



Aquifer characterization and DRASTIC vulnerability assessment within the low-permeable Enugu shale formation, Anambra Basin, Nigeria using electrical resistivity method

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ABSTRACT

This study focuses on aquifer characterization and vulnerability assessment modeling of the low-permeable Enugu shale, Anambra Basin, Nigeria, utilizing the Electrical Resistivity Method (ERM). The Enugu shale formation presents a unique challenge due to its low permeability, which impacts groundwater movement and storage. We employed ERM, specifically Vertical Electrical Sounding (VES), to determine the subsurface resistivity variations, which aided in identifying aquiferous zones and their depths. The findings reveal significant variability in aquifer depths ranging from 4.0 to 44.5 m. This suggests that most of the underground water in the region is from shallow sources. The apparent resistivity model reveals variation in the resistivity of the aquifer ranging from low resistivity (10 to 60 m) to high resistivity (100 to 190 m). The depth to the water table map reveals higher depths (40 m to 75 m) at Abapka, Emene, and part of New Heaven. The relatively low values of transmissivity (200 m²/day–900 m²/day) and hydraulic conductivity (0.08 m/day–1.0 m/day) recorded are clues of prolific regions for groundwater development with low water yield capacity. Areas with higher transmissivity and thicker aquifers may provide better water supply potential, but overall, the low permeability suggests limited groundwater movement, requiring careful management to avoid over-extraction and contamination. The DRASTIC index risk (DIR) model indicates low to high susceptibility to contamination (with DIR ranging from 28 to 201), necessitating strategic groundwater protection measures. The low-permeable Enugu shale exhibits significant variability in its hydraulic properties, impacting its vulnerability and usability.

Abbreviations

DRASTIC Eight parameters, namely Depth to groundwater, Net Recharge, Aquifer Media, Soil Media, Topography, Impact of vadose

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	Zone, and Hydraulic Conductivity
DIR	DRASTIC index Risk
DI	DRASTIC index
ERM	Electrical Resistivity Method

Introduction

Aquifer characterization and vulnerability assessment are critical components of groundwater resource management, particularly in regions with complex geological formations. The Enugu Shale region within the Anambra Basin, Nigeria, is characterized by low permeability, making it challenging to locate and assess aquifers using conventional methods. The ERM has been increasingly utilized for subsurface studies due to its effectiveness in identifying geological layers and groundwater-bearing formations [5,33]. Groundwater serves as a critical resource for agricultural, industrial, and domestic applications in Nigeria. However, the presence of low-permeable shale formations like the Enugu formation poses challenges for aquifer sustainability and vulnerability to contamination [13]. The study presents an evaluation of aquifer depth estimation and vulnerability modeling within the low-permeable Enugu shale region of the Anambra Basin, Nigeria. The research employs the Vertical Electrical Sounding (VES) to delineate aquifer characteristics, providing crucial information for sustainable water resource management. Analysis of resistivity data facilitates the identification of aquifer depths and potential contamination sources, contributing to regional planning and environmental conservation efforts. The Anambra Basin, located in southeastern Nigeria, encompasses the Enugu shale, characterized by low permeability. This formation significantly affects groundwater movement and storage capabilities [14]. Additionally, surface contamination from agricultural runoff and industrial activities necessitates the assessment of groundwater vulnerability in the region.

The VES is a geophysical technique widely used for subsurface exploration, particularly for aquifer characterization and groundwater studies. This non-invasive method measures the resistivity of geological materials, providing valuable information about the presence and depth of aquifers, their characteristics, and the potential for groundwater resources. Resistivity is the property of a material to resist the flow of electric current. Different geological materials have varying resistivity values based on factors such as mineral composition, porosity, water content, and salinity. In terms of groundwater, the resistivity is significantly influenced by the saturation of pore spaces with water [11,12]. Freshwater aquifers typically exhibit lower resistivity compared to dry or saline formations, making resistivity measurements a useful tool for distinguishing between various subsurface materials. The use of ERM proved effective in delineating the subsurface geology and identifying aquiferous zones. The integration of resistivity data with hydrogeological parameters facilitated a comprehensive vulnerability assessment, offering a robust framework for groundwater protection planning. The findings underscore the importance of continuous monitoring and the implementation of protective measures to mitigate contamination risks in vulnerable areas.

The geological formations in the Anambra Basin significantly affect groundwater availability and movement. The porosity and permeability of the sandstones, especially within the Ajali Formation, allow for substantial groundwater storage, while the low-permeability shales, such as those in the Enugu Formation, limit groundwater flow and act as barriers. The main aquifers in the Anambra Basin include the Ajali and Mamu formations [17,18,20]. These aquifers are essential for local water supply, supporting agricultural activities and drinking water resources. The geological characteristics of the Enugu shale present challenges for groundwater vulnerability, as pollutants from surface activities can easily migrate through fractures and faults into the groundwater system. Understanding the geology and hydrological connectivity is vital for assessing risks and implementing effective management strategies. This study demonstrates the utility of the ERM in estimating aquifer depths and modeling vulnerability in the low-permeable Enugu shale region of the Anambra Basin. The identified aquiferous zones, located within fractured shale layers at varying depths, present significant groundwater resources. The integration of ERM with hydrogeological data provides a comprehensive approach to groundwater resource management, essential for ensuring sustainable water supply and mitigating contamination risks in the Enugu shale region. Electrical resistivity data can also identify areas vulnerable to contamination. By mapping resistivity anomalies, potential sources of pollution can be correlated with aquifer locations, guiding resource management and protection efforts.

Aquifer vulnerability indicates how prone groundwater is to contamination from sources at or near the surface. Several factors affect this vulnerability, such as the characteristics of the soil and rock layers above the aquifer, the depth of the water table, the rate at which water is replenished, and the intrinsic properties of the aquifer [21,28]. In regions with low-permeable geologic layers, such as shale formations, assessing vulnerability is particularly challenging due to the complex hydrogeological conditions. Shallower water tables are typically more susceptible to contamination, as pollutants have a shorter distance to travel to reach the groundwater. In low-permeable geologic layers, the water table depth can vary significantly, influencing vulnerability assessments [31]. Recharge rates, which is the rate at which water percolates through the soil and rock layers to replenish the aquifer, are crucial. In low-permeable formations, recharge rates are typically lower, which can limit the dilution and dispersal of contaminants but also means contaminants can persist longer in the subsurface [35]. Geologic Media, the type and permeability of geologic materials overlying and comprising the aquifer influence on how easily contaminants can migrate. In low-permeable geologic layers like shale, the migration of contaminants is typically slower, but fractures and faults can provide pathways for rapid contaminant transport. Hydraulic Conductivity and Porosity: Hydraulic conductivity measures how easily water can flow through the pores or fractures in geological materials. Porosity refers to the percentage of the rock composed of open spaces. Low-permeable layers typically have low hydraulic conductivity and porosity, reducing the movement of water and contaminants. The DRASTIC model was believed to be the most accurate method to map vulnerability; it assumes a linear relationship between vulnerability and the measured parameter [2,3,29]. Evaluating groundwater vulnerability is the most effective method for safeguarding groundwater resources in regions prone to pollution or already

experiencing contamination. This study aims to estimate the depth of aquifers and model their vulnerability using ERM, providing valuable insights for sustainable groundwater management in the Enugu shale region.

Past studies on aquifer characterization and vulnerability assessments in the region have largely focused on examining the groundwater potential, flow dynamics, and recharge mechanisms within the basin, often using borehole data, pumping tests, and hydrochemical analyses. Again, earlier works by Chanchai et al [9] and Yuan et al [36] have utilized the DRASTIC model for vulnerability mapping but often relied on generalized or regional-scale datasets, which may not have fully accounted for localized variations in permeability and protective cover. Some studies have analyzed contamination risks using physicochemical parameters and land use changes, though many lack integrated geophysical validation. Unlike past studies that emphasized high-yield aquifers, this research specifically examines aquifers within the Enugu Shale Formation, which is known for low permeability. Resistivity with DRASTIC Analysis. This study uniquely incorporates electrical resistivity data into the DRASTIC model, improving accuracy in assessing aquifer vulnerability. It provides a more detailed, site-specific analysis of groundwater conditions, addressing the limitations of previous regional-scale assessments. By refining vulnerability assessment methods, the study offers more reliable data for policy-makers to enhance groundwater management strategies in the region.

