Topographical Influence on Groundwater Recharge: A Combined Slope and Hydrogeophysical Study in Umuahia South, Nigeria

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DOI: 10.56201/rjpst.v7.no4.2024.pg35.55

Abstract
Groundwater resources are crucial for sustaining domestic and agricultural activities in Umuahia South, Abia State, Southeastern Nigeria. The region's topography and subsurface characteristics significantly influence groundwater recharge and distribution. This study analyzes the slope variations and hydrogeophysical properties to assess groundwater potential and management strategies. The study aims to evaluate the impact of topographical and subsurface parameters on groundwater potential, focusing on slope analysis and hydrogeophysical characteristics in Umuahia South. The study employs a combination of slope analysis and Vertical Electrical Sounding (VES) to assess the area's groundwater potential. Slope analysis categorizes the terrain into five slope classes, while VES surveys examine apparent resistivity, aquifer depth, thickness, and associated hydrogeological parameters. The slope analysis reveals that the majority of the area has gentle slopes (1.87–3.49°), favorable for groundwater recharge. VES results indicate significant spatial variability in aquifer characteristics, with apparent resistivity ranging from 0.06 Ωm to 10.70 Ωm, depths from 17.61 m to 73.60 m, and aquifer thickness varying between 14.75 m and 45.00 m. High transmissivity at certain VES points suggests substantial groundwater potential, while lower values indicate areas with limited resources. The study highlights the correlation between slope and groundwater dynamics, where gentle slopes promote infiltration, enhancing recharge. The hydrogeophysical analysis underscores the heterogeneity of the subsurface, with varying aquifer characteristics influencing groundwater availability. The findings emphasize the need for targeted groundwater management strategies, particularly in areas with steep slopes and higher resistivity. Umuahia South exhibits favorable conditions for groundwater recharge, particularly in areas with low to moderate slopes. However, regions with steep slopes and high resistivity require careful management to mitigate water scarcity. The study provides valuable insights for optimizing groundwater exploration and ensuring sustainable use. This research integrates slope analysis with hydrogeophysical data to provide a comprehensive understanding of groundwater potential, offering a novel approach to groundwater resource management in Umuahia South.

Keywords: *Aquifer characteristics, Groundwater recharge, Hydrogeophysical survey, Transmissivity, Umuahia South*

1. Introduction

Groundwater is a crucial natural resource that supports various human and ecological needs. Its availability and sustainability are influenced by multiple factors, including climate, geology, land use, and topography (Igwe et al., 2020). Among these, topography plays a significant role in determining the recharge, flow, and distribution of groundwater. In regions like Southeastern Nigeria, where groundwater serves as a primary water source for domestic, agricultural, and industrial purposes, understanding the interplay between topography and groundwater dynamics is vital for effective water resource management (Osinowo & Arowoogun, 2020).

Topography, which refers to the arrangement of natural and artificial features of an area, directly impacts surface runoff, infiltration rates, and, consequently, groundwater recharge. In areas with diverse topographical features, such as hills, valleys, and plains, the slope of the land surface can influence the movement of water both above and below the ground (Fagbohun et al., 2017). For instance, gentle slopes tend to facilitate water infiltration into the subsurface, enhancing groundwater recharge, while steep slopes are more likely to promote rapid surface runoff, reducing the potential for infiltration and increasing the risk of erosion (Ibeh, 2020). These dynamics are particularly relevant in regions like Umuahia South, Abia State, Southeastern Nigeria, where the landscape is characterized by varying slopes and a complex geological structure.

Topography is one of the most significant factors controlling the movement and storage of water in the environment. In the context of groundwater recharge, topography determines the direction and speed of surface runoff, the potential for water infiltration into the subsurface, and the distribution of recharge zones (Ogungbade et al., 2022). The slope of the land, in particular, plays a crucial role in these processes. Gentle slopes typically allow for greater water infiltration, as the slow movement of surface water provides sufficient time for percolation into the soil. This process is essential for recharging aquifers, which store groundwater that can be accessed during dry periods (Harry et al., 2020). Conversely, steep slopes often result in rapid surface runoff, reducing the time available for infiltration and increasing the likelihood of erosion, which can further diminish the soil's ability to retain water (Nebeokike et al., 2020).

In Umuahia South, the topography varies from nearly flat to moderately steep, with the majority of the area characterized by gentle to moderate slopes. These gentle slopes are expected to have a positive influence on groundwater recharge by promoting infiltration and reducing runoff (Kudamnya et al., 2021). However, the presence of steeper slopes in certain parts of the study area may lead to localized variations in recharge potential. Understanding these variations is critical for identifying areas where groundwater resources are most likely to be abundant and those that may be at risk of depletion.

While topography provides insights into the potential for groundwater recharge at the surface level, hydrogeophysical methods offer a deeper understanding of the subsurface conditions that control groundwater storage and flow (Ameh et al., 2020). VES is one such method that has proven effective in delineating subsurface aquifer characteristics, including apparent resistivity, depth, and thickness of the aquifer layers. These parameters are crucial for assessing the groundwater potential of an area, as they determine the aquifer's capacity to store and transmit water (Ezema et al., 2020).

The apparent resistivity values obtained from these surveys provide information about the lithology of the subsurface materials and their water-bearing properties. Low resistivity values typically indicate the presence of conductive materials, such as clay or saturated sands, which are often associated with high groundwater potential (Bassey et al., 2019). High resistivity values, on the other hand, may indicate resistive materials like dry sands or fractured rocks, which are less likely to contain significant amounts of groundwater. The depth to the aquifer is another critical factor in groundwater exploration (Nwachukwu et al., 2019). Shallow aquifers, which are more easily accessible, are generally associated with higher groundwater potential. However, deeper aquifers, though harder to access, may offer more substantial and stable groundwater reserves. The thickness of the aquifer layers also plays a key role in determining the groundwater storage capacity of an area. Thicker aquifer layers generally have greater storage potential, making them more reliable sources of groundwater (Ngah & Eze, 2017).

By combining the slope analysis with the hydrogeophysical data, this study aims to develop a comprehensive understanding of the groundwater recharge dynamics in Umuahia South. The integration of these two approaches will help identify areas where the topography is conducive to groundwater recharge and where the subsurface conditions are favorable for groundwater storage. This information is crucial for developing sustainable groundwater management strategies that can address the water needs of the region's growing population while minimizing the risk of groundwater depletion and contamination. This study assesses how topography influences groundwater recharge in Umuahia South by analyzing the relationship between slope and aquifer characteristics through hydrogeophysical surveys. It categorizes the area into slope classes, evaluates their impact on recharge, and identifies zones with high groundwater potential or depletion risks. The findings are crucial for groundwater management, offering insights into sustainable water resource strategies. By combining slope analysis with hydrogeophysical data, the study presents a comprehensive approach that can be applied to similar regions, enhancing groundwater exploration and conservation efforts in diverse environments.

2. Study Area and Geology

Umuahia South is one of the seventeen local government areas (LGAs) in Abia State, situated in southeastern Nigeria. It is located approximately between latitudes 5°25'N and 5°35'N and longitudes 7°25'E and 7°35'E as shown in Figure 1. The area covers a geographic expanse that connects it to neighboring LGAs such as Ikwuano to the east and Umuahia North to the north. The capital city of Abia State, Umuahia, lies just north of Umuahia South, providing a strategic advantage in terms of accessibility and economic linkage.

The topography of Umuahia South is predominantly characterized by a gentle rolling landscape with elevations ranging from 50 to 200 meters above sea level. The region's terrain is typical of southeastern Nigeria, with a mix of flat and undulating areas that contribute to the drainage patterns and groundwater flow (Abija & Nwankwoala, 2018). The higher elevations are usually located towards the eastern parts, where the terrain gradually slopes downwards toward the west and southwest. This variation in elevation influences the distribution and movement of groundwater, as well as the location of surface water bodies.

Umuahia South experiences a tropical rainforest climate, characterized by two distinct seasons: the wet season, which runs from April to October, and the dry season, from November to March. The area receives an average annual rainfall of approximately 2,200 mm, with the heaviest rains occurring between June and September. Temperatures are generally high throughout the year, averaging between 26°C and 28°C, with minimal seasonal variation. The high humidity levels, often exceeding 80%, are a common feature of the region's climate.

