FUDMA Journal of Sciences (FJS)
ISSN online: 2616-1370
ISSN print: 2645 - 2944
Vol. 10 No. 2, January, 2026, pp 375 – 389
DOI: https://doi.org/10.33003/fjs-2026-1002-4482

HYDROGEOPHYSICAL INVESTIGATION OF GROUNDWATER POTENTIAL, LITHOLOGICAL STRATA AND AQUIFER VULNERABILITY IN PARTS OF DELTA NORTH DISTRICT, NIGERIA

***[1]Felix Iwebunor Chinyem, [2]Ezekiel Onoriode Abriku, 1 Glory O. Ovwamuedo, [3] Sikiru Adeoye Salami, [4] Chinedu Ojo Igili, [5] Victor Ndubuisi Nwugha, and [1]Jeffrey Onyedikachi Osieke**

[1]Department of Geology, Delta State University, Abraka, Delta State, Nigeria.
[2]Department of Physics, Delta State University, Abraka, Delta State, Nigeria.
[3]Department of Geology, University of Benin, Benin City, Edo State, Nigeria.
[4]Department of Energy and Petroleum Studies, Novena University, Ogume, Delta State, Nigeria.
[5]Department of Basic Sciences and Mathematics, Alvan Ikoku University of Education, Imo State, Nigeria.

*Corresponding authors' email: fichinyem@delsu.edu.ng, fichinyem@gmail.com

ABSTRACT

Groundwater in Delta North District of Nigeria, constitutes the main source of potable water to inhabitants, however increasing demographics, urbanization and poor water disposal practices have raised concerns about aquifer vulnerability, as well as declining water quality. The goal of this study is to investigate the groundwater potential, lithological strata and aquifer vulnerability, in parts of the district, using vertical electrical sounding (VES) technique. Twenty-five (25) VES, using Schlumberger array was employed to delineate subsurface geoelectric layers as well as infer the aquiferous units, while eight (8) boreholes were drilled to assess the lithology and aquifer properties of the study area. Geoelectric models interpreted, were correlated with the obtained well logs in order to validate the lithological strata and aquifer depths. Result revealed a heterogeneous subsurface geologic formation, comprising, top soil, clayey sand, lateritic clayey sand, coarse sand, medium-coarse sand, fine-medium sand and saturated deep sandy aquifers occurring at varying depths ranging from 66 m to 152 m and beyond.The aquifer resistivity, depth, transverse resistivity and transmissivity values obtained indicate that the groundwater potential varies from low to intermediate, distributed mainly within the southwestern, southeastern and northeastern regions,with aquifers having low longitudinal conductance values in the study area, suggestive of high vulnerability to surface contamination. The study therefore, provides foundational harmonised groundwater baseline data that can serve as reference model for future hydrogeological modeling, groundwater resource planning, contaminant risk assessment, and sustainable groundwater development within the study area.

Keywords: Sustainable Groundwater Development, Aquifer Vulnerability, Groundwater Potential, Delta North District

INTRODUCTION

Delta North District of Delta State, Nigeria lies within the broader Niger Delta sedimentary basin, a complex geological province dominated by unconsolidated stratigraphic successions of the Akata , Agbada and Benin Formations, respectively (Short and Stauble, 1967). These formations significantly influence groundwater occurrence and quality, and control the subsurface architecture (Anomohanran et al., 2017). The sands of varying grain sizes typically host the aquifers, while interbedded clays and silts act as semi-permeable layers that modulate recharge and protective capacity(Hassan et al., 2019). In this region, groundwater serve as a critical freshwater resource for domestic, agricultural and local industries use (Chinyem, 2024; Chinyem and Ovwamuedo, 2024; Chinyem et al., 2025a; Chinyem et al., 2025b). Nonetheless, rapid demographic growth, inadequate infrastructure and increasing anthropogenic pressures intensify demands and heighten vulnerability to contaminants(Babasola and Infeanyi 2024; Opoku et al ., 2024; Chinyem et al., 2025b) In spite of its natural abundance, accessibility to human use in terms of its good quality and quantity has been a problem due to increasing human demographics and other factors (Opoku et al., 2024; Chinyem et al., 2025b). Alternative sources of water to mankind, such as rivers and lakes, apart from the fact that they are not uniformly available to all residential towns and districts, are more easily polluted by human and other activities (Musa et al., 2023; Chinyem and Ovwamuedo, 2024; Hudu et al., 2024). In the study area, groundwater, surface water and rain water are the major sources of water supply to inhabitants. In communities where surface water is available, people walk to several kilometres in search of water. Furthermore, during the rainy season the inhabitants rely on rain-harvesting, whereby concrete underground wells are dug and rainwater is directed to the underground reservoirs through the gutters constructed at the base of corrugated iron sheet roofs, for their water needs. These underground reservoirs serve as water supply to inhabitants during the dry season. Additionally, the choice of some of the towns/locations chosen was because they experience seasonal water shortages due to increased population growth, unreliable and poor surface water and over-exploitation of existing boreholes, leading to low yields and abortive boreholes. Lack of detailed and adequate hydrogeophysical and geological investigation have led to low and abortive boreholes in the area. Hydrogeophysical investigation, therefore, becomes crucial in order to identify new sustainable aquifers that will meet the water needs of the communities.

Detailed hydrogeophysical analysis is a very useful tool for evaluation of groundwater potential as well as lithological strata. Hydrogeophysical investigations have been employed Chinyem (2013), Anomohanran (2014), Araffa et al (2024), Hudu et al., (2024); Ikuemonisan et al., (2025); and Rauf et al., (2025). Chinyem (2013) applied Vertical Electrical Soundings (VES) to hydrogeophysically investigate Asaba area. His findings revealed that the aquifer delineated were confined and also consistent with the borehole lithologic logs of drilled boreholes within the area. Anomohanran (2014) utilized VES, well logging and pumping test techniques to carry out hydrogeophysically, the aquifer parameters and lithological sequence in Abraka. The findings revealed a confined aquifer, that could yield adequate as well as good quality water to the community. Araffa et al. (2024) also conducted a hydrogeophysical investigation for groundwater assessment at Wadi EL Assuity, Egypt. The findings revealed an aquifer that comprised sandy clay, sand and clayey sand. The investigation equally revealed that the area is rich in a variety of groundwater resources in very high concentrations. Similarly, Hudu et al. (2024) applied primary and secondary resistivity parameters to assess aquifer potential and vulnerability within Kabba, Nigeria. Their results indicated that aquifer zones range from low to very good potential, and the protective capacity of overburden materials is generally weak, exposing groundwater to contamination risks. Moreso, Ikuemonisa et al.(2025) used integrated geoelectrical and hydraulic characteristics of basement aquifers to explore for groundwater in Kuje District, Abuja, Nigeria. The study found that weathered and fractured basement layers arethe main carriers with variable yield zones, and northern part of Kuje showed better aquifer potential and moderate vulnerabilitythan other sectors. Additionally, Rauf et al. (2025) used VES to delineate groundwater potential zones in Gombe, their research classified aquifer potential across different locations and recommended focusing groundwater development where resistivity indicators denote higher yield prospects.

Geophysical methods such as electrical resistivity (geoelectric), magnetic, seismic, remote sensing, electromagnetic etc. have been utilized in several geologic terrains (Sunkari et al., 2021; Mohamed et al., 2022; Chinyem, 2024; Chinyem and Ovwamuedo, 2024). Comparing the above-mentioned geophysical methods in terms of data quality as well as cost effectiveness, electrical resistivity method (VES) is ranked most popular (Sunkari et al. 2021; Jimoh et al., 2023; Chinyem et al., 2025a; Chinyem et al., 2025b; Jimoh et al., 2025).

Recent works (Sunkari et al., 2021; Mohamed et al., 2023; Egai et al., 2024; Gbadebo et al., 2024; Nazir et al., 2024; Ibrahim et al., 2025; Hudu et al., (2024); Ikuemonisan et al., (2025); and Rauf et al., (2025).) have shown the relevance of integrating geophysical surveys (VES) with borehole data for a comprehensive assessment of groundwater resources, delineated lithologic strata and aquifer properties in different geologic terrains. Their approaches provided a reproducible model that could be applied in groundwater potential evaluation in any region.

Prior studies (Freeborn, 2006; Anomohanran, 2013; Iserhien-Emekeme, 2014; Oseji and Egbai, 2019; Anomohanran et al., 2017) have been carried out on the groundwater system of the Delta North region. Their findings indicated a lateral lithologic heterogeneity in the region which was a result of gradational lithologic contact, caused by changes in sediment particle sizes. However, none of these studies focused on the hydrogeophysical investigation of groundwater potential, lithological strata and aquifer vulnerability using VES and borehole data. Spatial gap also exists in the prior works done on some selected towns, as some of the major towns in the area were not covered by the study. Again, localised lithologic detail persists as many investigations in the area, provide broad geologic layer interpretations, but lack fine-scale lithologic correlations that link resistivity signatures to specific sedimentary units and their hydrologic significance Moreso, unspecified idealized framework persist as prior studiesoften treat groundwater potential, lithologic delineation, and aquifer vulnerability as separate targets instead of weaving them into a coherent hydrogeological framework that informs sustainable resource management specific to coastal Delta North District, DELTA State, Nigeria.These unresolvd aspects highlight the need for coordinated strategy that simultaneously examines subsurface architecture, aquifer productivity, and susceptibility to degradation. This work becomes imperative as it aims to characterize the lithologic strata, evaluate groundwater potential andassessaquifer vulnerability as a single, integrated hydrogeophysical framework designed to support evidence-based groundwater management in Delta North, and not as isolated tasks. This integrated approach yields a holistic, idealised model i which subsurface geology informs resource potential, and together defining vulberability, thus pproducing actionable insights for sustainable groundwater development and protection planning in the coastal Delta North region.