Geology of the area

The Anambra Basin, located in southeastern Nigeria, is a significant geological and hydrological unit notable for its complex stratigraphy, economic resources, and hydrocarbon potential. The basin is characterized by its sedimentary geology, influenced by historical tectonic events, paleo-environmental conditions, and significant depositional processes. Understanding the geology of the Anambra Basin is crucial for resource exploration, environmental management, and geotechnical assessments. Nwajide [18] believes that Anambra Basin is situated within the Benue Trough, a major geological feature that developed during the late Jurassic to early Cretaceous periods because of rifting and extensional tectonics. The basin evolved through a series of geological events, including subsidence and sedimentation, which shaped its current geological structure [4]. The Benue Trough, where the Anambra Basin is a sub-basin, is believed to have formed during the breakup of the Gondwana supercontinent. Subsequent tectonic activities, including the closing of the Atlantic Ocean and the collision of the African and Eurasian plates, affected sedimentation patterns and the regional geology [8] (Fig 1).

The sedimentary deposits in the Anambra Basin are primarily of Cretaceous age (Albian to Maastrichtian) [30], and they can be grouped into different lithostratigraphic units: Ajali Formation, The Ajali Formation, primarily composed of coarse-grained sandstones and siltstones, forming the uppermost unit in many parts of the basin. It represents a fluvial system characterized by high-energy environments that deposit sandy materials. Mamu Formation underlines the Ajali Formation lies the Mamu Formation, which is predominantly made up of shales, mudstones, and inter-bedded sandstone layers. The Mamu Formation indicates a transition from fluvial to more estuarine or lagoonal environments. Underlying the Mamu Formation is the Nkporo Formation, which consists mainly of shales with coal seams, reflecting a deltaic environment conducive to the formation of organic-rich deposits [12]. The Enugu Formation underlined the Mamu Formation. The Enugu Formation, generally characterized by its low permeability, comprises clay stones and shales. This formation plays a crucial role in the hydrology of the basin, acting as an aquitard that influences groundwater flow. The Enugu Formation consists of dark shales and contains fossilized plant materials, suggesting it was deposited in a rich, organic environment. The Anambra Basin is marked by a diverse lithology ranging from sandstones, shales, and mudstones to coal deposits. The sedimentary layers exhibit various features, including graded bedding, crossbedding, and bioturbation, indicating different

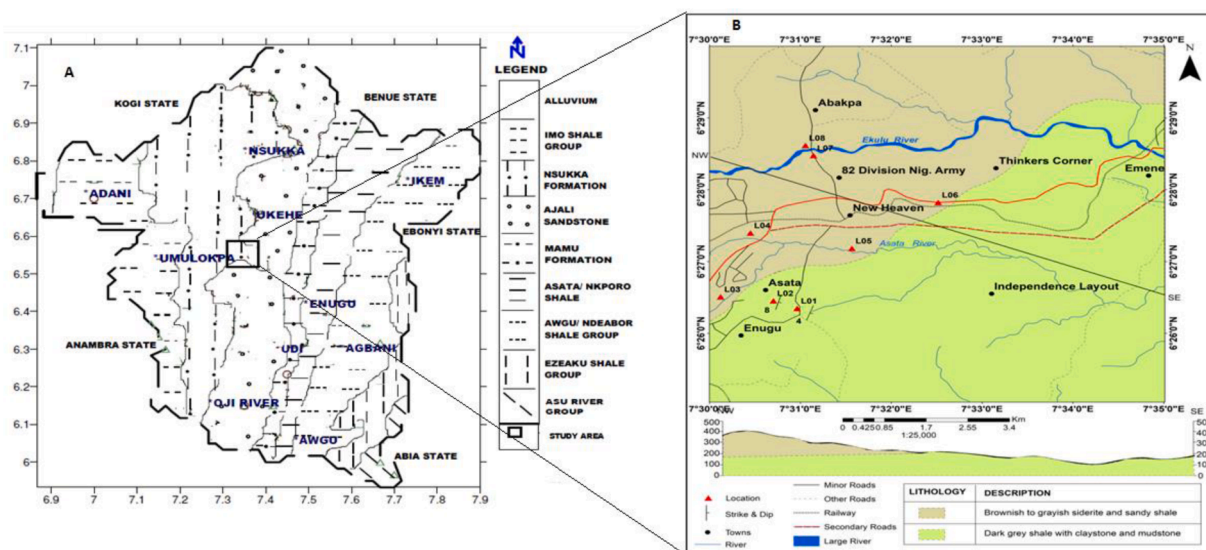


Fig. 1. A) Geologic map of Enugu State (Adapted from [14]). B) Local geological mapping of the study area.

depositional environments from fluvial to coastal and deltaic systems. Fossil assemblages within the sedimentary layers, including foraminifera and palynomorphs, provide insight into the paleoenvironment and age of the formations (Fig 1).

The basin's complex geology is shaped by tectonic history, depositional processes, and varying environmental conditions. Ongoing geological studies and explorations hold the promise of unlocking further understanding of the basin's natural resources and managing its ecological and hydrological systems effectively [19]. Understanding the intricate geology of the Anambra Basin is essential for sustainable groundwater development and optimizing resource use in southeastern Nigeria.

The Enugu Shale Formation is a Cretaceous-aged sedimentary unit within the Anambra Basin, characterized by low primary porosity and permeability due to its fine-grained, compacted nature. Key hydrogeological properties include low Permeability & Porosity. The shale matrix has very low permeability, restricting groundwater movement and storage within the formation. Groundwater occurrence is predominantly controlled by fractures and joints rather than primary porosity. Weathering and structural deformation enhance secondary porosity, creating localized groundwater storage and flow paths in the region [12]. Fractures and joints are the primary conduits for groundwater flow within the formation. They develop due to regional tectonic stress and can enhance water movement where interconnected. Due to its low permeability, groundwater flow is largely restricted to fractured zones rather than a widespread aquifer system. While fractures facilitate flow, they also increase the risk of contamination as pollutants can rapidly migrate through connected fracture networks [32].

Methodology

The research was carried out at different locations within the Enugu Shale region of the Anambra Basin. A total of twenty (20) Vertical Electrical Sounding (VES) points were carefully chosen based on preliminary geological surveys and ease of access. The Schlumberger array configuration was utilized for data collection, with electrode spacing varying from 1 to 100 m (Fig 2). This method involves centering the electrode array over a field station and progressively increasing the distance between the current electrodes, which in turn increases the depth of investigation. For each electrode spacing, the potential difference (ΔV) and the electrical current (I) were measured, and the apparent resistivity (Ωm) was calculated using the equation provided below (Eq. (1)).

$$\rho_a = G \frac{\Delta V}{I} (ohm - m) \quad (1)$$

Where, ρ_a = Individual layer apparent resistivity; G = the dimension factor; ΔV = potential difference; I = current

Hydraulic conductivity and porosity values were obtained from field data using the Dar-Zarrouk equation and associated formations to complement the resistivity data, as demonstrated by the works of Akakuru et al [5] and ([6]b); Fadele et al [15]; Mazac and Landa [16]; Okeke et al [22]; Onu et al [25]; and [24]; Usman et al [32]. The vulnerability assessment was conducted using the DRASTIC model, incorporating parameters such as watertable depth, net recharge, aquifer media, soil media, topography, impact of the vadose zone, and hydraulic conductivity. The Schlumberger array is the preferred choice for groundwater studies because it offers a good balance of depth penetration, resolution, and efficiency while minimizing field effort. Its ability to provide high-quality resistivity data makes it highly effective in identifying aquifers, delineating groundwater-bearing formations, and understanding subsurface hydrogeological conditions.

