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Okonkwo, John E. and Emmanuel, Efemena D. (2026) "Appraisal of aquifer protective capacity and groundwater potential using the vertical electrical sounding technique in Illah, Delta State, Nigeria," *Al-Bahir*. Vol. 8: Iss. 1, Article 9. Available at: <https://doi.org/10.55810/2313-0083.1118>

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ORIGINAL STUDY

Appraisal of Aquifer Protective Capacity and Groundwater Potential Using the Vertical Electrical Sounding Technique in Illah, Delta State, Nigeria

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Abstract

Groundwater is a critical resource in Illah, Delta State, where surface water is unreliable. This study aims to evaluate groundwater potential and aquifer properties using geoelectric methods, with a particular focus on Dar-Zarrouk parameters. Thirteen Vertical Electrical Sounding (VES) surveys were conducted using the Schlumberger array. Derived parameters, including resistivity, thickness, and Dar-Zarrouk indices, were analysed to characterise the aquifers' hydraulic properties. Four to five geoelectric layers underlie the study area. Aquifer resistivity ranged from 124 to 2499 $\Omega\cdot\text{m}$, thickness from 3.4 to 57.9 m, and transmissivity from 27.54 to 468.99 m^2/day . VES 4, VES 1, and VES 7 were identified as high-potential sites. Longitudinal conductance values (0.0038–0.2949 Ω^{-1}) indicated that most aquifers had poor to moderate protective capacity. High transmissivity zones with moderate overburden protection, such as VES 4 and VES 1, are ideal for borehole development. VES 2 and VES 9 had low transmissivity, suggesting low productivity. Spatial variations reveal Illah's complex hydrogeological structure influenced by the Imo Formation. Geoelectrical sounding and Dar-Zarrouk analysis offer a cost-effective approach for aquifer evaluation in Illah, facilitating data-driven groundwater resource planning. The integration of resistivity and Dar-Zarrouk parameters provides a robust geophysical framework for aquifer zoning in data-scarce rural settings.

Keywords: Aquifer transmissivity, Dar-Zarrouk parameters, Illah, Longitudinal conductance, Groundwater mapping

1. Introduction

Groundwater represents a crucial component of the Earth's freshwater resources and plays a vital role in sustaining human livelihoods, economic activities, and ecosystems [1,2]. In many developing countries, including Nigeria, it serves as the primary source of potable water for domestic, agricultural, and industrial use, especially in rural areas where surface water is scarce, seasonal, or polluted [3,4]. The increasing demand for groundwater, coupled with environmental degradation and population growth, has necessitated the need for sustainable exploration, development, and management of aquifer systems [5,6].

The assessment of groundwater resources involves not only identifying the location of aquifers but also evaluating their hydraulic characteristics, such as porosity, permeability, transmissivity, and protective capacity. These parameters are essential for determining the availability, productivity, and long-term viability of groundwater reservoirs [7,8]. Conventionally, such assessments are performed through borehole drilling and pumping tests. While these methods provide direct and reliable data, they are capital-intensive, time-consuming, and limited in spatial coverage. Consequently, geophysical methods, especially the electrical resistivity method, have become cost-effective and non-invasive alternatives, enabling rapid

Received 15 July 2025; revised 13 September 2025; accepted 15 September 2025.
Available online 19 January 2026

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<https://doi.org/10.55810/2313-0083.1118>

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subsurface characterisation across large areas [9,10]. Among the geophysical techniques available, the Vertical Electrical Sounding (VES) method under the electrical resistivity technique has gained prominence due to its sensitivity to subsurface lithological and hydrogeological variations [11]. This method involves injecting an electrical current into the ground and measuring potential differences at varying electrode spacings to estimate the apparent resistivity of the underlying formations [12]. The electrical resistivity of earth materials varies depending on their composition, porosity, degree of water saturation, and the nature of the pore fluids [13,14]. Consequently, resistivity soundings can be interpreted to reveal the presence and characteristics of aquiferous zones.

Aquifers, particularly those made up of unconsolidated sands, sandstones, or fractured rock formations, typically exhibit distinct resistivity ranges depending on their degree of saturation and clay content [11,15]. By analysing these resistivity patterns, geophysicists can stratify the subsurface, delineate aquifer boundaries, and infer key hydraulic properties [16,17]. However, the resistivity data alone may not fully represent the aquifer transmissivity or protective capacity. To address this limitation, researchers use Dar-Zarrouk parameters, which are derived from the resistivity and thickness of geoelectric layers [18]. These parameters not only help in characterising the aquifer system but also reduce the ambiguity associated with the non-uniqueness of resistivity data interpretation. They provide additional insights into aquifer productivity and vulnerability, particularly in regions where borehole data are limited or unavailable [19]. The calculated Dar-Zarrouk parameters were then used to evaluate aquifer transmissivity and protective capacity. Areas with high transverse resistance were interpreted as having better groundwater potential, while those with high longitudinal conductance were considered to be better protected against surface contaminants [9]. This approach enhances the understanding of subsurface hydrogeological conditions and provides a reliable basis for borehole siting and water resource planning.

Hydraulic properties such as porosity and permeability, which determine an aquifer's ability to store and transmit water, are primarily dependent on the texture, grain size distribution, compaction, and cementation of the host material. For example, poorly cemented or unconsolidated sand formations typically exhibit high primary porosity and permeability, making them ideal

aquifers [20]. Conversely, lithified or well-cemented formations may have low primary porosity but could still function as aquifers if secondary porosity exists due to fracturing, jointing, or weathering. Climatic conditions also influence the hydrogeological behaviour of a region. Recharge to aquifers depends on rainfall, evapotranspiration rates, vegetation cover, and topography. In regions with distinct wet and dry seasons, aquifer recharge can be seasonal and varies widely in both time and space [21]. Therefore, understanding the interplay between geology, geomorphology, and climate is essential in assessing the sustainability of groundwater resources.

This study aims to assess groundwater potential and estimate aquifer hydraulic characteristics using surface resistivity methods, particularly Dar-Zarrouk parameters. It provides a geophysical framework for practical groundwater evaluation in data-scarce areas, supporting informed decision-making for sustainable water resource management in rural and semi-urban communities.

2. Location and geology of the study area

Illah (sometimes referred to as Allah) is a semi-urban town located along the western bank of the River Niger in Delta State, southern Nigeria. Geographically, Illah lies at approximately 6.424°N latitude and 6.757°E longitude, occupying a moderately elevated terrain situated about 25 km north of the state capital, Asaba. The town is situated in the Oshimili North Local Government Area, as illustrated in Fig. 1. The Anioma people, an Igbo-speaking ethnic group native to the western bank of the River Niger, predominantly inhabit it.