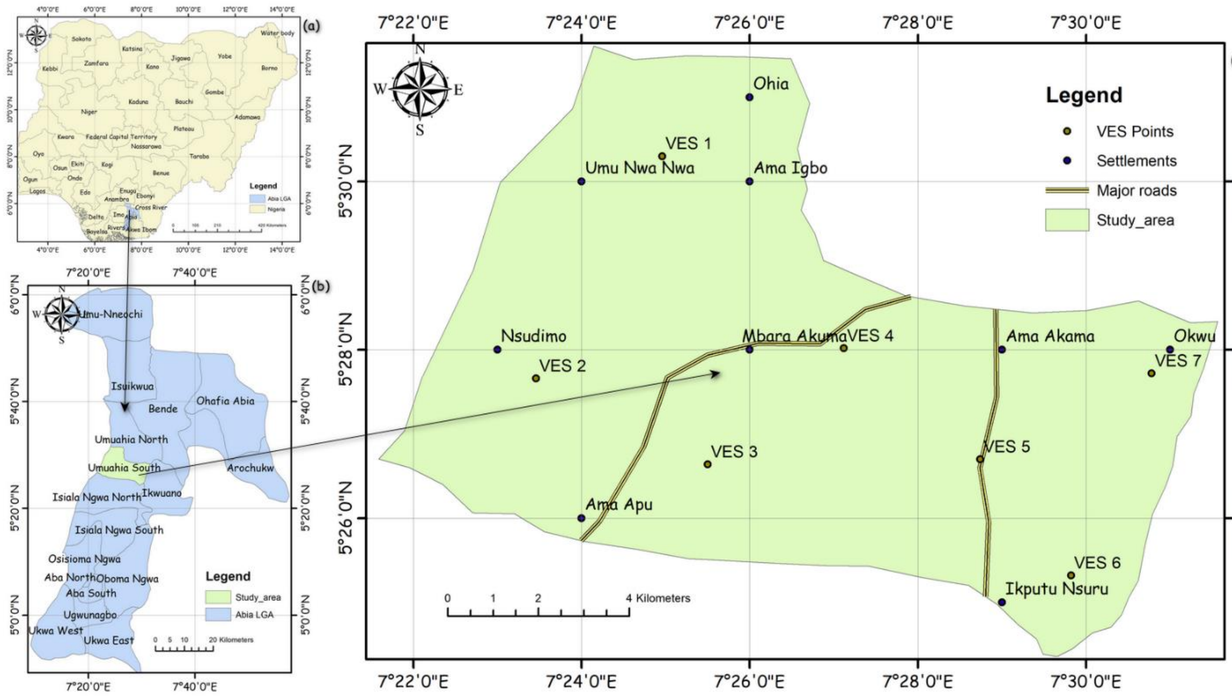

Figure 1: (a) Nigeria (b) Abia State (c) Umuahia South, showing major settlements, VES points, and roads.

The drainage system of Umuahia South is influenced by the region's topography and climatic conditions. Several rivers and streams traverse the area, forming part of the larger Imo River Basin. The most prominent water bodies include the Iyiukwu and Imo Rivers, which are perennial and provide vital water resources for domestic, agricultural, and industrial uses (Eke et al., 2015). Numerous smaller streams and seasonal tributaries also crisscross the area, contributing to the recharge of groundwater aquifers during the rainy season. The presence of these water bodies plays a crucial role in the local hydrology and is essential for sustaining the region’s agricultural activities (Eke et al., 2015).

The road network in Umuahia South is well-developed, connecting the LGA to major cities and towns within Abia State and beyond. The main arterial roads include the Umuahia-Ikot Ekpene Road, which runs through the area, linking it to Umuahia North and neighboring states like Akwa Ibom. Other significant roads include the Old Aba Road and the Nsirimo-Olokoro Road, which enhance intra- and inter-regional connectivity (Eke et al., 2015). These roads are crucial for the transportation of goods, services, and people, facilitating economic activities and contributing to the overall development of the region.

The geology of Umuahia South is predominantly composed of sedimentary formations that belong to the Niger Delta Basin. The primary geological units in the area include the Benin Formation (Coastal Plain Sands), which is characterized by unconsolidated sands with minor clay and gravel intercalations. This formation is significant as it serves as a major aquifer system, providing groundwater to the region (Ezebunanwa et al., 2019). The Benin Formation is known for its high permeability and porosity, which are favorable for groundwater storage and movement.

Underlying the Benin Formation is the Bende-Ameki Formation, consisting of sandstones, shales, and clays. This formation contributes to the complexity of the subsurface geology, influencing the distribution of groundwater resources (Odunze-Akasiugwu & Obi, 2017). The alternation of permeable and impermeable layers within the Bende-Ameki Formation creates confined and semi-confined aquifers, which are tapped through boreholes and wells for water supply.

The hydrogeological framework of Umuahia South is largely controlled by the interplay of the Benin and Bende-Ameki Formations. Groundwater occurs in both shallow unconfined aquifers and deeper confined aquifers. The shallow aquifers are typically recharged by direct infiltration of rainwater, while the deeper aquifers are recharged through lateral flow from higher elevations and vertical leakage from overlying formations (Wali et al., 2020). The hydraulic conductivity of the aquifer materials varies, with the Benin Formation exhibiting higher values due to its sandy composition, while the Bende-Ameki Formation has lower conductivity due to the presence of clay and shale layers (Opara et al., 2020).

Groundwater exploration and development in the area involve geophysical surveys, particularly VES, to delineate the subsurface layers and identify potential groundwater zones. The results from these surveys guide the placement of boreholes and wells, ensuring sustainable water extraction without compromising the aquifer integrity.

3. Methodology

3.1 Data Acquisition

The geophysical investigation employed the VES method using the ABEM-Terrameter (SAS1000-Signal Averaging System) for precise measurements. The Schlumberger array setup was utilized, extending electrodes up to 800 meters laterally. The process began with a 400-meter extension to the right, then an additional 400 meters to the left, creating detailed resistivity profiles that enabled the identification and characterization of subsurface geological formations (Mohammed & Taofiq, 2021). A grid of five VES stations operated concurrently to collect comprehensive data. Offset VES stations were used to account for the presence of valleys, slopes, and residential structures, ensuring accurate data collection. Measurements were conducted under optimal weather conditions to maintain result validity and reliability.

The Schlumberger array method's continuous adjustment of electrode spacing allowed for precise measurements of apparent resistivity (ρa), revealing valuable insights into subsurface resistivity variations. This method proved effective in navigating the area's rough terrain, facilitating the identification of significant changes in subsurface formations. The thorough resistivity profiles obtained are crucial for groundwater exploration and management, providing essential data for identifying productive aquifers and guiding sustainable water resource management strategies (Sanuade et al., 2019). Despite geographical and infrastructural challenges, the data collected was accurate and extensive, enhancing the understanding of subsurface geology.

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

This relationship allows for the estimation of resistance, aiding in the understanding of subsurface geological formations by electrical resistivity methods.

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

Equation (2) can be written as

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

Geometric factor,

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

The geometric factor (K) varies with electrode configurations and must be accurately determined for each setup. It is crucial for interpreting geophysical data in subsurface investigations, as it directly affects the accuracy of resistivity measurements and the understanding of subsurface conditions.

3.2 Data Processing

The IP2win software performed iterative computations, ranging from 1 to 29 cycles, to enhance accuracy and optimise the goodness-of-fit. This process calculated true resistivity layers, including their thicknesses and depths, known as Dar-Zarouk parameters. These refined results were critical for a detailed characterization of subsurface lithology and aquifer properties (Ebenezer & Martins, 2017). The comprehensive analysis of the geophysical data offered valuable insights into the subsurface environment, significantly improving the understanding of the survey outcomes and aiding in the assessment of groundwater resources.

3.3 The Dar Zarrouk Parameters

Dar-Zarrouk parameters are essential for assessing aquifer characteristics, including transmissivity and the protection provided by overlying materials. Derived from VES data, these parameters help hydrogeologists evaluate groundwater flow rates and the ability of geological formations to shield aquifers from contaminants and external influences.

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

Longitudinal Conductance (S)

$$S = \sum_{i=1}^{n} \frac{h_i}{\rho_i} \quad (6)$$

Transverse Resistance (T)

$$T = \sum_{i=1}^{n} \rho_i h_i \quad (7)$$

Longitudinal Resistivity

$$R_s = \frac{H}{S} \quad (8)$$

Transverse Resistivity

$$R_t = H \times S \quad (9)$$

Transmissivity quantifies an aquifer's ability to transfer water under hydraulic gradients. It is determined using resistivity (ρ_i) and thickness (h_i) values of each geological layer identified through geophysical surveys (Ekanem et al., 2019). This parameter is vital for evaluating groundwater flow potential and understanding water movement within the aquifer. Accurate transmissivity estimates are essential for crafting effective strategies for sustainable water management, ensuring both the efficient use and conservation of groundwater resources.

$$T = kh = \rho h \quad (11)$$

3.4 Slope Analysis

The slope data derived from the Digital Elevation Model (DEM) were analyzed to understand the terrain characteristics of the study area. Slope (S) was calculated using the equation:

$$S = arctan\left(\frac{\Delta z}{d}\right) \times \frac{180}{\pi} \quad (12)$$

where Δz represents the change in elevation and d is the horizontal distance. This calculation provided detailed insights into the terrain's gradient. The slope data were classified into categories (e.g., flat, gentle, moderate, steep) to assess the distribution of different slope classes across the study area.

