodes (A and B), mathematically expressed as $a = \frac{AB}{2}$. Similarly, b represents half the spacing between the potential electrodes (M and N), given by $b = \frac{MN}{2}$. These parameters are crucial for calculating the geometric factor, which is instrumental in determining the apparent resistivity of the subsurface. The electrical resistance (R) at each measurement point is then calculated using Ohm's Law, as the ratio of the measured voltage (V) to the applied current (I).

The electrical resistance (R) at each measurement point was calculated using Ohm's law:

$$R = \frac{V}{I} \tag{2}$$

where V is the measured potential difference (V), I is the injected current (A), and R is the electrical resistance (Ω).

The apparent resistivity (ρ_a) was subsequently computed as:

$$\rho_{a(s)} = K \times R \tag{3}$$

where *K* is the geometric factor of the Schlumberger electrode configuration.

For the Schlumberger array, the geometric factor is expressed as:

$$K = \pi\left(\frac{a^2}{b} - \frac{b}{4}\right) \tag{4}$$

where a represents half the spacing between the current electrodes (AB/2), and b represents half the spacing between the potential electrodes (MN/2).

The spatial arrangement of electrodes in the subsurface influences a parameter known as the geometric factor (K), which is essential for converting resistance measurements to apparent resistivity. The value of K varies depending on the specific electrode configuration employed.

3.2 Data processing

The acquired VES data were analyzed using the IP2Win software for processing and interpretation. The inversion and interpretation of VES data were carried out using the IP2Win software (Moscow State University, Department of Geophysics), a widely used one-dimensional inversion program for resistivity sounding interpretation (Bobachev et al., 2003). Apparent resistivity values, along with their associated AB/2 electrode spacings, were entered into the software for inversion and geoelectrical modeling. The program conducted iterative calculations, ranging from 1 to 29 iterations, to reduce the root mean square (RMS) error and improve the fit between observed field curves and theoretical models (Ezebunanwa et al., 2020). This inversion process produced true resistivity values and corresponding layer thicknesses and depths, which were subsequently used to calculate key Dar Zarrouk parameters such as transverse resistance and hydraulic conductivity.

The inversion process involved the iterative adjustment of layer resistivity and thickness until an acceptable fit between observed and calculated apparent resistivity curves was achieved (Jha et al., 2008). The final geoelectrical model obtained from the inversion represents a one-dimensional layered earth approximation. Resistivity (ρ_i) and thickness (h_i) values derived from the interpreted models were subsequently used to compute the Dar-Zarrouk parameters, namely longitudinal conductance and transverse resistance, following the formulation of Maillet (1947). These parameters were calculated for each VES location using the interpreted aquifer layer and overburden characteristics.

3.3 The Dar Zarrouk parameters

Dar Zarrouk parameters play a vital role in assessing aquifer properties, particularly transmissivity and the protective capacity of overlying materials (Olaniyan, 2020). These parameters are obtained from geoelectrical survey data and are computed using the following equations 5 to 8.

The total thickness (H) of the geoelectrical sequence was computed as:

$$H = \sum_{i=1}^{n} hi \quad (5)$$

Where hi is the thickness of the *i*th geoelectrical layer.

The longitudinal conductance (S) was calculated using:

$$S = \frac{h1}{\rho 1} + \frac{h2}{\rho 2} + \frac{h3}{\rho 3} + \cdots\cdots\cdots\cdots\cdots\cdots \frac{hn}{\rho n} = \sum_{i=1}^{n} \frac{hi}{\rho i} \quad (6)$$

where ρi is the resistivity of the *i*th layer.

The transverse resistance (T) was determined as:

$$T = \rho_1 h_1 + \rho_2 h_2 + \rho_3 h_3 + \cdots\cdots\cdots\cdots\cdots\cdots \rho_n h_n = \sum_{i=1}^{n} \rho_i h_i \quad (7)$$

where ρ_i and h_i represent the resistivity and thickness of the *i-th* geoelectric layer, respectively. The transmissivity (Tr) of an aquifer is calculated as the product of hydraulic conductivity (k) and the corresponding layer thickness (h):

$$Tr = kh \quad (8)$$

According to Oguama et al. (2020), geoelectric investigations can reliably estimate the true resistivity of an aquifer, which can then serve as a proxy for hydraulic conductivity (k) in situations where pumping test data are unavailable.

The Dar-Zarrouk parameters were derived from the interpreted layered models obtained through inversion. Equivalent models, as described by Maillet (1947), were not independently generated; rather, the interpreted geoelectric layers represent the best-fit inversion models constrained by field measurements and geological consistency.

In this study, Dar-Zarrouk parameters were calculated using the resistivity and thickness of the interpreted aquifer layer identified from inverted VES models and constrained by regional lithology. The approach does not reduce the layered structure into a simplified equivalent model; instead, it uses aquifer-specific parameters to estimate transmissivity, protective capacity, and hydraulic behavior at each VES location.

IP2Win inversion result illustrating the match between observed and calculated apparent resistivity curves and the derived geoelectric layer parameters used for estimating Dar-Zarrouk parameters, as shown in Figure 3.

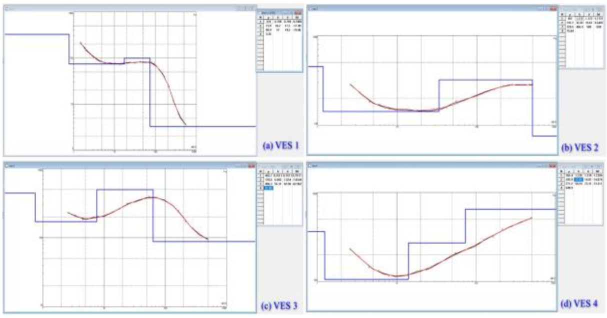

***Figure 3:** VES inversion curve showing observed and calculated apparent resistivity with an interpreted layer model.*

***Slika 3:** Inverzijska krivulja VES, ki prikazuje opazovano in izračunano navidezno upornost z interpretiranim modelom plasti.*

Figure 3 illustrates the workflow adopted in this study, showing the sequence from apparent resistivity measurements through inversion of the VES data to obtain true resistivity and layer thickness, followed by lithological interpretation and the computation of Dar-Zarrouk parameters.

3.4 Surface environmental datasets (slope and LULC analysis)

Slope data extracted from the Digital Elevation Model (DEM) were analyzed to assess the study area's terrain characteristics (Olla et al., 2020). The slope (S) was computed using the following equation:

$$S = arctan\left(\frac{\Delta z}{d}\right) \times \frac{180}{\pi} \quad (9)$$

where Δz is the elevation difference between adjacent cells and d is the horizontal cell spacing.

To evaluate the spatial distribution of slope gradients throughout the study area, the slope data were categorized into classes, such as flat, gentle, moderate, and steep.