Administratively, Illah is composed of nine villages: Ogbe-Olu, Ogbe-Orji, Onya, Ukpologwu, Umutedem, Ajaji, Umutei, and Umuagwu. The community has a rich cultural heritage and a long-standing history of subsistence farming and artisanal fishing. Agricultural products such as yams, rice, cassava, and fish are traded both locally and with neighbouring communities, particularly those across the river to the east. The town falls within the tropical savanna climatic zone, marked by two distinct seasons, wet and dry. Illah shares boundaries with Ebu to the north, Ugbolu and Asaba to the south, Akwukwu-Igbo to the west, and the River Niger to the east. The terrain is relatively flat, with ground elevations ranging from 8.4 to 16.9 m above sea level, and GPS-derived vertical accuracy ranging from 9.7 to 11.6 m. The area benefits from an accessible road network, facilitating movement between settlements, and features a combination of

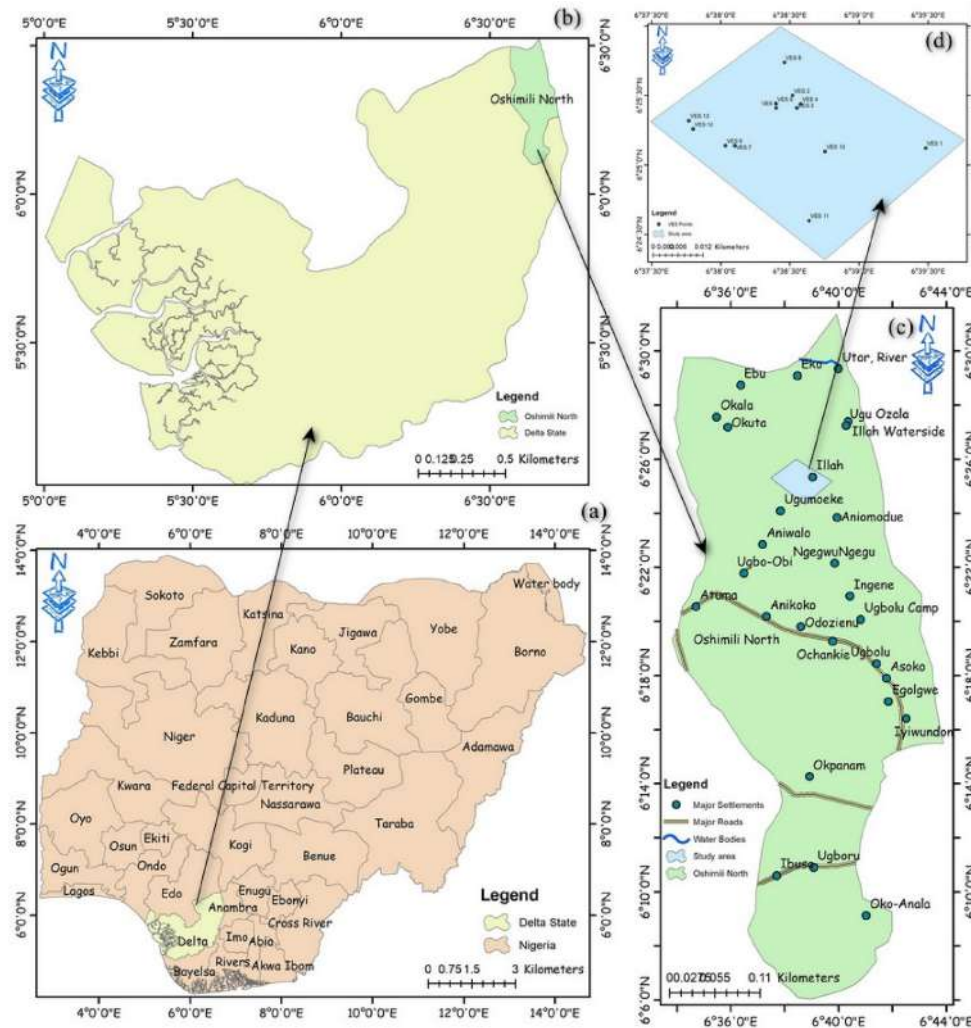


Fig. 1. Location map showing (a) Nigeria with Delta State highlighted, (b) Delta State with Oshimili North marked, (c) major settlements and road networks within Oshimili North LGA, and (d) layout of VES stations within the Illah survey area.

residential development, agricultural fields, and undeveloped plots.

Geologically, Illah is situated within the Niger Delta Basin, a large sedimentary basin characterised by complex depositional environments influenced by alternating marine and deltaic processes. The stratigraphy of the Niger Delta is classically subdivided into three central lithostratigraphic units that represent a prograding delta sequence from the Eocene to the present: the Benin Formation, the Agbada Formation, and the Akata Formation. The Benin Formation forms the uppermost unit and is made up of predominantly coarse-grained sands and gravels. It is highly porous and permeable, making it the most important aquifer in the region for potable groundwater supply [22]. Beneath it lies the Agbada Formation, consisting of interbedded sandstones and shales that serve as

both reservoir and seal units, depending on local lithological variations. At the base of the deltaic sequence is the Akata Formation, composed mainly of marine shale, silts, and occasional turbiditic sands [23]. It is interpreted as a deep marine unit and forms the source rock in much of the Niger Delta Basin.

In the Illah area specifically, the subsurface geology is dominated by the Imo Formation, a lateral onshore equivalent of the Akata Formation, consisting primarily of thick layers of shale and mudstone interbedded with isolated sandstone lenses [24]. These sandstone intercalations, such as the Ebenebe Sandstone and Amenyi Sands, have been identified as aquiferous zones that yield good-quality water. However, due to their discontinuous nature and depth, these sands are not intercepted uniformly across the region. They often occur as

deep-seated layers beneath relatively impermeable shales, making their identification and exploitation highly dependent on detailed geophysical surveys.

Where present, these aquiferous sandstone or shaly sand layers offer viable targets for borehole development. However, their limited lateral extent and depth require site-specific geophysical characterisation to guide successful drilling. Properly constructed boreholes in these formations can serve both domestic and small-scale commercial water supply needs, especially in communities where surface water is seasonal or contaminated. The location and spatial configuration of Illah within Oshimili North Local Government Area, as well as its relative position within Delta State and Nigeria at large, are depicted in Fig. 1. The figure also includes the distribution of VES stations used in the study, highlighting the area's topographic and hydrogeological layout, along with surrounding settlements, access roads, and the River Niger.

3. Methodology

3.1. Data acquisition

The geophysical investigation was conducted using the VES technique. Measurements were taken with the ABEM Terrameter SAS 1000 (Signal Averaging System), employing the Schlumberger array configuration. The survey emphasised achieving maximum lateral electrode separation, with a total spread length (L) of 800 m. From the central point, an initial extension of 400 m (L/2) was made to the right, followed by a corresponding 400-m extension to the left, thereby maintaining symmetry around the VES station [25]. A total of thirteen (13) VES stations were established across the study area in a grid-based pattern. However, due to topographical constraints such as valleys, gullies, and built-up areas, some VES points had to be offset from the grid to accommodate physical obstacles [26]. All geoelectrical measurements were conducted under favourable weather conditions to ensure data quality and instrument safety.

The depth of current penetration, also referred to as the depth of investigation, is directly proportional to the electrode spacing (A and B). The configuration and geometry of the four electrodes (two current and two potential) determine the vertical and lateral resolution of the subsurface. In the Schlumberger array, the apparent resistivity (ρ_a) at a given point, measured as electrode spacing is systematically increased, can be mathematically expressed as [27,28]:

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

Let us define two key variables, a and b, based on the electrode configurations used during the resistivity survey. The variable a represents half the distance between the current electrodes (AB/2), which is essential for calculating the geometric factor in the Schlumberger array. The variable b corresponds to half the spacing between the potential electrodes (MN/2) [29,15]. The measured resistance (R) is determined using Ohm's Law, expressed as the ratio of the potential difference (V) to the applied current (I):

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

Equation (2) can be written as

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

Geometric factor,

$$K = \pi \frac{a^2}{b} - \frac{b}{4} \quad 4$$

The geometric factor (K) is a function of the spatial arrangement of the electrodes in the ground. Its value varies depending on the specific electrode configuration used during the resistivity survey and must be calculated accordingly for each array type.