Calculation of aquifer hydraulic parameters from surface geophysical method

It is essential to estimate hydraulic characteristics such as hydraulic conductivity and transmissivity of the aquifer system. Usually this is obtained either from pumping tests or laboratory experiments. However, an alternative cheap and quick non-invasive approach was employed in this study as guided by previous works of Onuoha et al [27]; Okoro et al [23]; Usman et al [[34] and [33]]. Hence, it is normal practice to estimate aquifer hydraulic properties from established empirical and semi-empirical relationships (Fig 3). Akakuru et al [7] developed an analytical correlation linking aquifer transmissivity to transverse resistance, as well as another linking transverse resistance to hydraulic conductivity. Many other geophysicists have conducted similar research, including Mazac and Landa in 1979 and Onu and Ibezim in 2004.

$$K = 15752X + 1472.3 \quad (2)$$

From the work of Akakuru et al [7], Chinwuko et al [10]; and Usman et al [33] and [32], the relationship between hydraulic conductivity, transmissivity, and transverse resistivity was summarized in Eq. (3).

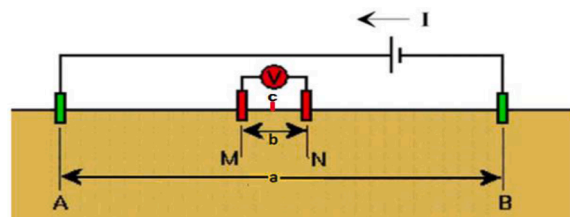


Fig. 2. Diagrammatic representation of Schlumberger array [11,26,28].

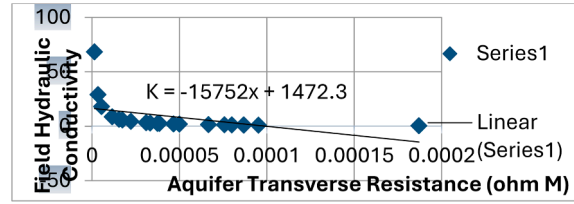


Fig. 3. The Relationship between Hydraulic (K) Conductivity and Resistance (R) gave generated equation 2.

$$T = K\sigma R = \frac{KS}{\sigma} = Kh \quad (3)$$

Where K represents hydraulic conductivity, I denotes the hydraulic gradient, A is the cross-sectional area perpendicular to the flow direction, J is the current density, E stands for electric field intensity, σ is the electrical conductivity (the inverse of resistivity), T is the aquifer transmissivity, h indicates the aquifer thickness, R is the transverse resistance of the aquifer, and S is the longitudinal conductance.

The Dar-Zarrouk equation is a fundamental geoelectrical concept used to estimate hydraulic conductivity (K) and transmissivity (T) in groundwater studies. It relates electrical resistivity to hydrogeological properties of aquifers, providing a way to infer groundwater potential from resistivity surveys.

From the Dar-Zarrouk equation, S and R are then calculated [12] Eqs. (4) and 5.

$$S = \frac{h}{\rho_a} \quad (4)$$

and

$$R = h\rho_a \quad (5)$$

Where h and ρ_a are thickness and apparent resistivities of various geo-electric layers, respectively.

Vulnerability assessment models

Several models are used to assess aquifer vulnerability, with the DRASTIC model being one of the most widely applied. The DRASTIC model evaluates vulnerability based on seven parameters: depth to water, recharge (net), aquifer media, soil media, topography (slope), impact of the vadose zone, and hydraulic conductivity. In DRASTIC Index Calculation, each parameter is assigned a rating and weight based on its relative significance in influencing vulnerability. Standard DRASTIC Weights approach was used in the study. This traditional DRASTIC model assigns fixed weights based on the original methodology developed by the U.S. Environmental Protection Agency (EPA). These values prioritize parameters such as Depth to Water, Impact of the Vadose Zone, and Hydraulic Conductivity as the most influential on groundwater vulnerability. The ratings are summed up to produce a vulnerability index, with higher values indicating greater vulnerability. In regions with low-permeable geologic layers like the Enugu shale, the vulnerability assessment must account for the potential presence of fractures and secondary porosity. While the primary porosity and permeability of shale are low, secondary features can create preferential pathways for contaminant migration. Therefore, vulnerability assessments should incorporate geological mapping and fracture analysis to identify areas of increased risk.

The DRASTIC index (DI) equation was summarized by Wei et al [35] as shown in Eq. (6).

$$DI = D_W D_R + D_W R_R + A_W A_R + S_W S_R + T_W T_R + I_W I_R + C_W C_R \quad (6)$$

Where DI = DRASTIC index; Subscript W = weight of the parameters; Subscript R = rate of the parameter; D = depth of water; R = net recharge; A = aquifer; S = soil; T = topography; I = vadose zone impact; C = conductivity.

The depth to the water table and hydraulic conductivity “C” can be approached from the geoelectric model section and Dar-Zarrouk equation calculation from Eqs. (1)–5, respectively; the net recharge was gotten from meteorological data [35], which provide the net recharge as in Eq. (7):

$$NR = P + ET + R_O \quad (7)$$

Where P = annual precipitation (in mm/year); ET = evapotranspiration (in mm/year); and RO = total runoff (in mm).

The aquifer (A), soil media (S), and impact of the vadose zone (I) were gotten from our geoelectric section; topography (T) was approached from our digital elevation model map.

Single Parameter Sensitivity Analysis which evaluates how changing an individual parameter’s weight affects the final vulnerability index was deployed to understand how individual parameter influences vulnerability. It involves systematically adjusting the weight of one parameter while keeping others constant. Follow by recalculating the vulnerability score and observing the variation and identifying which parameter has the most significant influence on the results.

Results

Vertical Electric Sounding VES(s) for twenty sounding points was conducted (Figs. 4 and 5). The porosity, moisture content in the pore spaces, and the rock matrix all affect the layer resistivity. The subsurface model curve and geoelectric section revealed subsurface layers ranging from three (5) layer models to six (6) layer models; the topsoil is mostly interpreted as lateritic, and the base, which has not reached a high conductive value across the twenty VES points, is interpreted as compacted shale (Fig 6). The aquiferous unit across the twenty VES is wet shale, and they occur across the study area (Table 1). The resistivity surveys revealed distinct subsurface layers, with the topsoil, weathered shale (wet shale), fractured shale, and fresh shale formations being identified. The interpreted resistivity data indicated that the aquiferous zones are primarily associated with the fractured shale layers or weathered wet shale, occurring at depths ranging from 30 to 80 m. The depth to the water table varied significantly across the study area, reflecting the heterogeneous nature of the subsurface geology (Fig 6).

The correlation of interpreted geo-electric units at VES 1, 11, and 8 (Fig 7a) showed that the top layer thickness in the three geo-electric sections along the profile is 1.0, 0.8, and 0.5 m, respectively. The underlying unit (the base geologic unit) is delineated as shale, and this occurs in the three geo-electric sections, although there are variations in their depths and thickness. Again, the wet shale zone shows varying thickness and depths. The depth of the wet shale in VES one is 32 m with a thickness of 20 m, while the depth of the wet shale in VES eleven is 48 m with a thickness of 35 m. That of VES eight has a thickness of 20 m and a depth of 40 m. The depth of the wet shale along the profile is not a horizontal level; it is undulating. The depth to the base was not reached in the VES, but they are interpreted as compacted shale because of their high conductivity value. Shale is identified as the underlying unit (the base geologic unit), and it is present in all three geo-electric sections, albeit to varying degrees of thickness and depth. It is 40 m deep and has a thickness of 20 m in VES 8. To verify the effectiveness of our approach, we correlated the lithologic section from the borehole near a sounding station at 82 Division with its interpreted geo-electric units at VES 8 (Fig 7b). We assumed that this resulted from the resistivity method's widespread application. The geologic section of the well drilled at 82 Division and the VES geoelectric section sound around the borehole are nearly correct. A shale unit with an apparent resistivity of 203 Ωm sits on top of the aquiferous layer.