Landsat 8 satellite imagery, with a spatial resolution of 30 meters, was employed to generate a composite image that offers a detailed representation of the Earth's surface. To enhance spatial accuracy, the imagery was georeferenced and projected onto the UTM/WGS 84 coordinate system using ArcGIS (Ulakpa et al., 2020). LULC classification was performed to map and differentiate various land cover types, such as water bodies, forests, croplands, and urban areas, at the pixel level, reflecting both natural features and human activities. Multiple classification algorithms were applied to improve categorization accuracy (Koko et al., 2022). An LULC change analysis was conducted to quantify the extent and distribution of land cover classes as of 2023.

4. Results and discussion

4.1. Aquifer geoelectric properties

Understanding the geoelectric characteristics of aquiferous zones is crucial for assessing groundwater potential and guiding sustainable water resource development. Table 1 presents the apparent resistivity, depth, and thickness values of aquifer layers obtained from VES across 7 locations in Ohafia, Southeastern Nigeria. Figure 3 also shows the modelled curve for VES 1 to 4. These parameters serve as indicators of lithological variations, saturation levels, and aquifer geometry. Variations in resistivity reveal the contrast between conductive, water-bearing formations and dry, resistive zones, while depth and thickness inform the ease of accessibility and groundwater storage capacity (Chandrasekar et al., 2021). The integration of these parameters aids in evaluating aquifer productivity and vulnerability to surface contamination.

Table 1 shows that aquifer resistivity values in the study area range from 99.40 to 1360.00 Ω·m, with moderate values dominating most VES locations, indicating predominantly sandy formations with varying degrees of saturation. Aquifer depth varies between 50.69 m and 92.00 m, while thickness ranges from 25.00 m to 86.20 m, suggesting significant spatial variability in aquifer geometry. Areas with greater thickness and moderate resistivity values generally indicate more favorable groundwater storage conditions.

***Table 1:** Apparent resistivity values of aquifer layers at VES locations in Ohafia.*

***Preglednica 1:** Vrednosti navidezne upornosti vodonosnih plasti na lokacijah VES v Ohafii.*

VES	Apparent Resistivity (Ω·m)	Depth (m)	Thickness (m)
VES 1	99.40	74.50	57.00
VES 2	386.00	92.00	86.20
VES 3	496.30	62.96	55.31
VES 4	271.20	73.31	59.24
VES 5	1360.00	50.69	25.00
VES 6	106.70	74.73	67.15
VES 7	164.50	78.80	54.70

4.1.1 Spatial variation of aquifer apparent resistivity

Figure 4 illustrates the spatial distribution of aquifer apparent resistivity across Ohafia, as derived from VES data. Table 1 presents the associated resistivity values for each VES point. These values range from 99.40 Ω·m at VES 1 (Elu) to 1360.00 Ω·m at VES 5 (near Abiriba), indicating substantial variation in the geoelectric properties of the subsurface across the study area.

Low resistivity zones, represented by deep red to orange shades, are concentrated in the southern and southwestern portions of Ohafia. These include areas such as Elu (VES 1, 99.40 Ω·m), Achị (VES 6, 106.70 Ω·m), and Eziama (VES 7, 164.50 Ω·m). These values suggest the presence of saturated clayey or silty formations, which are favorable for groundwater storage due to high porosity and conductivity. The presence of water bodies along the central axis, especially near VES 3 and VES 4, further supports enhanced infiltration and recharge conditions, reducing resistivity due to higher moisture content.

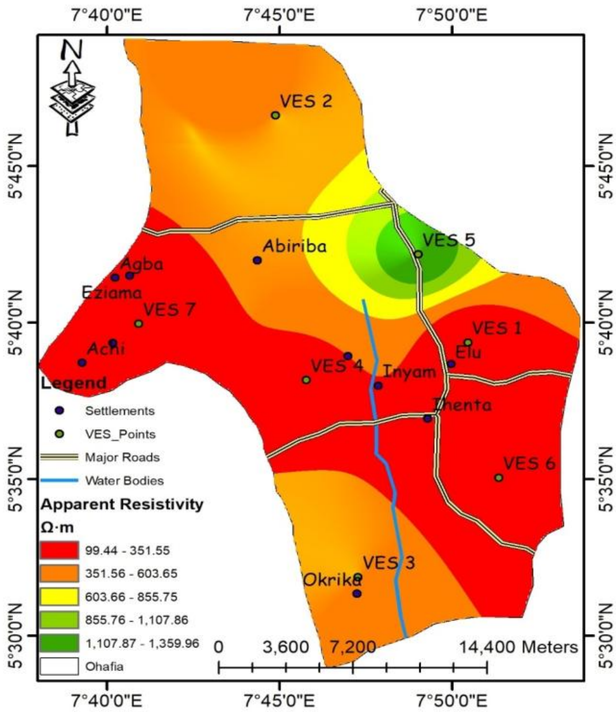

Figure 4: *Spatial distribution of apparent resistivity across the study area.*

Slika 4: *Prostorska porazdelitev navidezne upornosti na območju raziskave.*

Interpretation of the inverted VES models indicates that the study area is characterized predominantly by a single regional aquifer system occurring at varying depths and thicknesses across the VES locations. The observed resistivity range (99.4–1360 Ω·m) reflects lateral lithological heterogeneity within the same aquifer unit rather than the presence of multiple distinct aquifers. Variations in resistivity are attributed to differences in grain size distribution, clay content, degree of saturation, and weathering intensity across the study area (Ben-Owope & Agbasi, 2025).

Moderate resistivity zones (orange to yellow), seen in Okrika (VES 3, 496.30 Ω·m) and the Agba-Abiriba axis (VES 2, 386.00 Ω·m), may represent interbedded sands and clays, with variable water content. These formations might serve as semi-confined aquifers with intermediate groundwater potential.

High resistivity zones (green) are most prominent around VES 5 (1360.00 Ω·m), situated near Abiriba. These suggest dry or consolidated sandy formations or possibly unsaturated zones, which are less favorable for groundwater accumulation. This high-resistivity anomaly may also result from coarse, poorly conductive lithologies with limited clay content.

The road network, especially those traversing near VES 5, VES 2, and VES 3, could influence impermeability due to compaction and runoff, potentially reducing localized infiltration. In contrast, the proximity to streams near VES 3, 4, and 6 promotes downward percolation, improving aquifer recharge conditions and contributing to lower resistivity readings.

The wide variation in resistivity values across the study area reflects spatial heterogeneity in subsurface lithology and saturation conditions rather than separate aquifer systems (Raji & Abdulkadir, 2020). Lower resistivity values are associated with clayey or highly saturated formations, while higher resistivity values correspond to coarse-grained or partially saturated sandy units. Such variability is typical of sedimentary terrains in southeastern Nigeria, where lateral facies changes influence the aquifer's electrical properties (Akingboye & Osazuwa, 2021).

