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# The evaluation of groundwater potential: Integration of the electrical resistivity method and Geographic Information System (GIS) In Afikpo, Ebonyi State, Southeastern Nigeria

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## Abstract

This study assesses groundwater potential in the Afikpo area of Ebonyi State, southeastern Nigeria, using an integrated approach combining electrical resistivity (ER) and Geographic Information Systems (GIS). The study area spans 84.36 $km^2$, including towns like Ehugbo Afikpo, Afikpo, Ndibe, and Ozara, bounded by coordinates Latitude 5°50'00"N to 5°55'00"N and Longitude 7°54'00"E to 7°59'00"E. The primary goal was to evaluate groundwater potential using Vertical Electrical Sounding (VES) with the Schlumberger array and GIS-based Analytic Hierarchy Process (AHP). A total of 20 VES points revealed seven geoelectric layers, with the main aquiferous units identified as wet and saturated sandstones. Apparent resistivity values in these layers ranged from 0.27 Ωm to 3298.30 Ωm, with thicknesses between 5.25 m and 248.20 m. Hydraulic conductivity values ranged from 0.20 to 1324.36 m/day, and transmissivity ranged from 1.55 to 80926.69 $m^2$/day. The findings indicate that 15 out of 20 VES points have moderate to high groundwater potential (>50 $m^2$/day). The GIS-AHP analysis categorized the area as predominantly low to moderate potential (64.56 $km^2$), with smaller zones of very low (7.52 $km^2$), high (12.90 $km^2$), and very high (0.11 $km^2$) potential. Compared to other regions in the Benue Trough, Afikpo shows more favorable groundwater conditions. The integration of GIS-AHP and ER methods proved effective in assessing groundwater potential, highlighting the value of combining traditional geophysical techniques with modern GIS-based analysis.

**Keywords:** Groundwater Exploration; Groundwater Potential; Electrical Resistivity Method; Geographic Information System (GIS).

## 1. Introduction

This study evaluates groundwater potential in Afikpo, Ebonyi State, using a combination of GIS-based mapping and the electrical resistivity method, focusing on groundwater potential based on layer thickness. The results identify moderate-to-high potential zones in the southwestern region and lower-to-moderate zones in the southeastern area. The GIS raster approach captures detailed variations, while the contour-based method highlights broader trends. Despite some differences, both methods align in identifying high-potential zones, underscoring the value of a hybrid approach for more accurate groundwater resource assessment. The study area, covering 84.36 $km^2$ in southeastern Nigeria, is located between Latitude 5°50'00"N to 5°55'00"N and Longitude 7°54'00"E to 7°59'00"E. Major towns include Afikpo and Ehugbo, with a well-developed road network connecting the towns. The region is primarily drained by the Cross River, supplemented by smaller streams.

Groundwater is crucial for drinking and irrigation in rural areas, especially during dry seasons. However, urbanization and industrialization pressures are threatening water resources, making effective groundwater management essential

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(Akaolisa et al., 2022; Abdulrazzaq et al., 2020). Key factors in evaluating groundwater potential include recharge rates, aquifer storage capacity, and responsiveness to climate and water abstraction (Akaolisa et al., 2022).

This research integrates electrical resistivity geophysics and GIS to assess groundwater potential, offering insights into subsurface conditions and aiding groundwater management. Traditional methods like pumping tests can be expensive and time-consuming, while geophysical and GIS methods provide efficient alternatives (David et al., 2021; Abubakar et al., 2023). GIS integrates various datasets, including geomorphology, geology, soil, drainage, lineament, and LULC, essential for determining groundwater potential (Roy et al., 2020). Georesistivity relies on the relationship between rock properties and geoelectric characteristics, offering a practical way to estimate aquifer properties (Purvance & Andricevic, 2000).

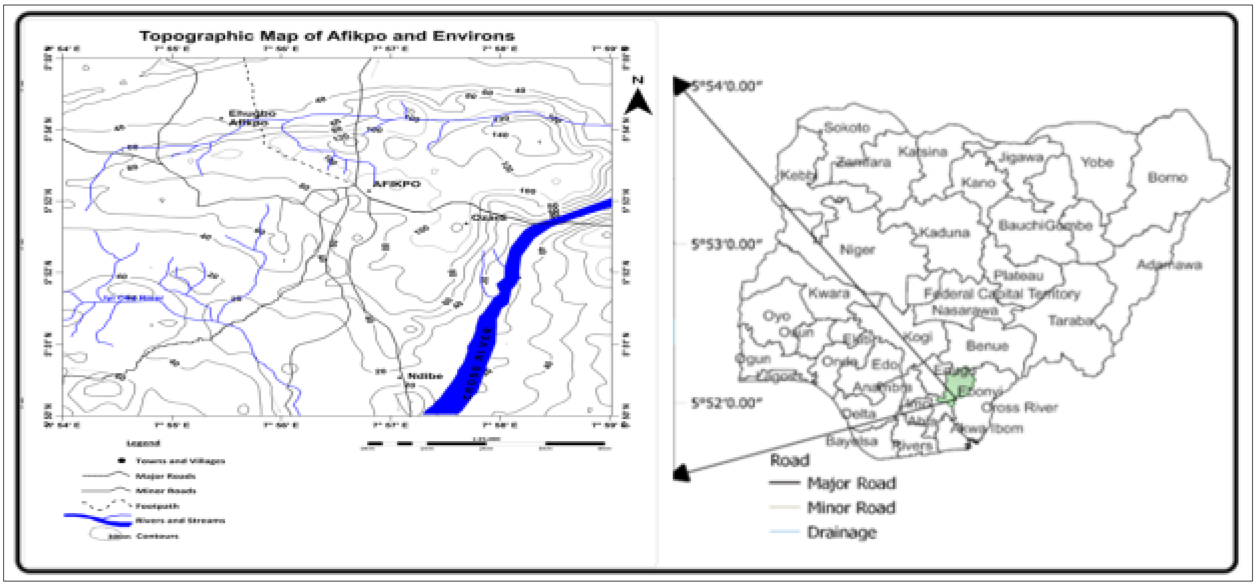


**Figure 1** Topographic Map of the study area

## 2. Literature Review

Several studies have assessed the groundwater potential in Afikpo and its surrounding areas, employing various geophysical and geological methods. Akaolisa et al. (2022) studied the Owutu-Ogbu area in Afikpo South, using geological mapping and geoelectrical sounding with the Schlumberger array configuration. Their findings identified fractured and jointed sandstones as the primary water-bearing units, with aquiferous layers occurring at depths of 50 to 60 meters, indicating groundwater potential for irrigation purposes. A more detailed study on the Afikpo Sub-basin analyzed the petrophysical properties of sandstones, shales, siltstones, and mudstones. This research, combining geological mapping and geoelectric resistivity surveys, found the sandstones had favorable characteristics for groundwater storage, with average porosity of 6.05%, hydraulic conductivity of $8.2 \times 10^5$ m/day, and transmissivity of $6.8 \times 10^7$ $m^2$/day, making them a viable aquifer (David et al., 2021). A hydrogeological and geophysical study of the Afikpo and Abakaliki regions revealed that the aquifer system consists of 3 to 7 geoelectric layers, with the third and fourth layers identified as the primary aquiferous units. The average depth of these layers was found to be 27.07 meters, with an average thickness of 15.61 meters (Osi-Okeke et al., 2021). Another study by Iduma et al. (2016) focused on the Afikpo and Ohaozara areas, identifying the sandstones of the Nkporo Formation as the main water-bearing units in the southern part of the area, characterized by greater thickness and higher resistivity values, suggesting better groundwater potential compared to the northern region.

Ekwe et al. (2020) applied electrical resistivity to determine the hydraulic conductivity and transmissivity in Afikpo, finding that the area had intermediate groundwater potential, suitable for meeting the water supply needs of small communities. Hydraulic conductivity ranged from 1.344 to 2.792 meters per day, and transmissivity ranged from 28.18 to 31.73 $m^2$ per day.

While these studies provide valuable insights into the groundwater potential of Afikpo, there is limited integration of advanced approaches. The combination of electrical resistivity with Geographic Information Systems (GIS) techniques, which incorporates geomorphological, soil, drainage, and land use data, could offer a more comprehensive understanding of groundwater resources, enhancing mapping and prediction across larger areas.

### 2.1. Geology and hydrogeology

#### *2.1.1. Local Geology*

The study area is part of the Afikpo Sub-basin, an eastern extension of the Anambra Basin in southeastern Nigeria, covering about 2,500 $km^2$. It includes stratigraphic sequences from the Albian to Campanian-Maastrichtian periods, contributing to its complex geology.

Key formations include the Nkporo Group (shales with water-bearing sandstone beds), Ajali Sandstone, Lower Coal Measures (coal seams and sandy layers), Ezeaku Group (calcareous shales and limestones), and the Asu River Group (shales, sandstones, and limestones).