The geophysical surveys conducted around the Enugu Shale Formation revealed distinct variations in subsurface resistivity, indicating heterogeneous aquifer properties (Fig 8). The resistivity data correlated with hydrogeological parameters such as groundwater levels, lithology, and land use to elucidate the aquifer's vulnerability to pollution. Around Astata, Alulu Nike, and Zoo Estate, the depth of the aquifer is relatively shallow (with a depth ranging from 4.00 to 2.00 m), while the deepest aquifer is found around Lavida Suites, Thinker Corner, and Premier Estate (with a depth ranging from 5.00 to 20 m) (Figs. 9 and 10). The aquifer thickness across the study area is uneven, and they tend to follow the topographic trend of the area (Fig 9). The aquifer thickness ranges from 3.03 to 21.20 m across the study area. Again, the aquifer resistivity also varies from 105 to 1809.90 Ωm (Table 1). A weighting and rating ratio was assigned to the seven DRASTIC index parameters so that we could model the acute vulnerability of the area. Aller et al. [3] provided the model. Again, Aller et al [3] define the class of vulnerability as summarized in Table 3. Results of vulnerability

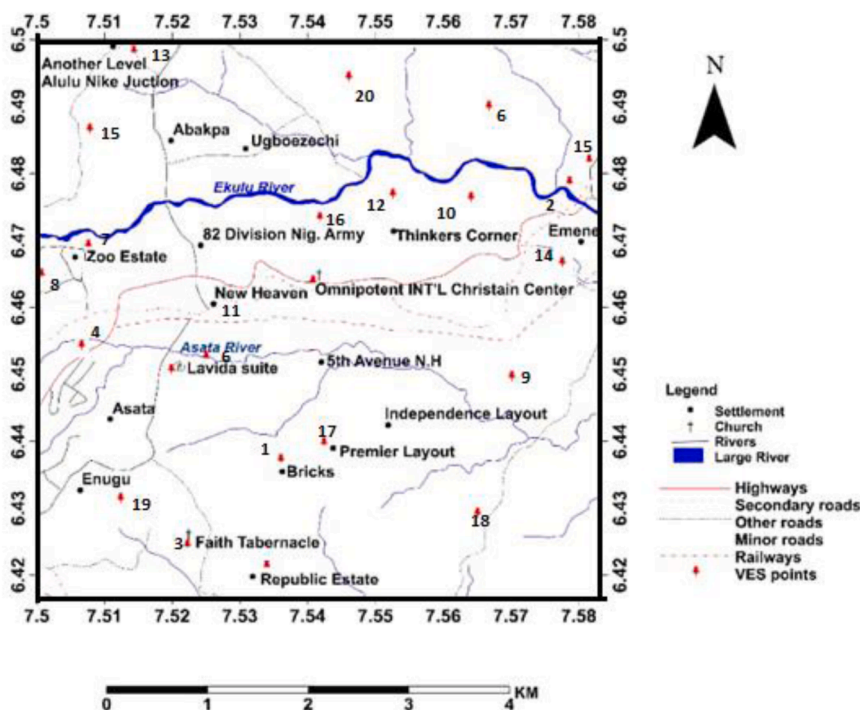


Fig. 4. Topographical map of the area showing VES Location.

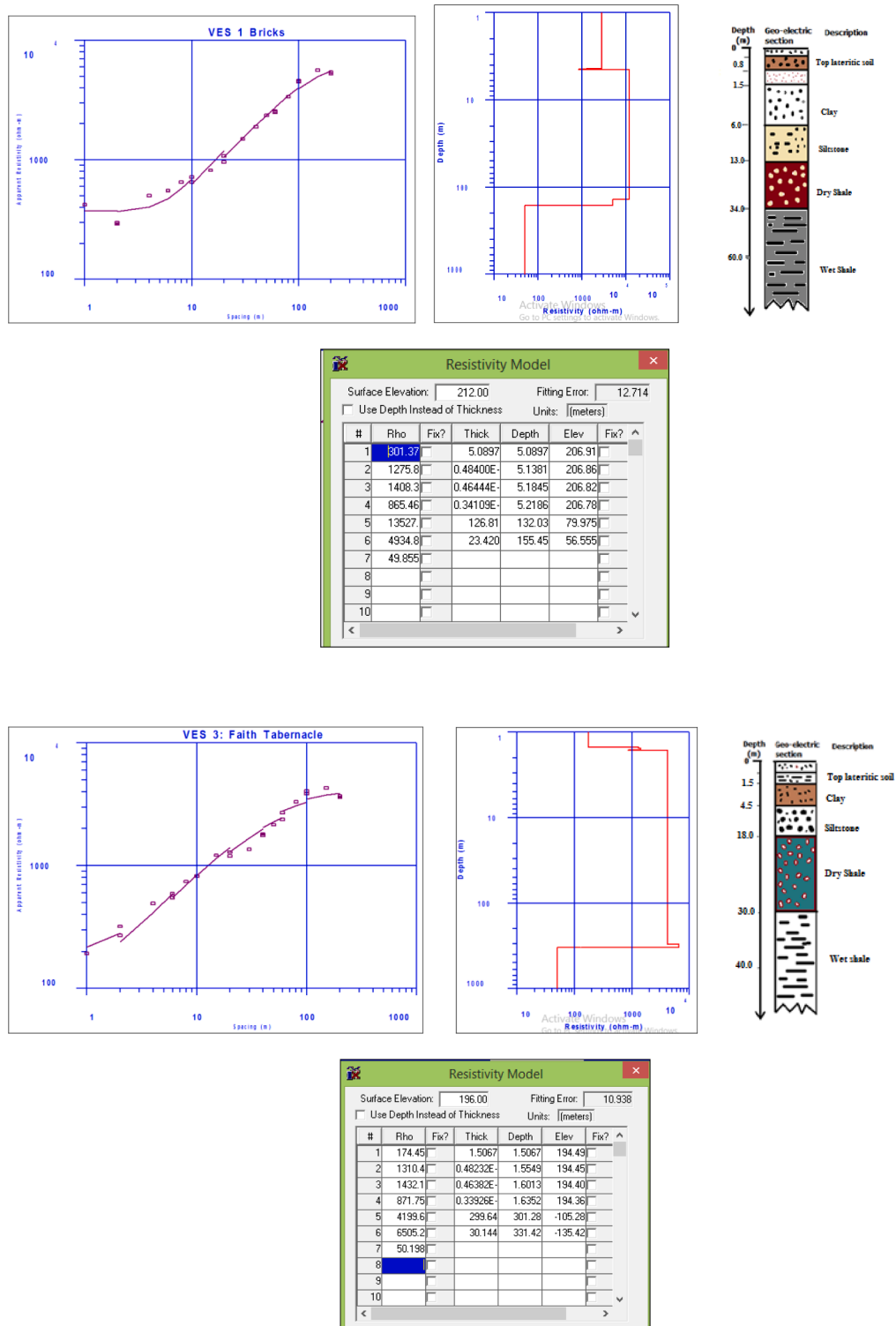
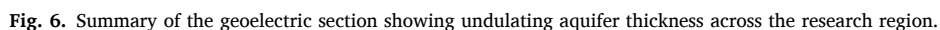
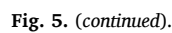


Fig. 5. Sample of the 1D inversion of apparent resistivity data of the VES curve and geo-electric section model around the research area.



assessment are given in Table 4. Again, Afolayan et al [1]; Aller et al [3] defines the class of vulnerability as summarized in Table 3.

The results highlight the variability in aquifer depths within the Enugu shale region, underscoring the need for localized groundwater management strategies. The fractured shale layers, despite their low primary permeability, provide significant groundwater storage potential due to secondary porosity. However, the moderate to high vulnerability indices suggest a considerable risk of contamination, particularly in areas with shallow aquifers (Asata, Alulul Nike, Zoo Estate areas) (Fig 9) and high recharge rates because of the low permeability of the shale formation. The resistivity profiles displayed significant variations, suggesting the presence of multiple aquifer units at varying depths. The estimated depth of the aquifer ranges from 4.00 to 55 m (Fig 10). The area is predominantly a shallow aquifer system, which is easily contaminated. The findings indicate that the Enugu shale region possesses aquifers that are relatively shallow but may be vulnerable to pollution due to anthropogenic activities. The integration of electrical

Table 1

Aquifer parameter calculation of the research area.