4.1.2 Spatial variation of aquifer depth and thickness

Figure 5(a) and 5(b) illustrate the spatial distributions of aquifer depth and thickness, respectively, across Ohafia, Southeastern Nigeria. These distributions, supported by the data in Table 1, are critical for understanding the groundwater storage capacity, recharge potential, and the feasibility of drilling operations across various parts of the study area.

As shown in Figure 5a, aquifer depths range from 50.69 m to 92.00 m, with the deepest aquifers recorded at VES 2 (92.00 m) near Abiriba, followed by VES 7 (78.80 m) at Eziama, and VES 6 (74.73 m) at Achị. These deeper aquifers generally indicate well-protected water-bearing formations, often less prone to contamination due to greater overburden. On the other hand, the shallowest aquifer depth was observed at VES 5 (50.69 m), suggesting that groundwater at this location, near Abiriba, is more accessible but potentially more vulnerable to surface contamination.

Aquifer thickness, presented in Figure 5b, reveals significant variation across the study area, with values ranging from 25.00 m to 86.20 m. The thickest aquifer occurs at VES 2 (86.20 m), also in Abiriba, indicating a potentially high-yield aquifer with considerable groundwater storage capacity. Other notable locations with substantial aquifer thickness include VES 6 (67.15 m) in Achị, and VES 4 (59.24 m) in Inyam. In contrast, VES 5 (25.00 m) recorded the thinnest aquifer, which could imply a limited groundwater reserve and potentially lower yield.

The presence of water bodies, particularly near VES 3 and VES 4, enhances recharge conditions and maintains aquifer saturation, thus supporting thicker saturated zones. The road network, notably along the VES 1 to VES 6 corridor, could contribute to local impermeability due to surface sealing and compaction, potentially reducing infiltration and influencing aquifer recharge in urbanized or paved areas.

Settlements such as Okrika (VES 3) and Elu (VES 1) exhibit intermediate depth and thickness values, suggesting that they are suitable for sustainable groundwater exploitation with moderate drilling requirements. In contrast, areas like Eziama (VES 7) and Achị (VES 6) show greater aquifer thickness and depth, making them favorable sites for borehole development with improved water quality protection.

4.2 Dar-Zarrouk parameters of the aquifer

Table 2 summarizes key hydrogeoelectric parameters obtained from the interpretation of VES data across various locations in Ohafia, Southeastern Nigeria. The parameters include longitudinal conductance, transverse resistance, hydraulic conductivity, and transmissivity, each offering valuable insights into aquifer behavior. Longitudinal conductance evaluates the overburden’s protective capacity against surface contamination, while transverse resistance and transmissivity describe the aquifer’s ability to transmit water. These relationships originate from the Dar-Zarrouk parameters introduced by Maillet (1947), which established the theoretical link between layer resistivity and thickness in electrical sounding. Subsequent studies demonstrated their hydrogeological relevance by relating resistivity-derived parameters to aquifer hydraulic properties, and their application remains widely adopted in contemporary groundwater investigations. Hydraulic conductivity reflects how easily groundwater can flow through porous media (Joshua et al., 2023).

As summarized in Table 2, longitudinal conductance values vary from 0.02 to 0.63 1/Ω, indicating a wide range of aquifer protective capacities across the study area. Transverse resistance ranges between 5,665.80 and 34,000.00 Ω·m², reflecting variations in aquifer thickness and resistivity. Hydraulic conductivity values range from 0.12 to 0.61 m/day, while transmissivity varies from 2.95 to 40.40 m²/day, indicating that aquifer productivity differs significantly among locations, with higher transmissivity values generally associated with thicker and more permeable sandstone units.

Table 2: *Dar-Zarrouk parameters of aquifer layers at VES locations in Ohafia.*

Preglednica 2: *Parametri vodonosnih plasti Dar-Zarrouka na lokacijah VES v Ohafii.*

VES	Longitudinal Conductance (1/Ω)	Transverse Resistance (Ω·m²)	Hydraulic Conductivity (m/day)	Transmissivity (m²/day)
VES 1	0.57	5665.80	0.61	34.62
VES 2	0.22	33273.20	0.42	36.07
VES 3	0.11	27450.35	0.36	20.05
VES 4	0.22	16065.89	0.49	28.78
VES 5	0.02	34000.00	0.12	2.95
VES 6	0.63	7164.91	0.60	40.40
VES 7	0.33	8998.15	0.56	30.53

4.2.1 Spatial distribution of aquifer longitudinal conductance and transverse resistance

The observed variation in transverse resistance reflects differences in thickness and resistivity of multiple aquifer horizons within the layered sedimentary sequence typical of the Ajali Sandstone and associated formations. The inverted VES models indicate alternating sandy and clayey units at different depths, suggesting the presence of several water-bearing layers rather than a single homogeneous aquifer. Consequently, the spatial distribution of Dar-Zarrouk parameters represents variations in hydraulic properties among these aquifer horizons controlled by lithological boundaries.

Figure 6a presents the distribution of transverse resistance values across the surveyed region. The transverse resistance values range from 5,666.98 to 33,999.24 Ω·m², which suggests a variable aquifer character and lithological composition. The lowest values (<11,000 Ω·m²) are concentrated in the northeast (around VES 2, near the Abiriba settlement) and southwest (around VES 3, near Okrika), while higher values (>28,000 Ω·m²) are observed in the central-southern zone surrounding VES 6 and the surrounding settlement.

Low transverse resistance values, such as those found in the Abiriba and Okrika zones, may indicate porous or weathered material with high transmissivity, suggesting areas of relatively higher recharge potential but possibly lower protection from surface contamination. Conversely, higher transverse resistance in areas like Thenta, Elu, and VES 6 may reflect compact or clay-rich formations, which act as protective barriers to the underlying aquifers.

Hydraulic conductivity, illustrated in Figure 5b, ranges from 0.12 to 0.61 m/day. The highest values (0.513–0.610 m/day) occur around VES 2 and VES 4, indicating zones with highly permeable aquifer media. These areas likely consist of coarse sand or gravel layers that facilitate rapid water transmission, making them suitable for productive borehole development. Meanwhile, the lowest hydraulic conductivity values (<0.22 m/day) are evident around VES 5 and Thenta, reflecting finer-grained or more compact formations that restrict water movement.

A comparative analysis of both parameters reveals an inverse spatial correlation in some parts of the study area. For instance, VES 2, located northwest of Abiriba, shows low transverse resistance but high hydraulic conductivity, pointing to a permeable but less protected aquifer unit. In contrast, VES 6, which exhibits high transverse resistance and low conductivity, suggests a more confined aquifer setting, offering better protection but a potentially lower yield.