Study Area Location and Geology

The study area is located in the northern part of Delta State, in the Niger Delta Basin (NDB), Nigeria. It is bounded by latitude 06°9'N to 06°25'N and longitude 06°7'E to 06°35'E (Figure 1), and accessible through the highway connecting Lagos to Asaba, minor roads and foot paths, thus enhancing the study area's accessibility for research purposes. Geologically, the study area from the northern flank, falls within localities where the NDB lithofacies gradually grade into that of the Anambra Basin. Thus, from the earth's surface, the area is underlain by the Benin Formation (BF), Ogwashi-Asaba Formation (OAF), and Ameki Formation (AF) respectively. The OAF of the Anambra Basin is the lateral equivalent of the Agbada Formation (Allen, 1965) of the NDB. Essentially, the geology of the NDB has been extensively described by various authors (Allen, 1965; Reyment, 1965; Short and Stauble, 1967; Burke et al., 1972; Chinyem, 2024; Chinyem et al., 2025b). Basically, the NDB consists of three diachronous stratigraphic units of the BF(Oligocene-Recent), Agbada Formation (Eocene - Recent), and AF (Palaeocene). Reyment (1965) reported that the Tertiary NDB consists of outcropping lithostratigraphic units of the BF (Oligocene - Recent), made up of Coastal Plain Sands, underlain by the OAF (Oligocene - Miocene), which is also known as Lignite series (Figure 2), consisting of clay, silt, sand and lignite seams. The OAF is thus underlain by the AF (Eocene - Early Eocene), consisting of calcareous clays and silts. Hydrogeologically, the data obtained from the Delta State Ministry of Water Resources (DSMWR, 2021) shows that the Static Water Level (SWL) of the first and second aquiferous layers lie averagely between 100 – 145 m and 175 – 220 m respectively in Ogwashi-Uku, 105 – 170 m and 220 – 240 m respectively in Ubulu-Uku, 66 -100 m and 105 – 130 m respectively in Agbor area, 92 – 130 m and 135 – 180

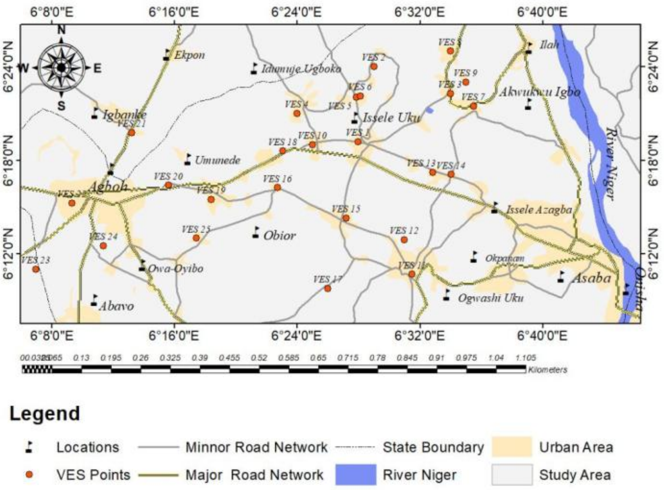


Figure 1: Map of the Study Area Showing VES Stations

m respectively in Issele-Uku region. A very high degree of SWL variability has been identified in these areas, thus, it is principally state-owned water boreholes that have penetrated beyond the first aquifer due to the huge cost involved. This has led to water scarcity and abortive water boreholes in regions like Ogwashi-Uku, Issele-Uku, Ubulu-Uku, Umunede, Onicha-Ugbo, Onicha-Uku etc as only few wealthy individuals could afford the cost of drilling their water wells beyond the first aquifer.

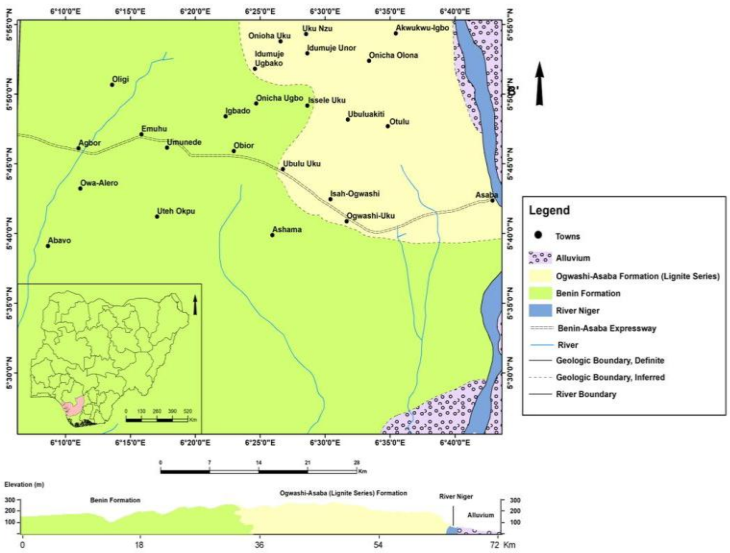


Figure 2: Geologic Map of the Study Area

MATERIALS AND METHODS

Vertical electrical sounding(VES), using the Schlumberger array, was adopted because electrical resistivity is highly sensitive to variations in lithology, clay content, porosity and groundwater saturation in unconsolidated sedimentary terrains such as in the Niger Delta Basin. In deltaic settings(Benin Formation), dominated by interbedded sands and clays, resistivity contrasts enable differentiation of aquifer from aquitards and estimation of aquifer thickness and depth(Reynolds, 2011). The Schlumberger array was selected due to its good vertical resolution to layered media, greater depth penetration with limited electrode movement, operational efficirncy in semi-urban and rural terrain.

The SAS 1000 Terrameter and its accessories were utilized for this study, because it has the capability of measuring with high accuracy and precision, the variations of subsurface resistivity at greater depth. Other materials applied include a Global Positioning System (GPS), measuring tapes, survey data sheets and a DC battery.

Twenty-five (25) vertical electrical sounding (VES), employing the Schlumberger array were acquired at the twenty-five locations, (Figure 2) with progressive current separation (AB/2) from 1 m to a maximum spacing of 500 m, sufficient to probe the expected aquifer depth. Potential electrode spacing (MN/2) was increased only when signal strength became insufficient.Apparent resistivity (ρ_a), was computed to ensure data quality; contact resistance was minimised through electrode grounding. Readings were repeated where anomalies or noise were suspected and field curves were inspected for consistency before site demobilization. The apparent resistivity (ρ_a) values, together with the current separation (AB/2) values were utilized to plot the apparent resistivity curves manually, on a logarithm sheet of paper. The data obtained from curve matching were used as input data in a computer software, WINRESIST, to obtain corresponding resistivity, thickness and depth of the subsurface layers.Initial layer parameters were estimated through curve matching and refined using iterative computer software, WINRESIST. Model acceptance was based on low mean square (RMS) misfit and geological plausibility. For each sounding, true layer resistivity (ρ_1) and thickness (h_1) were obtained. To assess aquifer characteristics ad protective capacity, Dar-zarrouk parameters were computed as used by Niwas and Singhal (1981).Transverse resistance was used as a proxy for transmissivity in sandy aquifers, longitudinal conductance was used to evaluate overburden protective capacity(vulnerability). Available borehole lithologic logs BH1, BH2 (Figure 5a and 5b) were used to correlate resistivity ranges with lithology,validate interpreted depths to aquifer units and confining layers, compare aquifer thickness from VES, with screened intervals, and where pumping test data were available, relate transmissivity to transverse resistance. The integration enhanced reliability and reduced interpretational ambiguity. Aquifer vulnerability was evaluated using intrinsic parameters derived from VES and borehole data. Protective capacity was classified using established longitudinal conductance (mhos) thresholds of >10; 5-10; 0.7-4.9; 0.2-0.69; 0.1- 0.19; and <0.1 as excellent; very good; good; moderate; weak and poor respectively (Henriet, 1976; Oladipo et al., 2004). Higher Lc values indicate thicker clayey overburden and lower contamination, and vice versa. Specifically, groundwater potential, lithological strata and aquifer vulnerability assessments were done with the aid of aquifer resistivity and thickness respectively. These parameters (aquifer resistivity, aquifer thickness) were used to obtain the secondary parameters, known as Dar-Zarrouk parameters. These parameters include Longitudinal conductance (Lc), Transverse resistance (Tr), Transmissivity (T), and Hydraulic conductivity (K). These parameters are crucial in aquifer potential and vulnerability assessment.

Longitudinal conductance (Lc) and Transverse unit resistance (Tr) were computed using equations 1 and 2 as used by Patra and Nath (1999); Musa et al. (2023a, 2023b); Chinyem (2024); Chinyem and Ovwamuedo (2024), Chinyem et al., (2025a, 2025b) as follows:

Longitudinal conductance (Lc) = $h/\ \rho = h \times \sigma$ (1)

Transverse resistance (Tr) = $h \times \rho$ (2)

Similarly, Transmissivity (T) and the hydraulic conductivity (K) were computed using equations 3 and 4 respectively, as used by Musa et al., (2023a, 2023b), Chinyem et al., (2025a, 2025b) as follows

$T = K\,\sigma\,R.,\ T = KS / \sigma$ (3)

$K = 386.40\rho^{-0.93283}$ (4)

where ρ and h are aquifer resistivity (Ωm) and thickness (m) respectively. σ is electrical conductivity(Ωm^{-1}).