The slope data were classified into categories such as flat, gentle, moderate, and steep to evaluate the distribution of different slope classes throughout the study area. This classification is essential for understanding terrain suitability for various land uses, such as agriculture or construction, and for identifying areas prone to erosion or other geological hazards (Nebeokike et al., 2020). By mapping these slope categories, researchers can better assess the impact of terrain on land management practices and environmental stability, guiding effective planning and mitigation strategies.

4. Results and Discussion

4.1 Slope analysis

The slope analysis of Umuahia South, Abia State, Southeastern Nigeria, reveals significant variations across the study area, with potential implications for groundwater recharge and distribution. The study area has been categorized into five slope classes: 0–1.87°, 1.87–3.49°, 3.49–5.63°, 5.63–9.21°, and 9.21–21.76°, as illustrated in Figure 2 and summarized in Table 1.

Table 1: Slope Classes and Corresponding Area Coverage in Umuahia South, Abia State

Slope (Degree)	Area (km^2)
0 - 1.87	43.45
1.87 - 3.49	48.93
3.49 - 5.63	25.94
5.63 - 9.21	8.50
9.21 - 21.76	2.13

The majority of the study area falls within the 1.87–3.49° slope range, covering 48.93 km^2, followed by the 0–1.87° slope range, which spans 43.45 km^2. These low to moderate slopes are crucial for groundwater recharge, as they allow for the infiltration of rainwater into the subsurface. The gentle slopes in these areas facilitate slower surface runoff, thereby enhancing the potential for water percolation into the aquifers (Ibeh, 2020). In contrast, steeper slopes (5.63–9.21° and 9.21–21.76°) occupy smaller portions of the study area, covering 8.50 km^2 and 2.13 km^2, respectively. These areas are characterized by rapid surface runoff, which limits the amount of water that can infiltrate the soil and recharge the groundwater system. The reduced infiltration in these zones may lead to localized water scarcity, particularly during dry seasons, and can exacerbate the vulnerability of groundwater resources (Ashaolu et al., 2020).

The areas with slopes between 3.49° and 5.63°, covering 25.94 km^2, represent a transitional zone where both surface runoff and infiltration processes are active. While these slopes may still contribute to groundwater recharge, the rate of infiltration may be lower compared to the gentler slopes, potentially leading to varying groundwater levels across this zone.

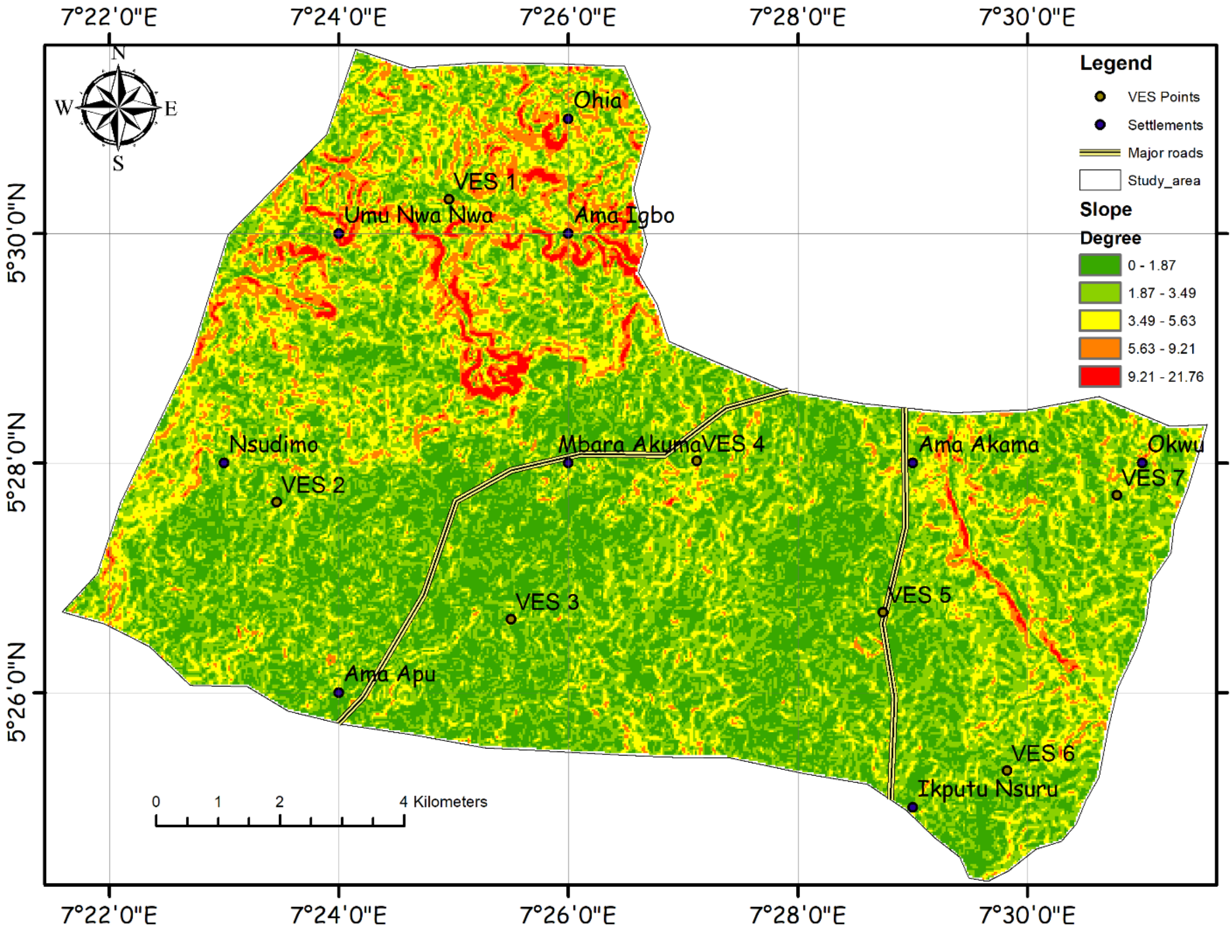

Figure 2: Slope Distribution Map of Umuahia South, Abia State

The variation in slope across Umuahia South suggests a complex interaction between topography and groundwater dynamics. In areas with gentler slopes, the prolonged contact time between water and the ground surface enhances the likelihood of infiltration, which is beneficial for maintaining groundwater levels. Conversely, in areas with steeper slopes, the rapid runoff can lead to erosion and reduced soil moisture retention, thereby hindering groundwater recharge (Ijioma, 2021).

The predominance of low to moderate slopes in the study area indicates a generally favorable condition for groundwater recharge. However, the presence of steeper slopes in certain areas necessitates careful land management practices to minimize erosion and optimize water conservation(Oyedele, 2019). Measures such as terracing, afforestation, and the construction of check dams could be implemented in these steeper regions to slow down runoff, promote infiltration, and enhance groundwater recharge.

The analysis also highlights the potential vulnerability of groundwater resources in areas with higher slopes. These regions may experience more pronounced fluctuations in groundwater levels due to the limited infiltration capacity. As a result, groundwater in these areas may be more susceptible to depletion during dry periods and over-extraction, which could affect the sustainability of water resources in the long term.

To address these challenges, it is important to integrate slope analysis into groundwater management strategies. By identifying areas with higher slopes and implementing appropriate conservation measures, it is possible to enhance groundwater recharge and reduce the risk of groundwater depletion. Additionally, monitoring changes in slope-related factors, such as land use and vegetation cover, can provide valuable insights into the long-term sustainability of groundwater resources in Umuahia South.

4.2 Hydrogeophysical Analysis of Aquifer Parameters

The VES survey conducted in Umuahia South, Abia State, Southeastern Nigeria, has provided valuable insights into the subsurface aquifer parameters, including apparent resistivity, depth, and thickness. These parameters are crucial for understanding the groundwater potential and overall hydrogeological conditions of the study area. The VES data, summarized in Table 2, reveals significant spatial variations in the apparent resistivity, depth, and thickness of the aquifer units across the surveyed locations, which are further illustrated in Figures 3, 4, and 5.