VES NO	TOWN	ELEVATION	LATITUDE	LONG	THICKNESS (m)	Aquifer depth (m)	Aquifer resistivity (Ω m)	Hydraulic conductivity	Transmissibility (L/S)	Storability
1	Bricks	212.000	6.437	7.537	14.795	18.727	6839.100	146.218* E-6	177.540	2.738*E-3
2	Emene	127.000	6.479	7.578	8.0195	18.209	258.820	3863.689* E-6	104.254	70.354* E-3
3	Faith Tabernacle	196.000	6.428	7.521	21.189	27.602	266.560	751.501* E-6	296.646	103.549* E-3
4	Fifth Avenue New Haven	147.000	6.454	7.544	7.3177	11.626	115.290	8673.779* E-6	109.766	100.841* E-3
5	Lavida Suites	147.000	6.449	7.504	15.231	33.773	645.950	1548.107* E-6	258.927	52.284* E-3
6	Ogbonna Str Emen	127.000	6.479	7.595	4.7752	12.353	53.4810	18,698.229* E-6	85.954	230.979* E-3
7	Zoo Estate Crown Bird	184.000	6.467	7.508	5.8966	10.843	214.490	4662.222* E-6	112.035	50.552* E-3
8	Zoo Estate	192.000	6.465	7.507	3.0375	9.0143	572.970	1745.292* E-6	60.750	15.733* E-3
9	Asata	201.000	6.405	7.487	70	4	150.000	6666.667* E-6	1470.000	26.667* E-3
10	Thinker Corner	226.000	6.466	7.5340	33	55	300.000	3333.333* E-6	726.000	183.333* E-3
11	New Heaven	170.000	6.453	5.585	20	40	200.000	5.000* E-3	460.000	2.000* E-1
12	Alor Street Thinker Corner	128.000	6.473	7.523	17.371	34.22	132.010	7575.184* E-6	416.904	259.223* E-3
13	Alulu Nike	201.000	6.505	7.514	75	15	115.000	8695.652* E-6	1875.000	130.435* E-3
14	Thinker Corner Via Airport	152.000	6.476	7.547	20.978	44.567	447.940	2232.442* E-6	545.428	99.493×10 ⁶ 3
15	Joe Udeh Close Thinker Corner	155.000	6.474	7.536	1.8795	4.7752	322.220	310.347* E-6	50.747	1.482* E-3
16	Premier Layout	177.000	6.439	7.546	18	24	105.000	952.381* E-6	504.000	228.571* E-3
17	Omnipotent Int'l Christain Cent	194.000	6.464	7.539	10.614	13.165	2909.200	343.737* E-6	307.806	4.525* E-3
18	Ugboezechi Abakpa	71.000	6.483	7.538	10.559	27.182	863.510	1158.064* E-6	316.770	31.479* E-3
19	Republic Estate	190.000	6.421	7.533	16.636	29.424	1809.900	552.517* E-6	515.716	16.257* E-3
20	Thinker Corner Hill	182.000	6.465	7.545	16.5	23	125.000	8.000* E-6	528.000	184.000* E-1

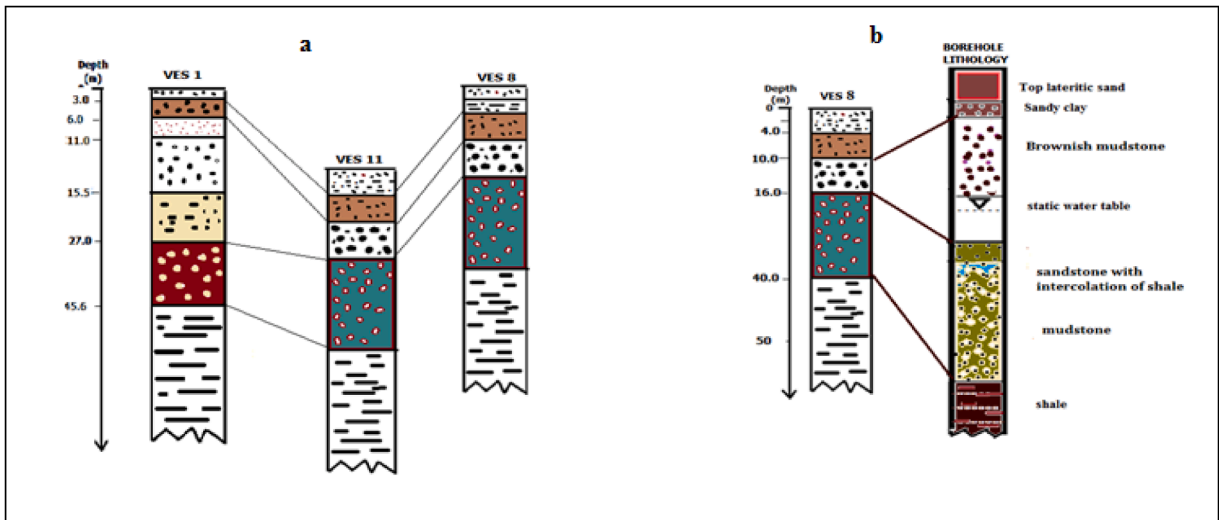


Fig. 7. a: comparison VES 1, VES 11, AND VES 8 b) comparison of borehole log around 82 divisions with VES 8.

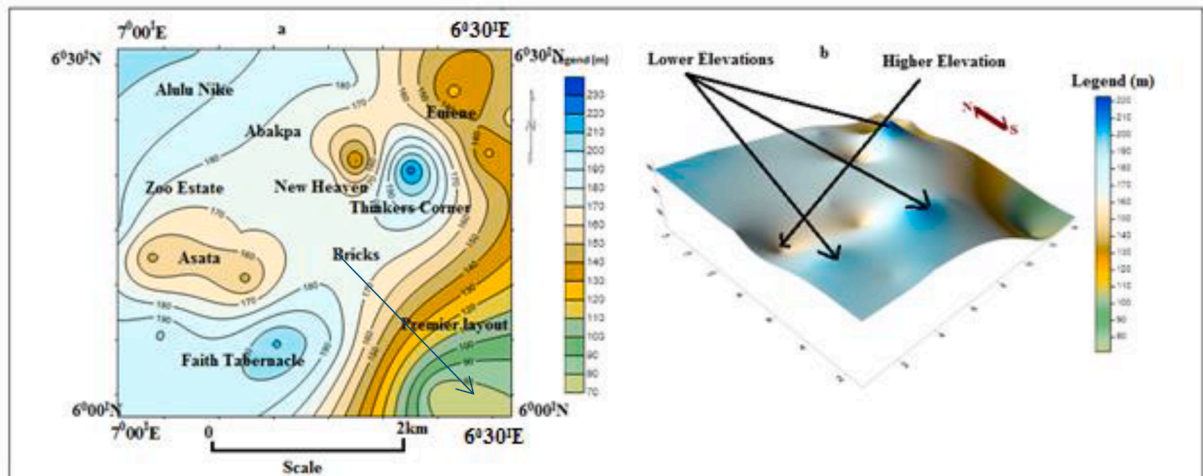


Fig. 8. a) Elevation map and b) 3D surface map of the study area.

resistivity data with vulnerability modeling enhances understanding of groundwater management within low-permeable formations.

Hydraulic Conductivity (Fig 11) variation indicates how easily water can move through pore spaces or fractures in the aquifer, while transmissivity reflects the ability of the aquifer to transmit water through its entire thickness. The depth of the aquifer ranges from 4 m around Upper Meniru to 55 m around Thinker Corner. The thickness of the aquifer follows a general morphological pattern that is topographically controlled because areas with higher elevation (Asata, Thinker Corner, Zoo Estate areas) show higher aquifer thickness, while areas with low elevation (Lavida Suite, Premier Layout Areas) have lower aquifer thickness. The shallowest depths to aquifer were observed (below 20 m) and are observed in most locations, except for Upper Meniru and Thinker Corner. This implies that most of the underground water in the area comes from shallow sources, and most of it is from the fractured Enugu shale formation, which serves as a reservoir in the region. Again, the transmissivity (Fig 12) varies significantly across locations, with the lowest value at 0.000146218 l/s (Bricks) and the highest at 0.018698229 l/s (Ogbonna Street, Emene areas). Transmissivity ranges from 50.7465 l/s (Joe Udeh Close Thinker Corner) to 1875 l/s (Alulu Nike). Higher transmissivity values indicate better water transmission through the aquifer, which is critical for evaluating water supply potential. Generally, low values suggest low permeability, consistent with low permeable Enugu shale [10]. The thickness of the aquifer (Fig 9), which helps to define the yield, varies widely from 1.8795 m at Joe Udeh Close Thinker Corner to 75 m at Alulu Nike. Most locations have moderate thickness, contributing to the overall transmissivity of the aquifer. The storage coefficient (Fig 13) (S) varies from 0.002738 (Bricks) to 0.259223 (Alor Street Thinker Corner). Higher (S) values suggest a greater volume of water that can be released from storage, indicating variability in storage capacity.