The values were subsequently utilized to generate contour maps(Figures 6,7,8,9), using surfer software to show the spatial distribution of the aquifer parameters.

Pumping test was also carried out in eight (8) separate water wells, drilled in eight communities (DSMWR, 2021), using Copper and Jacobs (1946) straight line analytical technique. Subsequently, aquifer parameters obtained, were determined and compared with geoelectric (VES) data.

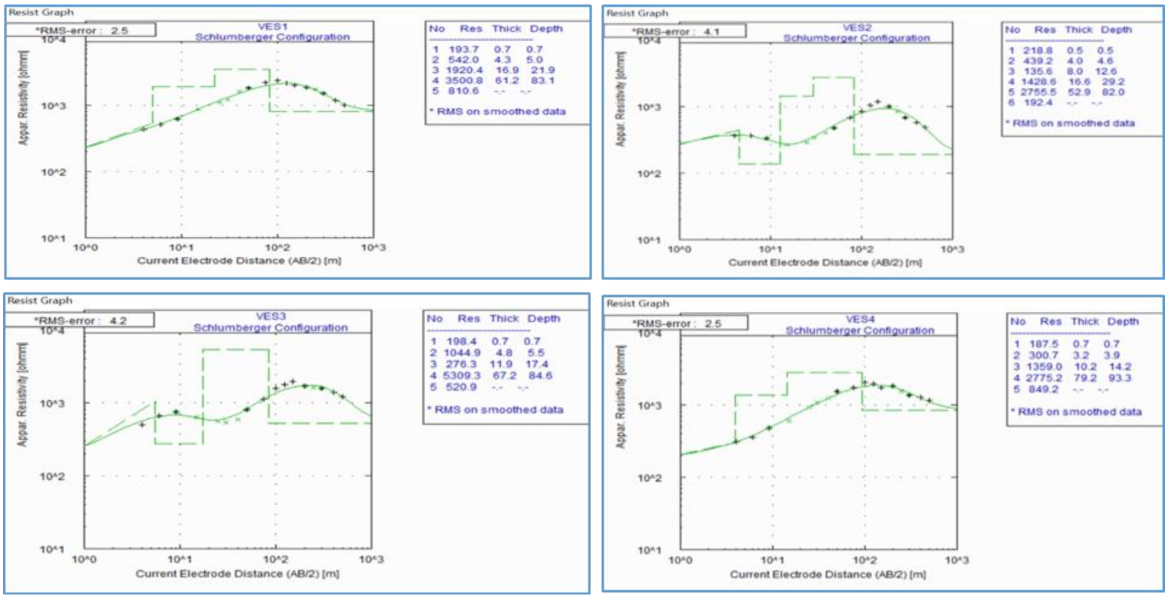


Figure 3: Computer Iteration Curve for VES 1-4

RESULTS AND DISCUSSION

The inverted result, from the VES data (Table 1, Figure 3) shows the dominance of five (5) geoelectric layers, with the remaining VES 2 and VES 25 having six (6) and four (4) geoelectric layers respectively. Similarly, four distinct field curve types were identified; AAK, KHAK, KHK and AK respectively. The AAK field curve type occurred most frequently, with the frequency of 22, while the KHAK, KHK and AK types appeared only once each.The different field curv types obtained, suggests geologically multi- layered sedimentary succession typical of the lithological heterogeneity of the Niger Delta Basin. From the correlation of inverted resistivity values with available borehole lithologic logs, the geoelectric layers identified (Figure 4) are top soil with resistivity and thickness values ranging from 93.1 - 236.6 Ωm and 0.5 - 0.9 m, the second geoelectric layer identified has resistivity value of 220.9 - 1044.9 Ωm and thickness range of 2.4 - 8.1m and consists of fine/clayey sand, the third layer has resistivity value of 135.6 - 2344.8 Ωm and 8.0 - 70.2 m thickness, consisting of lateritic clayey sand/coarse sand, the fourth layer has resistivity of 952.6 - 6693.7 Ωm and thickness range of 16.6 - 123.7 m, composed of medium - coarse sand, the fifth layer's resistivity range from 367.9 - 2753.5 Ωm and a thickness of 52.9 m, and consists of coarse sand, while the sixth layer has a resistivity of 192.4 Ωm, and identified as clayey/fine sand. with infinite thickness. The aquifer resistivity ranges from 1511 - 6694 Ωm with an average value of 2816.56 Ωm (Table 2). Similarly, the thickness and depths of the aquifer units vary considerably across locations in the study area, from one locality to another. Aquifer thickness and depths were used to generate the aquifer thickness and depth map respectively, which were subsequently employed to visualize the distribution of aquifer thickness and depths in the study area. The aquifer thickness (Figure 6) ranges between 52.9 m and 101.2 m, with the maximum thickness obtained at VES 11. Accordingly, aquifer depth occurrence spans from 75.4 to 123.8 m, with the great depth also recorded at the northwestern and marginally at northeasthern parts of the study area at VES 4 (Idumuje-Ugboko); VES 8(Ezi); VES 9 (Ukala- Okpuno); VES 10 (Onicha- Ugbo); VES 11 (Ogwashi- Uku) and VES 18(Igbodo), respectively, as shown in Figure 7. These interpretations were made after borehole validation with the VES data. The aquiferous units were identified as moderately to highly resistive layers (1511 - 6694 Ωm), indicating medium to coarse to gravelly sand with appreciable thickness (52.9 m and 101.2 m), and lateral continuity at depth ranging approximately from 75 to 124 m. These values (thickness, depth) reveal an area with good groundwater potential for drilling of potable water wells. Hence, groundwater exploration and exploitation should be targeted between 150 – 190 m, while for the remaining areas, the target depths should be between 100 – 140 m, for maximum groundwater abstraction. The aquifer system, thickness, depths, lithologies identified in the study area are consistent with earlier reports by Anomohanran (2013) in few selected towns in Delta North, Iserhien-Emekeme (2014) at Onicha - Ugbo, as well as Oseji and Egbai (2019) in Issele-Uku, Delta state.

Aquifer protective (vulnerability) assessment was evaluated using longitudinal conductance (Lc). Areas with low Lc values indicate thin or resistive overburden material and therefore reduced natural protection.The Longitudinal Conductance (Lc) value (Table 2, Figure 8) ranges from 0.01043 to 0.048782 Ω^{-1} with mean value of 0.03 Ω^{-1}. Lc is an important parameter in assessing aquifer's ability to be protected agains t surface contamination. According to Oladapo et al (2004) classification, (Table 3) the Lc values computed across the VES stations suggest that the aquifer units at most of the stations have poor aquifer protective capacity (APC) with the exception of VES 2, having slightly higher Lc value indicating weak APC (Table 4). This implies that the weathered materials in the study area lack clay, and so have high vulnerability to surface-derived contaminants. Thus boreholes/water wells sited within the region should be adequately gravel-packed to reduce contamination from surface sources. Similarly, the Lc map (Figure 8) indicates that the APC across the area varies from 0.01 - 0.045 Ω^{-1}, further confirming the area's vulnerability to contamination due to inadequate protection from agricultural activities, septic systems or surface run-off, which are particularly relevant in Delta North

The transverse unit resistance (Tr) value, ranges from 112728 - 511,161.20 Ωm^2. As noted by Simon et al. (2022), highest borehole yields usually come from regions with the highest Tr values.Transverse resistance values suggest increased transmissivity potential. Areas exhibiting thicker sand units and higher transverse resistance in the southwestern, southeastern and northeastern parts of the study were classified as having intermediate (moderate) groundwater potential, while some northwestern, northeastern, and northcentral zones (Table 2, Figure 9) were interpreted as having lower potential. Considering the result obtained, the regions in the study area will generally give a good borehole yield.

The hydraulic conductivity (Hc) value ranges from 0.01 - 0.42 m/day with an average of 0.26 m/day (Table 2). According to Adeniji et al. (2022), "Hc expresses the vertical movement of water in an aquifer, and this can be used to identify recharge potential of aquifers". Using the classification scheme of Singhal and Gupta (1999), in Table 5 the study area has aquifers of intermediate Hc, which suggests that aquifer materials have intermediate conductivity and can promote quick aquifer recharge potential. This report is consistent with prior studies by Anomohanran (2015), Anomohanran et al. (2017), and Chinyem (2024).

The transmissivity (T) value ranges from 7.49 - 30.78 m^2/day with an average of 19.05 m^2/day. T value provides an indication of its groundwater potential. It is influenced by the aquifer's thickness as well as its lithological characteristics, which is directly related to the aquifer's productivity, as higher transmissivity values suggest higher aquifer potential (Oborie et al., 2024). According to Krasny (1993) classification on T (Table 6), an intermediate T has been identified for the study area. The overall T value implies that the groundwater potential in the area is limited, mainly for small scale withdrawals to small communities or private use. This result correlates with the findings by Anomohanran (2013) and Chinyem (2024).