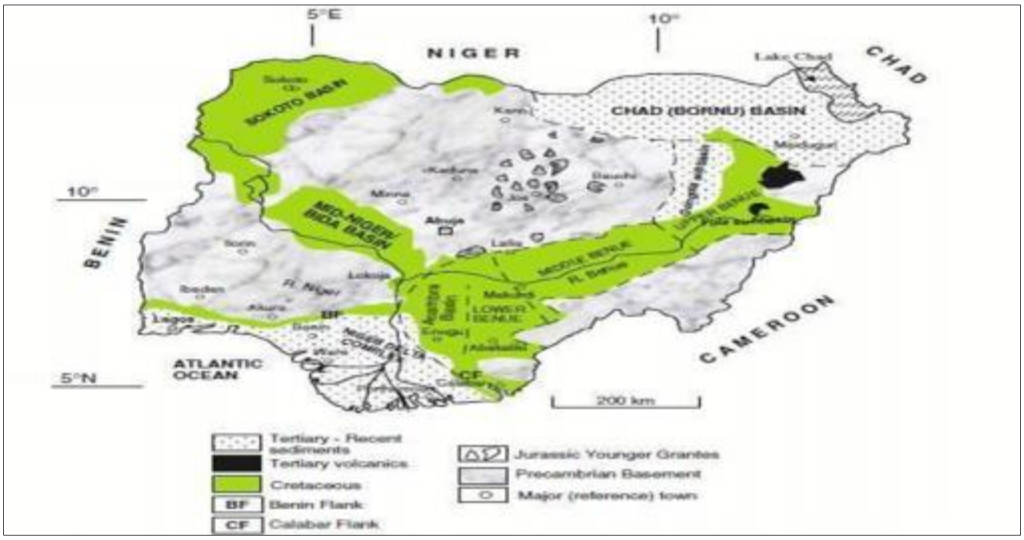


**Figure 2** Geological map of Nigeria showing the Precambrian basement complex, Jurassic Younger Granites, and Sedimentary Basins (Obaje, 2009)

#### *2.1.2. Hydrogeology of The study area*

The Afikpo area's hydrogeology has been widely studied, with the Nkporo Formation sandstones identified as the primary water-bearing units, particularly in the southern region where they are thicker and better sorted. In contrast, the northern region has lower groundwater potential. Ekwe et al. (2020) reported water table depths ranging from 11.5 to 52.1 meters, with aquifer thicknesses between 14 and 47.6 meters. Hydraulic conductivity values ranged from 1.344 to 2.792 meters per day, classifying the area as having intermediate groundwater potential. David et al. (2021) found average values of porosity, hydraulic conductivity, and transmissivity suggesting the Afikpo sandstones could serve as viable aquifers. The geoelectric studies identified 3 to 7 geoelectric layers, with the third and fourth layers as primary aquifers, ranging from 6.2 to 92.5 meters deep (Osi-Okeke et al., 2021). Productive aquifers are typically jointed and fractured sandstones found at depths of 50 to 60 meters (Akaolisa et al., 2022).

## 3. Materials and methods

### 3.1. Groundwater Potential Evaluation Using Resistivity Method

This study employed the Electrical Resistivity (ER) method, using Vertical Electrical Sounding (VES) with a Schlumberger array configuration. The principle behind ER surveys is that water increases rock conductivity, reducing resistivity. The Schlumberger array utilizes a pair of current electrodes (AB) and potential electrodes (MN), with the distance between AB gradually increased to measure deeper subsurface resistivities. Shown in figure 3.1.

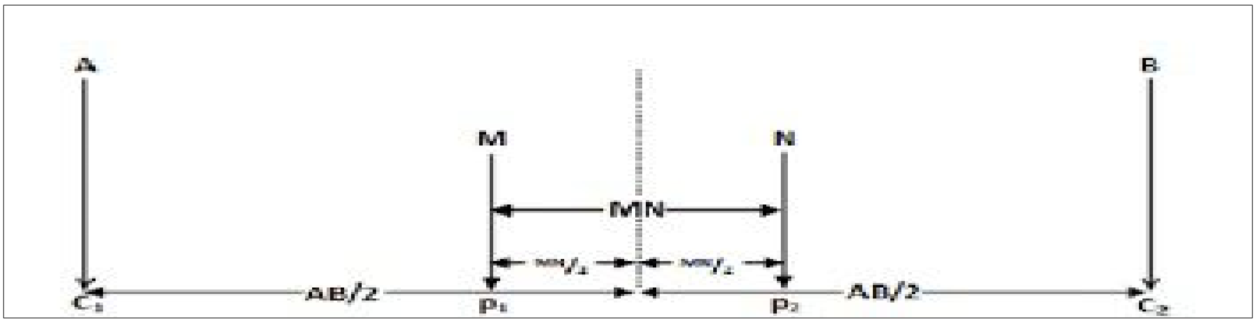


**Figure 3** Schlumberger array configuration. Schulumberger C., M. (1932)

A total of 20 VES were conducted across the study area with a maximum AB spacing of 500 meters, enabling investigation up to 250 meters deep. The Ohmega terrameter was used for precise resistivity measurements, with equipment including stainless steel electrodes, cables, and GPS for positioning. Apparent resistivity (ρa) was calculated using a geometric factor, as shown in Equation 1.

$$\rho a = \pi\left(\frac{a^2}{b} - \frac{b}{4}\right) \times R \dots\dots\dots\dots (1)$$

Where $\pi\left(\frac{a^2}{b} - \frac{b}{4}\right)$ is a constant, K (the geometric factor), $\rho a$ is the apparent resistivity, a is the half current electrode separation (AB/2), b is the potential electrode separation, and R is the meter reading in ohms.

The data were interpreted using curve matching, where the field data were compared to theoretical models to estimate the thickness and resistivity of subsurface layers. This method is reliable as resistivity variations due to moisture content are consistent across seasons.

Dar Zarrouk parameters, such as longitudinal conductance (S) and transverse resistance ($T_r$), were used to analyze layer resistivity and thickness. S indicates aquifer protection, while T correlates with transmissivity, helping assess aquifer yield. The following equations were used:

. The formulations for these parameters are straightforward:

$$S = \Sigma\frac{h_i}{\rho_i} \dots\dots\dots\dots (2)$$

$$T_r = \Sigma h_i \rho_i \dots\dots\dots (3)$$

To estimate hydraulic conductivity (K), an empirical relationship was used, and transmissivity (T) was calculated by multiplying K, S, and resistivity (ρ). Groundwater potential was classified based on transmissivity, with categories ranging from low (<50 $m^2$/day) to high (>500 $m^2$/day). Effective porosity (∅) was estimated using a relationship with hydraulic conductivity.

The equations are as follows:

$$K = 386.4 \cdot \rho^{-0.93283} \dots\dots\dots\dots (4)$$

$$T = K \cdot S \cdot \rho \dots\dots\dots\dots (5)$$

$$\emptyset = 25.5 + 4.5 \cdot \ln(K) \dots\dots\dots\dots\dots (6)$$

These methods allowed for detailed analysis of groundwater potential and informed decisions on groundwater resource management.

### 3.2. Groundwater Potential Evaluation using GIS

The groundwater potential map was created using QGIS 3.8 and ArcMap 10.4, employing seven parameters that influence groundwater potential: Geomorphology, Lineament Density, Lithology, Slope, Soil, Land Use/Land Cover (LULC), and Drainage Density. These parameters were derived from various sources such as the Nigeria Geological Survey Agency (NGSA, 2020), Shuttle Radar Topography Mission (SRTM) Digital Elevation Model (DEM), and Sentinel-2 Satellite Imagery. The layers were ranked based on their importance, with Geomorphology being the most influential and Soil being the least.

The Multi-Criteria Overlay analysis was performed using the Analytic Hierarchy Process (AHP), developed by Satty (1980), to delineate groundwater potential zones. AHP steps include creating a hierarchical structure, determining the relative importance of criteria via pairwise comparison, and assigning weights. The weights for each parameter were based on expert opinions, literature review, and field surveys. Hydrogeomorphology was given the highest weight, while Slope, Lineament Density, LULC, and Drainage Density received moderate weights, and Soil was assigned the lowest. The groundwater potential zones were generated using the Cumulative Score Index (CSI), which combined the ranks and weights of each parameter. The formula for CSI:

$$CSI = \sum (\textbf{Geology rank} \times \textbf{weight} + \textbf{Geomorphology rank} \times \textbf{weight} + \quad 7$$
$$\textbf{Soil rank x weight} + \textbf{Lineament density rank} \times \textbf{weight} +$$
$$\textbf{Drainage density rank} \times \textbf{weigh}\mathrm{t} + \textbf{LULC} \times \textbf{weight})$$

This method allowed the creation of a groundwater potential map based on the integrated analysis of the various factors influencing groundwater availability in the study area.