The proximity of these aquifer zones to settlements such as Achị, Eziama, Agba, and Inyam, as well as critical infrastructure like major roads and water bodies, further emphasizes the importance of understanding spatial aquifer dynamics for groundwater development and protection planning. For instance, areas near VES 4 and VES 7, located close to settlements and road networks, demonstrate moderate to high hydraulic conductivity and require careful groundwater abstraction strategies to prevent overexploitation or contamination.

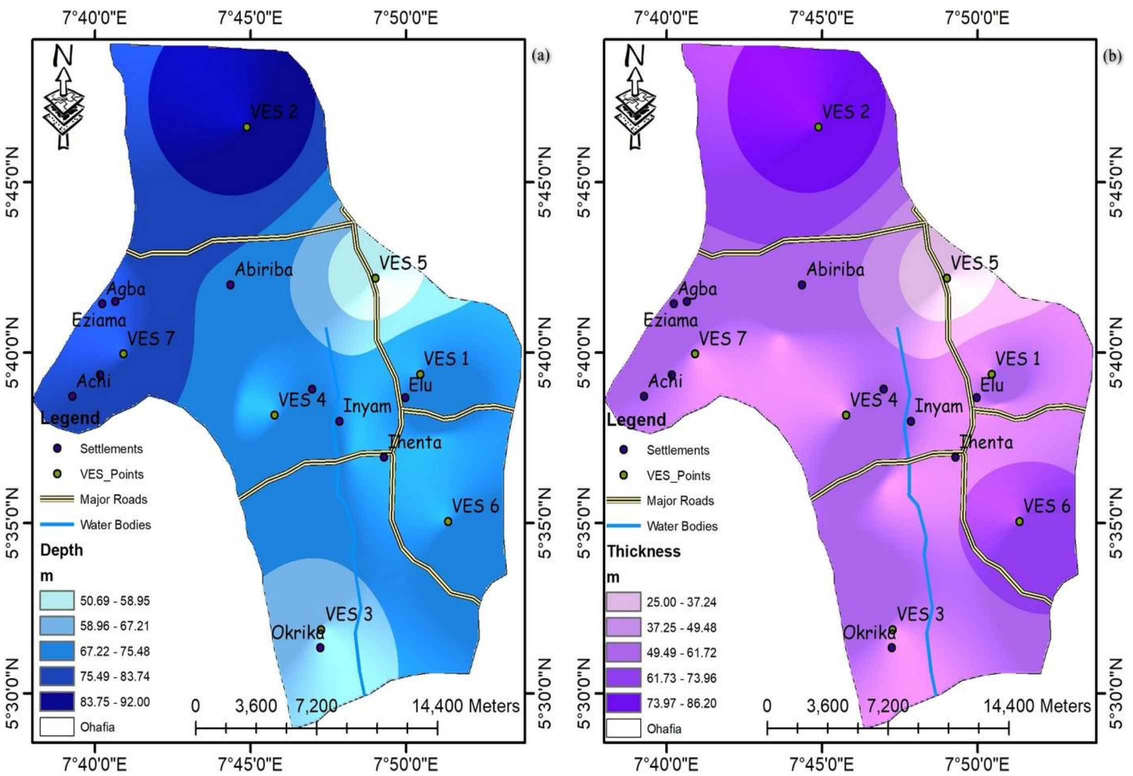

Figure 5: *Spatial distribution maps of aquifer depth (a) and thickness (b) in Ohafia.*

Slika 5: *Karti prostorske porazdelitve globine (a) in debeline (b) vodonosnika v Ohafiji.*

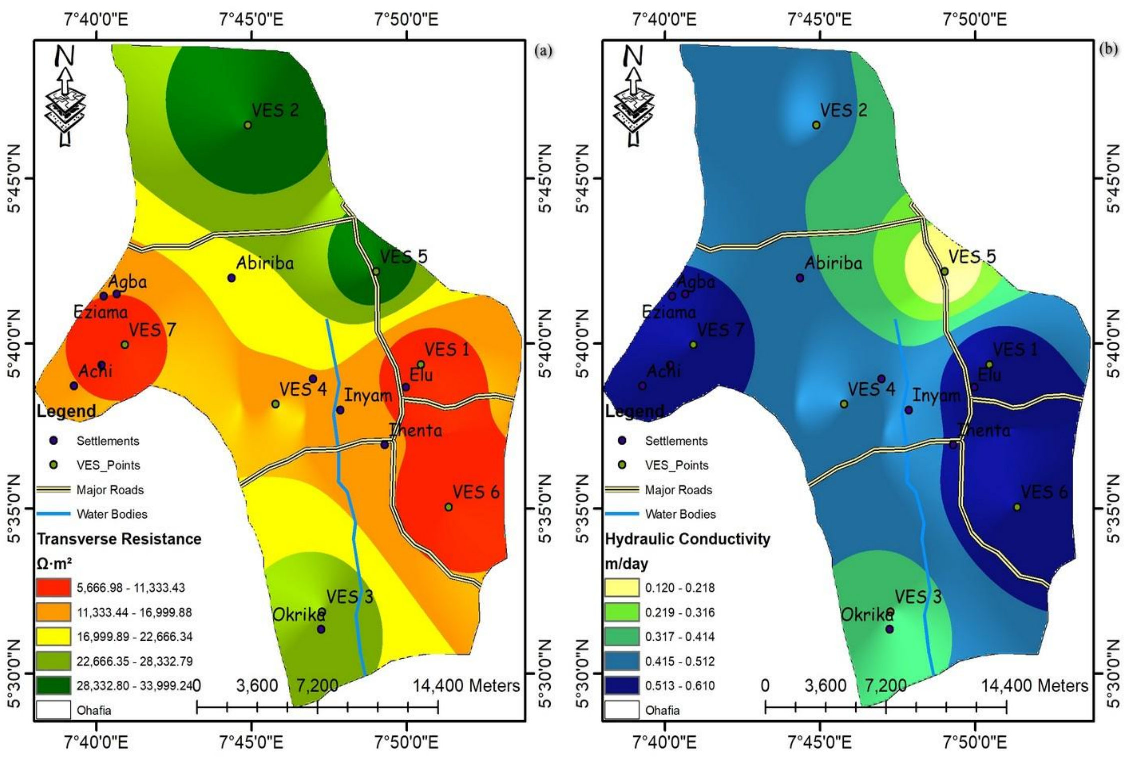

Figure 6: *Spatial distribution aquifer maps of (a) transverse resistance and (b) hydraulic conductivity.*

Slika 6: *Karti prostorske porazdelitve vodonosnika, ki prikazujeta (a) prečni upor in (b) hidravlično prevodnost.*