The result from the borehole logs (Figure 5) and pumping test data (Table 7) obtained from DSMWR (2021) for eight (8) locations (VES 1, 5, 6, 10, 11, 19, 22 and 25) showed that the study area is principally underlain by four to five lithologies, in which their depths strongly correlate with those identified through geoelectric method. For the validation of the geoelectric result, the obtained borehole log and pumping test data revealed that the area consists of top soil/silty clayey sand, fine sand/reddish lateritic clayey sand, coarse sand, medium - coarse sand, clayey sand/silty medium to fine sand. The aquifer depths, revealed by the borehole logs are thicker than that identified by the geoelectric result, as the degree of rock weathering varies from location to location. Furthermore, other aquifer parameters such as transmissivity as obtained from the pumping test data (Table7) showed close correlation with the resistivity data.

In comparison with other hydrogeological studies in Delta North District of Delta State,(Freeborn, 2006; Anomohanran, 2013; Iserhien-Emekeme, 2014; Oseji and Egbai, 2019; Anomohanran et al., 2017; and the Niger Delta (Hassan et al., 2019), the findings of this study align closely with established regional patterns of groundwater geometry, groundwater potential and vulnerability. Similarly, VES result revealed heterogeneous subsurface stratigraphy, with resistivity and Dar-Zarrouk parameters, indicating promising groundwater potential zones, with high transverse resistance, but overall poor protective capacity and high vulnerability to surface contaminations from agricultural activities ,septic systems or surface run-off, based on longitudinal conductance values. Furthermore, hydrogeophysical studies in Delta Central (Anomohanran (2015a; 2015b; Chinyem et al.,2023; Babasola and Infeanyi, 2024), also documented multi-layered sandy sequences with significant depths to productive aquifers, corroborating the prevalence of deltaic and Coastal Plain Sand aquifers across the Niger Delta. These collective studies reinforce that hydrogeophysical signatures of layered resistive structures, appreciable groundwater potential, and heightened vulnerability due to thin clay overburden and low clay protective cover are consistent features across the study area and the broader Niger Delta hydrological setting,

Table 1: **Summary of VES Lithology Interpretation**

Ves no	Layers	Resistivity (Ωm)	Thickness (m)	Depth (m)	Curve type (m)	Lithologic inference
1	1	193.7	0.7	0.7	AAK	Topsoil
	2	542	4.3	5	$\rho1 < \rho2 < \rho3 < \rho4 > \rho5$	Fine sand
	3	1920.4	16.9	21.9		Coarse sand
	4	3500.8	61.2	83.1		Coarse sand
	5	810.6	---	---		Medium sand
2	1	218.8	0.5	0.5	KHAK	Topsoil
	2	439.2	4	4.6	$\rho1 < \rho2 > \rho3 < \rho4 < \rho5 > \rho6$	Fine sand
	3	135.6	8	12.6		Clayey sand
	4	1428.6	16.6	29.2		Medium-coarse sand
	5	2755.5	52.9	82		Coarse sand
	6	192.4	---	---		Clayey sand
3	1	198.4	0.7	0.7	KHK	Topsoil
	2	1044.9	4.8	5.5	$\rho1 < \rho2 > \rho3 < \rho4 > \rho5$	Medium sand
	3	276.3	11.9	17.4		Clayey sand
	4	5309.3	67.2	84.6		Coarse sand
	5	520.9	---	---		Fine sand
4	1	187.5	0.7	0.7	AAK	Topsoil
	2	300.7	3.2	3.9	$\rho1 < \rho2 < \rho3 < \rho4 > \rho5$	Clayey Sand
	3	1359	10.2	14.2		Medium-coarse sand
	4	2775.2	79.2	93.3		Coarse sand
	5	849.2	---	---		Medium sand
5	1	101.2	0.6	0.6	AAK	Topsoil
	2	220.9	2.8	3.4	$\rho1 < \rho2 < \rho3 < \rho4 > \rho5$	Clayey sand
	3	1341.8	9.8	13.1		Medium-coarse sand
	4	2745.2	73.2	86.3		Coarse sand
	5	613	---	---		Fine-medium sand
6	1	134.1	0.8	0.8	AAK	Topsoil
	2	310.1	8.1	8.8	$\rho1 < \rho2 < \rho3 < \rho4 > \rho5$	Clayey sand
	3	2344.8	20.7	29.5		Coarse sand
	4	3483.4	52.8	82.3		Coarse sand
	5	466.1	---	---		Fine sand
7	1	204.7	0.7	0.7	AAK	Topsoil
	2	374.2	3.8	4.5	$\rho1 < \rho2 < \rho3 < \rho4 > \rho5$	Clayey sand
	3	1133.4	26.2	30.7		Medium-coarse sand
	4	2600.2	61.9	92.6		Coarse sand
	5	774.7	---	---		Medium sand
8	1	187.8	0.7	0.7	AAK	Topsoil
	2	314.5	3.4	4.1	$\rho1 < \rho2 < \rho3 < \rho4 > \rho5$	Clayey sand
	3	1164.7	15.9	20		Medium-coarse sand
	4	2163.8	98.5	118.5		Coarse sand
	5	778.3	---	---		Medium sand
9	1	216	0.6	0.6	AAK	Topsoil
	2	340.4	3.3	3.9	$\rho1 < \rho2 < \rho3 < \rho4 > \rho5$	Clayey sand
	3	1038.4	16	20.2		Medium sand
	4	1708.1	66	86.2		Coarse sand
	5	457.5	---	---		Fine sand
10	1	227.5	0.7	0.7	AAK	Topsoil
	2	348	4.1	4.8	$\rho1 < \rho2 < \rho3 < \rho4 > \rho5$	Clayey sand
	3	706	15.2	20		Medium sand
	4	2663.2	93.8	113.9		Coarse sand
	5	752.9	---	---		Medium sand
11	1	93.1	0.9	0.9	AAK	Topsoil
	2	508.6	2.4	3.3	$\rho1 < \rho2 < \rho3 < \rho4 > \rho5$	Fine sand
	3	1473.1	19.3	22.6		Medium-coarse sand
	4	5051.2	123.7	123.8		Coarse sand
	5	901.6	---	---		Medium sand
12	1	162.2	0.8	0.8	AAK	Topsoil
	2	386.9	5.9	6.7	$\rho1 < \rho2 < \rho3 < \rho4 > \rho5$	Clayey sand

Ves no	Layers	Resistivity (Ωm)	Thickness (m)	Depth (m)	Curve type (m)	Lithologic inference
	3	860.4	14.2	20.9		Medium sand
	4	6693.7	70	90.9		Coarse sand
	5	582.6	---	---		Fine sand
13	1	220.5	0.6	0.6	AAK	Topsoil
	2	380.3	6	6.7	$\rho1 < \rho2 < \rho3 < \rho4 > \rho5$	Clayey sand
	3	1080.9	17.2	23.9		Medium sand
	4	2357.3	82.5	106.4		Coarse sand
	5	676.2	---	---		Fine-medium sand
14	1	198.1	0.7	0.7	AAK	Topsoil
	2	389.5	4.8	5.5	$\rho1 < \rho2 < \rho3 < \rho4 > \rho5$	Fine sand
	3	971.2	15.9	21.5		Medium sand
	4	1511.3	73.8	95.3		Coarse sand
	5	457.6	---	---		Fine sand
15	1	195.5	0.7	0.7	AAK	Topsoil
	2	337	6.9	7.6	$\rho1 < \rho2 < \rho3 < \rho4 > \rho5$	Clayey sand
	3	761.2	13	20.6		Medium sand
	4	2532.4	61.9	82.5		Coarse sand
	5	367.9	---	---		Fine sand
16	1	236.6	0.7	0.7	AAK	Topsoil
	2	375.8	4.2	4.8	$\rho1 < \rho2 < \rho3 < \rho4 > \rho5$	Clayey sand
	3	734.6	11.4	16.3		Medium sand
	4	1909	78.7	94.9		Coarse sand
	5	745.5	---	---		Medium sand
17	1	108.7	0.7	0.7	AAK	Topsoil
	2	287.7	3.1	3.8	$\rho1 < \rho2 < \rho3 < \rho4 > \rho5$	Clayey sand
	3	1224.6	13.8	17.6		Medium-coarse sand
	4	2079.5	73.8	90.9		Coarse sand
	5	760	---	---		Medium sand
18	1	204.5	0.7	0.7	AAK	Topsoil
	2	358.3	4.8	5.5	$\rho1 < \rho2 < \rho3 < \rho4 > \rho5$	Clayey sand
	3	863	12.6	18.1		Medium sand
	4	2896.5	66.4	84.5		Coarse sand
	5	597.1	---	---		Fine sand
19	1	221.2	0.8	0.8	AAK	Topsoil
	2	326.3	3.6	4.4	$\rho1 < \rho2 < \rho3 < \rho4 > \rho5$	Clayey sand
	3	800.6	15.5	19.8		Medium sand
	4	2702.6	68.8	88.5		Coarse sand
	5	602.1	---	---		Fine-medium sand
20	1	164	0.8	0.8	AAK	Topsoil
	2	332.1	4	4.8	$\rho1 < \rho2 < \rho3 < \rho4 > \rho5$	Clayey sand
	3	1315.9	18.6	23.4		Medium-coarse sand
	4	2079.7	55.1	78.6		Coarse sand
	5	552.5	---	---		Fine sand
21	1	180.3	0.8	0.8	AAK	Topsoil
	2	287.5	4.2	5.1	$\rho1 < \rho2 < \rho3 < \rho4 > \rho5$	Clayey sand
	3	1006.3	23.4	28.5		Medium sand
	4	1787.3	77.5	105.9		Coarse sand
	5	445.5	---	---		Fine sand
22	1	165.8	0.8	0.8	AAK	Topsoil
	2	337.3	5.9	6.7	$\rho1 < \rho2 < \rho3 < \rho4 > \rho5$	Clayey sand
	3	2158.7	22.7	29.4		Coarse sand
	4	3091.1	66.1	95.5		Coarse sand
	5	648.6	---	---		Fine-medium sand
23	1	114.9	0.8	0.8	AAK	Topsoil
	2	312.4	3.9	4.7	$\rho1 < \rho2 < \rho3 < \rho4 > \rho5$	Clayey sand
	3	1798.9	14.4	19.1		Coarse sand
	4	2623.1	69.9	88.9		Coarse sand