3.2. Data processing

VES data were processed using IP2Win software, which facilitated the input of apparent resistivity values alongside their corresponding AB/2 electrode spacings for subsequent modelling. The software employed an iterative inversion process, involving between 1 and 29 iterations, to reduce misfit errors and enhance the curve-fitting accuracy between observed and calculated data [30]. Through this inversion procedure, the software generated estimates of actual resistivity values, as well as the thicknesses and depths of subsurface layers [31]. These outputs formed the basis for calculating Dar-Zarrouk parameters, essential for aquifer characterisation.

3.3. Dar Zarrouk parameters

Dar-Zarrouk parameters are crucial in evaluating key aquifer characteristics, such as transmissivity and the protective capacity of overlying geological layers [9]. These parameters are computed using the following relationships:

$$H = \sum_{i=1}^n h_i \tag{5}$$

Longitudinal Conductance (S)

$$S = \frac{h_1}{\rho_1} + \frac{h_2}{\rho_2} + \frac{h_3}{\rho_3} + \dots + \frac{h_n}{\rho_n} \tag{6}$$

Transverse Resistance (T)

$$T = \rho_1 h_1 + \rho_2 h_2 + \rho_3 h_3 + \dots + \rho_n h_n \tag{7}$$

Longitudinal Resistivity

where ρ_n and h_n Represent the thickness and resistance of a layer, respectively.

The aquifer transmissivity (T_r) is calculated as the product of the hydraulic conductivity (k) and the thickness of the aquifer layer (h):

$$T_r = kh \tag{8}$$

4. Results and discussion

4.1. Interpretation of VES data and subsurface lithology

This section presents the interpretation of the VES data acquired across the study area to evaluate subsurface lithology and groundwater potential. The apparent resistivity values obtained were modelled and inverted to generate geoelectrical parameters (as shown in Table 1), which were then used to infer the nature and depth of underlying formations. Emphasis was placed on identifying aquiferous zones and assessing their suitability for groundwater development [32].

Fig. 2 presents the modelled resistivity sounding curves for VES stations 1 through 4. The close alignment between the observed field data (black lines) and the modelled curves (red lines) reflects a strong goodness-of-fit, indicating a high level of

confidence in the reliability of the interpreted subsurface parameters.

Interpretation of the results revealed that the study area comprises between four and five geoelectric layers across most of the VES stations. These layers were identified and correlated with specific lithological units based on their resistivity values and thicknesses [9]. The uppermost layers, characterised by relatively low resistivity values ranging from approximately 49.4 Ωm to 404 Ωm , were typically identified as topsoil or lateritic soils. Underlying these, intermediate layers with resistivity values ranging from 124 Ωm to 9147 Ωm were generally associated with compacted silt, clayey sand, or fine-grained sediments, depending on the specific location.

The deeper layers across many VES locations displayed significantly higher resistivity values, ranging from 553 Ωm to 9343 Ωm , which were consistently interpreted as medium-to coarse-grained sand units. These layers are considered indicative of good aquifer zones, particularly in VES 1, VES 3, VES 5, and VES 13, where the thickness and lateral continuity of the sand units suggest high groundwater potential.

Fig. 3 depicts the geoelectric cross-sections generated from the inversion of VES data. These profiles provide a lithostratigraphic interpretation of each sounding location, revealing vertical and lateral distributions of subsurface materials [18]. In many cases, aquiferous sand layers appear at depths between 40 and 70 m, typically underlain or overlain by lower-resistivity materials such as silt or clay, which may act as protective confining layers, reducing vulnerability to surface contamination.

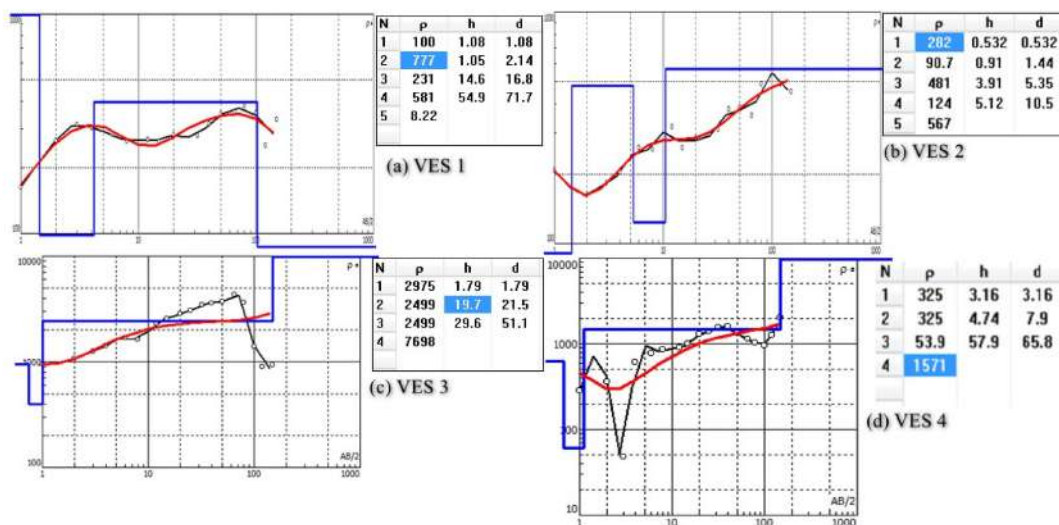


Fig. 2. Modelled resistivity sounding curves for selected VES stations (VES 1 VES 4), showing field data (black) and computed model (red).

Table 1. Aquifer geoelectric parameters of Illah.

VES No.	Aquifer Resistivity ($\Omega \cdot m$)	Aquifer Thickness (m)	Aquifer Conductivity (S/m)
VES 1	581.00	54.90	0.00172
VES 2	124.00	5.12	0.00806
VES 3	2499.00	29.60	0.00040
VES 4	539.00	57.90	0.00186
VES 5	1054.00	36.10	0.00095
VES 6	215.00	49.10	0.00465
VES 7	195.00	57.50	0.00513
VES 8	827.00	14.40	0.00121
VES 9	894.00	3.40	0.00112
VES 10	886.00	11.10	0.00113
VES 11	355.00	41.10	0.00282
VES 12	132.00	36.60	0.00758
VES 13	313.00	11.00	0.00319