Table 2: Aquifer Parameters from VES Survey in Umuahia South, Abia State

VES	Latitude (°N)	Longitude (°E)	Apparent Resistivity (Ωm)	Depth (m)	Thickness (m)
VES 1	5.505	7.416	0.06	47.20	41.20
VES 2	5.461	7.391	0.37	17.61	14.75
VES 3	5.444	7.425	2.66	20.70	17.90
VES 4	5.467	7.452	10.70	25.90	24.20
VES 5	5.445	7.479	7.57	35.30	33.50
VES 6	5.422	7.497	0.59	73.60	45.00
VES 7	5.462	7.513	2.84	41.00	30.80

4.2.1 Apparent Resistivity and Aquifer Characteristics

Apparent resistivity is a key parameter in geophysical surveys as it reflects the subsurface material's ability to resist the flow of electric current. In this study, the apparent resistivity values range from 0.06 Ωm to 10.70 Ωm across the seven VES points. These values indicate the presence of different lithological units with varying water-bearing capacities.

The lowest apparent resistivity of 0.06 Ωm was recorded at VES 1, suggesting a highly conductive subsurface material, likely indicative of clay or saturated sands with a high groundwater content. The presence of such low resistivity materials is favorable for groundwater exploration, as it suggests the availability of water-bearing formations. This is further supported by the moderate depth of 47.20 m and significant thickness of 41.20 m at this location, indicating a substantial aquifer.

In contrast, the highest apparent resistivity of 10.70 Ωm was observed at VES 4. This higher resistivity value suggests the presence of more resistive materials, such as dry sands or possibly fractured rocks with lower groundwater content. The depth to the aquifer at this location is 25.90 m, with a thickness of 24.20 m. Despite the higher resistivity, the thickness of the aquifer unit suggests the potential for groundwater, albeit with possibly lower yield compared to areas with lower resistivity.

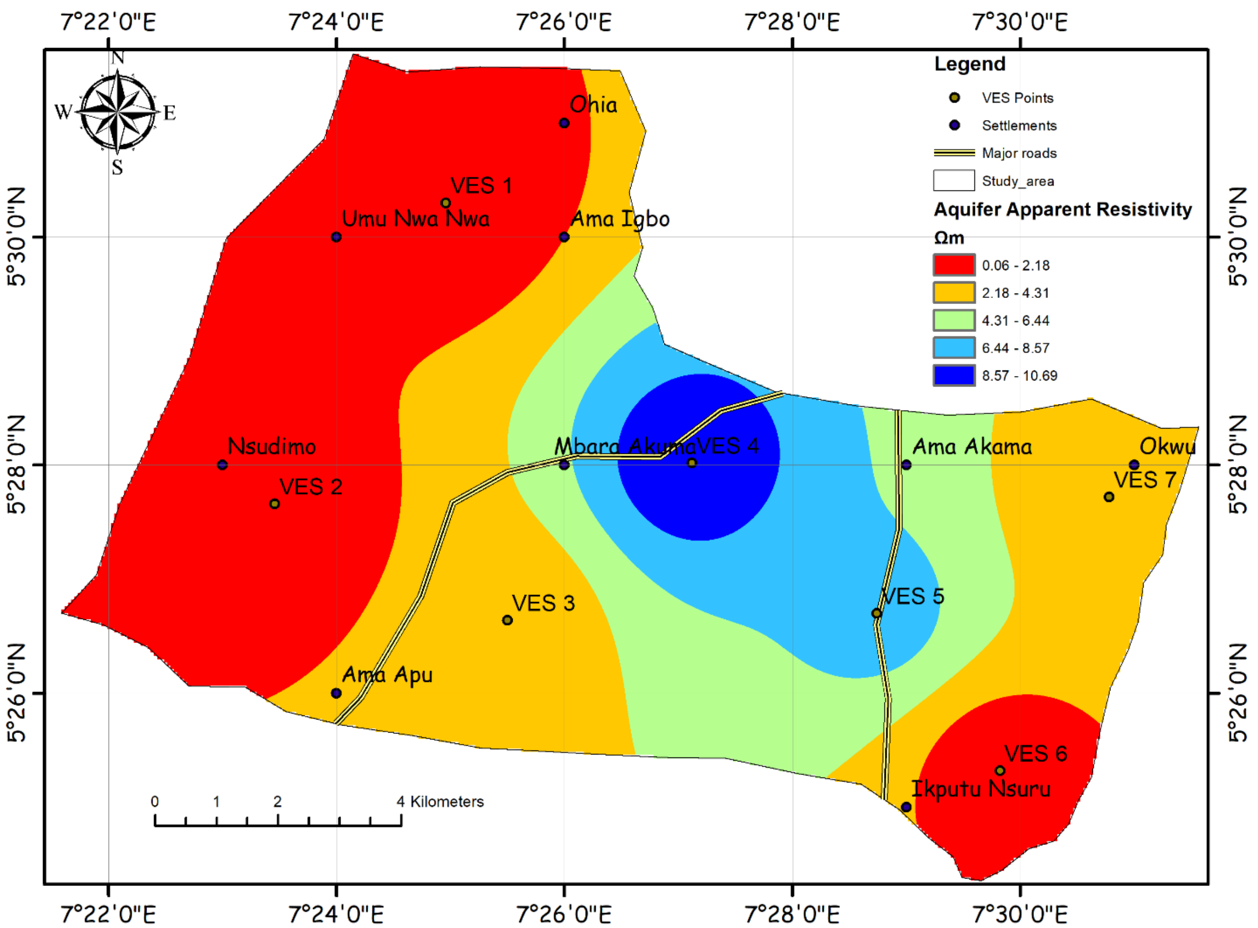

Figure 3: Spatial Distribution of Apparent Resistivity in Umuahia South, Abia State

VES 3 and VES 7 show intermediate apparent resistivity values of 2.66 Ωm and 2.84 Ωm, respectively, indicating a transition zone between highly conductive and resistive materials. The depth and thickness values at these points (20.70 m and 41.00 m depth, with 17.90 m and 30.80 m thickness, respectively) suggest moderate groundwater potential. The presence of intermediate resistivity values in these areas could indicate heterogeneous subsurface conditions, where layers of varying permeability and porosity exist.

4.2.2 Depth to Aquifer and Groundwater Potential

The depth to the aquifer is another critical parameter for assessing groundwater availability. The VES data reveals considerable variation in depth across the study area, ranging from 17.61 m at VES 2 to 73.60 m at VES 6. These variations in depth are indicative of the complex geological structure underlying Umuahia South.

The shallowest aquifer depth at VES 2 (17.61 m) suggests an accessible groundwater resource, which may be easily tapped for domestic and agricultural purposes (Adagunodo et al., 2018). However, the apparent resistivity at this point is relatively low (0.37 Ωm), which may indicate the presence of fine-grained sediments or clays that could affect the quality and yield of the groundwater (Ohwoghere-Asuma et al., 2020).