Ves no	Layers	Resistivity (Ωm)	Thickness (m)	Depth (m)	Curve type (m)	Lithologic inference
	5	766.8	---	---		Medium sand
24	1	186.4	0.7	0.7	AAK	Topsoil
	2	416.1	4.1	4.8	ρ1 < ρ2 < ρ3 < ρ4 > ρ5	Fine sand
	3	1075.5	28	32.8		Medium sand
	4	1680.9	80.6	113.4		Coarse sand
	5	605.2	---	---		Fine-medium sand
25	1	176.2	0.8	0.8	AK	Topsoil
	2	579.2	4.3	5.1	ρ1 < ρ2 < ρ3 > ρ4	Fine sand
	3	1713.5	70.2	75.4		Coarse sand
	4	952.6	---	---		Medium sand

Table 2: Summary of Dar-Zarrouk Geo-electric Parameters

VES station	Aquifer resistivity *ρ* (Ωm)	Aquifer thickness h (m)	Aquifer depth (m)	Aquifer conductivity σ = 1/ *ρ* (Ω-1)	Longitudinal conductance S = σh (Ω-1)	Transverse conductance R = h *ρ* (Ωm2)	Hydraulic conductivity,K at VES station(m/day)	Kσ	Transmissivity(m2/day)
1	3501	61.2	83.1	0.000286	0.017503	214261.2	0.190945	0.000055	11.78
2	2756	52.9	82	0.000363	0.019203	145792.4	0.238694	0.000086	12.54
3	5309	67.2	84.6	0.000188	0.012633	356764.8	0.129489	0.000024	8.56
4	2775	79.2	93.3	0.00036	0.028512	219780	0.237169	0.000085	18.68
5	2745	73.2	86.3	0.000364	0.026645	200934	0.239586	0.000087	17.48
6	3483	52.8	82.3	0.000287	0.015154	183902.4	0.191865	0.000055	10.11
7	2600	61.9	92.6	0.000385	0.023832	160940	0.252027	0.000097	15.61
8	2164	98.5	118.5	0.000462	0.045507	213154	0.299094	0.000138	29.42
9	1708	66	86.2	0.000585	0.03861	112728	0.372971	0.000218	24.57
10	2663	93.8	113.9	0.000376	0.035269	249789.4.0	0.246461	0.000093	23.23
11	5051	101.2	123.8	0.000198	0.020038	511161.2.0	0.135649	0.000027	13.8
12	6694	70	90.9	0.000149	0.01043	468580	0.104309	0.000016	7.49
13	2357	82.5	106.4	0.000424	0.03498	194452.5	0.276184	0.000117	22.75
14	1511	73.8	95.3	0.000661	0.048782	111511.8	0.418142	0.000276	30.78
15	2532	61.9	82.5	0.000394	0.024389	156730.8	0.258335	0.000102	15.99
16	1909	78.7	94.9	0.000524	0.041238	150238.3	0.336204	0.000176	26.44
17	2080	73.2	90.9	0.000481	0.035209	152256	0.310347	0.000149	22.69
18	2897	66.4	84.5	0.000345	0.022908	192360.8	0.227839	0.000079	15.19
19	2703	68.6	88.5	0.000369	0.025313	185425.8	0.243057	0.000089	16.5
20	2080	55.1	78.6	0.000481	0.026503	114608	0.310347	0.000149	17.08
21	1787	77.5	105.9	0.000559	0.043323	138492.5	0.357567	0.000199	27.56
22	3091	66.1	95.5	0.000324	0.021416	204315.1	0.214471	0.00069	14.09
23	2623	69.9	88.9	0.000381	0.026632	183347.7	0.249965	0.00095	17.42
24	1681	80.6	113.4	0.000595	0.047957	135488.6	0.378557	0.000225	30.48
25	1714	70.2	75.4	0.000583	0.040927	120322.8	0.371753	0.000217	26.11
Average	**2816.56**	**72.1**	**93.53**	**0.000405**	**0.02932**	**187669.02**	**0.26364**	**0.000175**	**19.054**

Table 3: Modified Longitudinal Unit Conductance/Protective Capacity Rating (Oladapo et al., 2004)

Longitudinal conductance	Protective capacity rating
> 10	Excellent
5 – 10	Very good
0.7 – 4.9	Good
0.2 – 0.69	Moderate
0.1 – 0.19	Weak
< 0.1	Poor

Table 4: Summary of Dar-Zarrouk geo-electric parameters

VES	Longitudinal Conductance, $S = \sum S_1, S_2..Sn$	Aquifer protective capacity rating (Oladapo et al., 2004)	Transmissivity (m^2/day)	Ground water potential (Krasny 1993)
1	0.037834	Poor	11.78	Intermediate
2	0.101025	Weak	12.54	Intermediate
3	0.063876	Poor	8.56	Low
4	0.050372	Poor	18.63	Intermediate

5	0.052556	Poor	17.48	Intermediate
6	0.056073	Poor	10.11	Intermediate
7	0.060543	Poor	15.61	Intermediate
8	0.073667	Poor	29.42	Intermediate
9	0.06679	Poor	24.57	Intermediate
10	0.071645	Poor	23.23	Intermediate
11	0.047539	Poor	13.8	Intermediate
12	0.047129	Poor	7.49	Low
13	0.069409	Poor	22.75	Intermediate
14	0.080985	Poor	30.78	Intermediate
15	0.065514	Poor	15.99	Intermediate
16	0.070873	Poor	26.44	Intermediate
17	0.063655	Poor	22.69	Intermediate
18	0.05432	Poor	15.19	Intermediate
19	0.059318	Poor	16.5	Intermediate
20	0.057546	Poor	17.08	Intermediate
21	0.085609	Poor	27.56	Intermediate
22	0.057546	Poor	14.09	Intermediate
23	0.085609	Poor	17.42	Intermediate
24	0.087588	Poor	30.48	Intermediate
25	0.052899	Poor	26.11	Intermediate