**Table 1** Weights assigned for different ground water control parameters in the present study

| Factors | Weight (%) | Highest rank | Rank |
|---|---|---|---|
| Geomorphology | | | |
| Low relief (1 - 4) | 36.28 | 5 | 5 |
| Moderate relief (4 -8) | | | 3 |
| High relief (> 8) | | | 1 |
| Geology | | | |
| Mamu Formation | 25.99 | 5 | 5 |
| Nkporo Formation | | | 3 |
| Eze-aku Formation | | | 1 |
| Drainage Density | | | |
| Very high (> 4.92) | 12.98 | 5 | 5 |
| High (3.69 - 4.92) | | | 4 |
| Moderate (2.46 - 3.69) | | | 3 |
| Low (1.23 - 2.46) | | | 2 |
| Very low (0.1 - 1.23) | | | 1 |
| Lineament | | | |
| Very high (> 3.64) | 9.46 | 5 | 5 |
| High (2.72 - 3.63) | | | 4 |
| Moderate (1.81 - 2.72) | | | 3 |
| Low (0.91 - 1.81) | | | 2 |

| | | | |
|---|---|---|---|
| Very low (0. - 0.91) | | | 1 |
| LULC | | | |
| Water bodies | 6.29 | 5 | 5 |
| Grassland | | | 4 |
| Forest | | | 4 |
| Urban | | | 2 |
| Agriculture land | | | 4 |
| Slope | | | |
| very low (16.38 -34.80) | 5.09 | 5 | 1 |
| low (10.24 - 16.38) | | | 2 |
| medium (6.14 - 10.24) | | | 3 |
| high (2.87 – 6.14) | | | 4 |
| very high (0 - 2.87) | | | 5 |
| Soil | | | |
| Cambisols | 3.91 | 5 | 3 |
| Nitisols | | | 5 |

**Table 2** Normalized Pairwise comparison matrix (seven layers) developed for AHP based groundwater potential zoning (Goepel, 2018)

| Matrix | | Geomorphology | Geology | Drainage density | Lineament density | LULC | Slope | Soil | 0 | TWI | Curvature | normalized principal Eigenvector |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | |
| Geomorphology | 1 | 1 | 2 | 4 | 4 | 5 | 5 | 7 | 0 | 0 | 0 | 36.28% |
| Geology | 2 | ½ | 1 | 3 | 3 | 5 | 5 | 5 | 0 | 0 | 0 | 25.99% |
| Drainage density | 3 | ¼ | 1/3 | 1 | 1 | 3 | 3 | 5 | 0 | 0 | 0 | 12.98% |
| Lineament density | 4 | ¼ | 1/3 | 1 | 1 | 1 | 2 | 3 | 0 | 0 | 0 | 9.46% |
| LULC | 5 | 1/5 | 1/5 | 1/3 | 1 | 1 | 1 | 2 | 0 | 0 | 0 | 6.29% |
| Slope | 6 | 1/5 | 1/5 | 1/3 | ½ | 1 | 1 | 1 | 0 | 0 | 0 | 5.09% |
| Soil | 7 | 1/7 | 1/5 | 1/5 | 1/3 | ½ | 1 | 1 | 0 | 0 | 0 | 3.91% |

### 3.3. Preparation of GIS Thematic layers

- **Geology**: The Afikpo area's geology falls within the Nkporo Group rock units, consisting of two main stratigraphic sequences: the 'Nkporo Shale-Owelli Sandstones' and 'Owelli Sandstones-Enugu Shale'. These sequences are of fluvio-deltaic origin, with the Nkporo Formation predominantly consisting of shaly units but also containing two aquiferous sandstone members. Previous studies indicate that the groundwater potential in this region is low, based on resistivity and pumping tests.
- **Geomorphology**: The geomorphology map was created using the GRASS GIS tool in QGIS, which classifies the area into three relief categories: low, moderate, and high. Lower relief areas were deemed to have higher groundwater potential, as they are more conducive to water infiltration.

- **Soil**: The soil map, based on the European Soil Data Centre, identifies two main soil types in the area: Cambisols and Nitisols. Both are well-drained and possess moderate to high groundwater potential due to their permeability and favorable structure for groundwater infiltration and storage.
- **Land Use Land Cover (LULC)**: The LULC map was generated from SENTINEL-2 satellite imagery and reclassified into five categories: urban/built-up areas, agricultural land, grassland, water bodies, and forests. This classification helps in understanding how different land uses influence groundwater recharge.
- **Drainage Density**: The drainage density map, created using QGIS and the SAGA plugin, was categorized into five ranges from very low to very high drainage density. Drainage density has an inverse relationship with groundwater potential, with lower drainage density indicating higher potential for groundwater recharge.
- **Lineament Density**: The lineament map was created using SRTM DEM data and hillshade techniques in ArcMap. Lineament density, which reflects the frequency of geological fractures, was categorized into five ranges. Higher lineament density is associated with higher groundwater potential, as fractures allow for increased water movement.
- **Slope**: The slope map, derived from the SRTM DEM using QGIS, reveals an inverse relationship with groundwater potential. Flatter areas, with lower slope values, provide more time for surface water to infiltrate the ground. The slope was categorized into five levels, with flatter areas offering the highest potential for groundwater recharge.

These analyses provide a comprehensive view of the factors influencing groundwater potential in the Afikpo area, using various geospatial tools and data sets.

## 4. Results and Discussion

### 4.1. Qualitative Interpretation of the VES Data

Table 4.1 presents the inversion results of the Vertical Electrical Sounding (VES) data, revealing seven layers with varying patterns across locations. Ndibe mainly exhibits KHKQH curves (VES1, VES4, VES5), with some variations. Iyi Obo shows a mix of QHKHK (VES1) and AKHKH (VES2). Afikpo primarily follows the KHKHK pattern (VES1, VES2, VES5), with occasional deviations. Ozara has consistent QHKHK curves (VES1, VES2), indicating stable conditions. Ehugbo shows diverse patterns, reflecting geological variability. KHKQH and QHKHK are the most frequent curve types, representing 60% of the data, while other types like HKHKH and KHKQQ make up the rest. These variations highlight subsurface heterogeneity, which impacts groundwater management. Curves with "A" or "H" typically indicate sand layers with higher resistivity and better groundwater potential, while "K" and "Q" suggest shales or clayey sands with lower potential. Inferred lithology includes topsoil, lateritic/shale, iron-stained sand, wet sandstone, and saturated sand, with wet and saturated sandstones as the main Groundwater-bearing units.

The IX1D (Interpex) software was used to generate a curve of apparent resistivity against electrode distance using the 20 recorded vertical electrical sounding data, some graphs are shown below:

