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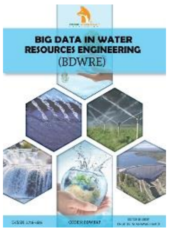

RESEARCH ARTICLE

UNRAVELING THE SUBTERRANEAN: A COMPREHENSIVE EXPLORATION OF AQUIFER PROPERTIES AND HYDROGEOLOGICAL DYNAMICS IN WARRI SOUTH, DELTA STATE, NIGERIA

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ABSTRACT

This paper investigates the complex relationship between apparent resistivity and electrode separation, revealing key underlying features. The research uses a range of field curve types to quantitatively and qualitatively analyse data from Vertical Electrical Sounding (VES). The study is divided into two sections: a qualitative interpretation section and a quantitative interpretation section, the latter of which focuses on the dynamics of aquifer potential in the Warri South region. Understanding the link between apparent resistivity and electrode separation is essential for hydro-geoelectric research. To increase the reliability of the results, curve matching, sophisticated modelling, and geological knowledge are used. Particularly, the predominance of HH curve types, followed by AH, HQ, KH, and KK configurations, provides a complete description of the hydrogeological terrain and a thorough description of subsurface features. To comprehend groundwater flow, distribution, and management, aquifer resistivity, thickness, depth, transverse resistance, longitudinal conductance, hydraulic conductance, and transmissivity are all researched. The complex interaction between resistivity levels and different rock types emphasises the dynamic nature of aquifer resistivity and disproves the idea that it has a set range. The patterns in the regional distribution of aquifer resistivity reflect the complexity of subsurface water supply. Aquifer thickness, depth, and transverse resistance, which highlight the complex interaction of geology and aquifer characteristics, are additional factors that aid in understanding hydrogeological processes. The hydrological potential of aquifers is discovered through variables like transmissivity and hydraulic conductivity, indicating the balance between geological characteristics and hydraulic gradients. These discoveries open the door to responsible water resource management and sustainable use by providing insights into the dynamics of hidden aquifers under the Earth's surface.

KEYWORDS

Transmissivity, Longitudinal Conductance, Hydraulic Conductance, Protective Capacity, Groundwater Supply Potential

1. INTRODUCTION

Water, the essence of life, is an essential component of all human undertakings. The worldwide issue of delivering enough and safe drinking water, on the other hand, remains unchanged (Umoren et al., 2017; Abdulrazzaq et al., 2020a; Ugbaja et al., 2021). A confluence of variables, including rising population, fast urbanization, and agricultural and industrial activity, has resulted in the pollution and depletion of surface water resources in Delta State, located in southern Nigeria (Akpabio et al., 2007, Aladeboyeje et al., 2020; Aladeboyeje et al., 2021). Collaboration between federal and state governments, as well as partnerships with regional and global donor organizations, has resulted in the installation of public boreholes in strategic locations such as schools, healthcare facilities, and village squares, with the goal of alleviating water scarcity (Ekwok et al., 2020). Despite significant financial investments, a concerning percentage of these boreholes either generate poor groundwater amounts or have proven fruitless.

Groundwater, one of nature's most essential and priceless treasures, sits under the surface of Delta State's beautiful terrain. Groundwater, which is found in the pores of rocks and soils under the water table, is an essential component of the natural water cycle(Abdulrazzaq et al., 2020b). Its ease of availability makes it vital for a wide range of uses, from supporting residential necessities to fuelling agricultural and socioeconomic development operations (Igboekwe and Ruth, 2011). Water needs for home consumption, agricultural irrigation, and industrial output are increasing in highly populated and industrialized nations across the world, including India, China, and several African countries (Das et al., 2017). Anthropogenic activities such as deforestation, industrialisation, and urban growth have a substantial impact on both the quantity and quality of groundwater resources, emphasizing the importance of long-term management (Olusola et al., 2017; Ijioma, 2021; Ifeanyichukwu et al.,

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2021). According to projections, 36% of the world's groundwater will be used for home purposes, 42% for agricultural irrigation, and 27% for industrial activities in the coming years, highlighting its diverse importance (Döll et al., 2012; Wada et al., 2012; Sharma et al., 2012). Groundwater supplies more than 50% of agricultural land irrigation in highly populated countries such as India, China, and the United States, highlighting its critical role in food security and economic sustainability (Döll et al., 2012; Wada et al., 2012).

Understanding the fundamental properties of water as well as the underlying geological formations that store this precious resource is critical to unraveling the complexity of groundwater(Agbasi et al., 2019; Ibuot et al., 2021). Groundwater exploration employs a variety of strategies, including geophysical techniques, empirical approaches, and novel remote sensing technologies based on satellite images (Arefayne and Abdi, 2015). Among these, remote sensing stands out as a game changer, altering how we get information about distant regions without making physical touch. Surface information is extracted from satellite photos, based on conclusions taken from the area's geomorphology, drainage patterns, lithology, vegetation cover, and structural geology (Farahani and Aghajani, 2019). It does not replace but rather supplements the traditional geophysical technique, particularly in large-scale studies spanning wide geographical domains (Obimba et al., 2017; Ahmed and Mansor, 2018). Remote sensing techniques provide a cost-effective way to analyze groundwater potential across wide areas by reducing the need for extensive and costly geophysical investigations.

As the globe grapples with rising water demands, several places, including Delta State, have turned to groundwater extraction to fulfill the requirements of an expanding population. This increased dependence emphasizes the importance of precisely characterizing groundwater potential zones. Geology, hydrogeology, and geophysics have traditionally played critical roles in discovering and defining these zones (GWPZ) (Nair et al., 2017).

The Warri South local government area in Delta State, Nigeria, appears as a vital region in the search for stable and abundant groundwater supplies, providing to a range of requirements ranging from family use to agricultural and industrial demands. In this complex context, hydro-geoelectric study, especially the Vertical Electrical Sounding (VES) approach, appears as a viable route for comprehensively assessing subsurface hydrological conditions and revealing hidden aquifer potential. As the world's population, urbanization, and economic advancement place increasing demands on limited water reservoirs, the need to explore the underground domain for sustainable and undiscovered groundwater sources grows. Using hydro-geoelectric technologies, such as the novel VES methodology, provides a non-intrusive way to explore beneath the Earth's surface, illuminating the geological layers and aquifer networks hidden beneath.

This expedition sets out on an odyssey to harness the latent prowess of hydro-geoelectric inquiry, with a particular emphasis on the VES approach, in order to gain significant insights into the characteristics, depths, and extents of aquifers buried inside the Warri South expanse. With this technique as a guide, our goal is to fill a gap in our understanding of spatial groundwater distribution, allowing for more informed decisions in water resource management and supporting sustainable development. As we begin on this scientific journey, the expectation of discovering priceless datasets motivates us ahead, not only increasing our understanding of hydrogeological processes but also lighting avenues toward efficient and conscientious aquifer reservoir utilization. The aim of this study is to explore the aquifer potential in Warri South, Delta State through hydro-geoelectric investigation.

2. LOCATION AND GEOLOGY OF STUDY AREA

Warri South is a Local Government Area (LGA) in Delta State, Nigeria. Its headquarters is in the city of Warri, which has coordinates of 5.544230° N, 5.760269° E. It is one of the most densely populated LGAs in Delta State, with a population of over 300,000 people.