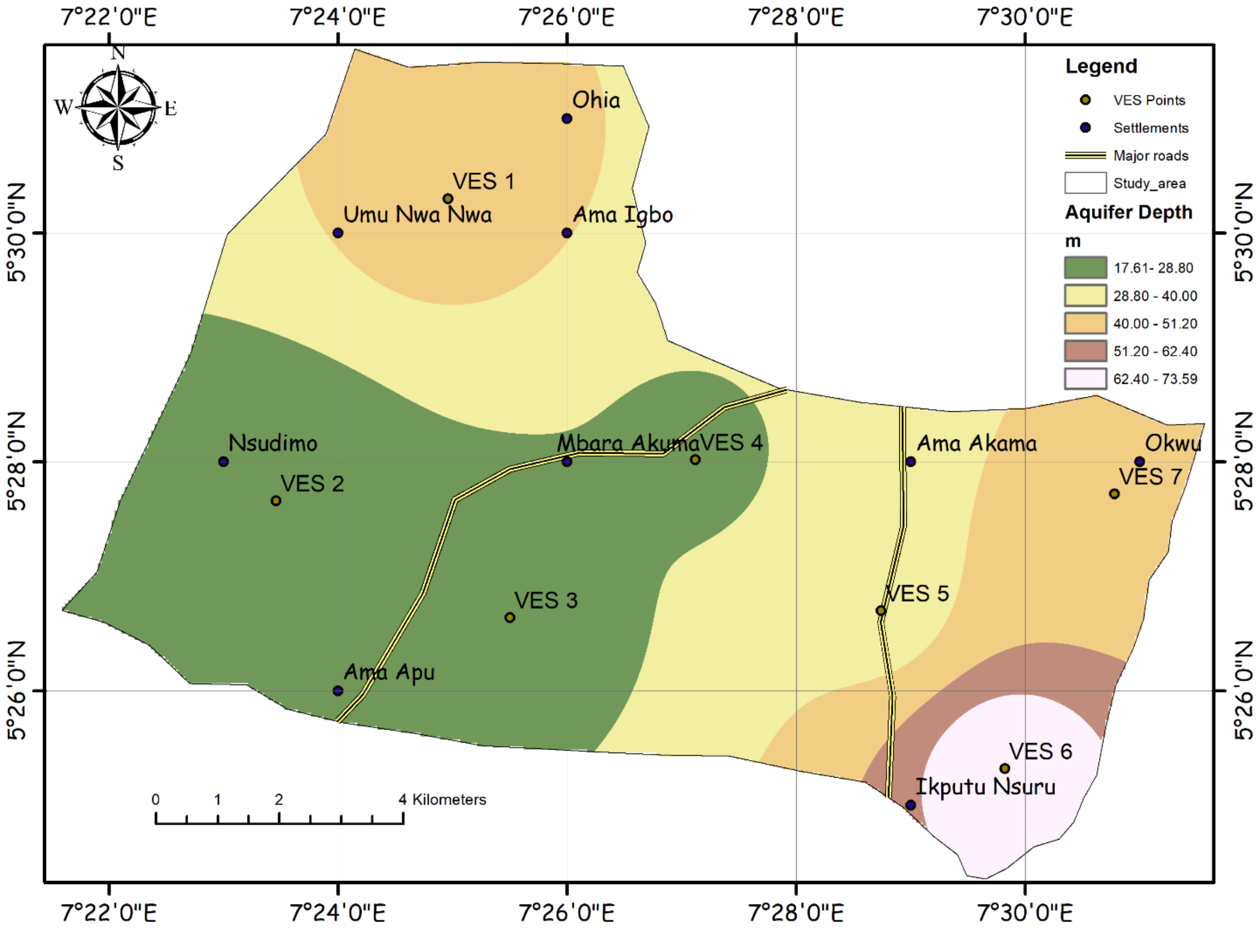

Figure 4: Spatial Variation in Aquifer Depth in Umuahia South, Abia State

Conversely, VES 6 exhibits the greatest depth to the aquifer at 73.60 m, along with a relatively low apparent resistivity of 0.59 Ωm. The substantial depth suggests that significant drilling would be required to access groundwater at this location. However, the thickness of the aquifer at this point is notable at 45.00 m, indicating a potentially large water-bearing formation. The combination of depth and thickness suggests that while the aquifer may be challenging to access, it could provide a reliable source of groundwater once tapped (Okiongbo & Akpofure, 2015).

The other VES points (VES 1, VES 3, VES 4, VES 5, and VES 7) show moderate depths ranging from 20.70 m to 47.20 m. These depths are within a range that is generally considered suitable for groundwater extraction, particularly for boreholes. The depth variation reflects the heterogeneity of the subsurface, with implications for groundwater exploration and management.

4.2.3 Aquifer Thickness and Storage Capacity

Aquifer thickness is directly related to the storage capacity of groundwater. The VES data indicates that aquifer thickness across the study area varies significantly, from as little as 14.75 m at VES 2 to as much as 45.00 m at VES 6. This variation in thickness is critical for understanding the groundwater storage potential of the region.

The greatest aquifer thickness at VES 6 (45.00 m) suggests a substantial groundwater reservoir. Combined with its depth, this location could serve as a significant groundwater source, capable of sustaining large-scale extraction for various uses. The substantial thickness also suggests a potentially high transmissivity, meaning that the aquifer can transmit water efficiently, making it a prime target for groundwater development.

In contrast, the smallest thickness recorded at VES 2 (14.75 m) suggests a more limited storage capacity, which could affect the long-term sustainability of groundwater extraction at this location. This, coupled with the shallow depth, may result in a more vulnerable aquifer system, susceptible to over-extraction and contamination (Oguama et al., 2019).

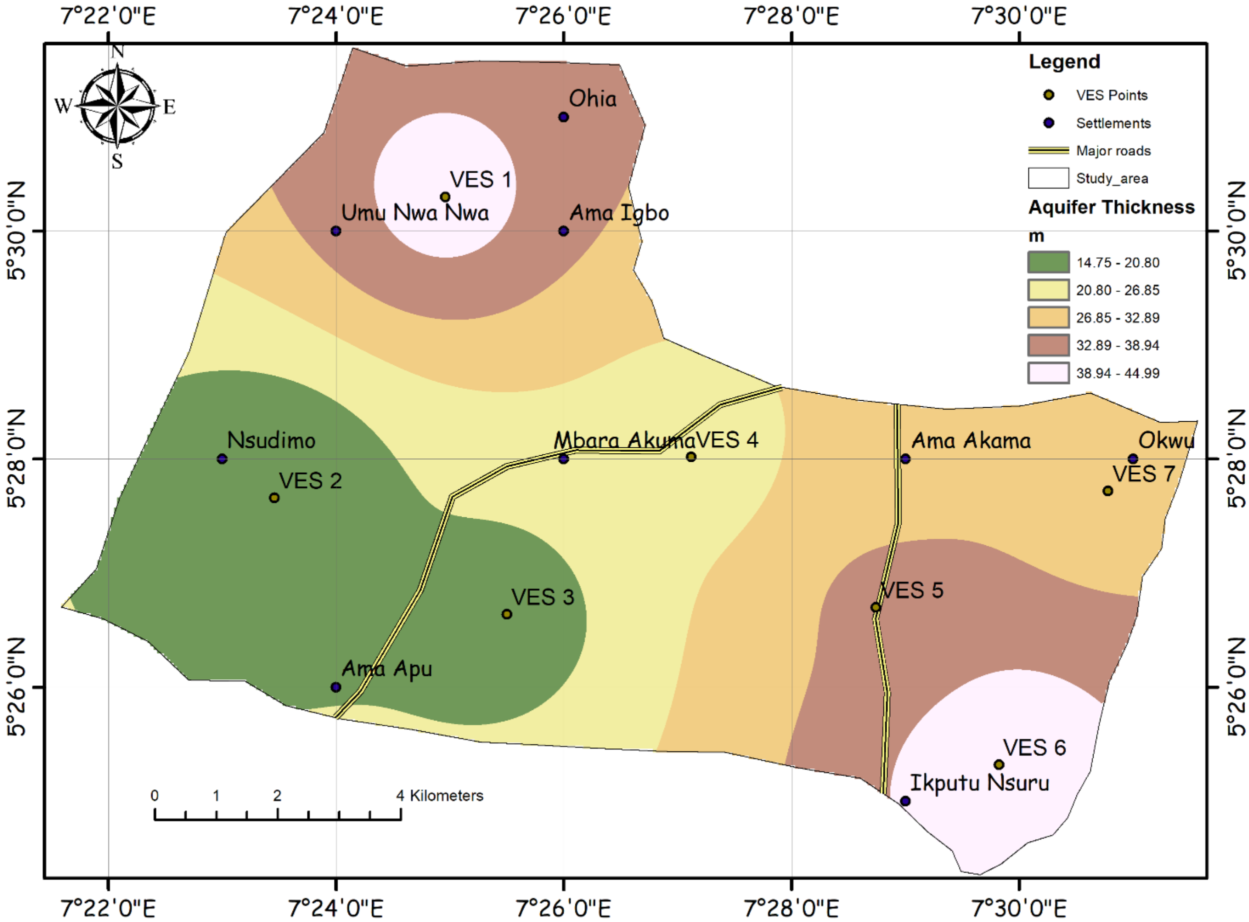

Figure 5: Spatial Variation in Aquifer Thickness in Umuahia South, Abia State

Intermediate thickness values at VES 1, VES 3, VES 4, VES 5, and VES 7 (ranging from 17.90 m to 41.20 m) indicate varying degrees of groundwater storage potential. The thickness at these points suggests that they could serve as viable sources of groundwater, particularly in areas where the demand is moderate. However, careful management would be required to ensure that these aquifers are not over-exploited, particularly in regions with lower apparent resistivity, which may be indicative of finer sediments with lower permeability.

4.3 Groundwater Potential and Protective Capacity

The analysis of longitudinal conductance, transverse resistance, hydraulic conductivity, and transmissivity reveals variations in the aquifer characteristics across the study area. These parameters are essential for assessing the protective capacity of the overburden, the ability of the aquifer to transmit water, and the overall groundwater potential. The results are summarized in Table 3 and spatially represented in Figures 6, 7, 8, and 9.