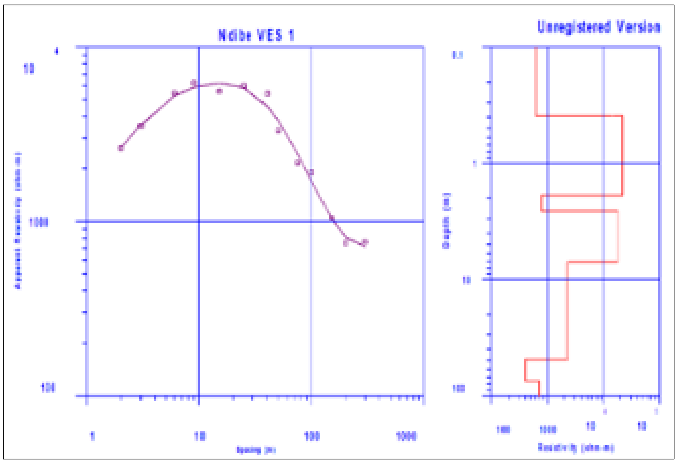


**Figure 4** Ndibe VES1 Resistivity curve type

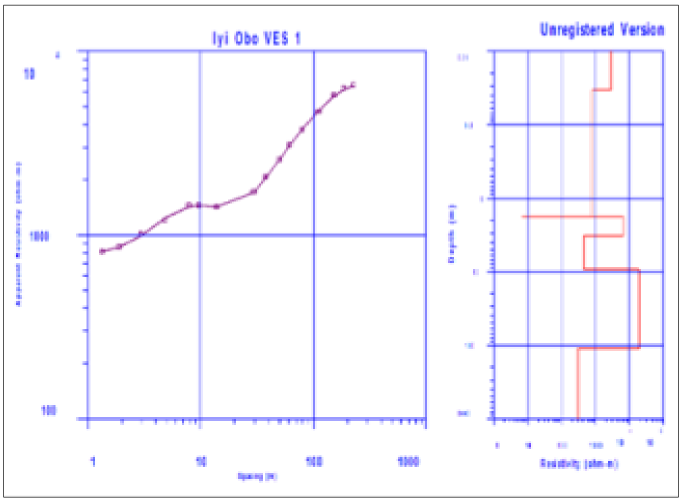


**Figure 5** Iyi Obo VES 1 Resistivity curve type

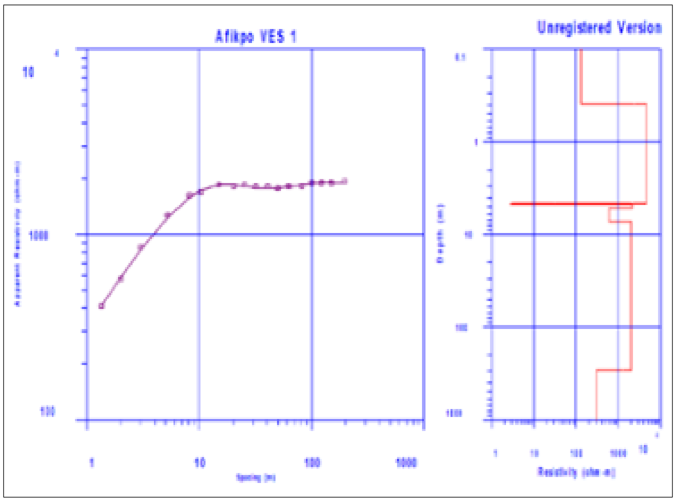


**Figure 6** Afikpo VES 1 Resistivity curve type

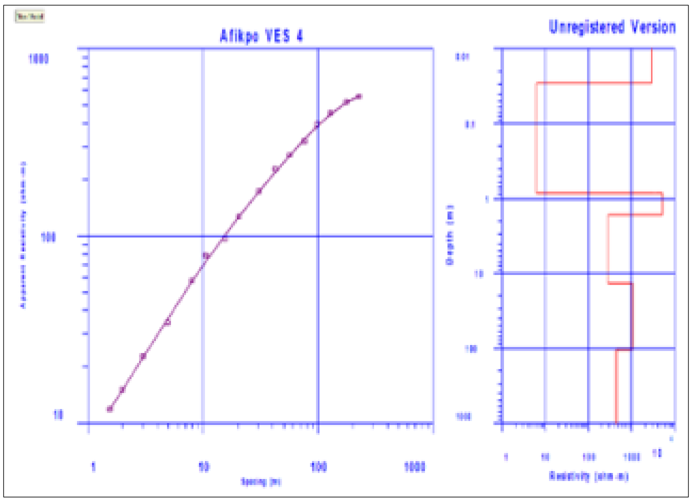


**Figure 7** Afikpo VES 4 Resistivity curve type

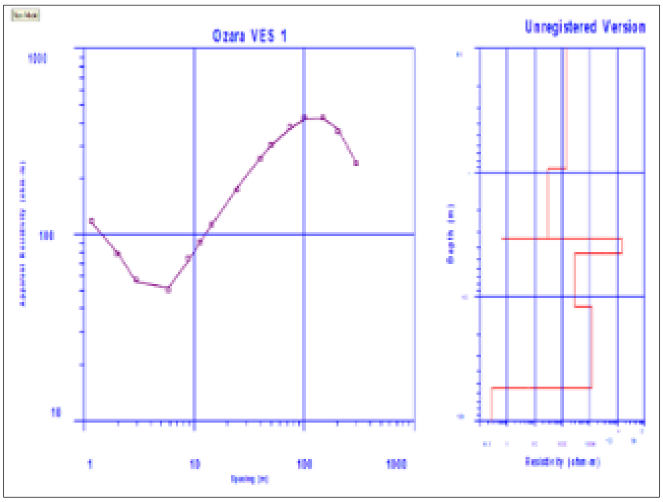


**Figure 8** Ozara VES1 Resistivity curve type

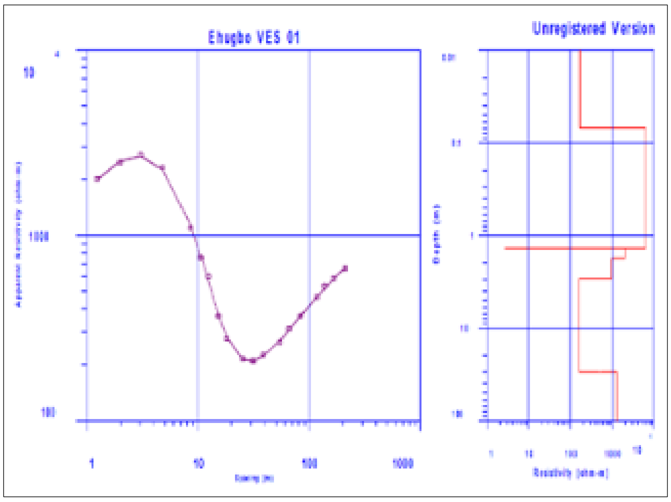


**Figure 9** Ehugbo VES1 Resistivity curve type

**Table 3** Summary of the geoeletric sounding data

| S/N | LOCATION | LATITUDE | LONGITUDE | NO. OF LAYERS | AQUIFER RESISTIVIT (Ωm) | THICKNESS (m) | DEPT (m) | CURVE TYPE |
|---|---|---|---|---|---|---|---|---|
| 1 | NDIBE VES1 | 5O 51' 00" | 7O 58' 10" | 7 | 469 | 29.01 | 43.45 | KHKQH |
| 2 | NDIBE VES2 | 5O 51' 30" | 7O 56' 46" | 7 | 20.6 | 5.25 | 20.23 | HKHKH |
| 3 | NDIBE VES3 | 5O 51' 26" | 7O 54' 58" | 7 | 0.369 | 78.17 | 96.8 | KHKQQ |
| 4 | NDIBE VES4 | 5O 50' 24" | 7O 55' 24" | 7 | 312.1 | 64.97 | 74.49 | KHKQH |
| 5 | NDIBE VES5 | 5O 51' 35" | 7O 56' 28" | 7 | 3298.3 | 7.67 | 39.59 | KHKQH |
| 6 | IYI OBO VES1 | 5O 52' 26" | 7O 54' 28" | 7 | 294.2 | 85.45 | 94.68 | QHKHK |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 7 | IYI OBO VES2 | 5O 51' 20" | 7O 54' 10" | 7 | 470 | 30.02 | 44.45 | AKHKH |
| 8 | AFIKPO VES 1 | 5O 53' 40" | 7O 57' 10" | 7 | 298.1 | 248.2 | 255.79 | KHKHK |
| 9 | AFIKPO VES 2 | 5O 53' 30" | 7O 58'50" | 7 | 0.296 | 25.33 | 34.84 | KHKHK |
| 10 | AFIKPO VES 3 | 5O 54' 20" | 7O 53' 30" | 7 | 139.7 | 46.46 | 56.66 | QHKHK |
| 11 | AFIKPO VES 4 | 5O 52' 35" | 7O 57' 18" | 7 | 438.1 | 91.06 | 105.09 | HKHKA |
| 12 | AFIKPO VES 5 | 5O 53' 32" | 7O 55' 22" | 7 | 419.1 | 26.73 | 68.9 | KHKQH |
| 13 | OZARA VES1 | 5O 52' 20" | 7O 57' 48" | 7 | 0.269 | 44.75 | 57.62 | QHKHK |
| 14 | OZARA VES2 | 5O 52' 10" | 7O 58' 50" | 7 | 0.291 | 33.64 | 82.78 | QHKHK |
| 15 | EHUGBO VES1 | 5O 54' 20" | 7O 52' 40" | 7 | 1240.4 | 27 | 29.92 | KHKQH |
| 16 | EHUGBO VES2 | 5O 53' 48" | 7O 54' 46" | 7 | 0.271 | 61.96 | 71.6 | QHKHK |
| 17 | EHUGBO VES3 | 5O 52' 24" | 7O 55' 06" | 7 | 0.267 | 55 | 61.04 | QHKHK |
| 18 | EHUGBO VES4 | 5O 53' 28" | 7O 54' 44" | 7 | 44.25 | 6.34 | 12.92 | KHKQQ |
| 19 | EHUGBO VES5 | 5O 53' 42" | 7O 56' 22" | 7 | 175.7 | 62.96 | 86.65 | KHKHK |
| 20 | EHUGBO VES6 | 5O 54' 03" | 7O 56' 00" | 7 | 286.8 | 100.7 | 107.15 | KHKHK |

### 4.2. Quantitative Interpretation of the VES Data

The study area's resistivity data varies significantly, with apparent resistivity ranging from 7.1 Ωm (VES5) to 23,107 Ωm (VES9), with an average of 2,168.17 Ωm. The thickness of geoelectric layers ranges from 0.62 m (VES8) to 75.6 m (VES15), with an average depth of 12.42 m and the depth to the top of the last layer varying from 10.21 m (VES1) to 86.37 m (VES5), averaging 35.06 m.