The research area encompasses the part of Warri South LGA Figure 1. The region's geographical extent is approximately 1,000 square kilometres, encompassing the Warri River's northern boundary, the Forcados River's eastern boundary, the Sapele River's southern boundary, and the Atlantic Ocean's western boundary. The geological parameters of the investigated area are complicated and variable. The Precambrian basement rocks, which date back more than 2 billion years, are the oldest rock formations in the given geographical area. Sedimentary rocks, notably sandstones, shales, and limestones, cover the rocks in issue. A Quaternary alluvial deposit of sand, silt, and clay covers the sedimentary strata.

The climate at the research site is tropical monsoon. The wet season lasts from May to October, whereas the dry season lasts from November to April. The average annual precipitation is 2,770 mm. The humidity level rises significantly, especially during the wet season. The research area's vegetation has a varied array of natural groups, including mangrove forests, rainforests, and grasslands. Mangrove forests are frequently found along coastlines. These habitats are distinguished by the presence of towering arboreal species that have evolved to survive in salty surroundings. The rainforests are located in the interior of the Local Government Area. The presence of towering, deciduous trees that offer protection for a varied range of species distinguishes these locations. The grasses grow in the drier areas of the Local Government Area (LGA). These entities are distinguished by the presence of low-lying grasses that are extremely resilient under dry environments. The natural environment has been significantly impacted by human activities in the Warri South Local Government Area (LGA). Both mangrove forests and rainforests have been removed for construction purposes. Grasslands have been converted into agriculture. As a result, the natural ecosystem of Warri South Local Government Area (LGA) is in grave danger.

For a variety of reasons, the research area is extremely important. The aforementioned source acts as a significant groundwater reserve for the surrounding area. Furthermore, it is worth emphasising that the region in issue is vital for agriculture and fisheries. The research area is home to a wide variety of animals, including some endangered species. The investigation of the aquifer potential in Warri South Local Government Area (LGA) is critical for various reasons. This will make it easier to estimate the region's groundwater resource availability. It will also make it easier to identify places with the greatest potential for aquifer development. In addition, the research will include recommendations for improving the region's groundwater reserves.

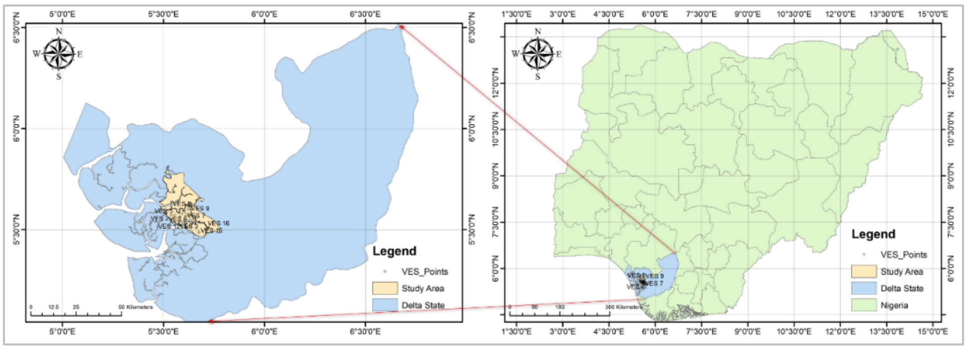

Figure 1: Map of the study area with VES points

3. METHODOLOGY

The research method included a preliminary review of relevant literature and the creation of a study area map. Following that, a field survey was conducted to gather empirical data and observations, outline geological features, assess hydro-geology variables, perform geo-electrical sounding, and analyse surface geological and geo-electrical data.

3.1 Geoelectrical Sounding

The VES surveys were carried out using a Schlumberger array with a maximum electrode spread of 200m. The primary goal of this study was to identify suitable locations for the installation of boreholes and hand-dug wells, with a focus on the southerly migration of groundwater within the defined research zone. The process involved the creation of traverses

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aligned with the regional striking direction, where specified spots were selected for the placement of current and voltage electrodes. The length of the electrodes was systematically varied, and corresponding resistance values were measured and recorded. The distance between the electrodes was systematically varied, and the apparent resistivity was determined by employing the geometric factor. The primary objective of these stages was to collect subsurface electrical property data with the aim of enhancing the comprehension of the groundwater potential within the research area. The acquisition of this data is of utmost importance in order to enhance the efficacy of strategic planning and advancement of water resources.

3.2 Data Acquisition

Vertical Electrical Sounding (VES) was used in the geophysical investigation. The measurements were made with the Schlumberger setup and the ABEM-Terrameter (SAS1000-Signal Averaging System) Electrical Resistivity equipment. The investigation included the electrode's maximum lateral extension (L), which reached a depth of 800 metres below the surface. While sprinting to the right, a distance of 400 metres, equal to half the entire distance (L/2), was covered. On the left side, additional 400 metres (L/2) were covered. A grid-based design was used to operate sixteen (16) VES stations. Nonetheless, due to the existence of valleys, slopes, and residential structures, the construction of offset VES was an inevitable necessity. All necessary geo-electric measuring measures were properly considered and implemented in line with suitable weather circumstances.

The depth of current penetration, also known as the depth of inquiry, is directly proportional to the distance between the current electrodes. The current degree of penetration is only determined by the spatial spacing of the A and B electrodes, whereas the total arrangement of all four electrodes determines the amount of research depth. The apparent resistivity (ρa) measured by Schlumberger array at a single location with systematically varying electrode spacing is given by:

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

where

a = (AB/2) - (half current electrode spacing)

b = MN - (spacing between potential electrodes).

The resistance (R) is derived from the current (I) and voltage (V) values using the relation.

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

Equation (3.2) can be written as

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

Geometric factor,

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

K is a geometric factor that depends on the electrodes position in the ground and can be calculated for any electrode arrangement.

3.3 Data Processing

The VES data obtained were processed using the IP2win software. This software was utilized to input the apparent resistivity values along with their corresponding AB/2 values for further modelling and iteration. The iteration process involved multiple computer iterations, ranging from 1 to 29, to minimize errors and improve the goodness-of-fit. Through this iterative procedure, true resistivity layers were derived, along with their respective thickness and depth values, which were used as Dar-Zarouk parameters.

3.4 Dar Zarrouk Parameters

Dar-Zarrouk parameters are useful for evaluating aquifer properties, including transmissivity and the protective capacity of overlying rock materials (Bello et al., 2019). These parameters can be determined as follows:

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

Longitudinal Conductance (S)

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

Transverse Resistance (T)

$$T = \rho 1h1 + \rho 2h2 + \rho 3h3 + \cdots\cdots\cdots\cdots\cdots \rho nhn = \sum_{i=1}^{n} \rho ihi \quad (7)$$

Longitudinal Resistivity

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

Transverse Resistivity

$$Rt = H * S \quad (9)$$

Where; ρi and hi are the layer resistivity and thickness respectively.

The aquifer transmissivity (Tr) is expressed as the product of the hydraulic conductivity (k) and the layer thickness (h).

Thus;

$$T = kh \quad (10)$$

According to Ullah et al., (2020) the true resistivity of aquifer derived from geoelectric investigation can be used as aquifer hydraulic conductivity (k) in the absence of a pumping test data.

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

4. RESULTS AND DISCUSSION

The complex correlation between apparent resistivity and the progressive distance between electrodes may be properly demonstrated using a wide range of field curve patterns.

After being represented as separate curve types and resistivity profiles, as shown in Figures 2, the field data of apparent resistivities is subjected to a comprehensive qualitative evaluation. The primary function of this interpretative step is to facilitate the initial evaluation of subsequent geoelectrical zones that have been identified beneath the Earth's crust.