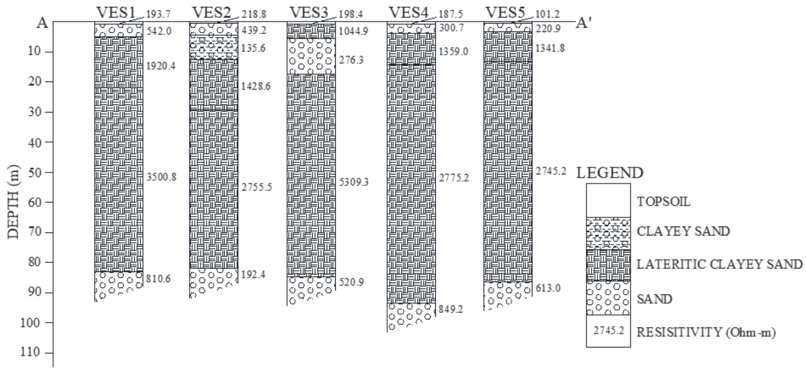


Figure 4a: Geo Section of VES 1-25

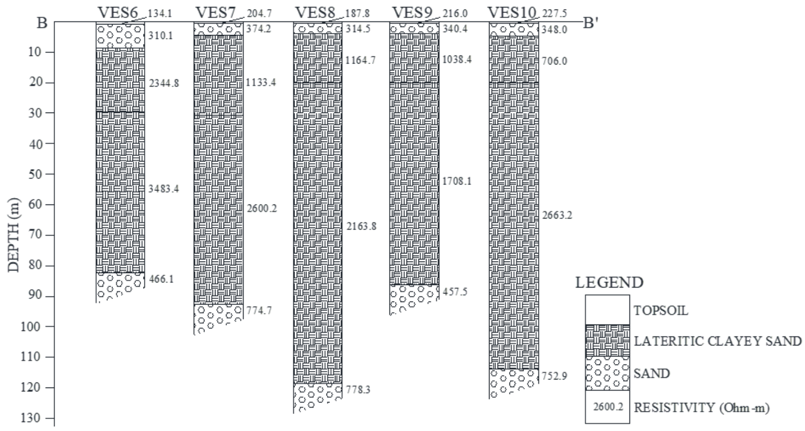


Figure 4b: Geo Section of VES 1-25

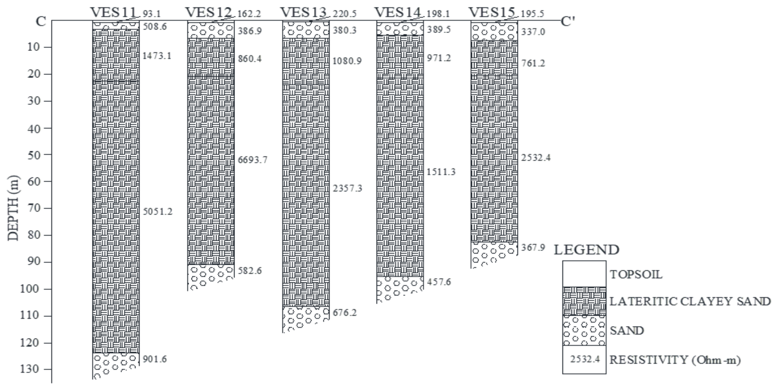


Figure 4c: Geo Section of VES 1-25

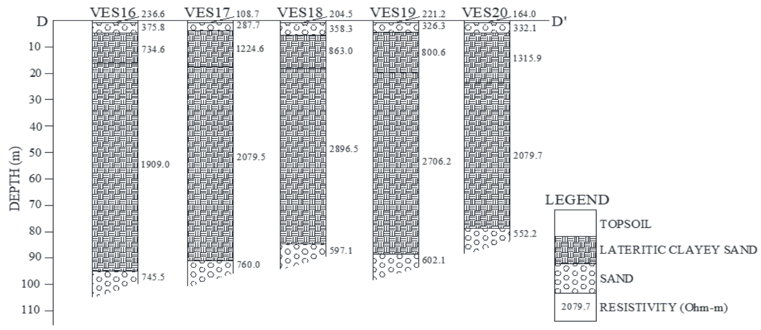


Figure 4d: Geo Section of VES 1-25

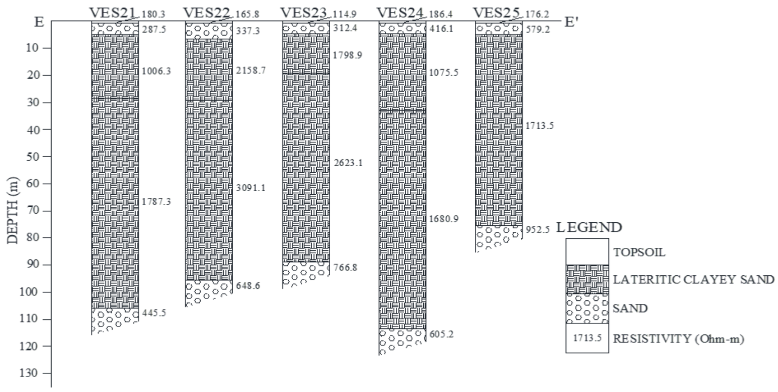
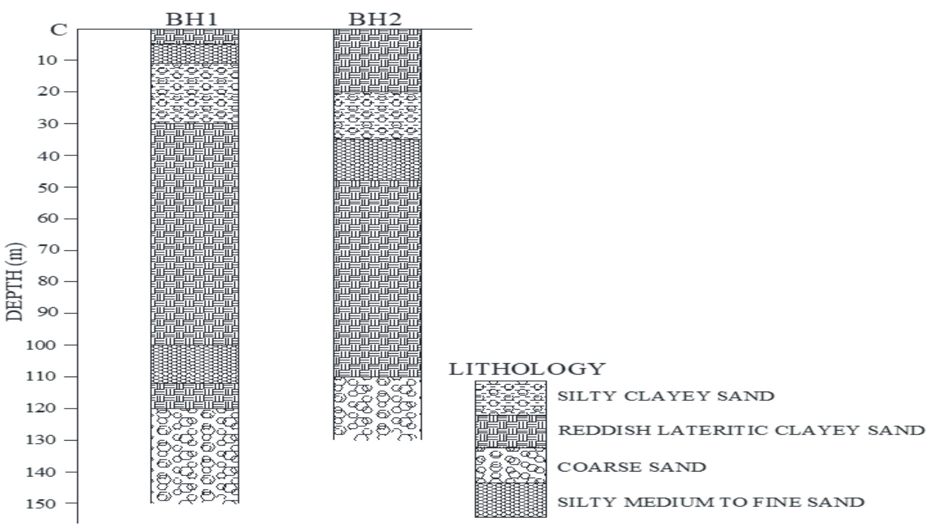