- **Profile 1** (VES8, VES2, VES3, VES7, VES9) shows a thin topsoil layer (482-9,569 Ωm), with wet silty sandstone ranging from 14.5 Ωm to 39,107 Ωm, indicating high clay content or dry sand. The saturated sand layer (28.4-1,195 Ωm) is thickest under VES8, showing potential for groundwater storage. The shaly sand layer has resistivity values between 43.1 Ωm and 1,070 Ωm.
- **Profile 2** (VES14, VES10, VES11, VES12, VES1, VES15) reveals varied resistivity in the topsoil (268-5,209 Ωm) and wet silty sandstone (9.55-8,456 Ωm), with thicker saturated sand layers (up to 75.6 m at VES15), indicating high groundwater storage potential in areas like VES11, VES12, VES1, and VES15.
- **Profile 3** (VES4, VES5, VES6, VES13) shows a thin topsoil layer (133-2,941 Ωm), with lateritic and iron-stained sands present at VES5 and VES4. The wet silty sandstone and saturated sand layers vary greatly, with substantial *thicknesses and resistivity ranging from 7.1 Ωm to 8,143 Ωm, suggesting moderate groundwater potential in these areas.*

Overall, significant groundwater potential is observed in areas with thicker, moderately resistive saturated sand layers, particularly in Profile 2 and Profile 1 beneath VES8.

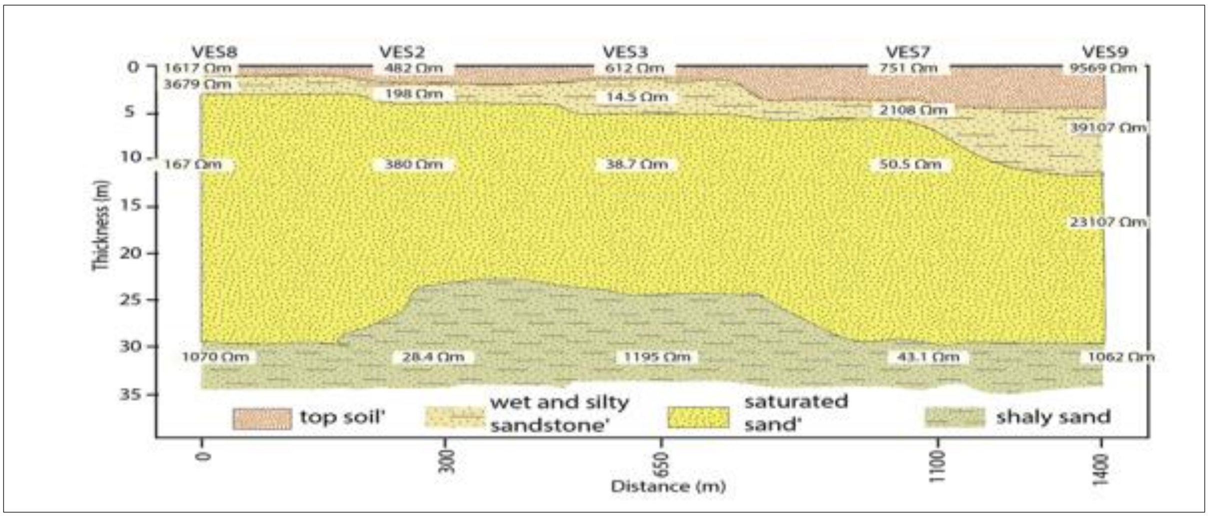


**Figure 10** Geoelectric cross-section (Profile 1) of collinear VES containing

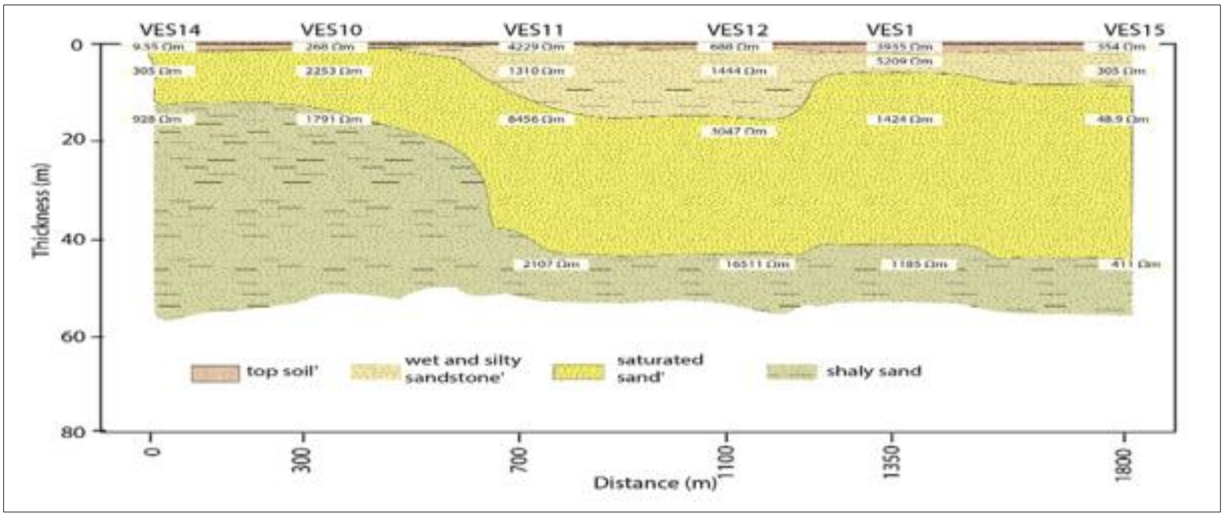


**Figure 11** Geoelectric cross-section (Profile 2) of collinear VES containing

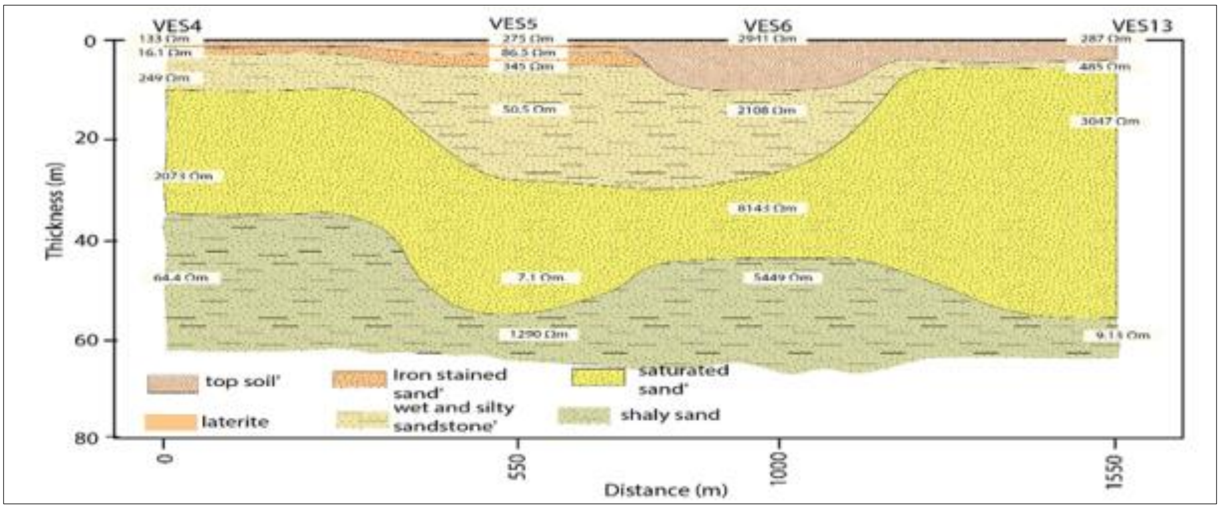


**Figure 12** Geoelectric cross-sections (Profile 3) of collinear VES containing

### 4.3. Thickness and Resistivity of Aquifer Geoelectric Layer

The primary aquifer units are wet silty sandstones and saturated sand. When both layers are present, resistivity is averaged, and thickness is the sum of the layers.

Key findings from Table 4.2:

- ***Resistivity*** *ranges from 0.27 Ωm (VES13) to 3298.30 Ωm (VES5), averaging 395.36 Ωm.*
- ***Thickness*** *ranges from 5.25 m (VES2) to 248.20 m (VES8), with an average of 56.48 m.*
- ***Depth*** *ranges from 12.92 m (VES18) to 255.79 m (VES8), with an average of 72.18 m.*

Isoresistivity and isopach maps show higher resistivity (>400 Ωm) in the southern region between Afikpo and Ndibe, and thicker aquifers (>45 m) in Afikpo trending northeast. Lower thicknesses (<30 m) are found around Ndibe, trending northwest.