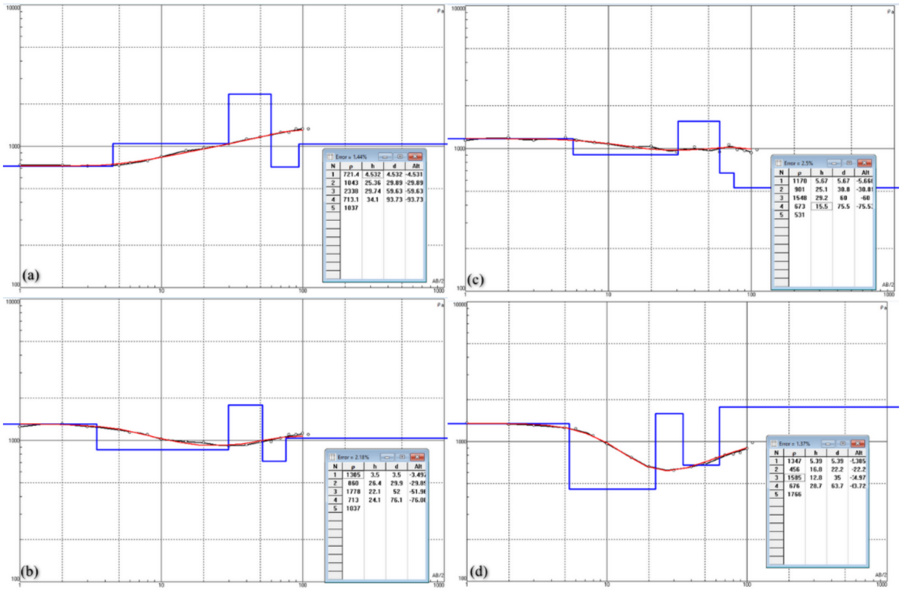
Afterwards, a comprehensive analysis is conducted to calculate the resistivity values, layer thicknesses, and depths of the relevant geoelectrical zones by utilizing the whole set of field curves. The inclusion of measurable characteristics enhances the comprehensiveness of the analysis pertaining to the composition and structure of the subsurface. The provided data serves the dual purpose of revealing the complexities of the Earth's subsurface and establishing the groundwork for the development of geoelectrical sections and instructive fence diagrams.

4.1 Qualitative Interpretation of Field Data

A comprehensive qualitative interpretation can be effectively attained for various categories of field curves, encompassing their distinctive layer compositions. The diverse curve types themselves hold valuable insights, offering a broad conceptual understanding regarding the depths attributed to distinct geoelectrical zones, a fact illustrated by the positions of their inflection points. Nonetheless, as Emenike (2001) emphasises, it is critical to exercise caution and consider the potential influence of lateral electric resistivity changes when investigating these locations of inflection. It is critical to note that these inflection points may reflect not only vertical changes, but also horizontal variations in resistivity values. The above remark emphasises the need of utilising a comprehensive approach of analysis that takes into account variations in geoelectrical characteristics both vertically and laterally. This method allows for a more exact and all-encompassing understanding of subsurface characteristics.

4.2 Modelled curve interpretation

The distinct characteristics inherent to each VES (Vertical Electrical Sounding) location are unveiled through a combination of curve matching and advanced computer modeling techniques, as visually represented in Figures 2. In this comprehensive interpretive process, the geological and geoelectric strata play a pivotal role, furnishing the essential groundwork for understanding. Additionally, the quantity of discernible layers within the curves, as well as the particular shape of the curves themselves, contribute significantly to the determination of various other properties. These encompass vital parameters like layer thickness, resistivity values, and depth information, as highlighted in the study by Osemeikhian et al. 1982.



(a) Error = 1.44%

N	ρ	h	d	Alt
1	721.4	4.532	4.532	-4.531
2	1043	25.36	29.89	-29.89
3	2338	29.74	59.63	-59.63
4	713.1	34.1	93.73	-93.73
5	1037			

(b) Error = 2.18%

N	ρ	h	d	Alt
1	1305	3.5	3.5	-3.49
2	860	26.4	29.9	-29.8
3	1778	22.1	52	-51.9
4	713	24.1	76.1	-76.0
5	1037			

(c) Error = 2.5%

N	ρ	h	d	Alt
1	1170	5.67	5.67	-5.66
2	901	25.1	30.8	-30.81
3	1548	29.2	60	-60
4	673	15.5	75.5	-75.5
5	531			

(d) Error = 1.37%

N	ρ	h	d	Alt
1	1347	5.39	5.39	-5.385
2	456	16.8	22.2	-22.2
3	1585	12.8	35	-34.97
4	676	28.7	63.7	-63.72
5	1766			

Figure 2: (a) VES 1, (b) VES 2, (c) VES 3, and (d) VES 4 computer simulated curves displaying modelled and theoretical curves

Table 1: Location, Resistivity, Depth and Thickness of Delineated Aquifer in the Study Area

VES	Longitude	Latitude	Resistivity (Ωm)	Depth (m)	Thickness (m)
VES 1	5.647	5.538	713.10	93.73	29.74
VES 2	5.517	5.582	713.00	76.10	24.10
VES 3	5.573	5.528	673.00	75.50	15.50
VES 4	5.539	5.571	676.00	63.70	28.70
VES 5	5.556	5.573	777.00	60.40	38.60
VES 6	5.592	5.578	823.40	81.70	20.74
VES 7	5.608	5.587	549.30	67.09	26.32
VES 8	5.622	5.601	789.00	59.10	39.50
VES 9	5.628	5.577	631.00	77.40	38.90
VES 10	5.61	5.568	723.00	64.50	21.70
VES 11	5.582	5.564	885.00	75.50	20.90
VES 12	5.591	5.538	688.00	77.80	38.40
VES 13	5.647	5.551	872.20	101.00	50.60
VES 14	5.631	5.52	1044.00	80.00	35.00
VES 15	5.676	5.487	794.00	62.20	22.40
VES 16	5.71	5.504	794.00	63.60	28.80

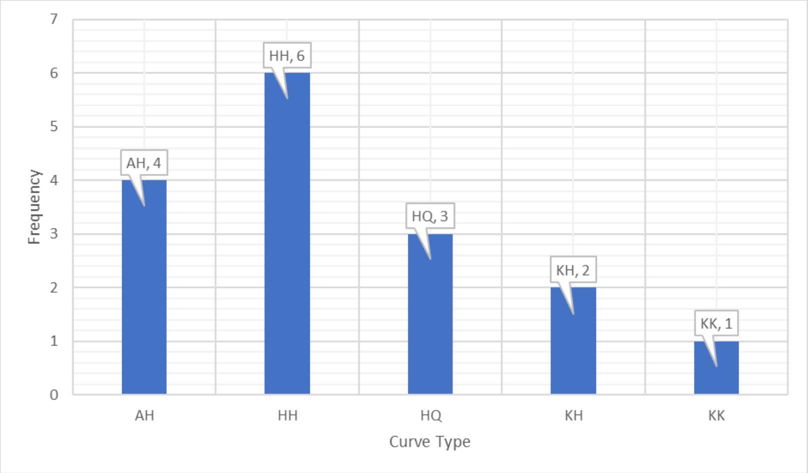


Figure 3: Histogram of different curve types in the study area

The analytical investigation is further fortified by the identification of distinct curve types, which span a spectrum from simple to intricately detailed forms. Each VES curve, a representation of subsurface electrical resistivity variations, is systematically categorized into five distinct layers. The prevailing curve type, designated as HH, takes precedence and is notably observed in a substantial 37.5% of all VES conducted within the researched area, as visually depicted in Figure 3. Additionally, the curve types AH, HQ, KH, and KK, while exhibiting varying degrees of complexity, contribute to the interpretive landscape with proportions of 25%, 18.75%, 12.5%, and 6.25% respectively, collectively offering a comprehensive panorama of the subsurface characteristics.