Table 3: Aquifer Parameters Derived from VES in Umuahia South, Abia State, Southeastern Nigeria

VES	Longitudinal Conductance (mhos)	Transverse Resistance (Ωm²)	Hydraulic Conductivity (m/day)	Transmissivity (m²/day)
VES 1	671.01	2.53	0.691	28.48

VES 2	40.30	5.40	0.691	10.19
VES 3	6.73	47.61	0.689	12.33
VES 4	2.26	258.94	0.682	16.50
VES 5	4.43	253.60	0.684	22.93
VES 6	76.66	26.42	0.691	31.08
VES 7	10.85	87.47	0.689	21.21

4.3.1 Longitudinal Conductance and Protective Capacity

Longitudinal conductance is a parameter that reflects the protective capacity of the overburden above the aquifer. High values of longitudinal conductance indicate good protective capacity, meaning that the aquifer is well-protected from potential surface contamination. In the study area, the longitudinal conductance values range from 2.26 mhos to 671.01 mhos, indicating significant spatial variability.
The highest longitudinal conductance, recorded at VES 1 (671.01 mhos), suggests an area with very good protective capacity. This implies that the aquifer in this region is less susceptible to contamination from surface pollutants, making it a safer source of groundwater for domestic and agricultural use. On the other hand, the lowest value of 2.26 mhos at VES 4 indicates a relatively weak protective capacity, making the aquifer more vulnerable to contamination. This region would require careful monitoring and management to prevent groundwater pollution, particularly from agricultural runoff or industrial activities.

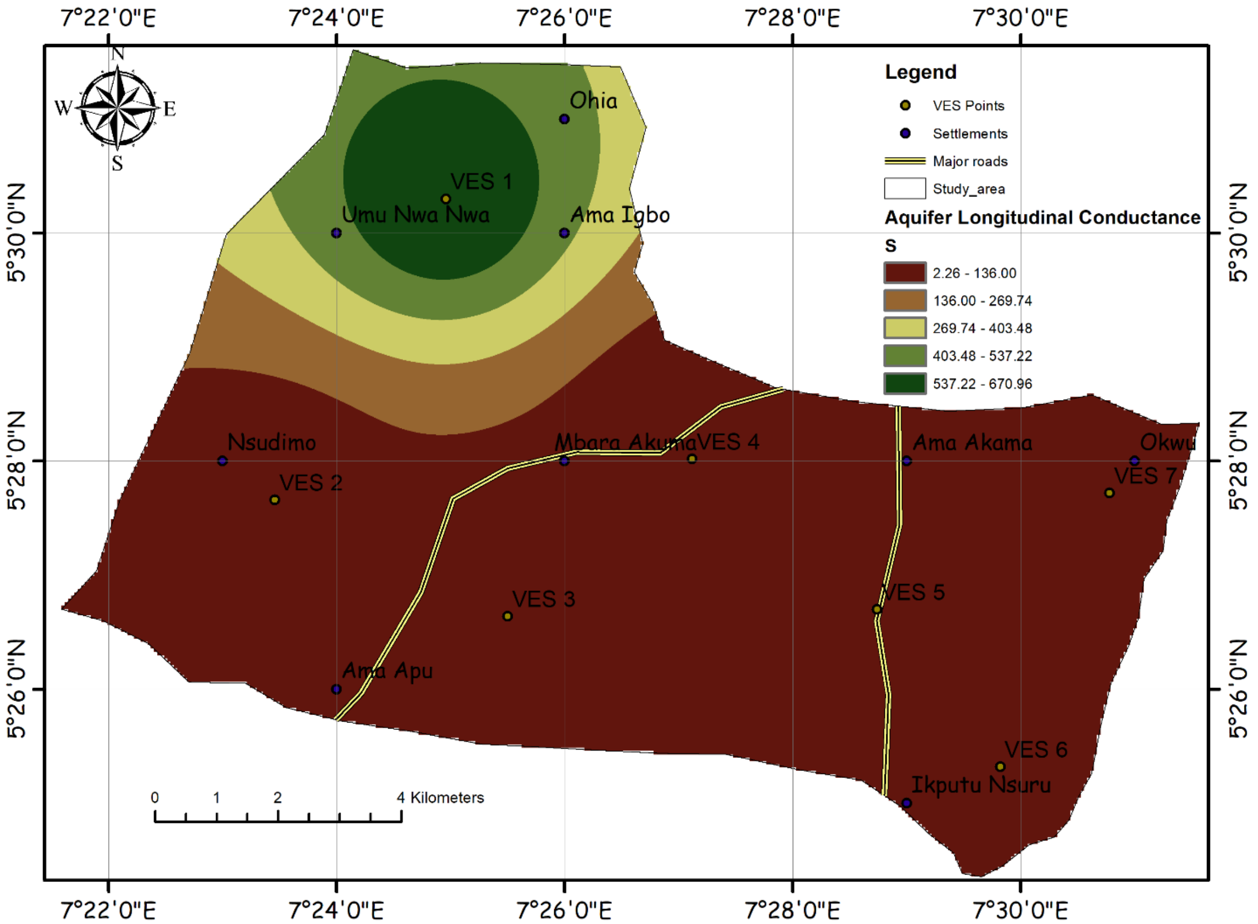

Figure 6: Spatial Distribution of Longitudinal Conductance in Umuahia South, Abia State

The variation in longitudinal conductance across the study area underscores the importance of considering this parameter in groundwater management strategies. Areas with lower conductance may need additional protective measures, such as restrictions on certain land uses or the installation of protective barriers to reduce the risk of contamination.

4.3.2 Transverse Resistance and Aquifer Characteristics

Transverse resistance is another critical parameter that provides insight into the resistivity and thickness of the aquifer layers. It reflects the aquifer's ability to transmit electrical current and, by extension, its potential to transmit water. The transverse resistance values in the study area range from 2.53 Ωm² to 258.94 Ωm², indicating a wide range of aquifer properties.

The highest transverse resistance observed at VES 4 (258.94 Ωm²) suggests the presence of resistive materials, such as consolidated sands or fractured rocks, which may have lower water content but could still be significant groundwater sources due to their transmissivity. This high resistance, combined with a moderate longitudinal conductance, suggests a complex subsurface structure where groundwater may be present in confined conditions, making it potentially challenging to extract but still valuable for long-term use (Nwachukwu et al., 2019).