**Table 4** Resistivity, thickness, and depth to the bottom of the aquifer geoelectric layer

| S/N | LOCATION/VES | Resistivity, ρ (Ωm) | Thickness, h (m) |
|---|---|---|---|
| 1 | NDIBE VES1 | 469 | 29.01 |
| 2 | NDIBE VES2 | 20.6 | 5.25 |
| 3 | NDIBE VES3 | 0.37 | 78.17 |
| 4 | NDIBE VES4 | 312.1 | 64.97 |
| 5 | NDIBE VES5 | 3298.3 | 7.67 |
| 6 | IYI OBO VES1 | 294.2 | 85.45 |
| 7 | IYI OBO VES2 | 470 | 30.02 |
| 8 | AFIKPO VES 1 | 298.1 | 248.2 |
| 9 | AFIKPO VES 2 | 0.3 | 25.33 |
| 10 | AFIKPO VES 3 | 139.7 | 46.46 |
| 11 | AFIKPO VES 4 | 438.1 | 91.06 |
| 12 | AFIKPO VES 5 | 419.1 | 26.73 |
| 13 | OZARA VES1 | 0.27 | 44.75 |
| 14 | OZARA VES2 | 0.29 | 33.64 |
| 15 | EHUGBO VES1 | 1240.4 | 27 |
| 16 | EHUGBO VES2 | 0.27 | 61.96 |
| 17 | EHUGBO VES3 | 0.27 | 55 |
| 18 | EHUGBO VES4 | 44.25 | 6.34 |
| 19 | EHUGBO VES5 | 175.7 | 62.96 |
| 20 | EHUGBO VES6 | 286.8 | 100.7 |

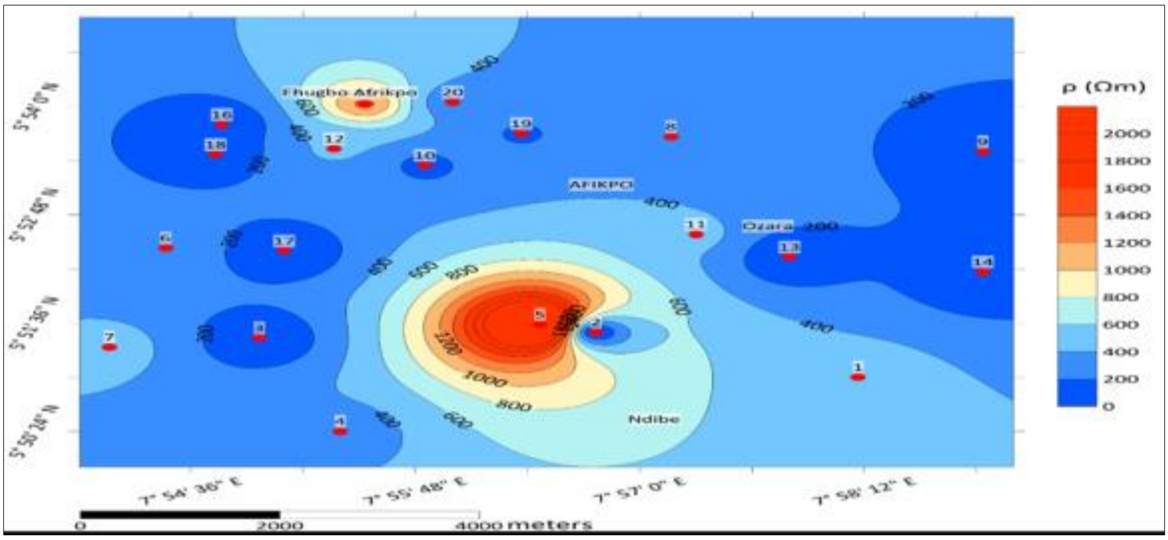


**Figure 13** Aquifer geoelectric layer resistivity map of the study area

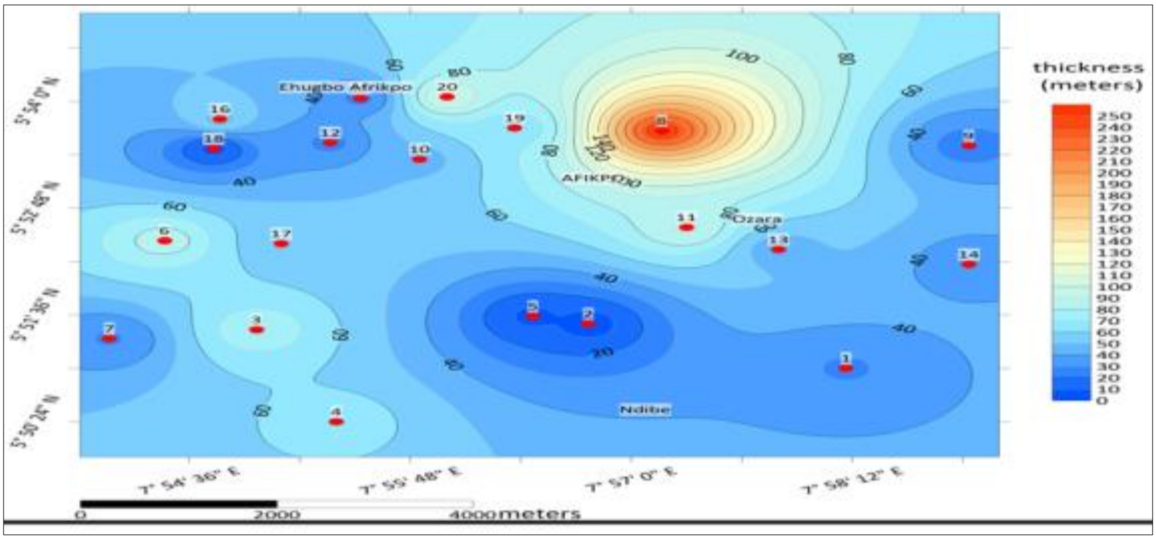


**Figure 14** Aquifer geoelectric layer thickness map of the study area

### 4.4. Dar Zarrouk Parameter and Hydraulic Properties of the Aquiferous Geoelectric Layer

Table 4.3 shows the Dar Zarrouk parameters and hydraulic properties of the aquiferous layer. Longitudinal conductance ranges from 0.002 to 228.6 mho (average: 56.48 mho), and transverse resistance varies from 7.50 to 73,988.42 $\Omega m^2$ (average: 15,170.63 $\Omega m^2$). Higher transverse resistance values (>20,000 $\Omega m^2$) indicate areas of higher groundwater potential.

Hydraulic conductivity ranges from 0.20 to 1324.36 m/day (average: 370.24 m/day), and transmissivity varies from 1.55 to 80,926.69 $m^2$/day (average: 18,126.14 $m^2$/day). According to Offodile's classification (1976), 15 out of 20 VES points fall within moderate to high groundwater potential (>50 $m^2$/day). The highest transmissivity is observed in the eastern and western parts, with the lowest in the central region.

Porosity ranges from 22.37% to 39.55% (average: 30.58%). These findings indicate areas of significant groundwater potential, with some regions requiring targeted exploration due to limited yield.

**Table 5** Dar Zarrouk parameters and hydraulic properties of the aquifer geoelectric layer

| S/N | Location/VES | Longitudinal Conductance, (mho) | Traverse Resistance, Tr (Ωm2) | Hydrualic conductivity, K (m/day) | Transmissivity, T (m2/day) |
|---|---|---|---|---|---|
| 1 | NDIBE VES1 | 0.06 | 13605.69 | 1.25 | 36.13 |
| 2 | NDIBE VES2 | 0.25 | 108.15 | 22.98 | 120.67 |
| 3 | NDIBE VES3 | 211.84 | 28.84 | 979.33 | 76554.02 |
| 4 | NDIBE VES4 | 0.21 | 20277.14 | 1.82 | 118.3 |
| 5 | NDIBE VES5 | 0 | 25297.96 | 0.2 | 1.55 |
| 6 | IYI OBO VES1 | 0.29 | 25139.39 | 1.92 | 164.41 |
| 7 | IYI OBO VES2 | 0.06 | 13606.70 | 1.30 | 37.13 |
| 8 | AFIKPO VES 1 | 0.83 | 73988.42 | 1.9 | 471.72 |
| 9 | AFIKPO VES 2 | 85.57 | 7.5 | 1202.91 | 30469.64 |
| 10 | AFIKPO VES 3 | 0.33 | 6490.46 | 3.85 | 179.07 |
| 11 | AFIKPO VES 4 | 0.21 | 39893.39 | 1.33 | 120.84 |
| 12 | AFIKPO VES 5 | 0.06 | 11202.54 | 1.38 | 36.97 |
| 13 | OZARA VES1 | 166.36 | 12.04 | 1315.17 | 58853.78 |
| 14 | OZARA VES2 | 115.6 | 9.79 | 1222.18 | 41114.01 |
| 15 | EHUGBO VES1 | 0.02 | 33490.8 | 0.5 | 13.57 |
| 16 | EHUGBO VES2 | 228.63 | 16.79 | 1306.11 | 80926.69 |
| 17 | EHUGBO VES3 | 205.99 | 14.69 | 1324.36 | 72839.56 |
| 18 | EHUGBO VES4 | 0.14 | 280.55 | 11.26 | 71.41 |
| 19 | EHUGBO VES5 | 0.36 | 11062.07 | 3.11 | 195.93 |
| 20 | EHUGBO VES6 | 0.35 | 28880.76 | 1.97 | 198.41 |