4.3 Aquifer and Dar-zarrouk Parameters

The Dar-zarrouk characteristics include a number of major features with important consequences in the field of hydrogeology (Akaolisa et al., 2022a). Aquifer resistivity, conductivity, thickness, transmissivity, longitudinal conductance, transverse resistance, and hydraulic conductance are among the characteristics stated above.

Tables 2 provide a comprehensive representation of these characteristics, including data that serves as a foundation for understanding aquifer dynamics. This comprehensive compilation gives hydrogeologists, academics, and decision-makers with a data-driven lens through which they may traverse aquifer dynamics, contributing to informed water resource management and sustainable groundwater exploitation.

Through the comprehensive study and effective utilization of the many qualities shown by aquifers, we are able to unleash the potential to unravel the enigmatic hydrogeological phenomena that exist under the Earth's surface. This endeavor facilitates the development of a more sophisticated comprehension of the intricate patterns and dynamics of subsurface water flow and distribution.

Table 2: Dar-Zarrouk Parameters for The Research Area's Aquifers

VES	Longitudinal Conductance (mhos)	Transverse Resistance (Ωm^2)	Hydraulic Conductivity (m/day)	Transmissivity (m^2/day)
VES 1	0.042	21207.59	0.274	8.13
VES 2	0.034	17183.30	0.274	6.59
VES 3	0.023	10431.50	0.288	4.47
VES 4	0.042	19401.20	0.287	8.24
VES 5	0.050	29992.20	0.252	9.72
VES 6	0.025	17077.32	0.237	4.92
VES 7	0.048	14457.58	0.338	8.91
VES 8	0.050	31165.50	0.248	9.79
VES 9	0.062	24545.90	0.304	11.84
VES 10	0.030	15689.10	0.270	5.86
VES 11	0.024	18496.50	0.219	4.57
VES 12	0.056	26419.20	0.283	10.85
VES 13	0.058	44133.32	0.222	11.25
VES 14	0.034	36540.00	0.178	6.23
VES 15	0.028	17785.60	0.246	5.52
VES 16	0.036	22867.20	0.246	7.09

4.4 Aquifer Resistivity

Aquifer resistivities exhibit a significant degree of variability, primarily stemming from the inherent electrical properties and composition of the geological formations. This intrinsic relationship between rock types and their respective resistivities is a governing factor in shaping the resistivity values observed in Vertical Electrical Sounding (VES) data (Akaolisa et al., 2022b). Moreover, the distinctive contours and shapes of the model curves, as well as the localized geological characteristics, exert a notable influence on the recorded resistivity values.

This intricate interplay of factors underscores the absence of a singular, predetermined range for aquifer resistivity. The span of aquifer resistivity values is conspicuously diverse, as evidenced by the VES measurements. A comprehensive analysis reveals that within this spectrum, the VES 7 dataset registers the lowest resistivity measurement at 549.30 Ωm. Conversely, the VES 14 dataset boasts the highest recorded resistivity, amounting to an impressive 1044.00 Ωm, as vividly depicted in the illustrative Figure 4.

A compelling pattern emerges when scrutinizing the spatial distribution of aquifer resistivity. The central core of the study area stands out as a region characterized by remarkably elevated aquifer resistivity values. This prominent feature holds sway over the southeastern quadrant of the study area, which exhibits a notably heightened, albeit moderately so, aquifer resistivity. The interplay between these localized resistivity patterns and the geological attributes bolsters the understanding of aquifer dynamics in this region.

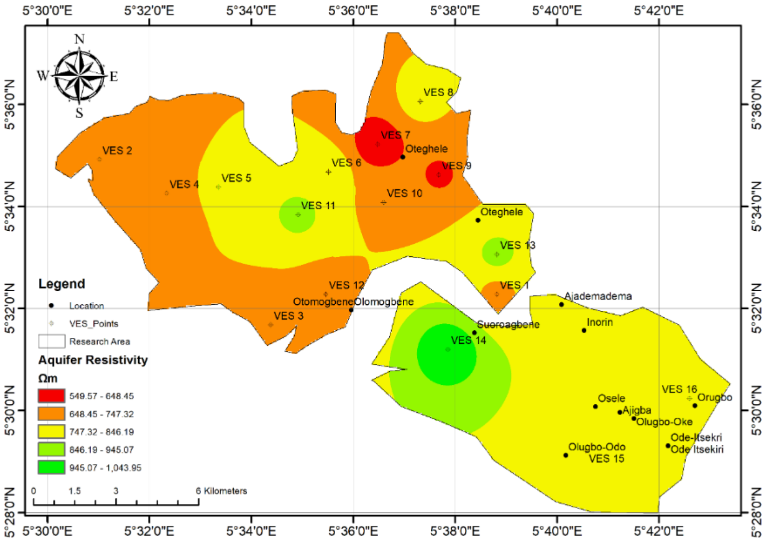


Figure 4: Map of aquifer resistivity of the study area.

4.5 Aquifer Thickness

The extent of subsurface water reservoirs in your current location is referred to as the aquifer thickness, representing a critical hydrogeological parameter. The notion of isopachs proves invaluable in delineating areas characterized by uniform aquifer thickness. This technique facilitates the depiction of regions sharing the same thickness values, thereby enhancing our understanding of subsurface water distribution. An illustrative representation of the aquifer thickness across the research area is thoughtfully presented in Figure 5.

Upon a comprehensive examination of this cartographic depiction, distinct disparities in aquifer thickness come to the forefront. Specifically, the aquifer thickness associated with VES 3 emerges as the slenderest, registering a measurement of 15.50 meters. In stark contrast, VES 13 commands attention with its remarkable aquifer thickness of 50.60 meters, serving as a testament to the spatial variability in subsurface water reservoirs.

Remarkably, a prevailing trend materializes upon closer inspection of the spatial distribution of aquifer thickness. The epicenter of this intriguing pattern rests within the central expanse of the study area, where a profusion of aquifers characterized by a moderate thickness assumes prominence. This central core emerges as a nexus of subsurface water resources, substantiating the pivotal role it plays in the overall hydrogeological dynamics of the region. The interplay between geological attributes and the observed aquifer thickness further accentuates the complexity of groundwater distribution within this specific locale.