Low hydraulic conductivity observed at Thinkers Corner, Faith Tabernacle, and Asata areas implies that the aquifer is less

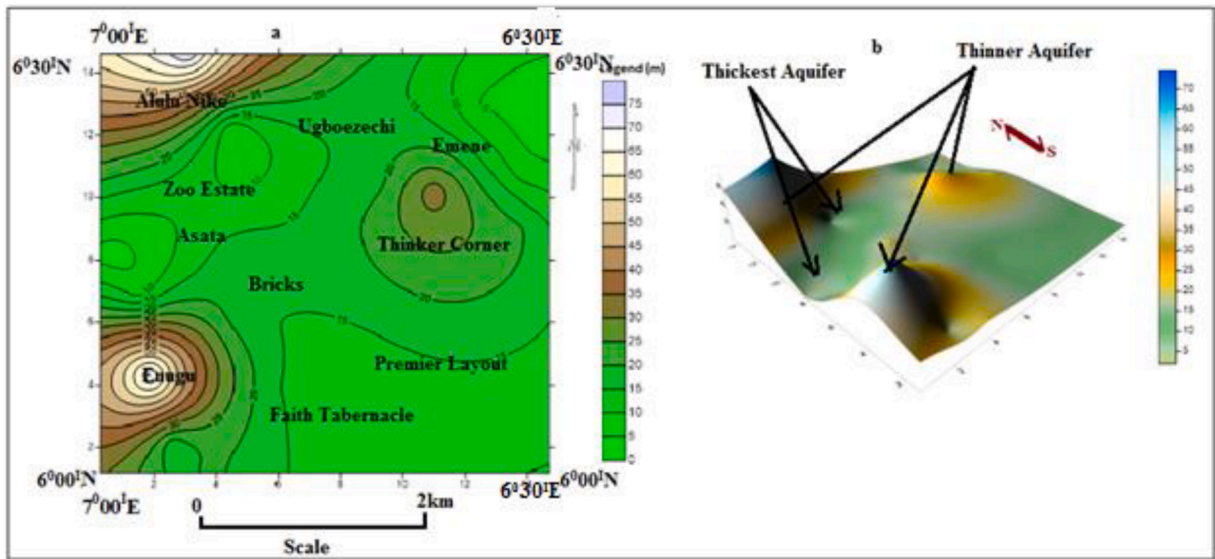


Fig. 9. a) Aquifer thickness map and b) 3D subsurface thickness map of the study area.

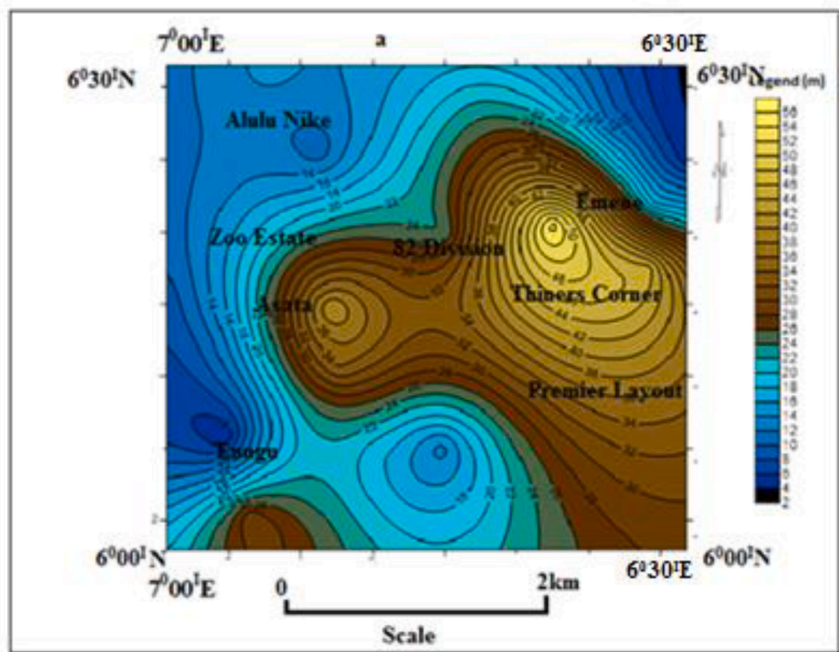


Fig. 10. a) Aquifer depth map of the study area, Map generated.

permeable, which reduces the potential for contamination spreading but also limits water supply [13,22]. Shallower aquifers are more susceptible to surface contamination, whereas deeper aquifers may be more protected but harder to access. The apparent resistivity model (Table 1) reveals variation in the resistivity of the aquifer, ranging from an area of low resistivity of 10 to 60 m (around Abakpa, Emene, and part of New Heaven) to an area of high aquifer resistivity of 100 to 190 m (around Enugu capital territory and independent layout). Aquifer thickness across the study area is not a horizontal level; it is undulating. Shallower depth exists around Enugu and independent layout of thickness ranging from 10 m to 25 m. Owing to the depth to water table map generated, which ranges from 40 to 75 m below mean sea level, Abakpa, Emene, and a portion of New Heaven have deeper water tables than the rest (Fig 10). Whereas in Enugu and Independent layout areas, the depth to the water table with respect to mean sea level is shallower, ranging from 20 m to 55 m (Table 1). Thicker aquifers with higher transmissivity can store and transmit more water, which is beneficial for water supply but

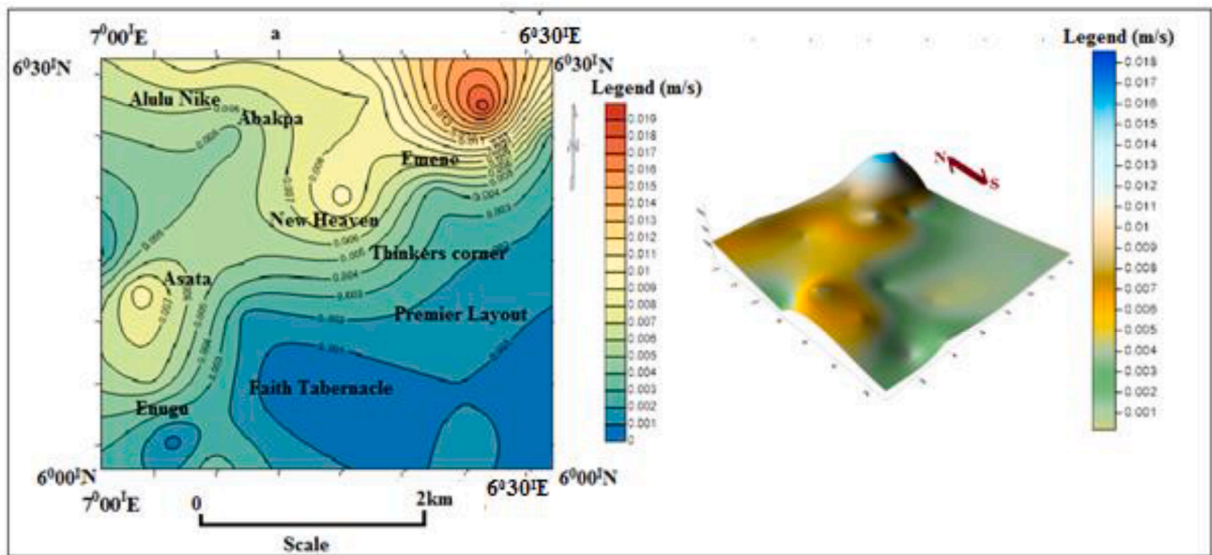


Fig. 11. a) hydraulic conductivity map; b) 3D subsurface hydraulic conductivity model of the study area.