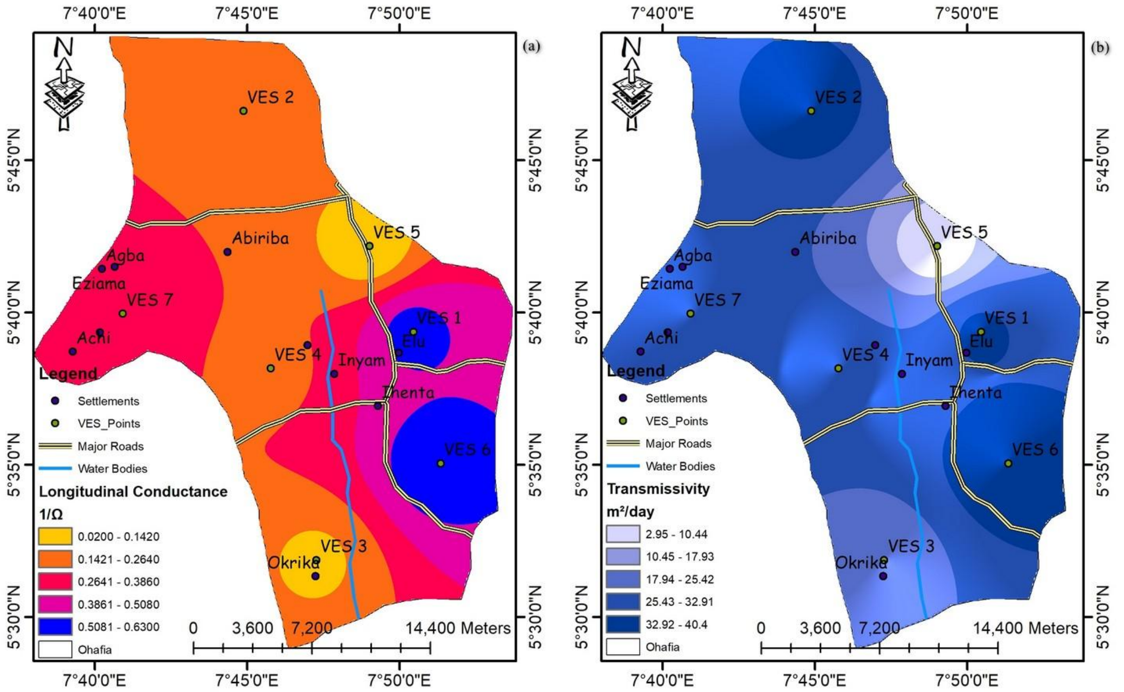

***Figure 7:** Spatial distribution aquifer maps of (a) longitudinal conductance and (b) transmissivity.*

***Slika 7:** Karti prostorske porazdelitve vodonosnika, ki prikazujeta (a) vzdolžno prevodnost in (b) prepustnost.*

Table 2 provides specific values of transverse resistance and corresponding hydraulic conductivity for selected VES points. The highest hydraulic conductivity (0.61 m/day) corresponds to a low transverse resistance value (5,665.80 Ω·m²), supporting the notion that aquifers in this zone are highly transmissive but less protected. Conversely, the lowest hydraulic conductivity (0.12 m/day) is associated with a transverse resistance value of 34,000 Ω·m², indicative of compact lithology offering limited permeability.

Interpretation of resistivity values was guided by the known lithological framework of the area, where moderate to high resistivity values correspond to sandstone aquifer units, while relatively lower resistivity values indicate clayey or shale-rich layers acting as aquitards. This integration of inverted VES parameters with regional geological information reduces ambiguity in interpreting spatial variations of electrical properties.

4.2.2 Spatial distribution of longitudinal conductance and transmissivity

The inverted VES models indicate that aquifer layers correspond predominantly to moderately resistive sandstone units occurring beneath the overburden and above clayey or shale-rich layers. While the spatial maps of longitudinal conductance and transmissivity represent equivalent subsurface responses, aquifer productivity assessments were based on transmissivity values calculated from the thickness and hydraulic properties of the identified aquifer layer only.

Figure 7a displays the variation in longitudinal conductance, while Figure 7b illustrates the distribution of transmissivity across the Ohafia area. These interpretations are supported by data in Table 2, which presents hydraulic conductivity and transmissivity values at each VES point.

Equivalent longitudinal conductance derived from Dar-Zarrouk parameters reflects the combined protective capacity of overburden layers above the aquifer. Higher values are associated with fine-grained, conductive materials such as clay that inhibit vertical infiltration of pollutants. In Figure

7(a), longitudinal conductance values range from 0.02 at VES 5, near Abiriba, to 0.63 at VES 6, located in Achị. The highest protective capacities are observed at VES 6, followed by VES 1 in Elu (0.57) and VES 7 in Eziama (0.33). These areas exhibit relatively favorable aquifer protection and are underlain by materials capable of filtering contaminants. In contrast, the lowest conductance value recorded at VES 5 corresponds with a yellow zone on the map, indicative of coarse, sandy formations with minimal protective capacity. Aquifer development in such areas should include measures such as deeper drilling and casing to avoid contamination.

Transmissivity, which describes the ability of an aquifer to transmit water horizontally, is a function of both hydraulic conductivity and aquifer thickness. As shown in Figure 7(b), transmissivity values in the study area vary from 2.95 m²/day at VES 5 to 40.40 m²/day at VES 6. The most productive aquifers are found in Achị (VES 6), which exhibits the highest transmissivity, followed by Abiriba (VES 2), Elu (VES 1), and Eziama (VES 7). These locations indicate aquifers capable of supporting substantial water yields and are ideal for domestic and commercial groundwater exploitation. On the other hand, VES 5 displays the lowest transmissivity, suggesting limited groundwater potential despite its high transverse resistance. This disparity highlights the importance of evaluating multiple hydrogeoelectric parameters when assessing aquifer productivity.

The interaction between anthropogenic and natural features also influences these parameters. The network of roads running through areas such as VES 1, VES 4, and VES 6 may impede infiltration due to surface sealing and compaction, potentially limiting recharge in those regions. However, the proximity of VES points like VES 3 and VES 4 to water bodies enhances natural infiltration and supports higher conductivity and transmissivity values, particularly around the Okrika and Inyam settlements. This observation underscores the beneficial impact of natural recharge zones on aquifer performance.

4.3 Spatial distribution of drainage density in relation to longitudinal conductance and transmissivity

Figure 8 illustrates the spatial distribution of drainage density in Ohafia, Southeastern Nigeria, and its relationship with longitudinal conductance and transmissivity across selected VES points. Drainage density, expressed in km/km², provides insight into the degree of surface runoff and infiltration potential, which significantly affects groundwater recharge. The figure also overlays contour lines representing longitudinal conductance (red) and transmissivity (blue), enabling an integrated analysis of hydrological and geoelectrical parameters.