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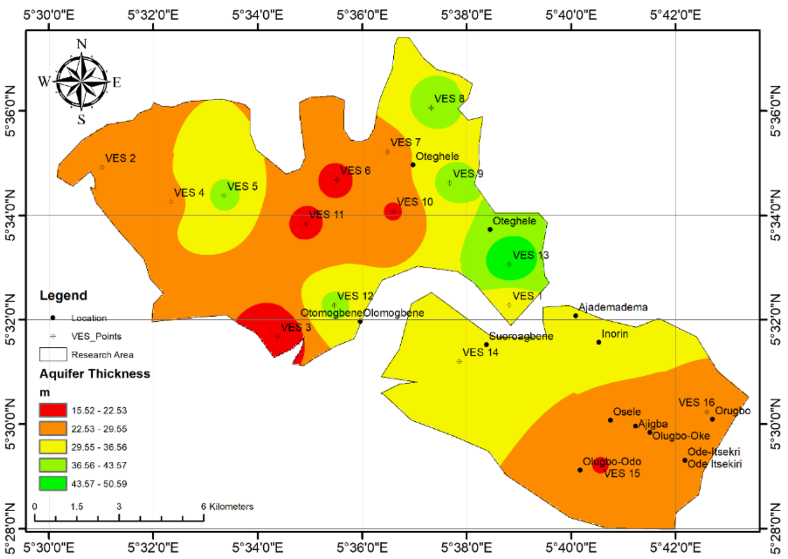

Figure 5: Map of aquifer thickness of the study area.

4.6 Aquifer Depth

The measurement of aquifer depth signifies the vertical extent spanning from the saturated zone, where water fills the pores and crevices of the Earth, to the aerated zones situated above the water table, which lies beneath the water table. Precipitation acts as a driving force, instigating a captivating sequence of events: rainwater infiltrates through crevices within the soil and bedrock, following the dictates of gravity as it journeys deeper into the Earth. Accumulating gradually, water congregates within lower reaches, heralding the formation of the saturation zone, where subsurface spaces are brimming with water.

An intricate dance between natural elements ensues, underscored by the ebb and flow of precipitation. The water table's position experiences fluctuations as rain patterns shift, consequently influencing the quantum of water finding its way into the saturation zone. The water table's proximity to the Earth's surface is a dynamic parameter, intricately tied to climatic rhythms. In parallel, the water table's altitude fluctuates in response to withdrawals or utilization of water from the saturation zone, ushering in a symphony of hydrological dynamics.

Figure 6 captures this multifaceted narrative by visually encapsulating the aquifer depth distribution within the study region. The visual cues unearth intriguing observations. At VES 8, the aquifer depth unveils its shallowest dimension, measuring a mere 59.10 meters. In stark contrast, the exploration at VES 13 plunges to unprecedented depths, marking an impressive 101.00 meters.

A distinct geographical pattern unfolds as we traverse the study area from the central core. An unmistakable crescendo in aquifer depth values reverberates within the central heartland, painting a vivid portrait of its hydrogeological significance. Yet, as we venture from this epicenter towards the southeastern and northwestern fringes, the aquifer depths embark on a gradual descent, elegantly echoing the harmonious rhythm of hydrological forces at play.

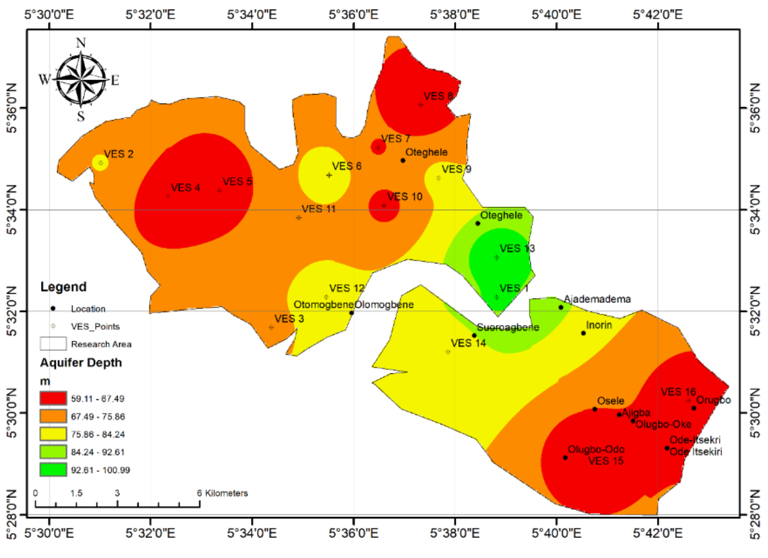

Figure 6: Map of aquifer depth of the study area.

4.7 Aquifer Transverse Resistance

An important aquifer parameter employed for gauging the lateral variability in resistance between different locations is known as transverse resistance. This parameter arises from the product of aquifer resistivity and its thickness across a given expanse (Adewumi et al., 2023). The culmination of these factors played a pivotal role in the derivation of the values presented in Table 2.

The depiction of transverse resistance across the study area is eloquently captured in Figure 7. Noteworthy patterns emerge as we scrutinize the spatial distribution of this parameter. Specifically, VES 3 stands out with the lowest recorded aquifer transverse resistance, a value of 10431.50 Ωm^2. In stark contrast, VES 3 commands attention with the highest recorded aquifer transverse resistance, an impressive measure of 44133.32 Ωm^2.

Delving further into the intricacies of this phenomenon, a compelling geographical trend surface. The eastern fringes of the study area exhibit a distinctive propensity for elevated aquifer transverse resistance values. This spatial delineation of resistance nuances underscores the complex interplay between geological attributes and aquifer properties within this specific locale, further enriching our understanding of the hydrogeological dynamics at play.

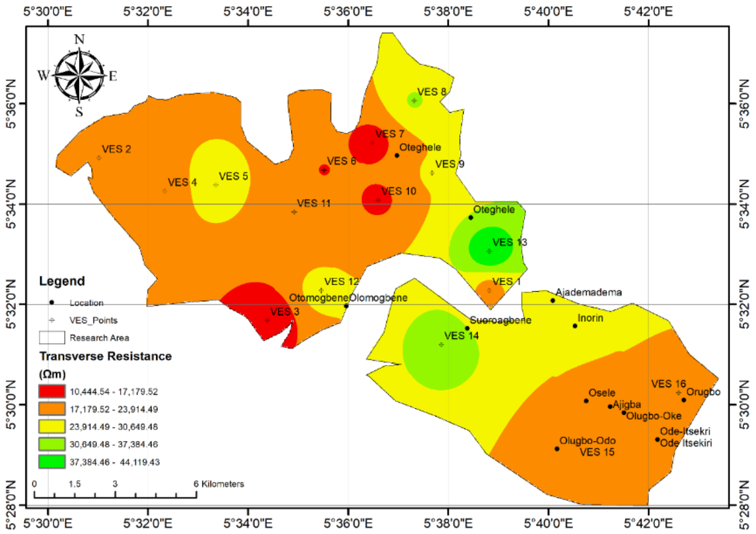

Figure 7: Map of aquifer transverse resistance of the study area.

4.8 Aquifer Longitudinal Conductance

Utilizing the fundamental geoelectric measures of layer thickness and resistivity, an additional significant geoelectric parameter known as longitudinal conductance can be derived. This secondary parameter serves as a valuable indicator of the conductivity exhibited by subsurface formations (Jimoh et al., 2023). The process of calculating longitudinal conductance involves a judicious combination of these foundational metrics and is instrumental in comprehending the electrical characteristics of the Earth's subsurface.

The intricate interplay of layer thickness and resistivity unveils the longitudinal conductance spectrum within the region under scrutiny. This dynamic parameter spans a range from 0.023 to 0.062 mho, as artfully depicted in Figure 8. This range of longitudinal conductance values encapsulates the diverse electrical properties exhibited by the subterranean layers, mirroring the intricate geological tapestry that underlies the research area.