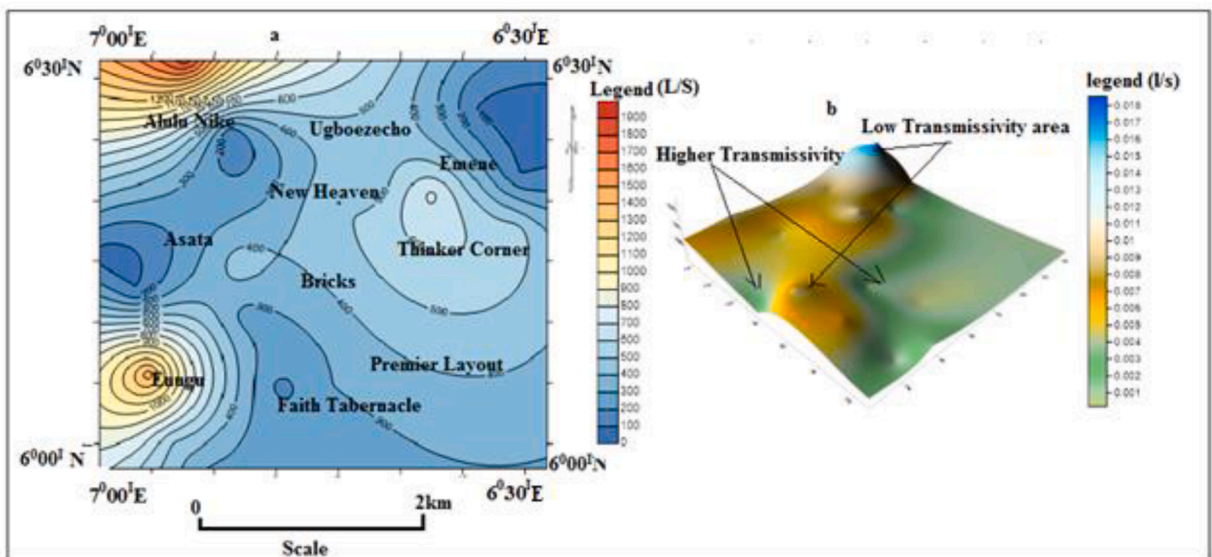


Fig. 12. a) Transmissivity map; b) 3D subsurface Transmissivity model of the study area.

also needs careful management to prevent over-extraction. Relatively low transmissivity readings (ranging from 200 to 900 m²/day) and hydraulic conductivity values (0.08 and 1.0 m/day) suggest a productive location for groundwater development in areas with limited water production capacity. Similarly, the areas with high transverse resistance, hydraulic conductivity, and transmissivity are expected to give favorable borehole yields (Thinker Corner, New Heaven, Premier layout areas). Higher storage coefficients (Fig 13) indicate greater water release potential, which is beneficial during droughts but requires careful. The low-permeable Enugu shale exhibits significant variability in its hydraulic properties, impacting its vulnerability and usability. Areas with higher transmissivity and thicker aquifers may provide better water supply potential, but overall, the low permeability suggests limited groundwater movement, requiring careful management to avoid over-extraction and contamination. Very high vulnerability is revealed around Fifth Avenue, New Haven, Asata, and Joe Udeh Close Thinker Corner. The average DIR in the area is 202, and this falls within the very high class [3] (Fig 14). Bricks, Emene, Ogbonna Str Emen, Zoo Estate Crown Bird, Zoo Estate, Alulu Nike, Omnipotent Int'l Christian Cent, Faith Tabernacle, Premier Layout, and Thinker Corner Hill areas reveal moderate to high DIR with DI ranging from 98–167. Low to very low DIR is recorded around Lavida Suites, Ugboezechi Abakpa, Republic Estate, Thinker Corner, New Heaven, Alor Street, and Thinkers Corner. It was believed that contaminants and contaminate transport will be very low within this area. Table 2

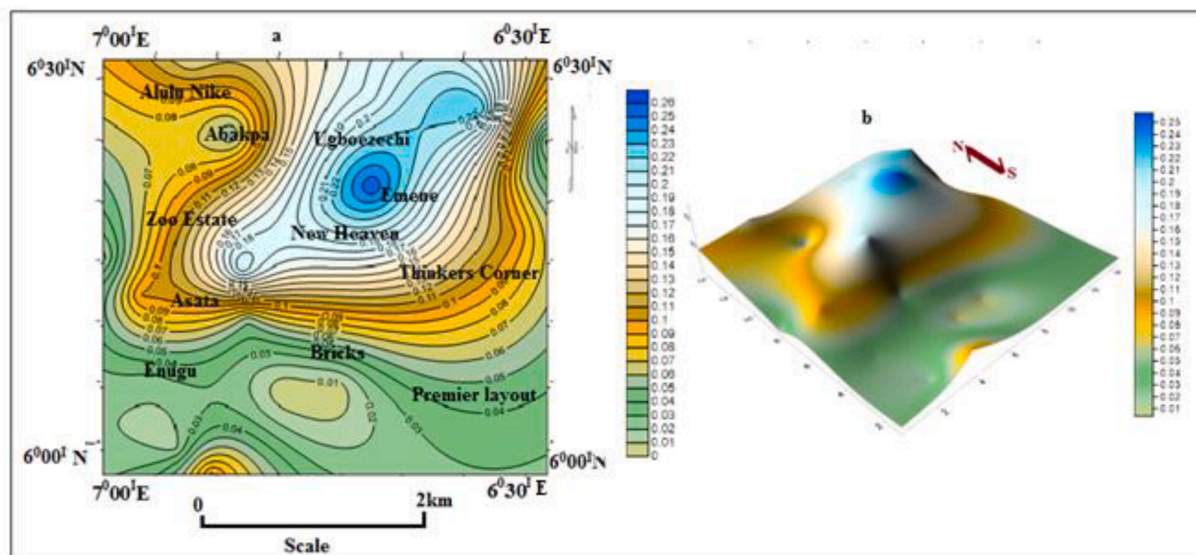


Fig. 13. a) Aquifer storability capacity map; b) 3D storability subsurface model map of the study area.

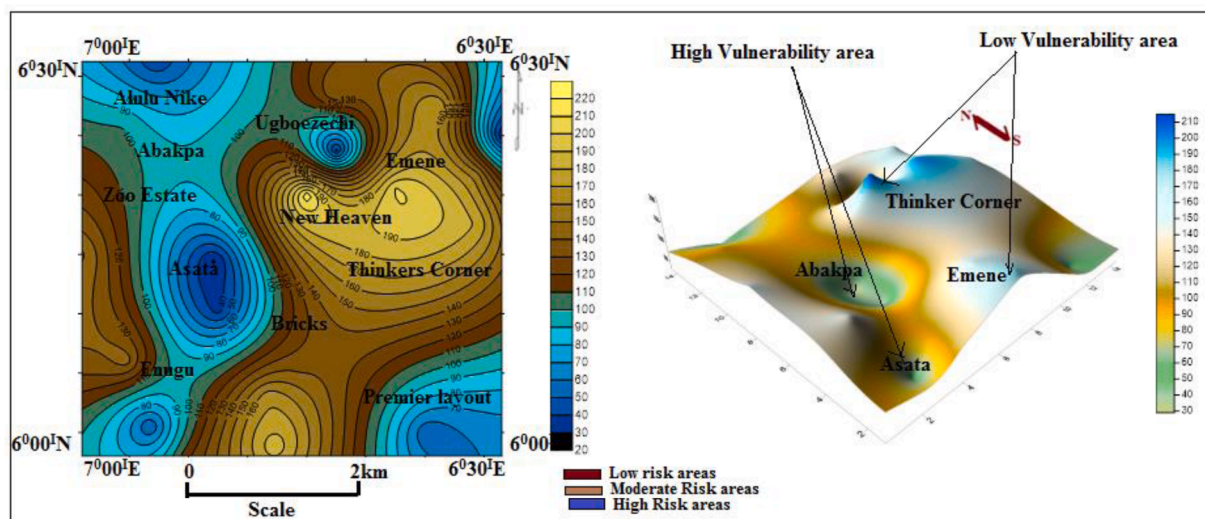


Fig. 14. DRASTIC Index Risk (DIR) map showing vulnerability level of the area.