Drainage density in the study area ranges from 0.00 to 302.04 km/km², increasing from light to dark blue tones on the map. The highest drainage densities are concentrated in the southeastern and northeastern parts of Ohafia, particularly near VES 6 (Achị), VES 1 (Elu), and VES 5 (Abiriba). These zones are characterized by closely spaced drainage lines, indicating high surface runoff and low infiltration potential. High drainage density may result from impervious or steep terrains, reducing the likelihood of groundwater recharge and potentially increasing aquifer vulnerability, especially in areas with low longitudinal conductance (George et al., 2022).

For instance, VES 5, located in a high drainage density zone, exhibits a low longitudinal conductance value (0.02 1/Ω) and low transmissivity (2.95 m²/day). This combination implies poor protective capacity and limited aquifer productivity, likely due to both coarse overburden materials and insufficient recharge from surface runoff. Similarly, VES 1 and VES 6 are also within high drainage density zones. Still, their high longitudinal conductance values (0.57 and 0.63 1/Ω, respectively) and elevated transmissivity (34.62 and 40.40 m²/day) suggest that, despite surface runoff dominance, the presence of favorable subsurface lithologies (e.g., clay or fine sand) enhances aquifer performance and protection.

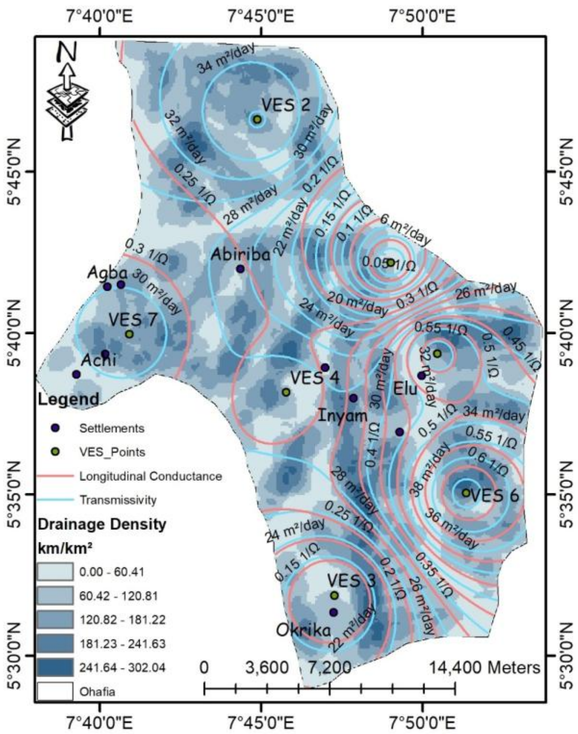

Figure 8: *Spatial distribution of drainage density overlaid with longitudinal conductance and transmissivity contours.*

Slika 8: *Prostorska porazdelitev gostote rečne mreže, s konturami vzdolžne prevodnosti in prepustnosti.*

In contrast, low drainage density zones are found in the south-central and western portions of Ohafia, notably around VES 2 (Abiriba), VES 3 (Okrika), and VES 4 (Inyam). These areas indicate lower runoff and higher infiltration potential, favorable for groundwater recharge. VES 2, in particular, combines low drainage density with moderate longitudinal conductance (0.22 1/Ω) and high transmissivity (36.07 m²/day), implying that infiltration-driven recharge plays a critical role in aquifer sustainability in this zone. Similarly, VES 3 and VES 4 show moderate transmissivity and conductance, consistent with their lower surface runoff characteristics.

The influence of roads and water bodies is also evident in the spatial pattern. Areas intersected by major roads, particularly VES 1, VES 4, and VES 6, may experience reduced infiltration due to surface sealing and impervious pavement, potentially affecting groundwater recharge. However, zones adjacent to natural water bodies, especially near VES 3 (Okrika) and VES 4 (Inyam), benefit from enhanced percolation, which contributes to the moderate transmissivity values observed. These regions demonstrate that proximity to surface water can offset the effects of high drainage density or anthropogenic surface alteration.

4.4 Land use/land cover (LULC) influence on aquifer characteristics

Figure 9 presents the Land Use/Land Cover (LULC) classification for Ohafia in 2024, overlaid with contours of longitudinal conductance and transmissivity derived from VES analysis. This figure integrates surface land characteristics with subsurface hydrogeophysical behavior, enabling a spatial understanding of how anthropogenic and natural land use patterns influence aquifer protection and productivity across the study area. The classification distinguishes between bare ground, built-up areas, crops, rangeland, trees, and water bodies, each contributing differently to infiltration, runoff, and potential contamination.

The quantitative breakdown of LULC classes in Ohafia is provided in Table 3. Dominating the landscape is tree cover, occupying 395.714 km², which constitutes the majority of the study area. This land use type is primarily found in the central, southern, and western parts of Ohafia, including the vicinity of VES 3 (Okrika), VES 4 (Inyam), and VES 7 (Achị). The dense vegetation in these areas contributes to high infiltration and aquifer recharge, with minimal surface runoff, which is reflected in the moderate to high transmissivity values (e.g., 28–36 m²/day) and high longitudinal conductance (e.g., 0.5–0.6 1/Ω), indicating favorable aquifer protection and productivity.

In contrast, built-up areas, covering 64.033 km², are concentrated around Elu (VES 1), Abiriba (VES 2 and VES 5), and parts of Okrika. These regions exhibit impervious surfaces such as roads and buildings, reducing natural infiltration and potentially increasing runoff. This condition is evident at VES 5, where the built-up influence coincides with low longitudinal conductance (0.02 1/Ω) and low transmissivity (2.95 m²/day), signaling poor aquifer protection and limited groundwater yield. Similarly, Elu (VES 1), while built-up, still benefits from subsurface conditions with moderate protection and high transmissivity, suggesting that favorable lithology may compensate for land cover limitations.

Rangelands account for 103.138 km², primarily in the eastern and southeastern areas near VES 6 (Achị). These areas are characterized by open vegetation and grasses, which allow moderate infiltration. VES 6, located in a rangeland zone, exhibits the highest transmissivity (40.40 m²/day) and the highest longitudinal conductance (0.63 1/Ω), indicating an optimal combination of favorable land cover and subsurface conditions for groundwater development.

Cropped areas, although limited in extent (2.791 km²), appear scattered across the central region, particularly near VES 4 and Inyam. These areas generally support infiltration due to loose topsoil and moderate land disturbance. VES 4 shows moderate conductance (0.22 1/Ω) and transmissivity (28.78 m²/day), reflecting the moderate recharge potential typical of cultivated lands.

Water bodies, though covering only 0.056 km², are important recharge zones. These are primarily located near VES 3 and VES 4, where transmissivity ranges from 20.05 to 28.78 m²/day. The influence of nearby rivers and streams facilitates direct recharge, enhancing the aquifer's productivity despite moderate conductance values. The spatial alignment of water bodies with high transmissivity contours supports the notion that natural recharge zones enhance aquifer performance, particularly in areas with minimal urban development.