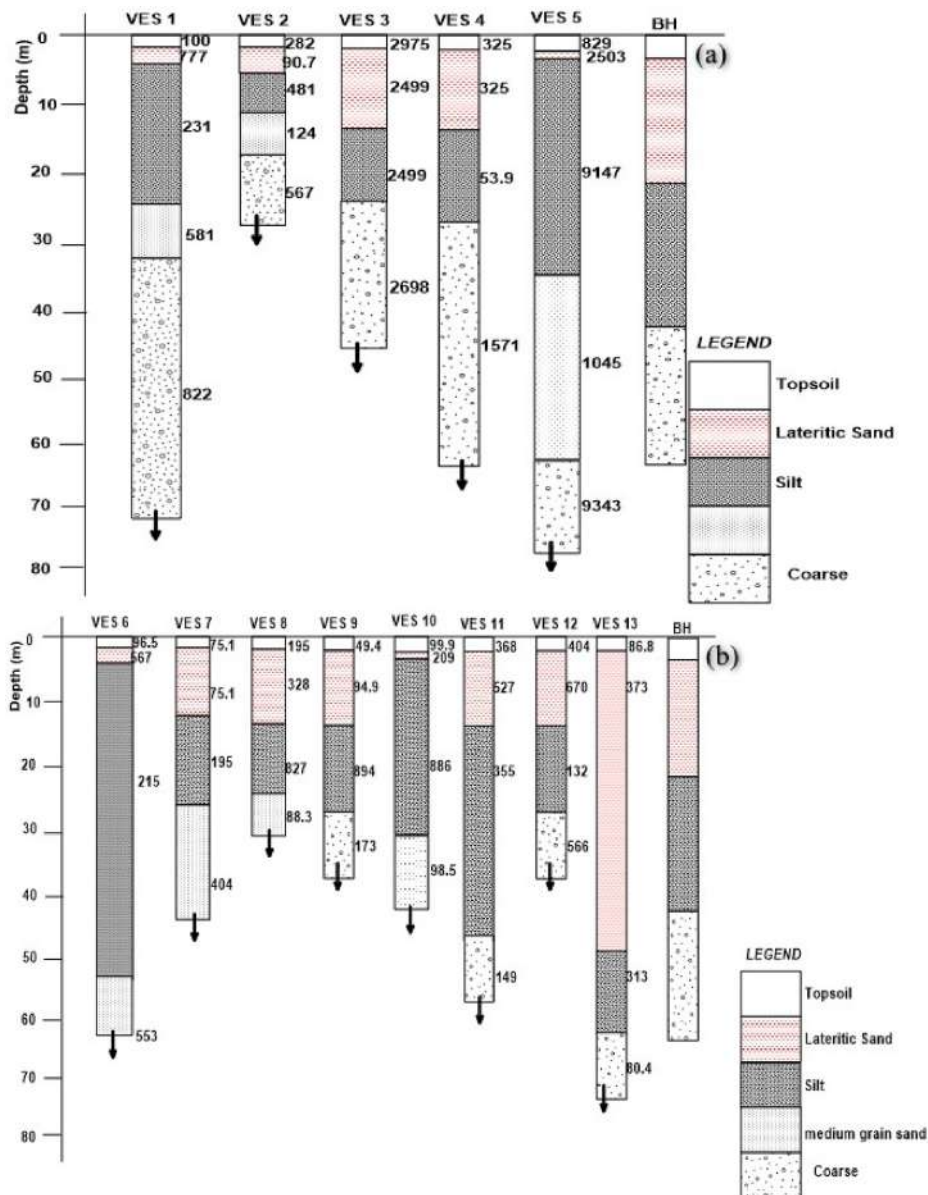


Fig. 3. Geoelectric cross-sections of the study area showing interpreted subsurface lithologies and aquiferous zones across all 13 VES locations.

In VES 1, a five-layer model was delineated, with a thick basal unit of 822 Ωm , interpreted as coarse sand, located at a depth of approximately 72 m. In VES 3, actual resistivity values exceeding 2400 Ωm were recorded in the deeper layers, also indicating a well-consolidated medium-to coarse-grained sand. Similarly, VES 5 and VES 13 revealed very high resistivity values, exceeding 9000 Ωm , and thick saturated zones, suggesting that these locations are favourable for high-yield borehole development.

In contrast, VES 2 and VES 4 exhibited lower resistivity values in their deeper layers, 124 567 Ωm and 1571 Ωm , respectively, which are likely associated with moderately saturated sands or sandy clay. These may still yield water but are expected to have lower productivity compared to the more resistive sand zones identified elsewhere [33]. Furthermore, VES 7 and VES 9 showed a predominance of low to moderate resistivity values, indicative of lateritic or clay-rich materials, which are generally considered to have poor groundwater potential due to their low permeability.

Across most stations, the vertical lithological progression followed a consistent sequence: topsoil lateritic soil compacted silt or clayey sand medium/coarse-grained sand. This stratigraphy is typical of sedimentary environments such as the Niger Delta Basin, where cyclic deposition results in alternating permeable and impermeable layers [8,34].

The identification of medium to coarse-grained sands at depth, along with their high resistivity signatures, supports the presence of confined aquifers in several parts of the study area. These aquifers are significant in rural and peri-urban settings where reliable groundwater sources are essential and surface water may be scarce, seasonal, or contaminated [35]. However, the heterogeneity of the Imo Formation, which underlies the area, means that these aquifer units may not be continuous throughout the study area. Therefore, localised geophysical assessment remains critical to reduce the risk of unsuccessful borehole drilling [9,36].

The observed curve types, such as KHA, HKH, AKH, KH, and QH, also provide diagnostic insights into the resistivity structure with depth. Curve types like KH and HKH, which were common across several VES locations, typically indicate a resistive-conductive-resistive layering pattern. This configuration aligns well with the interpretation of aquiferous sand layers under clayey overburden, a favourable structure for confined groundwater systems.

4.2. Spatial distribution and hydrogeological implications of aquifer parameters

The spatial variation in aquifer resistivity, thickness, and conductivity provides critical insights into the subsurface hydrogeology of Illah and its suitability for groundwater development. This section discusses the results of these parameters, derived from thirteen VES stations, and interprets their implications for aquifer properties and groundwater potential.

4.2.1. Aquifer resistivity distribution

The spatial distribution of aquifer resistivity, illustrated in Fig. 4, reveals substantial heterogeneity across the study area. Resistivity values range from 124 $\Omega\cdot\text{m}$ to 2499 $\Omega\cdot\text{m}$, indicating variability in lithological composition and degrees of water saturation. The highest resistivity values, observed at VES 3 (2499 $\Omega\cdot\text{m}$) and VES 5 (1054 $\Omega\cdot\text{m}$), suggest the presence of dry or well-consolidated coarse sands and gravels, which are characteristic of productive aquifers with low clay content and high permeability. Conversely, VES 2 (124 $\Omega\cdot\text{m}$) and VES 12 (132 $\Omega\cdot\text{m}$) exhibit the lowest resistivity values, indicating clay-rich or highly saturated formations. Such formations typically have a high ion content and a lower groundwater yield potential. VES 1, VES 4, and VES 6 show moderate resistivity values between 200 and 600 $\Omega\cdot\text{m}$, suggesting either moderately saturated sand units or sandy clay mixtures [37].

Spatially, resistivity tends to increase toward the central and northeastern portions of the study area (around VES 3; VES 5, and VES 1), while decreasing toward the western and southeastern regions (e.g., VES 2; VES 12). This pattern reflects lithologic transitions and varying degrees of aquifer saturation.