Around Asata and New Heaven areas, the depth of the aquifer ranges from 4.0 to 11.626 m; the areas with shallower aquifers may be more vulnerable to contamination. There is high transmissivity in the New Heaven and Asata areas (109.7655 and 1470 L/S, respectively). Locations with high transmissivity tend to show very high vulnerability, except for Joe Udeh Close Thinker Corner, which has moderate transmissivity (50.7465 L/S) but very high vulnerability due to shallow depth. Again, high hydraulic conductivity is recorded around New Heaven: 0.008673779 Asata: 0.006666667. High hydraulic conductivity values are associated with very high vulnerability. Thinker Corner Hill, Alulu Nike, and Emene with aquifer depths of 15 m, 23 m, and 18.209 m have relatively shallow to moderately deep aquifer depths, supporting the trend that shallower aquifers tend to have higher vulnerability. Low vulnerability is recorded around Lavida Suites, Ugboezochi, and Republic Estate; these locations have relatively deeper aquifer depths (ranging 34.22 to 40.00 m), suggesting lower vulnerability (Fig 14). The transmissivity and hydraulic conductivity in these areas are relatively high

Table 2

DRASTIC criteria for vulnerability assessment [3].

Vulnerability class	Low	Moderate	High	Very High
Calculated vulnerability	47–92	93–136	137–184	.184

Table 3
Vulnerability class definition (Aller et al. 2021).

Vulnerability class	Definition
Very High	It affects most water contaminants and acts quickly in many instances of pollution.
High	It is vulnerable to a wide spectrum of pollutants in different pollution environments, except for those that are quickly absorbed or transformed.
Moderate	It can become sensitive to some toxins, but only if they are discharged or leached on a regular basis.
Low	Conservative pollutants are only vulnerable in the long run if they are continually and widely emitted or leached
Very Low	The confining layer does not include any notable vertical groundwater flow leaks.

(transmissivity and hydraulic conductivity range from 258.927 to 515.716 l/s and to 0.001548107, respectively) (Table 4). By examining these factors, we can see that while transmissivity and hydraulic conductivity are important, aquifer depth often has a significant influence on the vulnerability classification. Shallower aquifers tend to have higher vulnerability, while deeper aquifers have lower vulnerability. A higher transmissivity area revealed around an area with deeper aquifer depth is often associated with lower vulnerability, while higher hydraulic conductivity can correlate with lower vulnerability. The DRASTIC vulnerability index values ranged from 28 to 201, indicating low to very high vulnerability to contamination. Areas with higher vulnerability indices corresponded to regions with shallower water tables, higher recharge rates, and more permeable overlying materials (Fig 14).

The low-permeability Enugu Shale Formation is naturally resistant to groundwater movement, but faults and fractures significantly modify flow dynamics by acting as either barriers or conduits. In fractured zones, groundwater flow is enhanced, but so is vulnerability to contamination, making structural geology a critical factor in groundwater resource management and protection strategies. While the study provides valuable insights into groundwater conditions in the Enugu Shale Formation, its accuracy is limited by the inability of the DRASTIC model to fully capture fracture flow dynamics and the intrinsic low permeability of the formation. Future work should focus on incorporating fracture flow models and additional geophysical methods to enhance the assessment of groundwater vulnerability in such complex hydrogeological settings.

Conclusions

Understanding aquifer characteristics and vulnerability is crucial for sustainable water resource management. This study focuses on the aquifer characterization and vulnerability modeling of the permeable Enugu Shale Formation in the Anambra Basin, Nigeria, utilizing the electrical resistivity method. The electrical resistivity method is a valuable geophysical technique for subsurface investigation and has been employed to delineate aquifer properties and vulnerability in various geological settings. In this research, geophysical surveys were conducted using the electrical resistivity method to investigate the Enugu Shale Formation's hydrogeological characteristics. The results obtained from the geophysical surveys were integrated with hydrogeological data to construct aquifer vulnerability models that can aid in effective groundwater resource management. The study findings provide insights into the hydrogeological properties of the Enugu Shale Formation and offer a valuable contribution to the understanding of aquifer

Table 4
Calculated DRASTIC index risk (DIR) parameter revealing the class of risk vulnerability in the region.

S/ N	Town Name	Lat	Long	Aquifer depth (m)	Hydraulic Conductivity (C)	Transmissivity (L/ S)	DRASTIC Index (DI)	Class of Risk
1	Bricks	6.437	7.537	18.727	146.218* E-6	177.540	167.000	high
2	Emene	6.479	7.578	18.209	3863.689* E-6	104.254	152.000	high
3	Faith Tabernacle	6.428	7.521	27.602	751.501* E-6	296.646	116.000	Moderate
4	Fifth Avenue New Haven	6.454	7.544	11.626	8673.779* E-6	109.766	187.000	very high
5	Lavida Suites	6.449	7.504	33.773	1548.107* E-6	258.927	36.000	low
6	Ogbonna Str Emen	6.479	7.595	12.353	18,698.229* E-6	85.954	169.000	high
7	Zoo Estate Crown Bird	6.467	7.508	10.843	4662.222* E-6	112.035	152.000	high
8	Zoo Estate	6.465	7.507	9.014	1745.292* E-6	60.750	145.000	high
9	Asata	6.405	7.487	4.000	6666.667* E-6	1470.000	201.000	very high
10	Thinker Corner	6.466	7.5340	55.000	3333.333* E-6	726.000	28.000	very low
11	New Heaven	6.453	5.585	40.000	5.000* E-3	460.000	36.000	very low
12	Alor Street Thinker Corner	6.473	7.523	34.220	7575.184* E-6	416.904	41.000	very low
13	Alulu Nike	6.505	7.514	15.000	8695.652* E-6	1875.000	178.000	high
14	Thinker Corner Via Airport	6.476	7.547	44.567	2232.442* E-6	545.428	30.000	very low
15	Joe Udeh Close Thinker Corner	6.474	7.536	4.775	310.347* E-6	50.747	218.000	very high
16	Premier Layout	6.439	7.546	24.000	952.381* E-6	504.000	98.000	moderate
17	Omnipotent Int'l Christain Cent	6.464	7.539	13.165	343.737* E-6	307.806	140.000	high
18	Ugboezochi Abakpa	6.483	7.538	27.182	1158.064* E-6	316.770	52.000	low
19	Republic Estate	6.421	7.533	29.424	552.517* E-6	515.716	50.000	low
20	Thinker Corner Hill	6.465	7.545	23.000	8.000* E-6	528.000	139.000	high

vulnerability in the Enugu shale Formation, Anambra Basin. The Hydrogeophysical survey revealed that the study area is underlain by predominantly the Enugu shale Formation. The target aquifer in the study area is the thick column wet shale and part immature fracture shale. While the compacted shale serves as the base. Aquifer vulnerability in low-permeable geologic layers, such as the Enugu shale region of the Anambra Basin, requires a comprehensive and multifaceted approach. Assessing vulnerability involves understanding the interplay between geologic media, recharge rates, and potential contamination pathways, with models like DRASTIC providing valuable frameworks. Characterizing aquifers in these regions demands detailed hydrogeological mapping, geophysical surveys, and hydraulic testing to capture the complexities of fracture-controlled flow and limited permeability. The integration of these methods and considerations provides a robust foundation for sustainable groundwater management, ensuring that aquifer resources are protected from contamination and utilized efficiently. In regions with low-permeable formations, this integrated approach is essential for balancing water supply needs with the protection of vulnerable groundwater resources.

Competing interest statement

The authors have no conflict of interest to declare in this research.

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Authors contributions

AOU, conceptualize the work, Data interpretation and Modeling; CCE, edited the manuscript and reviewed the entire manuscript; EMA, manuscript writing and Modelling; GBA, Visualization and data analysis; CJC, Visualization and editorial; LUO, Manuscript drafting and map production; AIC, did the data analysis and wrote the original draft; KOI, map production and manuscript review; III, Produce original manuscript

Ethics declarations

No, I declare that the authors have no competing interests as defined by Journal body, or other interests that might be perceived to influence the results and/or discussion reported in this paper.

Declaration of competing interest

The authors have no conflict of interest to declare in this research. we declare that the authors have no competing interests as defined by Journal body, or other interests that might be perceived to influence the results and/or discussion reported in this paper.

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