Bare ground, occupying only 0.014 km², has a negligible effect on aquifer properties at the regional scale. These patches are largely found at localized zones and do not significantly alter recharge dynamics or protective capacity.

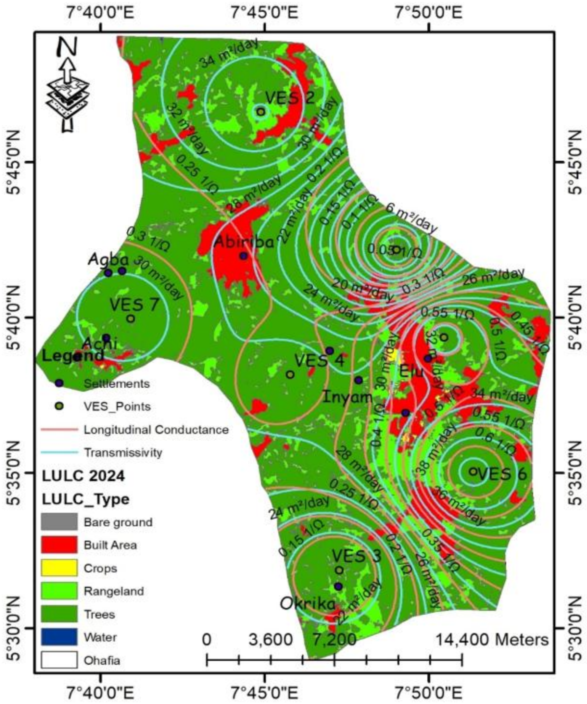

Figure 9: *LULC classification map of Ohafia, showing overlay of longitudinal conductance and transmissivity contours.*

Slika 9: *Karta rabe zemljišč in pokritosti tal (LULC) v Ohafii, s konturami vzdolžne prevodnosti in prepustnosti.*

Table 3: *Area and percentage coverage of land use/land cover (LULC) types in Ohafia (2024).*

Preglednica 3: *Površina in delež pokritosti po vrstah rabe tal in talnega pokrova (LULC) v Ohafii (2024).*

LULC Type	Area (km²)	Percentage (%)
Water	0.056	0.01%
Trees	395.714	73.44%
Crops	2.791	0.52%
Built Area	64.033	11.89%
Bare Ground	0.014	0.00%
Rangeland	103.138	19.14%
Total	535.746	100.00%

Table 3 indicates that tree cover dominates the study area, accounting for approximately 73.44% of the total land area, followed by rangeland (19.14%) and built-up areas (11.89%). The predominance of vegetated land cover suggests favorable conditions for infiltration and recharge over large portions of the study area, whereas built-up areas represent localized zones of reduced infiltration potential.

Additionally, the overlay of road networks reveals that built-up corridors, notably those cutting across VES 1, VES 4, and VES 6, could introduce localized impermeability through surface compaction and channelized runoff. However, these effects are more pronounced in high-density urban areas like Elu and Abiriba. In contrast, road infrastructure near forested and rangeland zones appears to have less of a negative impact due to the surrounding land's capacity for absorption.

The composite analysis of LULC and aquifer parameters confirms a strong relationship between surface land use and subsurface aquifer behavior. Areas dominated by natural vegetation (trees and rangelands) generally show higher conductance and transmissivity, indicating both better aquifer protection and higher productivity. Conversely, built-up areas are correlated with reduced aquifer recharge and vulnerability to contamination, especially where subsurface materials lack sufficient protective capacity.

4.5 Aquifer characteristics and influencing factors

Groundwater is an essential resource, particularly in developing regions like southeastern Nigeria, where the demand for potable water and irrigation is rapidly increasing. The exploration and development of groundwater must therefore be supported by thorough hydrogeophysical assessments that integrate subsurface parameters with surface environmental influences. The present study in Ohafia leverages geoelectrical techniques, land use data, and drainage analysis to understand the vulnerability, productivity, and sustainability of the local aquifer systems.

As emphasized in studies by Maillet (1947) and later refined by researchers like Niwas and Singhal (1985), longitudinal conductance serves as a proxy for the protective capacity of overburden material. Higher conductance values, often linked to clay-rich and water-saturated zones, suggest enhanced filtration and a lower risk of contamination from surface pollutants. In contrast, lower conductance values are indicative of coarse, resistive, and poorly consolidated formations, which cannot retard percolating contaminants. This makes them highly vulnerable to anthropogenic activities and climatic variability (Akintorinwa et al., 2020).

Transverse resistance, meanwhile, is more aligned with aquifer transmissivity and is typically influenced by both layer resistivity and thickness. High transverse resistance can indicate thick, resistive aquifers capable of storing significant groundwater volumes, although this does not inherently guarantee good protection (Ekwe et al., 2020). This dual relationship underscores the importance of interpreting geoelectrical results in tandem with surface environmental indicators.

Several researchers have demonstrated that LULC patterns exert a direct influence on infiltration capacity, runoff rates, and ultimately recharge potential (Siddik et al., 2022; Tumsa et al., 2022). In the Ohafia study, areas dominated by forest and rangeland, such as those near VES 3, VES 4, and VES 6, were found to exhibit relatively high longitudinal conductance and transmissivity values. The prevalence of vegetation in these zones reduces surface sealing, encourages infiltration, and supports subsurface saturation, all of which increase aquifer sustainability. These findings align with earlier research by Smith and Boers (2023), who emphasized that vegetated areas tend to exhibit more stable and resilient hydrological cycles.

In contrast, built-up regions within Ohafia, particularly those surrounding Elu, Abiriba, and parts of Okrika, demonstrate a different dynamic; urbanization typically introduces impervious surfaces such as paved roads and concrete structures, which limit infiltration and accelerate surface runoff. Within the current study area, these built-up zones are associated with reduced conductance values and, in some cases, lower transmissivity, reflecting the negative impact of anthropogenic development on aquifer recharge potential.

Drainage density, which quantifies the total length of streams and channels per unit area, is a strong indicator of surface runoff intensity. High drainage density typically correlates with rapid runoff, low infiltration, and reduced groundwater recharge (Sahoo et al., 2023). In Ohafia, high drainage density zones, such as those around VES 1, VES 5, and VES 6, indicate areas where surface water may not significantly contribute to groundwater storage unless compensated for by favorable subsurface conditions. Interestingly, while VES 6 lies within a high drainage density area, its exceptionally high conductance and transmissivity suggest that subsurface lithology and land cover, likely rich in fine-grained, saturated soils, override the limitations imposed by surface hydrology.