4.2.2. Aquifer thickness variation

Aquifer thickness varies considerably across the study area, as shown in Fig. 5, ranging from 3.4 m at VES 9 57.9 m at VES 4. The thickest aquifers are concentrated in the central zone (VES 3; VES 4; VES 7), where medium-to coarse-grained sands were identified in the geoelectric models. These areas are most likely to yield substantial groundwater volumes, especially in confined aquifer conditions [38]. Moderate aquifer thicknesses, ranging from 25 to 46 m, are found around VES 6, VES 11, and VES 5, indicating substantial saturated zones capable of supporting domestic and small-scale agricultural supplies. Thinner aquifers (<15 m), such as those at VES 2; VES 9, and VES 10,

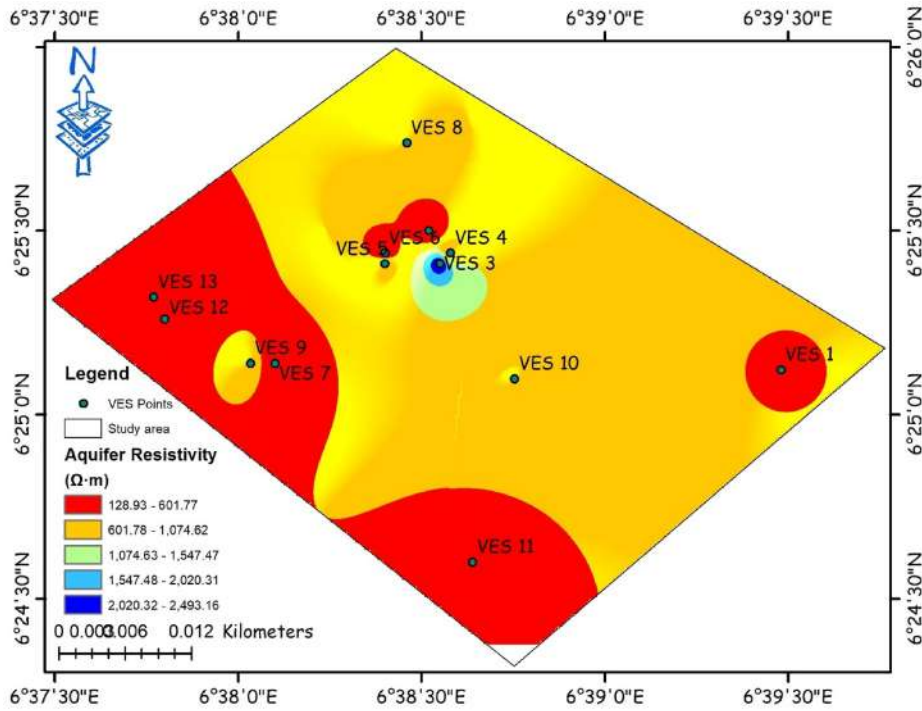


Fig. 4. Spatial distribution of aquifer resistivity in Illah.

are likely to be limited in yield and more susceptible to seasonal variations and contamination from surface sources [37,39].

From a spatial standpoint, aquifer thickness is most significant in the central-eastern part of the

study area, decreasing toward the northwest and southeastern margins. This trend may be influenced by subsurface structural variations or paleo-channel formations that concentrate fluvial sand deposits in certain zones [19].

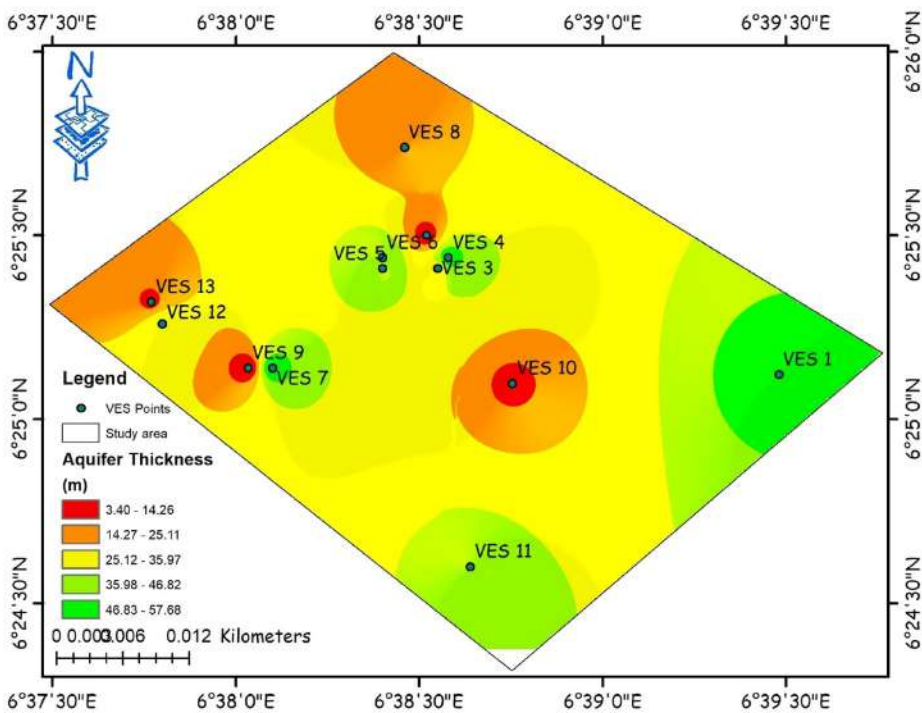


Fig. 5. Spatial distribution of aquifer thickness in Illah.

4.2.3. Aquifer conductivity and water quality implications

Aquifer conductivity is inversely related to resistivity and is strongly influenced by porosity, permeability, and the ionic concentration of groundwater. As shown in Fig. 6, conductivity values in the study area range from 0.00040 S/m at VES 3 to 0.00806 S/m at VES 2. High conductivity at VES 2, VES 12, and VES 7 suggests elevated levels of dissolved solids, likely from clayey sediments or water rock interaction, and may reflect lower water quality in these zones. The low conductivity at VES 3, VES 5, and VES 1 indicates the presence of clean, coarse-grained sand formations with low salinity and improved water quality [40]. These areas also correspond with high resistivity zones, reinforcing their interpretation as favourable aquifer targets.

The northwestern and southwestern zones exhibit relatively high conductivity values, while the central and eastern zones display lower values. This spatial pattern is consistent with resistivity trends. It confirms the suitability of the central-eastern zone (around VES 3; VES 4; and VES 5) for future groundwater exploitation, both in terms of yield and quality.

When aquifer resistivity, thickness, and conductivity are considered jointly, certain zones emerge as particularly favourable for groundwater development. VES 3 and VES 4 stand out due to their

thick aquifers, high resistivity, and low conductivity, traits associated with clean, well-sorted sands and high groundwater yield potential. VES 5 also performs well across all parameters, making it another priority area for future borehole drilling. In contrast, VES 2, VES 12, and VES 9 exhibit thin aquifers, low resistivity, and high conductivity, indicating the presence of clayey or silty layers with limited water-bearing capacity. These zones may require further geophysical or hydrochemical assessment before any groundwater development, especially to evaluate the risk of contamination or seasonal drying [41].

From a planning perspective, areas around VES 3, VES 4, and VES 5, located in the central part of Illah, are ideal for siting community boreholes, small-scale irrigation, and other groundwater-dependent infrastructure. Their spatial clustering enhances the feasibility of integrated water supply systems. On the other hand, zones such as VES 2 and VES 12 should be approached cautiously or considered only after detailed, site-specific investigations.