Figure 4e: Geo Section of VES 1-25



(a) **(b)**

Figure 5: Borehole Lithologic Log (a)BH-1 at Agbor, (b)BH-2 at Issele-Uku

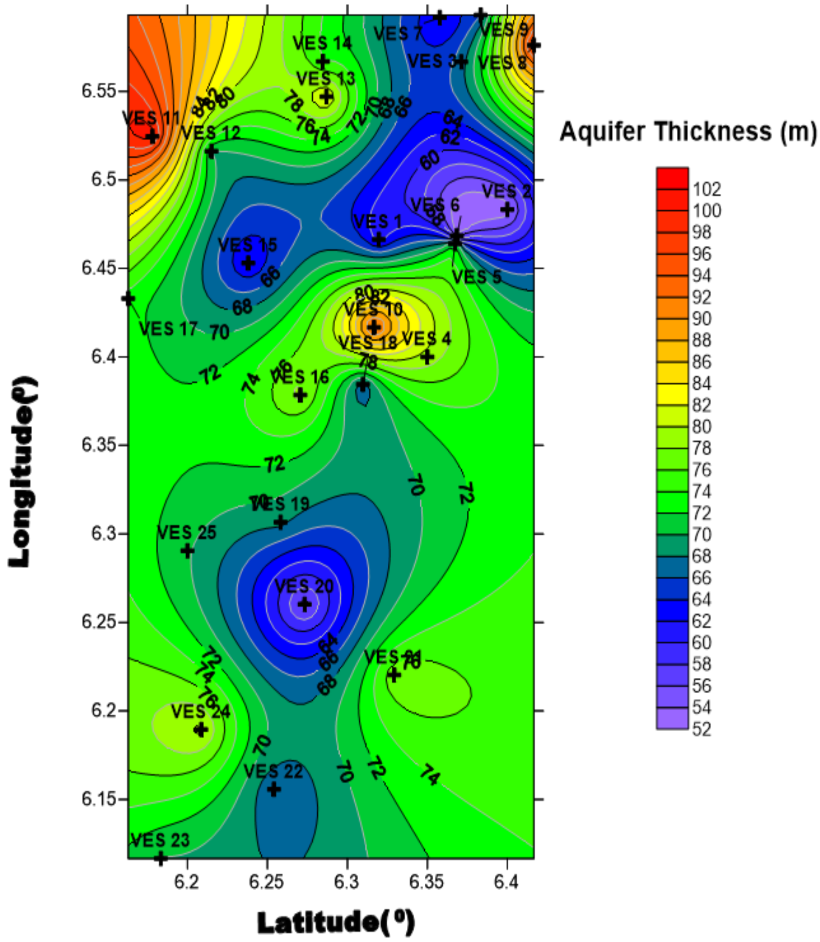


Figure 6: Aquifer Thickness Map of the Study Area

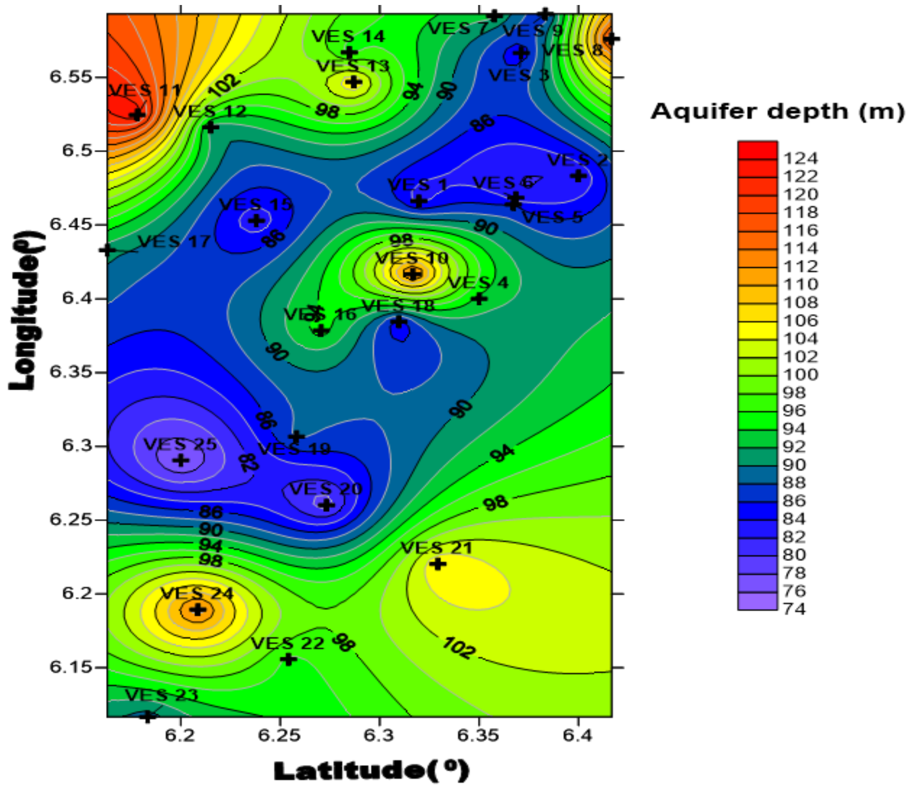


Figure 7: Depth to Aquifer Map of the Study Area

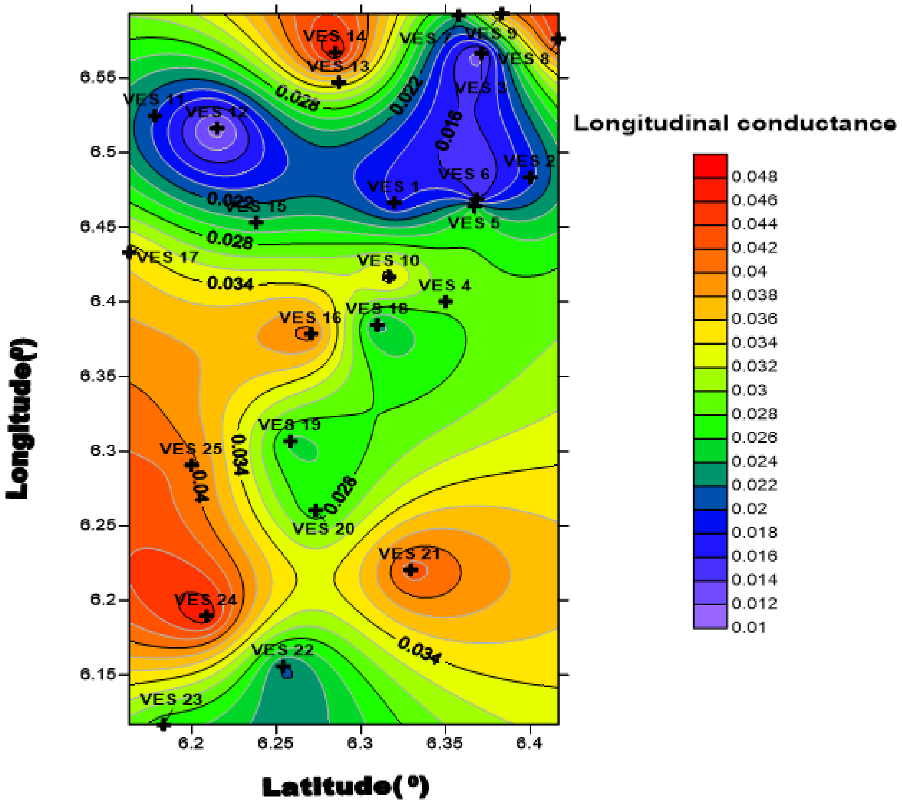


Figure 8: Longitudinal Conductance Map of the Study Area

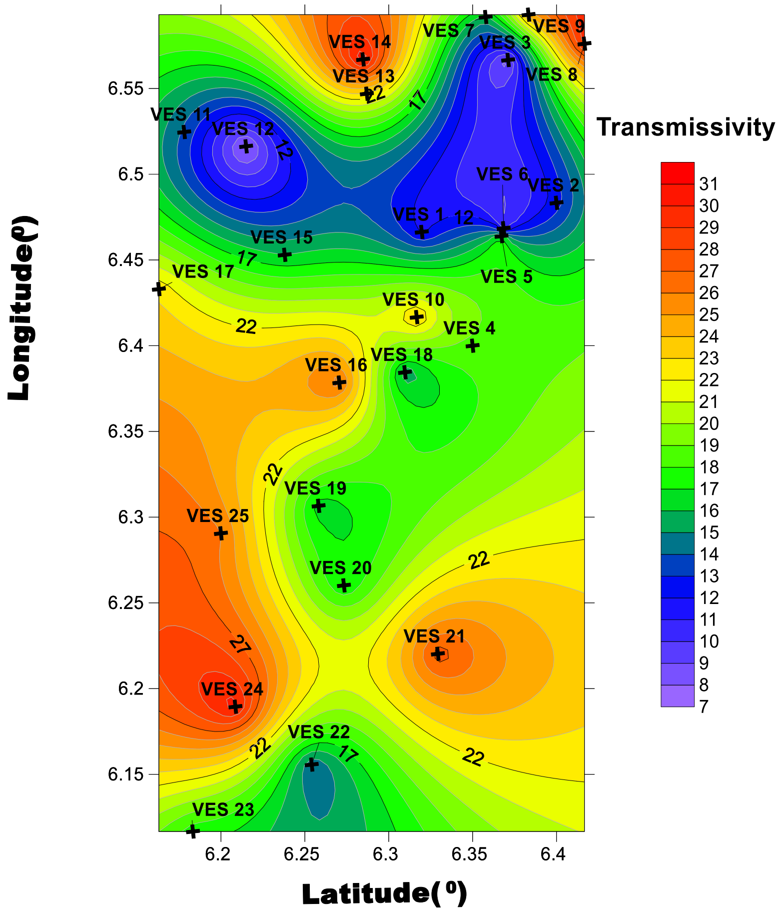


Figure 9: Transmissivity Map of the Study Area

Table 5: Classification of Hydraulic Conductivity (Singhal and Gupta, 1999).

S/N	Hydraulic Conductivity (m/day)	Class	Designation
1	> 1000	I	Very high
2	10 – 1000	II	High
3	0.1 – 10	III	Intermediate
4	0.001 – 0.1	IV	Low
5	0.00001 – 0.001	V	Very low

Table 6: Classification of Transmissivity Magnitude (Krasny, 1993)

S/N	Magnitude of Transmissivity (m^2/day)	Class	Designation
1	> 1000	I	Very High
2	100 – 1000	II	High
3	10 – 100	III	Intermediate
4	1 – 10	IV	Low
5	0.1 – 1	V	Very low
6	< 0.1	VI	Imperceptible

Table 7: Some Pumping Test Data from Drilled wells in Parts of the Study Area (Courtesy DSMWR, 2021).

S/N	Well location	Borehole depth (m)	Transmissivity (m^2/day)	Static water level (m)	Dynamic water level (m)	Draw Down level (m)
1	Issele-Uku	206	10.88	92	106	14
2	Umunede	236	13.5	105	120	15
3	Uteh-Okpu	135	24.5	66	74	8
4	Agbor-Alisime	212	11.4	100	122	22
5	Idumuje-Unor	250	12.5	152.5	176	24
6	Onicha-Uku	236.6	18.6	138	161	23
7	Ogwashi-Uku	194	17.3	140	162	22
8	Onicha-Ugbo	230	25	138	161	23

CONCLUSION

The study demonstrates that integrated VES interpretation and borehole caliberation provide a practical basis for delineating groundwater potential, resolving lithostratigraphic variability and classifying aquifer vulnerability in parts of Delta North District. Spatial contrasts in overburden thickness and protective capacity indicate that groundwater development should be site-specific,with caution on zones of thin confining layers and high vulnerability indices. The results support evidence-based siting of boreholes and priorization of monitoring in susceptible/vulnerable areas. Further work should incorporate seasonal hydrochemical validation and high resolution geophysical surveys for integrated vulnerability assessment such as GOD index mapping, to refine vulnerability mapping and strengthen groundwater management decisions under increasing anthropogenic pressure from agricultural activities, septic systems or surface run- off, which are particularly prevalent in Delta North, Nigeia.

.

ACKNOWLEDGEMENT

The manuscript has benefitted immensely, from the reviewers comments with appreciation. The authors wish to gratefully acknowledge the authorities of Delta State Ministry of Water Resources (DSMWR), Asaba for making some borehole logs and pumping test data available for this study. Additionally,the perspectives presented in this study are shaped by the authors' combined research experience and scholarly engagement with colleagues. While every effort has been made to be comprehensive, it is possible that some key publications and concepts were inadvertently omitted, as well as methodological limitations such as the absence of borehole data in some areas for validation. The authors accept full responsibility for any biases, omissions, oversights, or inaccuracies contained therein.

Declaration of Competing Interest

The authors declare that they have no conflict of interest and that the study did not receive any funding from external source.

REFERENCES

Adeniji A.A; Ajani O.O; Adagunodo T.A; Agbolade J.O. & Ayeni A.M. (2002). Application of Dar-Zarrouk parameters for groundwater protective potential within Crystalline Basement Formation, Southwestern Nigeria. *Journal of Sciences, Islamic Republic of Iran*, 33(3), 245-257

Allen J.R.L. (1965). Late Quaternary Niger Delta and Adjacent areas. *AAPG Bulletin*, 49(5), 547-600

Anomohanran O. (2013). Investigation of groundwater potential in some selected towns in Delta North District of Nigeria. *International Journal of Applied Science and Technology*, 3(6), 61-66

Anomohanran O. (2014). Hydrogeophysical investigation of aquifer properties and lithological strata in Abraka, Nigeria. *Journal of African Earth Sciences*, 102; 247-253. https://doi.org/10.1016/j.jafrearsci.2014.10.006

Anomohanran, O. (2015). Hydrogeophysical investigation of aquifer properties and lithological strata in Abraka, Nigeria. Journal of African Earth Sciences, 102, 247-253

Anomohanran, O.(2015). Hydrogeophysical and hydrogeological investigations of groundwater resources in Delta Central, Nigeria. Journal of Taibal University for Science, 9 (1), 57-68

Anomohanran, O; Ofomola, M.O; & Okocha, F.O. (2017).Investigation of groundwater in parts of Ndokwa District in Nigeria, using geophysical logging and electrical resistivity methods. Implications for groundwater exploration . Journal of African Earth Sciences, 129, 108-116

Araffa S.A; Sabet H.S; EL Zahar A.M; Sharkawy M.S & Hasan N.M. (2024). Hydrogeophysical investigations for assessment of groundwater aquifer at Wadi EL Assuity, Egypt. *NRIAG Journal of Astronomy and Geophysics*, 13(1), 165-181. https://doi.org/10.1080/20909977.2024.2402157

Babalola, O.V. & Ifeanyi, N.G. (2024). Assessment of groundwater potential and vulnerability, using electrical resistivity techniques: A case study of FUPRE campus and Agbarho axis, Delta State, Nigeria. *Hydrology*, 13(1), 22-33