This spectrum of longitudinal conductance values presents a window into the conductivity variations across the studied terrain. Such fluctuations are indicative of the diverse lithological composition and structural complexities that shape the subsurface conductivity patterns. By extending our grasp beyond the primary geoelectric metrics to encompass secondary parameters like longitudinal conductance, we gain a more nuanced perspective on the intricate geoelectric dynamics unfolding beneath the Earth's surface.

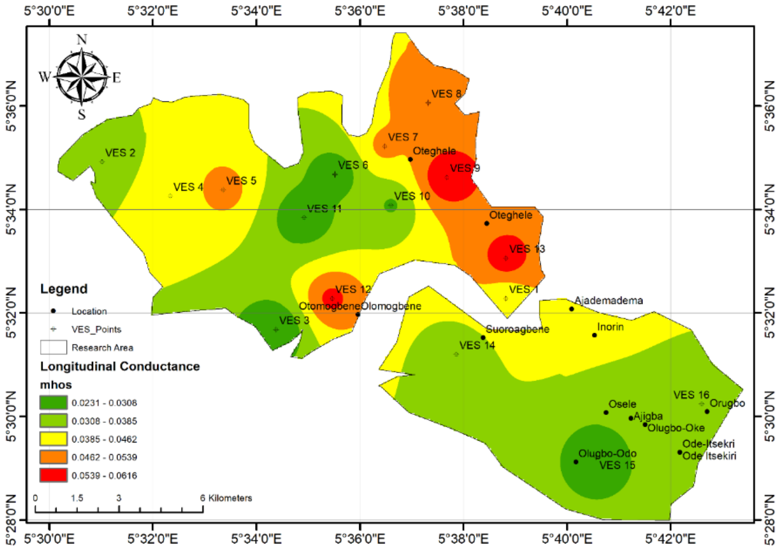

Figure 8: Map of aquifer longitudinal conductance of the study area.

4.9 Aquifer Hydraulic Conductivity

Within the confines of this geographical expanse, a dynamic range of hydraulic conductivity is evident, spanning from 0.178 to 0.338 meters per day, as vividly illustrated in the intricate mosaic of Figure 9. This parameter, a quintessential metric in hydrogeology, unveils the capacity of subsurface materials to facilitate the movement of groundwater. A profound interplay of geological factors, both at a local and regional scale, orchestrates this intricate hydraulic symphony.

Elevating our understanding, hydraulic conductivity emerges as an eloquent indicator intricately intertwined with the surrounding lithology. The correlation between hydraulic conductivity and the localized lithological fabric is strikingly evident, with attributes like resistivity, transverse resistance, and transmissivity playing pivotal roles in shaping the hydraulic conductive behaviors observed. Yet, the narrative does not end there – the vertical expanse, manifesting as aquifer thickness and depth, further embellishes the hydraulic conductivity tapestry, extending its influence over the ease with which groundwater traverses.

Delving into the empirical origins of Figure 9, it becomes apparent that this compilation is an amalgamation of diverse sources. In some instances, Uma (1989), through extrapolation, contributed to the numeric values presented therein. Alternatively, data points hailing from locales where hydraulic heads were meticulously measured in the year 1989 enrich this mosaic. A tantalizing prospect emerges from these origins - the potential to calculate hydraulic conductivity for proximate points or regions sharing consistent geological attributes. In cases where direct measurements may be absent, this practice finds utility as an invaluable tool for inference and estimation, thereby enhancing our grasp of the hydraulic dynamics that underlie the geological fabric. This method extends its application across the geospatial tapestry, illuminating uncharted realms with insightful estimations.

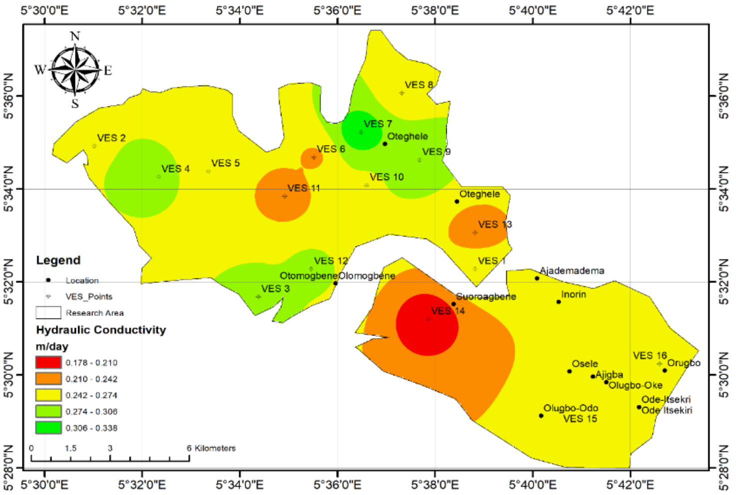

Figure 9: Map of aquifer hydraulic conductivity of the study area.

4.10 Aquifer Transmissivity

Transmissivity, a pivotal hydrogeological parameter, offers a profound glimpse into the innate potential of an aquifer to facilitate the seamless transmission of groundwater across its complete saturated vertical extent. This metric embodies a critical measure of the quantity of groundwater capable of traversing a defined section of an aquifer within a specified timeframe, all under the governing influence of particular hydraulic conditions. A rich interplay of geological and hydrological nuances orchestrates the transmissivity tapestry, revealing the extent to which subsurface materials can accommodate and propel the flow of groundwater.

Embedded within this hydrogeological framework, transmissivity assumes the role of a definitive descriptor. It captures the dynamic equilibrium between the geological formations' inherent properties, the expansive saturated zone, and the prevailing hydraulic gradients. This marriage of factors culminates in the quantification of groundwater movement potential within distinct segments of the aquifer.

Drawing our gaze to the meticulously composed canvas of Figure 10, the intricate geographical mosaic of aquifer transmissivity within the research area comes to life. This vivid portrayal is the result of a harmonious blend of data points meticulously garnered through extensive investigation. Within this illustrative tapestry, a captivating spectrum of values unveils itself, ranging from 4.49 square meters per day at the probing VES 3 location to an impressive 11.84 square meters per day at the revealing VES 9 location.

The insights encapsulated within this transmissivity spectrum unravel an intricate narrative of hydrogeological interactions. Each data point resonates with the geological nuances of its specific locale, a testimony to the symphony of hydraulic dynamics that traverse the subterranean landscape. As the transmissivity values dance across the geographical canvas, they not only enrich our understanding of groundwater movement but also serve as an essential compass guiding further exploration into the depths of aquifer behavior and hydrological interconnectedness.

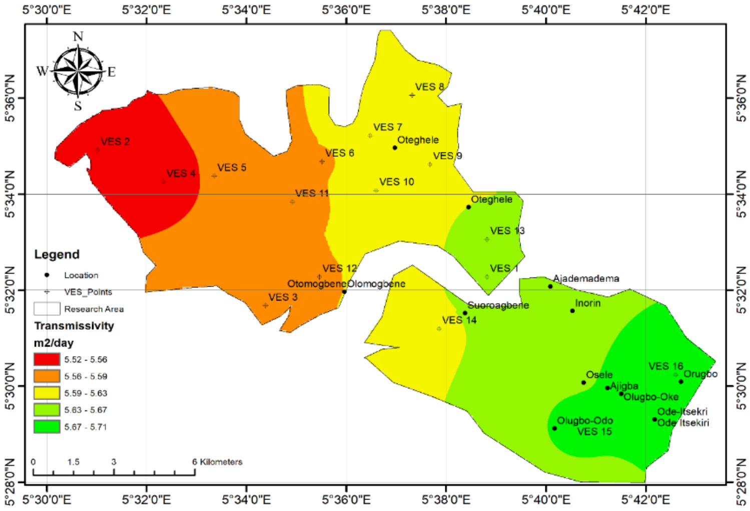

Figure 10: Map of aquifer transmissivity of the study area.