This spatial analysis reveals that aquifer properties in Illah vary significantly across short distances, highlighting the importance of site-specific geophysical investigations. The combination of thick, resistive, and low-conductivity aquifers in the central portion of the study area confirms the

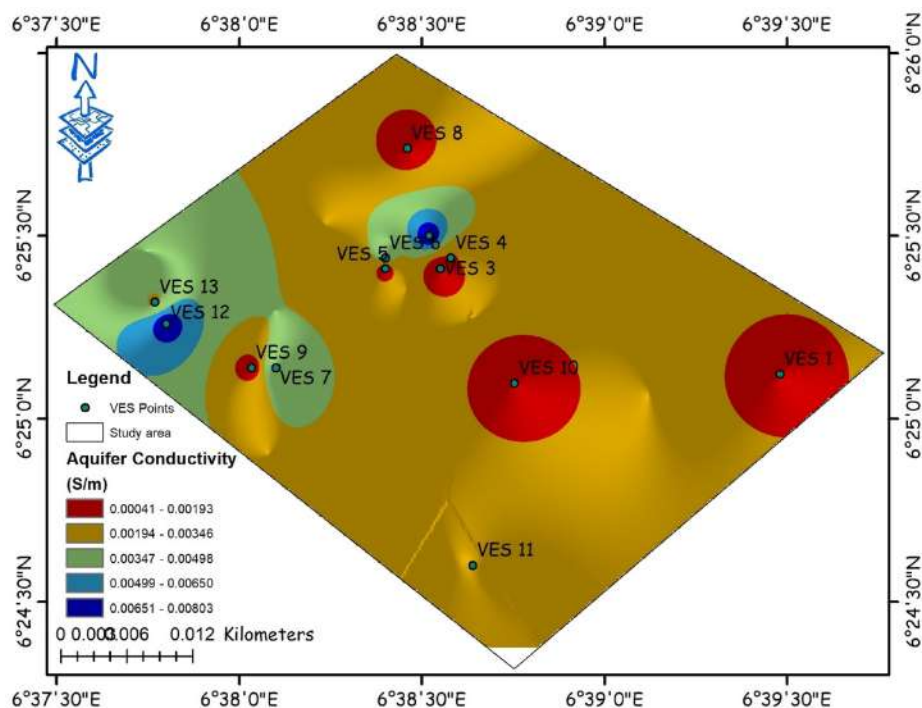


Fig. 6. Spatial distribution of aquifer conductivity (S/m) in Illah.

existence of promising groundwater zones [14]. Meanwhile, lower-quality zones in the peripheries reflect the heterogeneous nature of the underlying Imo Formation.

4.3. Spatial distribution and implications of Dar-Zarrouk parameters

The evaluation of aquifer protective capacity and groundwater transmission efficiency requires more than resistivity and thickness analyses alone. To gain deeper insights into the hydraulic behaviour of subsurface formations, this study computed Dar-Zarrouk parameters, namely Longitudinal Conductance, Transverse Resistance, Transmissivity, and a derived Diagnostic Parameter, from resistivity sounding data [42]. These parameters help to characterise the quality, protective capacity, and productivity of the aquifers beneath Illah.

4.3.1. Longitudinal conductance and aquifer protective capacity

Longitudinal conductance (S), calculated as the ratio of layer thickness to resistivity, serves as an indicator of the protective capacity of overburden layers against surface contaminants. Higher values suggest better shielding due to the presence of conductive materials such as clay or silty clay, which hinder pollutant migration [43]. As shown in

Fig. 7, longitudinal conductance in the study area ranges from $0.0038 \Omega^{-1}$ (VES 9) to $0.2949 \Omega^{-1}$ (VES 7). The highest values occur in the central-western and southern parts, particularly around VES 6, VES 7, and VES 12, indicating regions with moderate to good aquifer protection due to thicker or more conductive overburden. In contrast, VES 3, VES 10, and VES 9 exhibit very low conductance ($<0.02 \Omega^{-1}$), indicating poor protective capacity and increased vulnerability to contamination, particularly in areas with intensive land use.

Moderate values around VES 1 and VES 4 (0.0945 and $0.1074 \Omega^{-1}$, respectively) suggest moderate protection and could be viable for groundwater extraction with adequate sanitary controls.

4.3.2. Transverse resistance and aquifer transmissivity potential

Transverse resistance (R), computed as the product of aquifer thickness and resistivity, provides a measure of the aquifer's capacity to transmit groundwater. It also reflects the competence and mechanical strength of the formation [17]. In Fig. 8, transverse resistance varies from $634.88 \Omega \cdot m^2$ (VES 2) to a peak value of $73,970.40 \Omega \cdot m^2$ (VES 3). Notably, the eastern and central regions, especially around VES 3, VES 4, and VES 5, show high transverse resistance ($>30,000 \Omega \cdot m^2$), indicating thick and resistive aquifer units that are structurally stable and potentially productive.

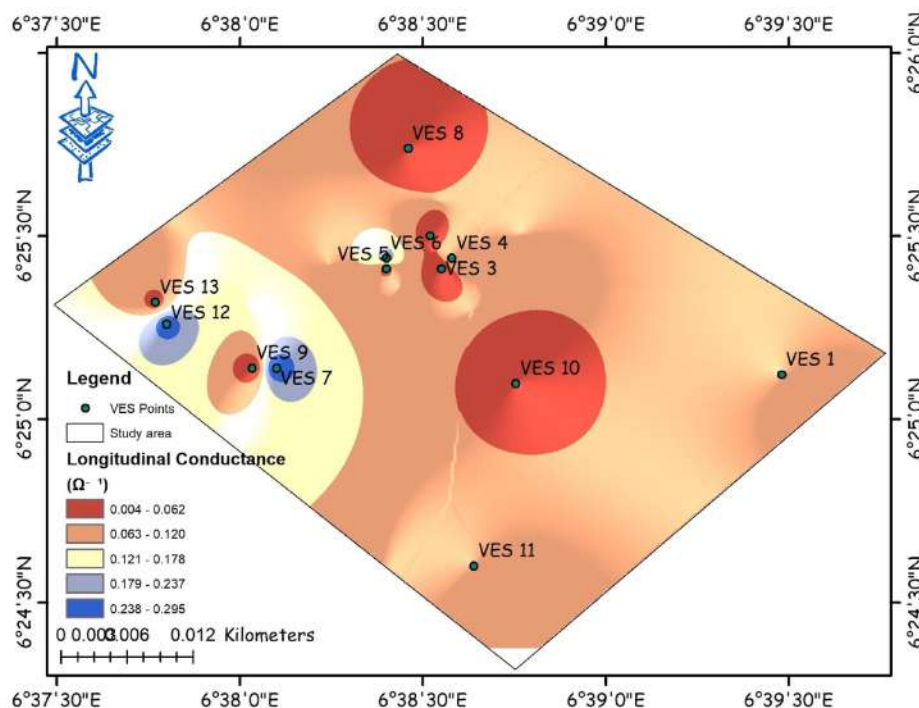


Fig. 7. Spatial distribution of longitudinal conductance across the study area.