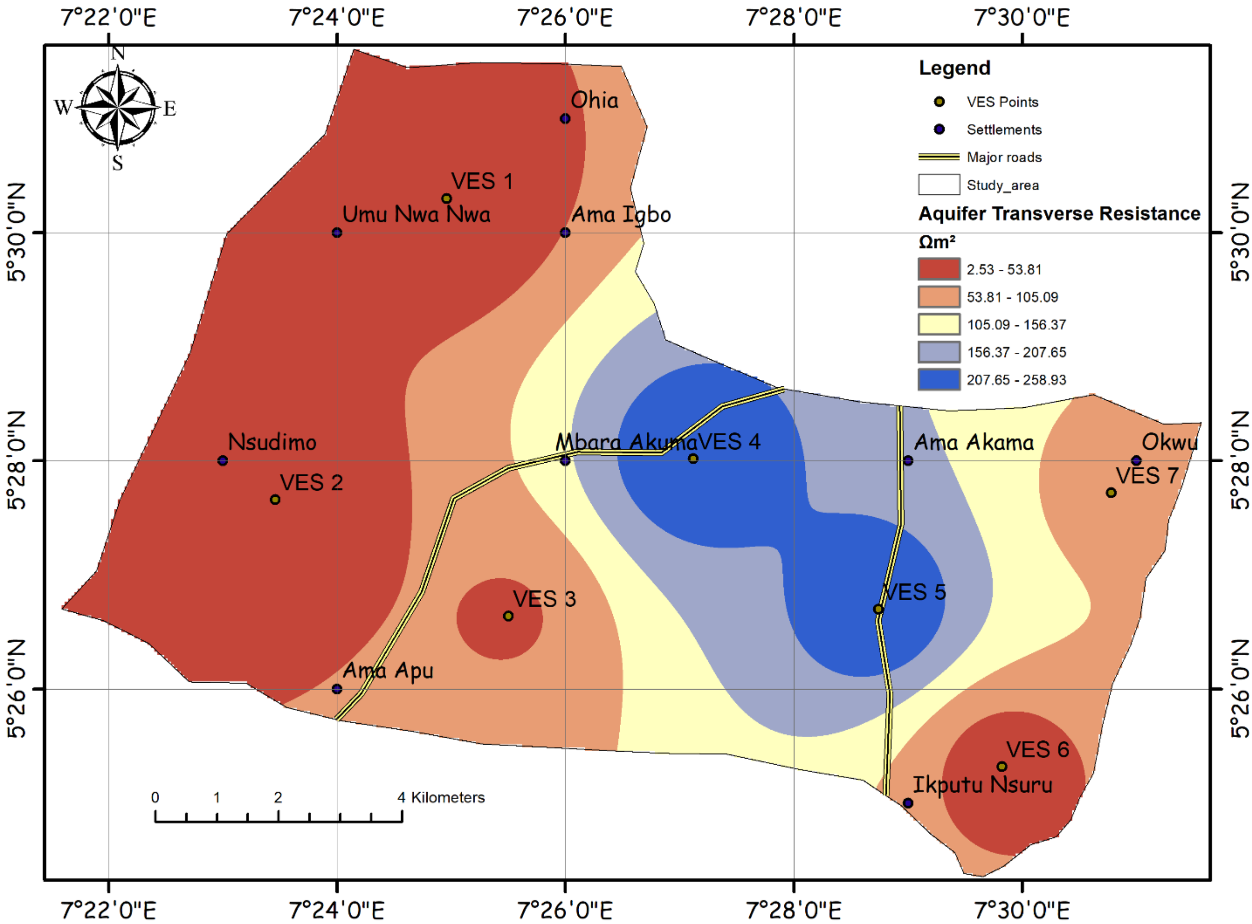

Figure 7: Spatial Variation in Transverse Resistance in Umuahia South, Abia State

In contrast, the lowest transverse resistance at VES 1 (2.53 Ωm²) indicates the presence of more conductive materials, likely saturated sands or clays, which may be more readily accessible for groundwater extraction. However, the high longitudinal conductance at this point also suggests a well-protected aquifer, making it a promising location for sustainable groundwater development.

The variation in transverse resistance highlights the diverse geological conditions in Umuahia South, with implications for groundwater exploration and well siting. Areas with high transverse resistance may require more sophisticated extraction techniques, while those with lower resistance could be targeted for more conventional groundwater extraction methods (Ndubueze et al., 2019).

4.3.3 Hydraulic Conductivity and Aquifer Permeability

Hydraulic conductivity is a measure of the aquifer's ability to transmit water through its pore spaces and fractures. It is a crucial parameter for understanding the ease with which groundwater can flow through the aquifer. In this study, hydraulic conductivity values are relatively consistent across the VES points, ranging from 0.682 m/day to 0.691 m/day.

This narrow range of hydraulic conductivity suggests that the aquifer materials across the study area have similar permeability characteristics. This consistency implies that once groundwater is accessed, it can be expected to flow at a similar rate through the aquifer, regardless of the location within the study area. However, the actual groundwater yield will also depend on the thickness of the aquifer and the specific local conditions (Iserhien-Emekeme et al., 2020).

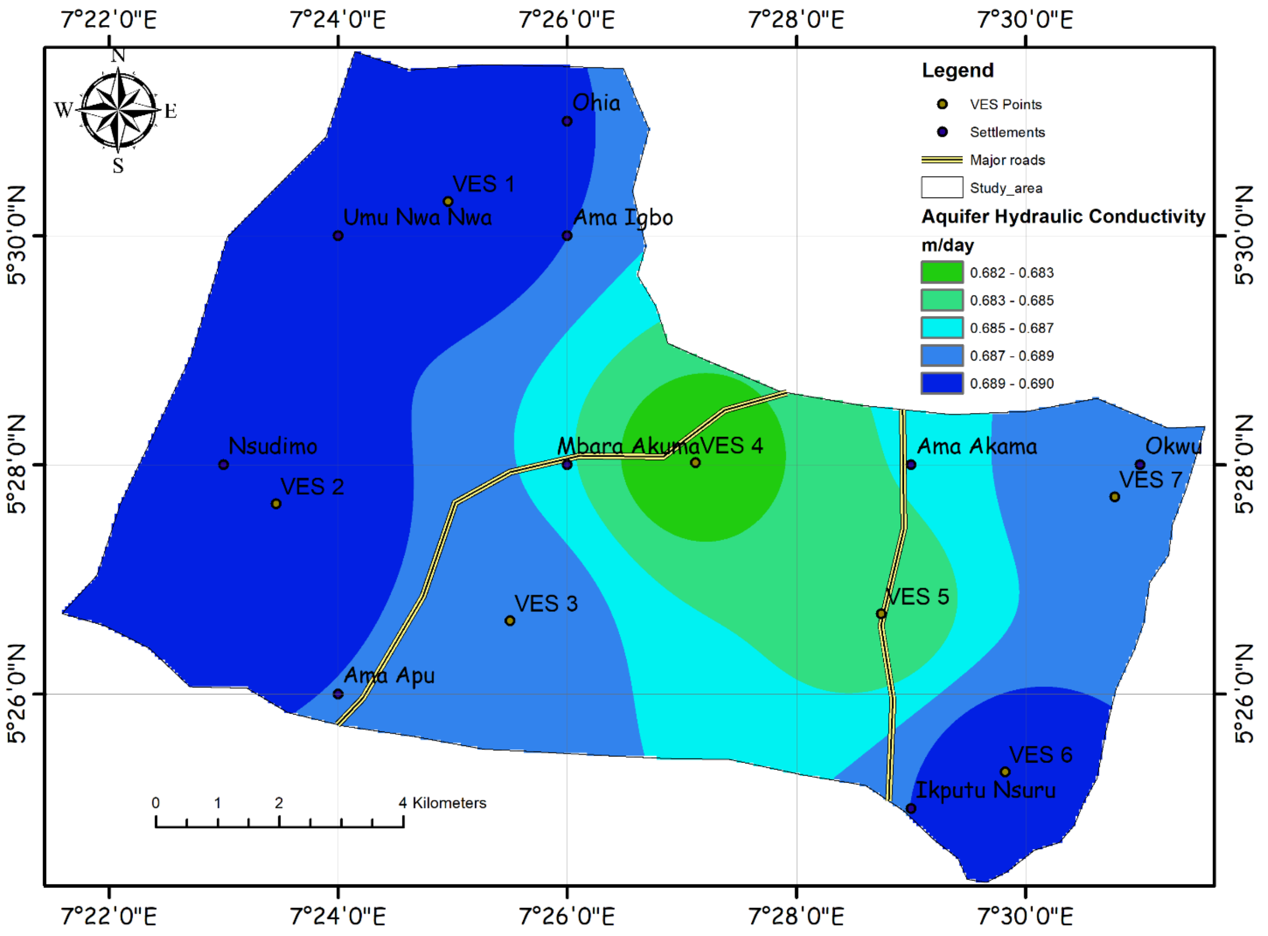

Figure 8: Spatial Variation in Hydraulic Conductivity in Umuahia South, Abia State

The uniformity in hydraulic conductivity also suggests that the geological formations underlying Umuahia South are relatively homogenous in terms of their permeability. This homogeneity simplifies the prediction of groundwater behavior across the area, making it easier to plan and manage groundwater resources effectively.

4.3.4 Transmissivity and Groundwater Potential

Transmissivity is a product of hydraulic conductivity and aquifer thickness, representing the aquifer's ability to transmit water across its entire thickness. It is a critical parameter for assessing the groundwater potential of an area, as it directly relates to the volume of water that can be extracted from the aquifer.

The transmissivity values in Umuahia South vary from 10.19 m²/day at VES 2 to 31.08 m²/day at VES 6, indicating a range of groundwater potentials across the study area. The highest transmissivity at VES 6 suggests a location with significant groundwater potential, where large volumes of water can be extracted efficiently. This area could be targeted for high-yield wells, making it a priority for groundwater development, particularly in areas with high water demand.

On the other hand, the lowest transmissivity at VES 2 suggests a more limited groundwater potential, where extraction rates may need to be carefully managed to avoid over-exploitation. This location may be more suitable for low-demand uses or as a supplementary water source, rather than a primary one.