4.11 Soil Corrosivity And Protective Capacity

Table 3 shows the aquifers' protective capacity and soil corrosivity in the studied region. This data is used to estimate the amount of soil corrosivity in the region at shallow depths, particularly when metal pipes or underground utilities are required for groundwater development or other engineering applications. According to Rahaman (1988), non-corrosive zones have higher resistivity values, whereas corrosive areas have lower resistivity levels. The efficiency of an earth medium's safeguarding is dependent on its capacity to slow and cleanse a percolating fluid (Olorunfemi et al., 1999).

According to Henriet (1975), an overburden's ability to guard against pollutant penetration is inversely related to its hydraulic conductivity and is impacted by its thickness. Clayey materials often have poor permeability, resistivity, hydraulic conductivity, and longitudinal unit conductance. As a result, a linear relationship exists between protective capacity and longitudinal conductance. As a result, a particular region's protective capacity increases in proportion to its longitudinal conductivity under overload conditions. According to Braga (2008), electrical resistivity is a key feature of many geological materials that aids in the assessment of their state in relation to alteration, fracture, and water saturation levels.

Furthermore, lithology distinction can be accomplished without the need for costly excavation or labor-intensive holes. The VES Schlumberger array gives various important metrics, including as electrical resistivity, ground water level depth, and the Dar Zarrouk parameter longitudinal conductance, which are very important in the early stages of environmental research. The longitudinal conductance parameter resistivity approach of Darzarrouk is used to create relationships between electrical resistivity and hydrogeological parameters such as porosity, permeability, transmissivity, and hydraulic conductivity. As a result, the associations are formed by analogical reasoning, which draws parallels between the equations regulating the flow of electric current in a conductive media and the movement of groundwater through a porous substance. Geoelectric data collected at the surface can be used to evaluate the hydrodynamic parameters of an aquifer (Porsani et al., 2012).

The term "protective capacity" refers to an aquifer's ability to prevent and purify dirty groundwater that infiltrates from the surface. The qualities of the materials or layers that comprise an aquifer's overburden determine its susceptibility to contamination. The ability of an aquifer to provide protection, according to Oladapo & Akintorinwa (2007), is directly related to the longitudinal conductance of the overlying units.

The protective capacity rating of an aquifer serves as a critical indicator of its ability to shield surrounding soil and groundwater from potential corrosive effects. The accompanying soil corrosivity classification further illuminates the compatibility of the aquifer with the local geological environment. In the case of the vertical electrical soundings (VES) conducted across the study area, the prevailing theme is one of uniformly poor protective capacity ratings coupled with a characterization of practically noncorrosive soil conditions as shown in Table 3.

Table 3: Rating of Protective Capacity and Soil Corrosivity

VES	Protective Capacity Rating	Soil Corrosivity
VES 1	Poor	Practically Noncorrosive
VES 2	Poor	Practically Noncorrosive
VES 3	Poor	Practically Noncorrosive
VES 4	Poor	Practically Noncorrosive
VES 5	Poor	Practically Noncorrosive
VES 6	Poor	Practically Noncorrosive
VES 7	Poor	Practically Noncorrosive
VES 8	Poor	Practically Noncorrosive
VES 9	Poor	Practically Noncorrosive
VES 10	Poor	Practically Noncorrosive
VES 11	Poor	Practically Noncorrosive
VES 12	Poor	Practically Noncorrosive
VES 13	Poor	Practically Noncorrosive
VES 14	Poor	Practically Noncorrosive
VES 15	Poor	Practically Noncorrosive
VES 16	Poor	Practically Noncorrosive

The consistent categorization of the aquifers as having a "Poor" protective capacity rating signifies a shared vulnerability in terms of safeguarding the surrounding environment against potential corrosive agents. This rating points towards the limited ability of these aquifers to neutralize or mitigate the effects of corrosive substances that could infiltrate the groundwater. While the exact nature of this susceptibility requires further investigation, this initial assessment underscores the need for careful management of potential contaminant sources that might interact with the aquifer system.

Complementing this protective capacity rating, the classification of the aquifer soil as "Practically Noncorrosive" serves as a reassuring note in the discussion. This designation implies that the soil, despite being within an aquifer of poor protective capacity, exhibits a reduced propensity for causing corrosion-related issues. This is a positive aspect that contributes to a better understanding of the local hydrogeological conditions and supports the preservation of groundwater quality.

The consistent trend across all the VES points in terms of both poor protective capacity and noncorrosive soil is indicative of a shared geological context that shapes the aquifer characteristics. The possible drivers behind this observed pattern could include specific mineralogical compositions, hydrochemical interactions, or geological formations that influence the overall protective capacity and corrosive potential.

4.12 Rating for Groundwater Supply Potential and Protective Capacity

The evaluation of groundwater potential at each sounding point hinged upon the calculated transmissivity of the aquifer underlying these locations. Table 4 encapsulates the outcomes of this transmissivity analysis, specifically employing Vertical Electrical Sounding (VES) data to demarcate the varying groundwater supply potential across the study area. To provide a more comprehensive context, Table 5 and Figure 11 complement this analysis by presenting an overarching categorization of aquifers based on their transmissivity ratings.

The discernible pattern across these tables underscores a prevailing theme within the study area: a majority of aquifers have been categorized as having a "Low" designation in terms of their transmissivity. This implies a limited capacity for these aquifers to transmit groundwater effectively. Consequently, the corresponding groundwater supply potential for these aquifers is oriented towards smaller withdrawals, primarily catering to local water supply for private consumption. The homogeneity of this "Low" designation emphasizes the importance of conscientious water usage practices in these areas to ensure the sustainability of the aquifer system and the groundwater it supports.

Table 4: Classification of Aquifer Transmissivity in The Study Area

VES	Designation	Groundwater Supply Potential
VES 1	Low	Smaller withdrawal for local water supply (private consumption)
VES 2	Low	Smaller withdrawal for local water supply (private consumption)
VES 3	Low	Smaller withdrawal for local water supply (private consumption)
VES 4	Low	Smaller withdrawal for local water supply (private consumption)
VES 5	Low	Smaller withdrawal for local water supply (private consumption)
VES 6	Low	Smaller withdrawal for local water supply (private consumption)
VES 7	Low	Smaller withdrawal for local water supply (private consumption)
VES 8	Low	Smaller withdrawal for local water supply (private consumption)
VES 9	Intermediate	Smaller withdrawal for local water supply (small community, planst, etc.)
VES 10	Low	Smaller withdrawal for local water supply (private consumption)
VES 11	Low	Smaller withdrawal for local water supply (private consumption)
VES 12	Intermediate	Smaller withdrawal for local water supply (small community, planst, etc.)
VES 13	Intermediate	Smaller withdrawal for local water supply (small community, planst, etc.)
VES 14	Low	Smaller withdrawal for local water supply (private consumption)
VES 15	Low	Smaller withdrawal for local water supply (private consumption)
VES 16	Low	Smaller withdrawal for local water supply (private consumption)

However, amidst this predominant characterization, exceptions arise that add a layer of complexity to the narrative. Notably, VES points 9, 12, and 13 deviate from the overarching "Low" trend and bear an "Intermediate" designation. This elevated classification signifies a comparatively higher transmissivity, thereby imparting these specific aquifers with the capacity to support withdrawals for local water supply needs beyond individual households. These aquifers are poised to accommodate the water demands of small communities, plants, and similar entities, which broadens their utility within the local water supply context.