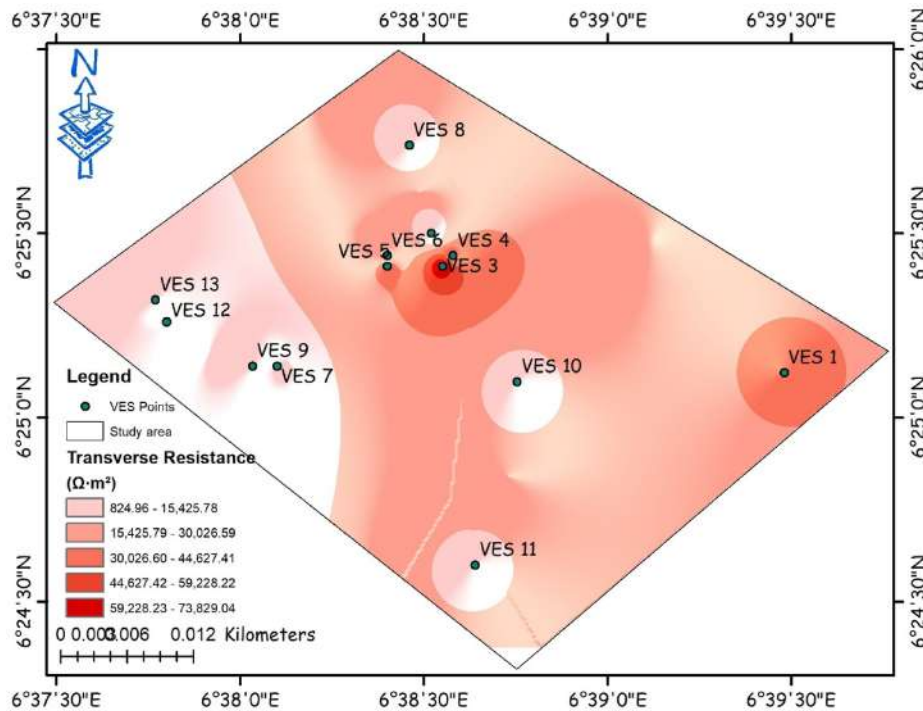


Fig. 8. Spatial distribution of transverse resistance indicating aquifer competence.

Low values in VES 2, VES 9, and VES 13 suggest less competent or thinner aquiferous formations, possibly mixed with fine sediments or clays, resulting in reduced transmissive potential. These zones may be less suitable for high-capacity boreholes and require additional hydrochemical verification before development [44].

4.3.3. Transmissivity and groundwater productivity

Transmissivity (T), the product of aquifer thickness and hydraulic conductivity, is a critical parameter that directly quantifies the amount of water an aquifer can yield to wells. It integrates both the physical dimensions and hydraulic properties of the aquifer material [45]. According to Fig. 9, transmissivity across Illah ranges from a minimum of 27.54 m²/day (VES 9) to a maximum of 468.99 m²/day (VES 4). High transmissivity zones, particularly around VES 1, VES 4, VES 6, and VES 7, demonstrate the most promising locations for groundwater exploitation. These locations combine moderate-to-high thickness and resistivity, characteristics typically associated with clean, saturated sands and gravels.

In contrast, VES 2 and VES 9, despite having modest resistivity, show extremely low transmissivity values due to the small thickness of the aquifer layers [9]. These locations are not recommended for high-yield boreholes without further validation through test pumping.

It is worth noting that while VES 3 has the highest transverse resistance, its transmissivity is relatively lower (239.76 m²/day) due to likely lower hydraulic conductivity compared to other high-T zones, such as VES 4 or VES 7. This highlights the value of using multiple Dar-Zarrouk parameters in tandem.

4.3.4. Diagnostic parameter and integrated suitability assessment

To assist in integrated aquifer assessment, a diagnostic parameter was developed as a composite index that combines transmissivity, resistivity, and longitudinal conductance characteristics. This dimensionless parameter helps in classifying zones based on relative suitability for groundwater development [46]. As depicted in Fig. 10, diagnostic parameter values range from 0.0032 (VES 3) to 0.0653 (VES 2). While high values often reflect good conductance (i.e., aquifer protection), they can also occur in less productive zones where transmissivity is low. For instance, VES 2 and VES 12 show high diagnostic values due to high longitudinal conductance, yet have modest transmissivity, suggesting protection but limited yield.

In contrast, areas such as VES 4 and VES 1, which have both moderate diagnostic values and high transmissivity, are the most suitable for borehole development. These sites offer a balance between protective cover and productive aquifers.

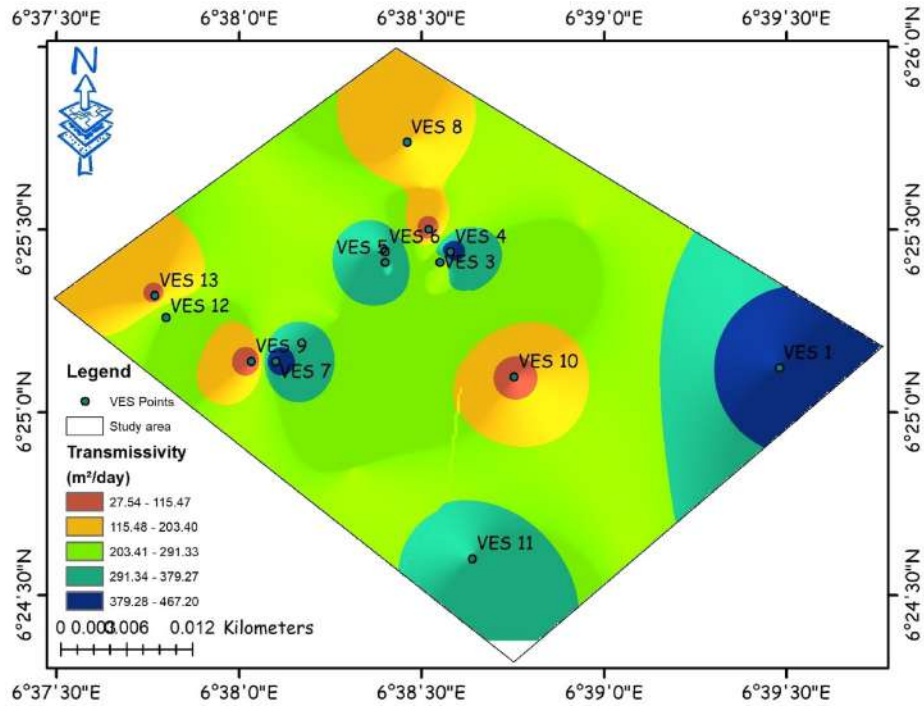


Fig. 9. Spatial distribution of aquifer transmissivity showing groundwater productivity zones.

Intermediate zones such as VES 6 and VES 7, with diagnostic values of 0.0377 and 0.0415, respectively, also show favorable development potential and are especially relevant for rural or community-scale water supply projects.

4.4. Aquifer protective capacity and contamination vulnerability

The longitudinal conductance (S) derived from VES data is a key index of aquifer protective

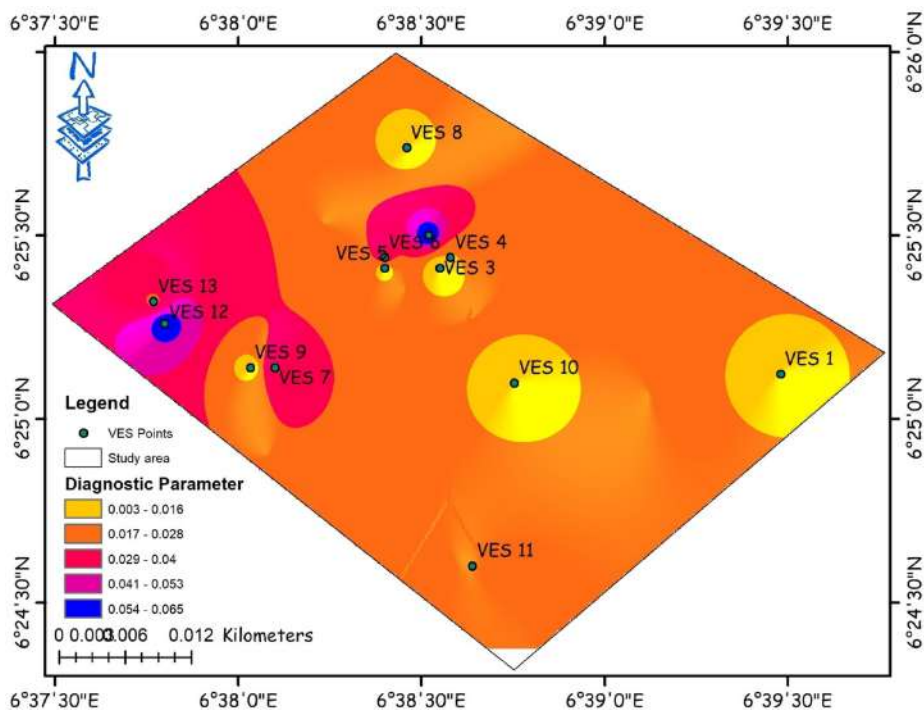


Fig. 10. Spatial variation of diagnostic parameter indicating overall aquifer suitability.