It is important to note that while proximity to water bodies generally enhances aquifer recharge, this is contingent upon the geological characteristics of the surrounding terrain. Studies have shown that rivers and wetlands can serve as vital recharge zones, especially in unconfined aquifers where hydraulic connectivity exists (Boubacar et al., 2019; Goni et al., 2021). In the Ohafia region, VES points located near rivers, such as VES 3 and VES 4, show moderate to high transmissivity, reinforcing the value of natural recharge corridors. This observation is consistent with Liu et al. (2022), who argued that riverine and floodplain areas often act as dynamic interfaces between surface and groundwater systems, particularly in tropical and subtropical climates.

However, the mitigating effect of anthropogenic barriers such as roads cannot be overstated. Compacted roadbeds and drainage infrastructure tend to reroute water flow, reducing infiltration opportunities even in otherwise permeable soils. The hydrological consequences of such development have been detailed in studies by Yang and Zhang (2011), who demonstrated that road networks can significantly alter subsurface moisture regimes, particularly in rural catchments. In Ohafia, this is evident along corridors like VES 1 to VES 4, where road construction may impede recharge processes despite the presence of nearby vegetation or streams.

Another notable dimension of this discussion is the spatial variation in transmissivity, which determines the ability of an aquifer to transmit water horizontally. Transmissivity is a function of both hydraulic conductivity and aquifer thickness, and is directly related to the volume of water that can be extracted for human use. High transmissivity values, such as those observed at VES 6 (Achị), VES 2 (Abiriba), and VES 1 (Elu), suggest that these locations hold promise for sustainable groundwater development.

However, transmissivity alone does not determine water quality or vulnerability. The case of VES 5 (Abiriba) is particularly illustrative. Despite its high transverse resistance, the aquifer exhibits low longitudinal conductance and transmissivity, indicating a thick but poorly conductive layer with limited recharge potential and poor protective capacity. Such findings highlight the necessity of integrating multiple geophysical and environmental indicators to make informed water resource management decisions, as emphasized by Falebita et al. (2020), in multi-parameter aquifer evaluations.

Moreover, the integration of land cover data, topography, and resistivity-based aquifer assessments in this study supports the growing trend toward multi-layered spatial analysis in groundwater research. As GIS and remote sensing tools become more accessible, future studies can expand upon this approach to include additional variables such as soil type, groundwater quality, and seasonal variability. Such comprehensive assessments are essential for building resilient water supply systems in the face of climate change and increasing urbanization, as suggested by Adebayo et al. (2020).

4.6 Methodological limitations and uncertainty

Although the integrated geophysical and geospatial approach adopted in this study provides valuable insights into aquifer characterization, certain methodological limitations should be acknowledged. VES technique assumes a one-dimensional layered earth model and therefore has limited vertical resolution, particularly where thin layers or sharp lithological transitions occur. Consequently, some subsurface heterogeneities may not be fully resolved in the inversion results.

In addition, cultural noise arising from nearby roads, settlements, and buried infrastructure may influence resistivity measurements at some locations, potentially introducing minor uncertainties in interpreted layer parameters. However, care was taken during data acquisition to minimize such effects by selecting suitable electrode positions and validating inversion fits through RMS error reduction.

LULC classification was derived from Landsat imagery with a spatial resolution of 30 m. While appropriate for regional-scale analysis, this resolution may not capture small-scale land cover variations, which could introduce uncertainty in localized recharge interpretations. Despite these limitations, the integration of multiple datasets (VES, drainage density, DEM, and LULC) reduces reliance on any single dataset and improves the robustness of groundwater potential assessment. Future studies may benefit from higher-resolution geophysical surveys and finer-scale remote sensing data to further refine aquifer characterization.

5. Conclusion

This study employed integrated hydrogeophysical and spatial analysis techniques to investigate the groundwater potential and aquifer protective capacity across Ohafia Local Government Area in Southeastern Nigeria. Using VES, supported by LULC classification, drainage density mapping, and topographic analysis, a comprehensive understanding of aquifer behavior under both natural and anthropogenic influences was achieved. The results demonstrated significant spatial variability in aquifer properties such as resistivity, thickness, depth, longitudinal conductance, and transmissivity. These variations were closely linked to the underlying geology, surface features, and human-induced changes. Low resistivity and high conductance zones, typically associated with clayey and saturated formations, were identified in southern and central Ohafia, indicating favorable conditions for aquifer protection and recharge. In contrast, areas with high resistivity and low conductance, such as around VES 5 near Abiriba, suggested dry, coarse, and poorly protected aquifer conditions with limited recharge potential. Topographic patterns also influenced groundwater dynamics. Elevation differences shaped the drainage patterns and recharge zones, with low-lying areas and valleys (e.g. VES 3 and 4) benefiting from runoff convergence and infiltration, thus supporting aquifer replenishment. Conversely, steeply sloping areas experienced higher runoff and reduced infiltration. These observations were reinforced by drainage density analysis, which showed that regions with low drainage density correlated with higher infiltration potential and more productive aquifer conditions. LULC analysis further highlighted the role of surface cover in influencing groundwater behavior. Tree-covered and rangeland areas supported higher infiltration rates, contributing to improved recharge and aquifer performance. Conversely, built-up and impervious surfaces in urban centers like Elu and Abiriba limited natural recharge, particularly where subsurface conditions were already unfavorable. Nevertheless, in a few built-up areas such as VES 1, high transmissivity and conductance were observed, suggesting that favorable subsurface lithology can, to some extent, mitigate surface limitations. Overall, the study concludes that sustainable groundwater development in Ohafia requires a location-specific approach that integrates subsurface geoelectrical data with surface land characteristics and hydrological conditions. Areas with a combination of high longitudinal conductance, moderate transmissivity, vegetative cover, and low drainage density should be prioritized for water resource development. Meanwhile, regions with low protection and recharge potential should undergo further hydrogeological investigation and may require artificial recharge or protective well construction strategies. This study underscores the value of integrated spatial and geophysical methods in guiding effective groundwater planning and management.

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CRediT authorship contribution statement

Charity Nkiru Nwokeabia: Conceptualization, Methodology, Formal analysis, Writing – original draft, Visualization. Okechukwu Ebuka Agbasi: Data curation, Investigation, Software, Writing – review & editing, Supervision, Corresponding author. Ojo Odunayo Tope: Validation, Resources, Writing – review & editing, Project administration.

Data availability

The Vertical Electrical Sounding (VES) data and derived Dar-Zarrouk parameters used in this study are available from the corresponding author upon reasonable request. GIS and remote sensing datasets, including the Digital Elevation Model (DEM), drainage density, and 2024 land use/land cover (LULC) data, were obtained from publicly available sources and can be accessed online through relevant open data repositories.

Declaration of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. No generative AI tools were used in the writing or preparation of this manuscript.

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