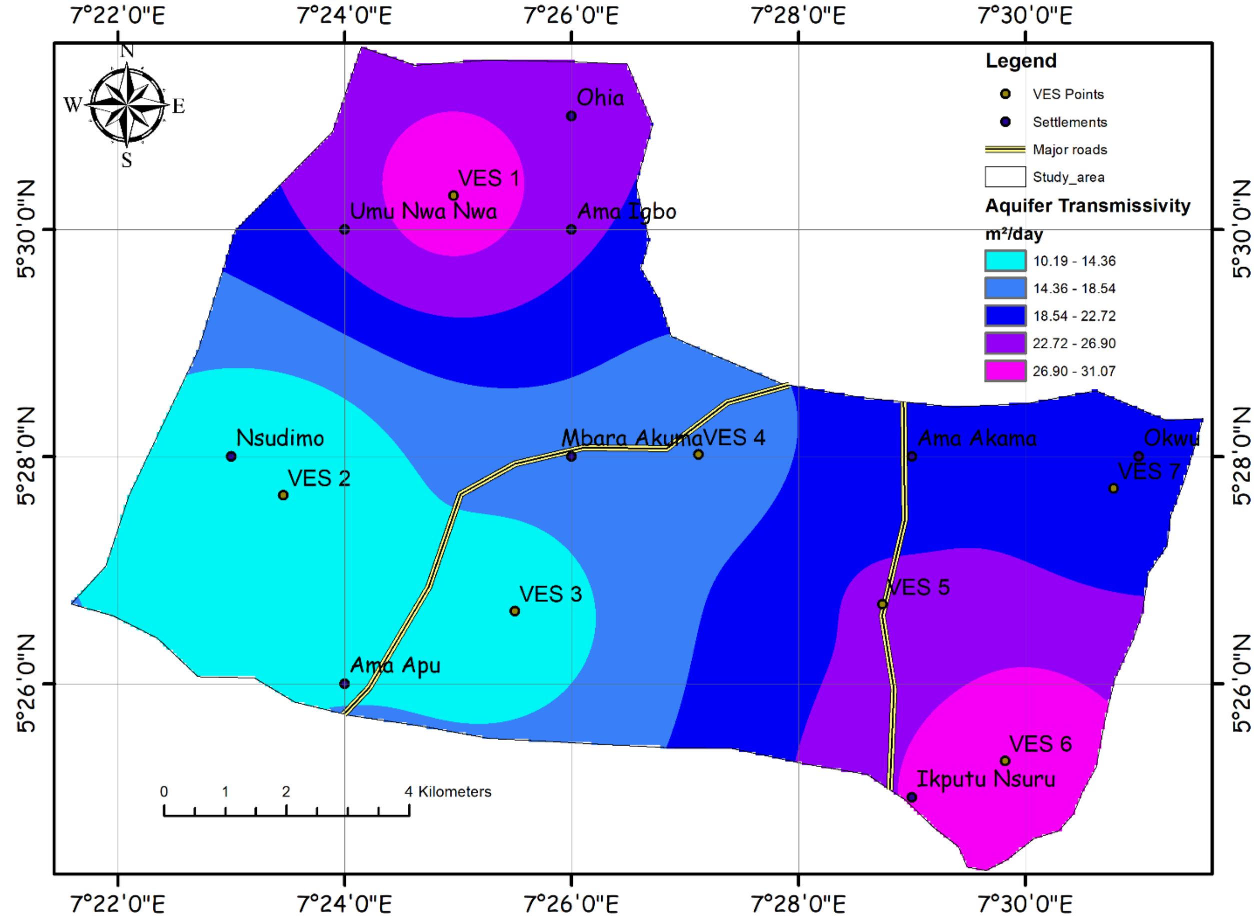

Figure 9: Spatial Distribution of Transmissivity in Umuahia South, Abia State

The variation in transmissivity across the study area highlights the need for targeted groundwater exploration, focusing on areas with higher transmissivity for larger-scale water supply projects. It also underscores the importance of understanding local geological conditions to optimize groundwater extraction and ensure sustainable use (Abdulrazzaq et al., 2020).

4.2.4 Hydrogeological Implications

Spatial differences in apparent resistivity, depth, and thickness further highlight the area's hydrogeological complexity. Locations with low resistivity and substantial aquifer thickness, such as VES 1 and VES 6, are promising for high-yield boreholes and reliable water supply. Conversely, higher resistivity zones, like VES 4, suggest more limited groundwater availability, necessitating careful exploration and management strategies.

The analysis of longitudinal conductance, transverse resistance, hydraulic conductivity, and transmissivity provides crucial insights into the hydrogeological conditions in Umuahia South. This detailed assessment reveals significant spatial variability, reflecting the complex subsurface geology and its implications for groundwater exploration, extraction, and management. Areas with high longitudinal conductance and low transverse resistance, such as VES 1, present the most favorable conditions for groundwater extraction. These sites offer good protective capacity and accessible aquifer materials, making them ideal for groundwater development, especially for domestic and agricultural uses where water quality and availability are crucial.

In contrast, regions with low longitudinal conductance and high transverse resistance, like VES 4, pose challenges for groundwater extraction. These areas may require advanced extraction techniques and additional protective measures to prevent contamination, particularly if they are near potential pollution sources. The consistent hydraulic conductivity across the study area simplifies groundwater management by providing predictable flow rates. However, the variation in transmissivity indicates that not all areas will yield the same volume of water. This variation must be considered in development plans to ensure sustainable extraction rates and avoid over-exploitation.

5. Conclusion

The comprehensive analysis of slope, hydrogeophysical, and aquifer parameters in Umuahia South, Abia State, Southeastern Nigeria, has revealed critical insights into the region's groundwater potential and associated challenges. The study highlights the intricate relationship between topography, subsurface conditions, and groundwater dynamics, emphasizing the need for targeted management strategies to optimize water resource utilization in the area.

The slope analysis indicates that the majority of the study area is characterized by low to moderate slopes (0–3.49°), which are highly favorable for groundwater recharge. These gentle slopes allow for greater infiltration of rainwater into the subsurface, thereby sustaining the aquifers that are vital for domestic and agricultural water supply. However, the presence of steeper slopes (5.63–21.76°) in certain parts of the region presents challenges, as rapid surface runoff in these areas reduces the potential for groundwater recharge. The steep slopes are also prone to erosion, further exacerbating the vulnerability of groundwater resources. Therefore, implementing land management practices such as terracing, afforestation, and the construction of check dams is crucial in these areas to enhance groundwater recharge and mitigate the risk of erosion.

The hydrogeophysical analysis through VES surveys provided detailed information about the subsurface aquifer characteristics, including apparent resistivity, depth, and thickness. These parameters are critical for assessing groundwater potential and planning extraction activities. The variation in apparent resistivity values across the study area reflects the presence of different lithological units with varying water-bearing capacities. For instance, low resistivity values at VES 1 and VES 6 suggest the presence of saturated sands or clays with high groundwater content, making these areas prime targets for groundwater extraction. Conversely, higher resistivity values at VES 4 indicate more resistive materials, such as dry sands or fractured rocks, which may limit groundwater availability and require more careful exploration and management.

The depth to aquifer and aquifer thickness further underscore the complexity of the subsurface conditions in Umuahia South. The study area exhibits significant variability in aquifer depth, ranging from 17.61 m to 73.60 m, and aquifer thickness, ranging from 14.75 m to 45.00 m. These variations highlight the need for tailored extraction approaches, as some areas may require deep drilling and advanced techniques to access the aquifers, while others may offer more easily accessible groundwater resources. The areas with thicker aquifers, such as VES 6, present substantial groundwater storage potential, making them suitable for high-yield wells that can support large-scale water supply projects.

The analysis of longitudinal conductance, transverse resistance, hydraulic conductivity, and transmissivity provides further insights into the protective capacity of the overburden and the aquifer's ability to transmit water. Areas with high longitudinal conductance and low transverse resistance, such as VES 1, are particularly promising for sustainable groundwater development, offering both good protective capacity against contamination and accessible aquifer materials. On the other hand, regions with low longitudinal conductance and high transverse resistance, such as VES 4, pose significant challenges due to their susceptibility to contamination and limited groundwater availability. These areas may require additional protective measures and careful monitoring to prevent over-exploitation and ensure the long-term sustainability of groundwater resources.

The study of Umuahia South's groundwater potential reveals a complex interplay between topography, subsurface conditions, and aquifer characteristics. While the predominance of low to moderate slopes offers favorable conditions for groundwater recharge, the variability in hydrogeophysical parameters necessitates a nuanced approach to groundwater management. Targeted exploration, careful extraction practices, and the implementation of land management strategies in areas with steeper slopes or challenging subsurface conditions are essential to optimizing groundwater resources in the region. By integrating these findings into local water resource management plans, stakeholders can enhance groundwater recharge, reduce the risk of resource depletion, and ensure the long-term sustainability of water supply in Umuahia South.

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