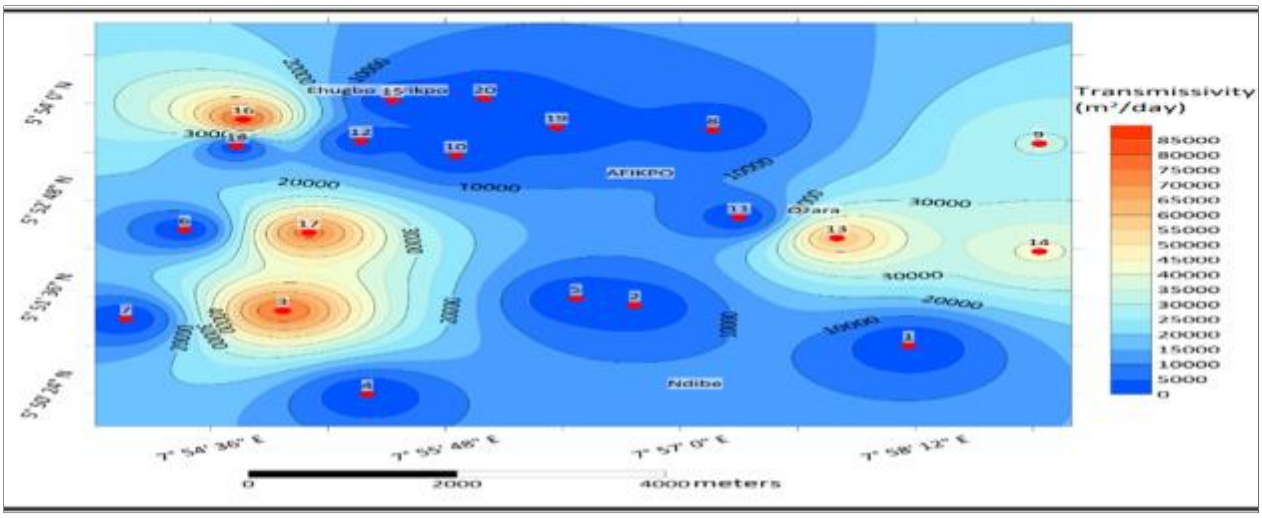


**Figure 15** Aquifer geoelectric layer transmissivity map of the study area

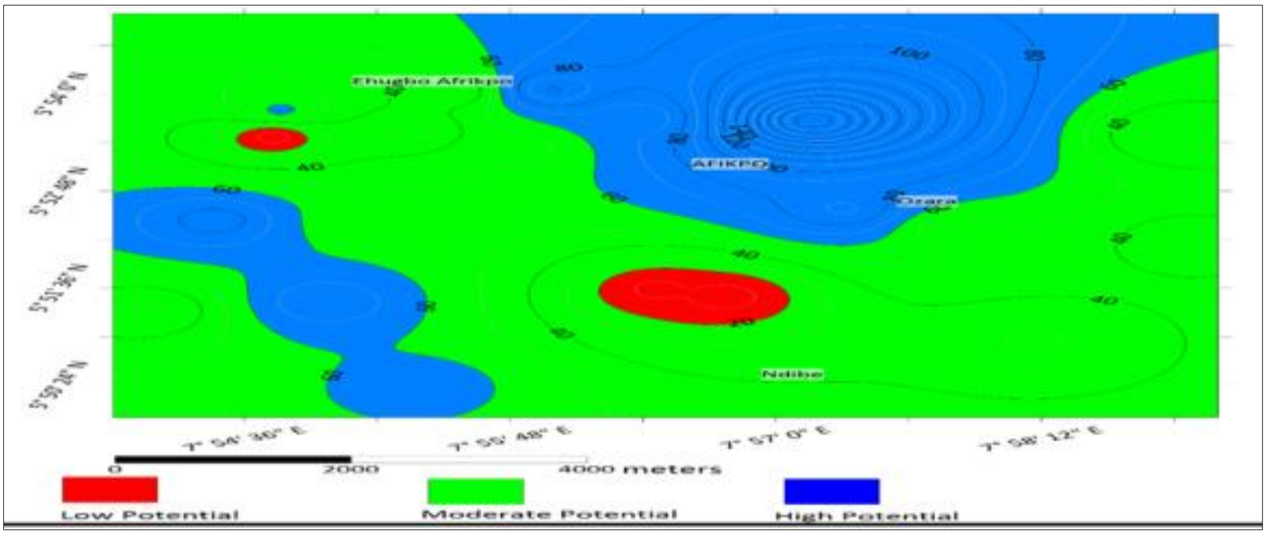


**Figure 16** VES, Groundwater potentials map

### 4.5. Result of GIS Groundwater potential using Analytic Hierarchy Process (AHP)

The GIS-based groundwater potential evaluation using the Analytic Hierarchy Process (AHP) categorized the study area based on several thematic layers:

- **Geomorphology**: Low relief (13.6 sq km), moderate relief (57.9 sq km), and high relief (14.3 sq km).
- **Geology**: Mamu Formation (4.23 km$^2$), Nkporo Formation (75.98 km$^2$), and Eze-Aku Formation (4.15 km$^2$).
- **Drainage Density**: Predominantly very low (19.64 sq km), with smaller areas in low to very high categories.
- **Lineaments**: Dominant NE-SW trend.
- **Slope**: Mostly low slopes, with high slopes in linear features.
- **Land Use**: Extensive urbanization limiting groundwater potential.
- **Soils**: Nitisols and Cambisols, both supporting moderate groundwater potential.

The groundwater potential was divided into five zones: very low (7.52 km$^2$), low (37.60 km$^2$), moderate (26.96 km$^2$), high (12.90 km$^2$), and very high (0.11 km$^2$). The low potential zone is the largest, while moderate to high zones cover 39.86 km$^2$ (46.85%).