The alignment between the localized "Intermediate" designations for VES points 9, 12, and 13 in Table 4 and the broader "Intermediate" category in Table 5 reaffirms the robustness of the assessment. This convergence lends credibility to the findings, emphasizing the accuracy and relevance of the groundwater potential classifications.

This comprehensive analysis not only informs the understanding of groundwater potential but also underscores the importance of sustainable water resource management. It highlights the need for tailored approaches to water usage and conservation strategies, particularly in areas designated as having "Low" groundwater supply potential. It also recognizes the role of aquifers with "Intermediate" designation in supporting more diverse and slightly larger-scale withdrawals for local water supply, necessitating a balance between usage and preservation.

Table 5: Classification of Aquifer Based on Transmissivity (Modified after Todd 1980; Freeze and Cherry 1979)

Transmissivity (m^2/day)	Aquifer Rating	Groundwater Supply Potential
1000	Very good	Withdrawal of great regional importance
100 – 1000	Good	Withdrawal of lesser regional importance
10 – 100	Intermediate	Withdrawal of local water supply (small community, plants etc)
1 – 10	Low	Smaller withdrawal for local water supply (private consumption)
0.1 – 1	Very low	Withdrawal for local water supply (private consumption)
< 0.1	Impermeable	Sources for local water supply are difficult

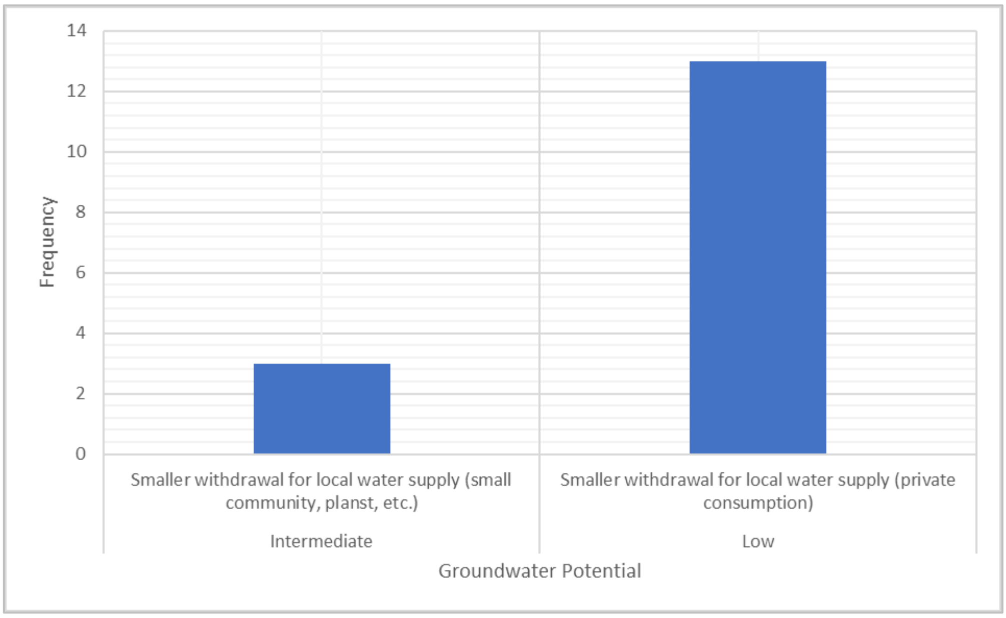

Figure 11: Histogram for groundwater supply potential and designation of aquifers in the study area.

5. CONCLUSION

In the pursuit of understanding subsurface hydrogeological dynamics, this study embarked on a comprehensive exploration of aquifer properties, unraveling a multifaceted narrative hidden beneath the Earth's surface. The relationship between apparent resistivity and electrode separation emerged as a crucial avenue, shedding light on subsurface attributes through various field curve types. These curves, systematically categorized and analyzed, enabled qualitative and quantitative interpretations of Vertical Electrical Sounding (VES) data in two distinct stages - Qualitative Interpretation and Quantitative Interpretation.

Challenges associated with intricate curve scenarios involving multiple layers were met with the integration of lithological data from wells, enhancing the interpretive process. The synergistic approach of combining qualitative and quantitative aspects deepened our comprehension of subsurface dynamics, culminating in a coherent depiction of geological features.

Curves such as HH, AH, HQ, KH, and KK played a pivotal role, revealing subsurface characteristics and facilitating parameter determinations like layer thickness and resistivity values. While these curve types offered a comprehensive panorama of subsurface properties, the influence of lateral resistivity variations on inflection points remained a crucial consideration. The interpretive journey encompassed curve matching, advanced modeling, and geological insights, highlighting the complexity of the VES process.

Several elements have been recognised as critical areas of study in the subject of aquifer characterization, collectively offering information on the complex hydrogeological topography under the Earth's surface. The critical relevance of aquifer resistivity, conductivity, thickness, transmissivity, longitudinal conductance, transverse resistance, and hydraulic conductance in comprehending the various mechanisms governing groundwater flow and distribution has been proven.

The intrinsic relationship between rock types and aquifer resistivity underscored the significant variability in resistivity values obtained from VES data. Model curves, alongside localized geological attributes, contributed to the recorded resistivity values, dispelling the notion of a predetermined resistivity range. The spatial distribution of aquifer resistivity unveiled patterns that offered valuable insights into aquifer dynamics within the study area.

The concept of isopachs facilitated the visualization of aquifer thickness variations, contributing to an enhanced understanding of subsurface water distribution. Aquifer depth measurements highlighted the dynamic interplay between saturation and aeration zones, driven by hydrological forces influenced by rainfall and withdrawals.

Parameters such as transverse resistance, longitudinal conductance, hydraulic conductivity, and transmissivity further enriched our understanding of aquifer behavior, capturing the intricate interplay between geological properties and subsurface water movement. Each parameter resonated with specific geological nuances, collectively painting a vivid picture of hydrogeological interconnectedness.

As we delved deeper into the exploration of aquifer properties, their protective capacity emerged as a crucial consideration, intertwined with soil corrosivity. Vertical electrical soundings consistently unveiled poor protective capacity ratings alongside noncorrosive soil conditions, urging us to manage potential contaminant sources that could interact with aquifer systems.

In the assessment of groundwater potential, transmissivity calculations guided our understanding, with most aquifers designated as having "Low" transmissivity. This classification underscored the need for judicious groundwater consumption and resource management. Exceptions within "Intermediate" designations, notably VES points 9, 12, and 13, hinted at localized potential for broader water supply, aligning localized assessments with broader categorizations.

In sum, this hydro-geoelectric investigation offered a comprehensive exploration of aquifer potential in Warri South, Delta State. Through a meticulous analysis of aquifer properties, we gained profound insights into the intricate dynamics of subsurface water flow, distribution, and groundwater potential. Armed with this knowledge, we are better equipped to make informed decisions regarding water resource management, sustainable groundwater utilization, and the preservation of groundwater quality. This journey into the depths beneath our feet has illuminated the enigmatic hydrogeological phenomena that shape our environment, forging a deeper connection to the hidden world beneath the Earth's surface.

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