capacity: it integrates overburden thickness and resistivity to gauge how effectively surface contaminants are retarded by the subsurface. In general, high S values indicate thick, clay-rich layers that act as an impermeable “cap,” while low S values reflect thin or sandy cover that offers limited protection [47]. Studies routinely classify S into protective categories, $S > 0.7$ $1.0 \Omega^{-1}$ indicates good to excellent protection, $S = 0.2$ $0.7 \Omega^{-1}$ reflects moderate protection, and $S < 0.1$ $0.2 \Omega^{-1}$ denotes weak or poor protection. In such frameworks, zones with low S are considered highly vulnerable to contamination, while those with moderate or high S provide significant shielding [48].

In Illah, spatial interpretation of longitudinal conductance values (see Fig. 7 and Table 2) reveals distinct variations in protective capacity across the 13 VES stations. The highest conductance values, such as $0.2949 \Omega^{-1}$ at VES 7, $0.2773 \Omega^{-1}$ at VES 12, and $0.2284 \Omega^{-1}$ at VES 6, suggest moderate aquifer protection. These values fall below the threshold for excellent protection but indicate a presence of moderately thick, low-resistivity overburden, likely composed of clayey or silty layers. On the other hand, several locations exhibit very low conductance values, including VES 3 ($0.0118 \Omega^{-1}$), VES 10 ($0.0125 \Omega^{-1}$), and VES 9 ($0.0038 \Omega^{-1}$). These sites fall within the weak to poor protection category, highlighting their susceptibility to surface-sourced contamination. The overburden in these areas is likely thin or composed of coarse, permeable material, such as sand or gravel, with limited filtration capacity.

Interestingly, VES 2, despite being one of the least hydrogeologically productive sites in terms of transmissivity and aquifer strength, recorded a moderate protective conductance ($0.0413 \Omega^{-1}$). This suggests that, while the aquifer yield may be low, the site may still be suitable for limited water use

(e.g., hand-dug wells), especially if protected from pollution sources.

From a planning perspective, high-conductance zones such as VES 7, VES 6, and VES 12 could be considered for shallow well development, provided that sanitary protection measures are enforced. These areas benefit from a moderately protective overburden but may require complementary hydraulic tests to ensure yield adequacy. In contrast, zones such as VES 3, VES 10, and VES 9 should be avoided for shallow abstraction, or at the very least, subject to strict monitoring and water quality testing [41]. When integrated with transmissivity and transverse resistance data, it becomes clear that VES 4 offers a balanced hydrogeological profile, characterised by moderate protective conductance ($0.1074 \Omega^{-1}$), high transmissivity ($468.99 \text{ m}^2/\text{day}$), and strong transverse resistance. This makes it the most favourable site for sustainable groundwater development. VES 1 and VES 7 also demonstrate high suitability due to a combination of strong transmissivity and protective capacity. In contrast, VES 9 and VES 2, despite some degree of overburden protection, suffer from low transmissivity and weak aquifer composition, rendering them less favourable. VES 13 also presents limited hydraulic performance with marginal protective capacity, suggesting the need for caution or further site-specific investigation.

The protective capacity of aquifers in Illah, as assessed through longitudinal conductance, varies significantly across the study area. This variation reflects the heterogeneous composition of the Imo Formation and highlights the importance of site-specific data for informed groundwater development [9]. Areas with moderate to high conductance offer better protection from pollution and are suitable for strategic borehole siting, while low-conductance zones demand greater caution due to their increased vulnerability.

Table 2. Dar-Zarrouk parameters of Illah derived from VES data.

VES No.	Longitudinal Conductance (Ω^{-1})	Transverse Resistance ($\Omega \cdot \text{m}^2$)	Transmissivity (m^2/day)	Diagnostic Parameter
VES 1	0.0945	31896.90	444.69	0.0139
VES 2	0.0413	634.88	41.47	0.0653
VES 3	0.0118	73970.40	239.76	0.0032
VES 4	0.1074	31208.10	468.99	0.0150
VES 5	0.0343	38049.40	292.41	0.0077
VES 6	0.2284	10556.50	397.71	0.0377
VES 7	0.2949	11212.50	465.75	0.0415
VES 8	0.0174	11908.80	116.64	0.0098
VES 9	0.0038	3039.60	27.54	0.0091
VES 10	0.0125	9834.60	89.91	0.0091
VES 11	0.1158	14590.50	332.91	0.0228
VES 12	0.2773	4831.20	296.46	0.0614
VES 13	0.0351	3443.00	89.10	0.0259

5. Conclusion

This study offers a comprehensive geophysical assessment of aquifer characteristics and groundwater potential in Illah, Delta State, Nigeria, utilizing Vertical Electrical Sounding (VES) and Dar-Zarrouk parameter analysis. The research successfully delineates the subsurface lithology, identifies potential aquifer zones, and estimates key aquifer parameters such as resistivity, thickness, and transmissivity. The results highlight substantial variability in aquifer properties across the study area, with some zones exhibiting high groundwater potential, notably VES stations 1, 3, 4, and 7, characterized by high resistivity and transmissivity. In contrast, regions like VES 2 and VES 9 demonstrate lower transmissivity and weaker aquifer structures, making them less suitable for large-scale water extraction. The study's integration of Dar-Zarrouk parameters, such as longitudinal conductance and transverse resistance, enhances the reliability of aquifer characterization, revealing both the productivity and protective capacity of the aquifers. These findings provide valuable insights into the subsurface conditions and groundwater vulnerability, crucial for efficient groundwater management in rural and semi-urban settings. By applying surface resistivity techniques and Dar-Zarrouk analysis, this research offers a cost-effective and non-invasive method for evaluating aquifer potential, which can significantly aid groundwater exploration in data-scarce regions. The study's contributions are vital for guiding the development of sustainable water resources in Illah, supporting informed decisions on borehole siting, and ensuring long-term water supply solutions for local communities. Surface resistivity methods and Dar-Zarrouk modeling provide a cost-effective, non-invasive approach to identifying viable aquifer zones in data-scarce and rural areas like Illah, offering a potential solution to local water scarcity challenges.

Source of Funding

There is no funding.

Conflict of Interest

The authors declare that they have no conflict of interest.

Ethical Approval

Not applicable.

Data Availability

All data used in this research are available.

Author Contributions

John Ejiofor Okonkwo: Conceptualizations, Data Collection, Data Interpretation, Resources, Methodology, Writing of first draft and reviewing the final draft.

Efemena Destiny Emmanuel: Resources, Funding, Data Collection, Methodology, Writing of first draft and reviewing the final draft.

Acknowledgments

The authors would like to thank all those who assisted in conducting this work.

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