Burke K; Dessauvagie T.F.J. & Whiteman A.J. (1972). Geological history of Benue valley and adjacent areas in T.J.F. Dessauvagie & A.J. Whiteman (Eds). African Geology, Ibadan University Press, 206-218

Chinyem F.I & Ovwamuedo G.O. (2024). Evaluation of aquifer characteristics and groundwater protective capacity in Abavo, Nigeria. *International Journal of Geosciences*, 15, 841-860

Chinyem F.I. (2013). Hydrogeophysical investigation of Asaba area, Delta State, Nigeria. *Indian Journal of Science and Technology*, 6(5), 4453- 4458

Chinyem F.I. (2024). Determination of aquifer hydraulic parameters and groundwater protective capacity in parts of Nsukwa Clan, Nigeria. *Environmental Monitoring and Assessment*, 196. https://doi.org/10.1007/s/0661-024-12411-w

Chinyem F.I; Ohwoghere-Asuma O; Nwankwoala H.O; Salami S.A; Nwugha V.N & Itimi W.O. (2025). Groundwater quality assessment around Lake Mkpitime, Nigeria, using integrated geophysical and hydrochemical approaches. *Journal of Tropical Resources and Sustainable Science*, 13(1), 183-201

Chinyem F.I; Ovwamuedo G.O; Akudo E.O; Ofomola M.O; Nwugha V.N; Agbosa R.T; Salami S.A. (2025). Evaluation of aquifer hydraulic parameters and groundwater protective capacity from shallow groundwater exploration in parts of Ejeme-Aniogor, Western Niger Delta, Nigeria. *FUW Trends in Science & Technology Journal*, 10(1), 160-168

Chinyem, F.I., Ohwoghere-Asuma, O., Ovwamuedo, G., Ugbome, D. O., Nwugha, V. N., Efobo, O. (2023). Evaluation of aquifer hydraulic parameters in Site 3, Delta State University (DELSU), Abraka, western Niger Delta, Nigeria, using pumping test and well logging methods. *FUW Trends in Science and Technology Journal*, 8 (1): 101 – 106

Cooper H.H; & Jacob C.E. (1946). A generalized graphical method for evaluating formation constants and summarizing well-field history. *Transactions American Geophysical Union*, 27(4), 256-534

DSMWR (2021). Delta State Ministry of Water Resources borehole drilling report, Asaba, 80

Egai A.O; Paaru M; Victor-Gow A. (2024). Aquifer delineation using Vertical Electrical Sounding (VES) and correlation of borehole logs in Opolo -Epie, Yenagoa, Bayelsa State, Nigeria. *Global Journal of Earth and Environmental Science*, 9(2): 69-81

Freeborn O.F. (2006). Geoelectric investigation of groundwater in Aniocha South Local Government Area, Delta State, Nigeria. *Global Journal of Geological Sciences*, 4(2), 209-219

Gbadebo A.M; Olurin O.T; Badmus G.O; & Salami S. (2024). Geoelectric investigation of the groundwater potential in Eti-Osa, Lagos State, Nigeria. *Natural and Applied Sciences*, 4(2), 1-6. https://doi.org/10.53982/aijnas.2024.0403:01-j

Hassan, I. (2020). Modeling the potential impacts of climate change on surface and groundwater resources in the Niger Delta part of Nigeria. Unpublished doctoral thesis, University of Strathclyde

Henriet, J.P. (1976). Direct applications of the Dar-Zarrouk parameters in groundwaer surveys. *Geophysical Prospecting*, 24, 344-353

Hudu A.S; Fabian A.A; Kizito O.M; Jacob B.J. (2024). Application of primary and secondary resistivity parameters in evaluating aquifer potential and vulnerability within Kabba, North Central, Nigeria. *FUDMA Journal of Sciences*, 8(4), 221-234

Ibrahim D.M; Nemoto T; & Raghavan V. (2025). Hydrogeophysical analysis of vertical electrical soundings for groundwater potential and aquifer vulnerability evaluation in the Federal Capital Territory, Abuja, Nigeria. *International Journal of Geoinformatics*, 21(1),97-110. https://doi.org/10.52939/ijg.v21i1.3797

Ikuemonisan, M.S; Kizito, M.O; Akpah, F.A; & Jimoh, J.B.(2025). Integrated geoelectrical and hydraulic characterization of basement aquifers for groundwater exploration in Kuje District, Abuja, Nigeria. *FUDMA Journal of Sciences, 9 (11)*

Iserhien-Emekeme R.E. (2014). Electrical resistivity survey for predicting aquifer at Onicha-Ugbo, Delta State, Nigeria. *Journal of Applied Mathematics and Physics*, 2, 520-527

Jimoh J.B; Musa O.K; & Ahmed II J.B. (2025). An integrated method for mapping groundwater potential in part of Abuja, Central Nigeria. *Scientia Africana*, 24(1), 339-362

Jimoh M.O; Opawale G.T; Ejepu J.S; Abdullahi S; & Agbasi O.E. (2023). Investigation of groundwater potential using geological, hydrogeological and geophysical methods in Federal University of Technology, Minna, Bosso campus, North Central, Nigeria. *HydroResearch* 6, 255-268. https://doi.org/10.1016/j.hydres. 2023.09.002

Krasny J. (1993). Classification of transmissivity magnitude and variation. *Groundwater*, 31(2), 230-236

Mohamed A; AL Deep M; Othman A; Taha A.I; Alshehri F; & Abdelrady A. (2022). Integrated geophysical assessment of groundwater potential in Southwestern Saudi Arabia. *Sec. Solid Earth Geophysics*, 10. https://doi.org/10.3389/feart.2022.937402

Musa K.O; Ahmed II J.B; Akpah F.A; Akudo E.O; Obasi A.I;

Jatto S.S; Nanfa A.C; & Jimoh J.B. (2023). Assessment of groundwater potential and aquifer characteristics using inverted resistivity and pumping test data within Lokoja Area, North-Central, Nigeria. *Communication in Physical Sciences*, 9(3), 336-349

Musa K.O; Obasi I.A; Auduson A.E; Jatto S.S; Akudo E.O; Akpah F; & Jimoh J.B (2023). Integrating geoelectrical and borehole data in the characterization of basement-rock aquifers in the Lokoja Area, North Central, Nigeria. *Geosystems and Geoenvironment*, 2. https://doi.org/10.1016/j.geogeo.2023.100217

Nazir J; Ali M; Sarwar A; Khan S; Rehman K; Fahim B; & Igbal B. (2024). Delineation and validation of GIS- based groundwater potential zones under arid to semi-arid environment using multi-influence factors approach. *Geology, Ecology and Landscapes*, 9(4), 1194- 1210. https://doi.org/10.1080/24749508.2024.2392382

Niwas, S; & Singhal, D.C. (1981). Estimation of aquifer transmissivity from Dar-Zarrouk parameters in porous media. *Journal of Hydrology*, 50, 393-399

Oborie E; & Oghale L. (2024). Estimation of aquifer transmissivity using geoelectrical sounding and pumping test. *Journal of Research in Environmental and Earth Sciences*, 10(1), 26-33

Oladapo M.I; Mohammed M.Z; Adeoye O.O; & Adetola B.A. (2004). Geoelectrical Investigation of the Ondo State Housing Corporation Estate, Ijapo Akure, Southwestern Nigeria. *Journal of Mining and Geology*, 40(1), 41-48

Opoku P.A; Shu L; & Amoaku-Nimako G.K. (2024). Assessment of groundwater potential zones by integrating hydrogeological data, Geographic Information Systems, remote sensing and analytical hierarchical process techniques in the Jinan Karst Spring Basin of China. *Water*, 16(4). https://doi.org/10.3390/w16040566

Oseji J.O; & Egbai J.C. (2019). Aquifer characterization based on geoelectric survey data in Issele-Uku, Delta State, Nigeria. *AIP Advances*, 9, 085124. https://doi.org/10.1063/1.5094583

Patra H.P; & Nath S.K. (1999). Schlumberger geoelectric sounding in water In: Principles, interpretation and applications. Balkema Publishers, Rotterdam, 153

Rauf, K.O; Abir, I.A; Muhammad, A.K; Rabiu, J.A; & Nur, M.S.(2025).Delineatin of groundwater protection zones using vertical eleectricalsoundins (VES) in Gombe. *FUDMA Journal of Sciences, 9 (4)*

Reyment R.A. (1965). Aspects of the Geology of Nigeria. Ibadan University Press, 133

Reynolds, J.M.(2011). An introduction to applied and environmental geophysics (2nd ed.), Wiley- Blackwell

Short K.C & Stauble A.J. (1967). Outline of Geology of Niger Delta. *AAPG Bulletin*, 51, 761-799

Short, K.C. & Stauble, A.J. (1967). Outline of geology of Niger Delta. *AAPG Bulletin*, 51(5), 761-779

Simon S.S; Ishaku J.M; Seli A.B; & Boniface F. (2022). Evaluation of groundwater potentials using Dar-Zarrouk parameters in Mapeo and Environs, North-Eastern Nigeria. *Dutse Journal of Pure and Applied Sciences*, 8(3b), 124-135
Singhal B.B.S. & Gupta R.P. (1999). Applied hydrogeology of fractured rocks, 154

Sunkari E.D; Kore B.M; Abioui M. (2021). Hydrogeophysical appraisal of groundwater potential in the fractured basement aquifer of the Federal Capital Territory, Abuja, Nigeria. *Results in Geophysical Sciences*, 5. https://doi.org/10.1016/j.ringps.2021.100012