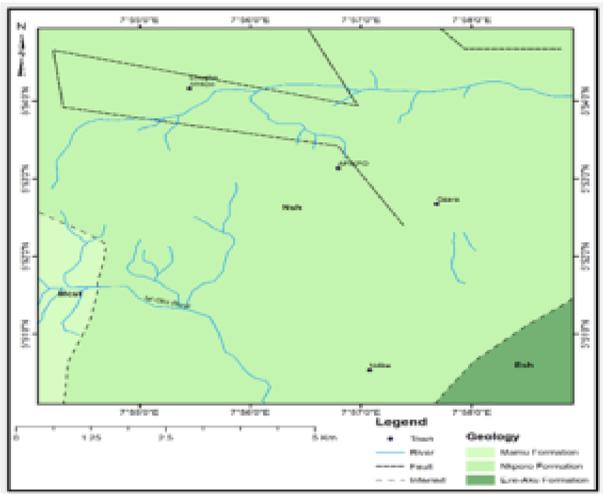


**Figure 17** Geologic map (Source: NGSA, 2020)

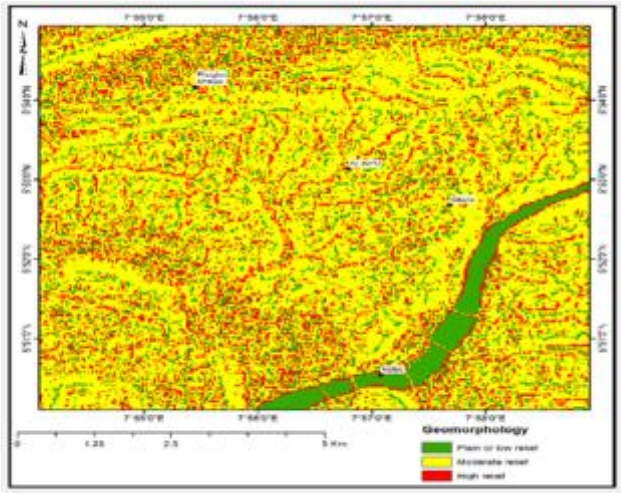


**Figure 18** Geomorphology map

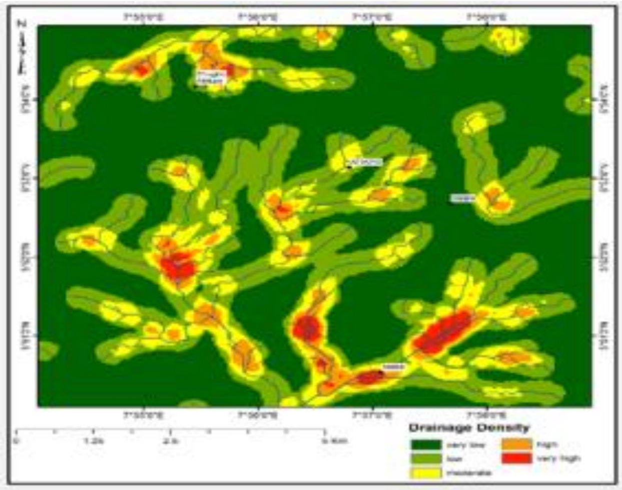


**Figure 19** Drainage density map

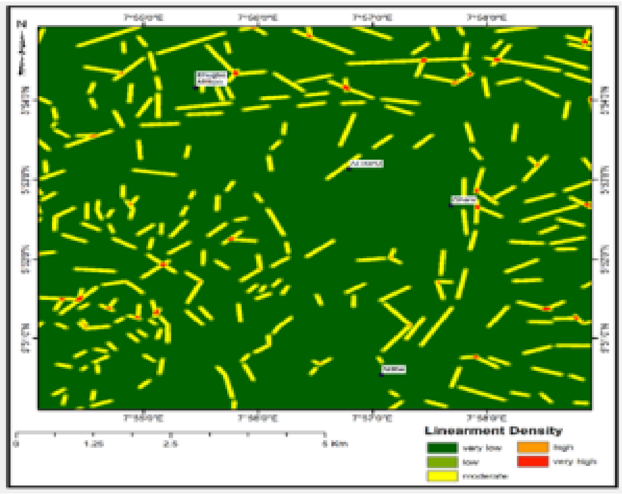


**Figure 20** Lineament density map

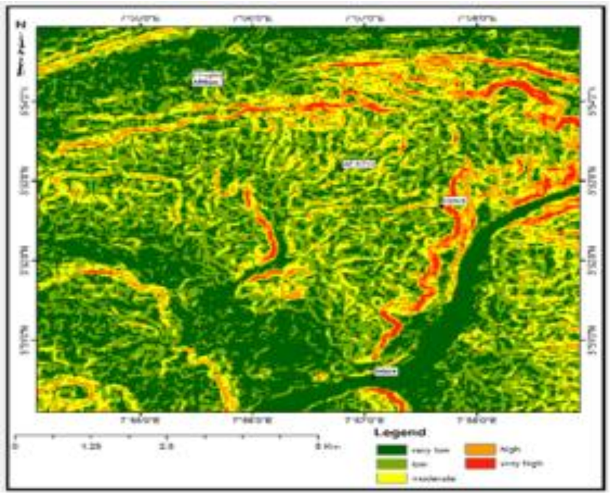


**Figure 21** Slope map

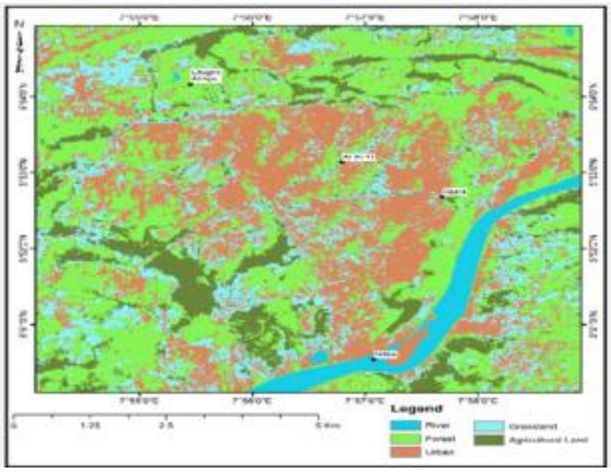


**Figure 22** Land Use and Land Cover map

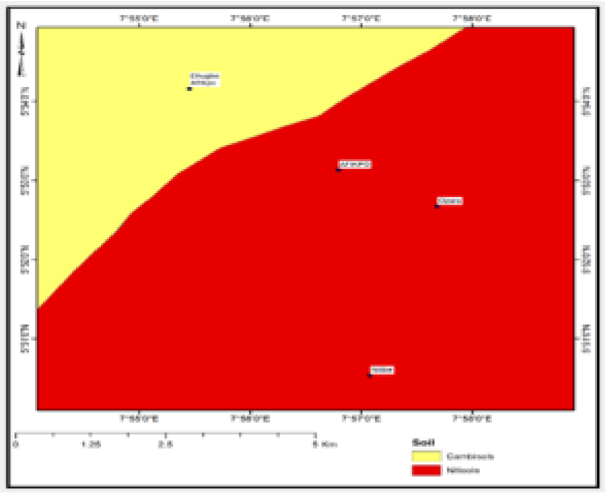


**Figure 23** Soil map (Source: ESDAC, 2018)

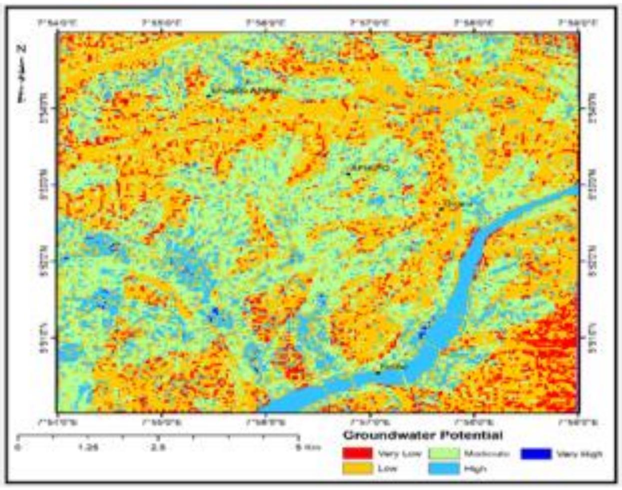


**Figure 24** GIS, Groundwater potentials map

### 4.6. Integration of GIS and Resistivity Groundwater Potentials

Figure 4.7 presents the integration of GIS-based and resistivity thickness-based groundwater potentials. The maps show moderate-to-high potential areas around Afikpo, its surroundings, and the southwestern regions, with lower-to-moderate zones in the southeast. The raster-based method captures finer variations, while the contour method highlights regional trends. Despite differences in spatial representation, the alignment of high-potential regions supports the validity of identified groundwater-rich zones, suggesting a hybrid approach for more accurate assessment.

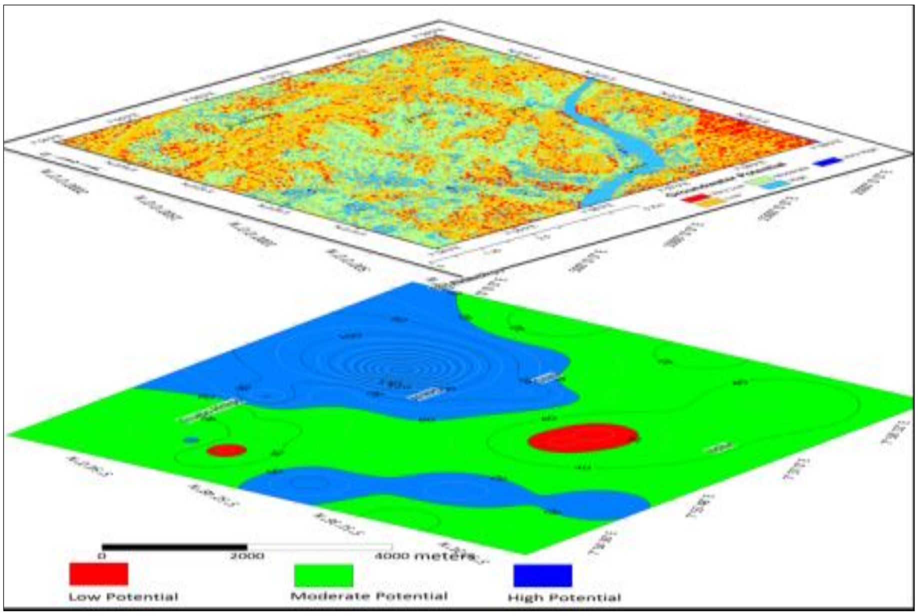


**Figure 25** The juxtapostions of the groundwater potential maps (VES & GIS)

## 5. Discussion

This study identified 7 geoelectric layers in the Afikpo area, including topsoil, lateritic/shale, and various sandstones, with wet and saturated sandstones as the main aquifers. Resistivity values ranged from 7.1 Ωm to 23,107 Ωm, with an average of 2,168.17 Ωm, and layer thickness varied from 0.62 m to 75.6 m (average 12.42 m). The aquiferous layers had resistivity values between 0.27 Ωm and 3,298.30 Ωm, with an average of 395.36 Ωm, and thicknesses ranging from 5.25 m to 248.20 m (average 56.48 m). The longitudinal conductance ranged from 0.002 to 228.6 mho, and transverse resistance from 7.50 to 73,988.42 $\Omega m^2$. Hydraulic conductivity and transmissivity varied from 0.20 to 1,324.36 m/day and 1.55 to 80,926.69 $m^2$/day, respectively. 16 out of 20 VES points showed moderate to high groundwater potential, matching the GIS-based groundwater potential analysis. This analysis, using the Analytic Hierarchy Process (AHP), classified the area into categories of very low, low, moderate, high, and very high potential, with most of the study area (64.56 $km^2$) falling in the low to moderate zones.

## 6. Conclusion

This study provides a detailed evaluation of the groundwater potential in the Afikpo area using both traditional geophysical methods and a GIS-based approach with the Analytic Hierarchy Process (AHP). The resistivity data revealed 7 geoelectric layers, with wet and saturated sandstones identified as the primary aquiferous units. The hydraulic conductivity and transmissivity measurements indicated that most of the area has moderate to high groundwater potential. These findings were corroborated by the GIS-AHP analysis, which categorized the majority of the study area as having low to high groundwater potential, with only smaller zones showing very low or very high potential.

## Compliance with ethical standards

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### *Disclosure of conflict of interest*

The authors declare no conflict of interest.

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