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Hydrogeophysical Assessment of Groundwater Potential and Aquifer Protective Capacity in Some Towns in Bayelsa State, Niger Delta, Nigeria

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Abstract
This study investigated the geoelectrical and hydrogeological characteristics of the aquifer system in Amassoma–Tombia, Niger Delta, using vertical electrical sounding (VES) to evaluate groundwater potential, aquifer protective capacity, and implications for sustainable groundwater development. Five VES locations (VES1–VES5) were investigated, and the interpreted parameters included aquifer resistivity, thickness, transverse resistance (TR), longitudinal conductance (S), hydraulic conductivity, and transmissivity. The results revealed considerable spatial variations in the geoelectrical properties of the subsurface. Aquifer resistivity ranged from 418 to 1,710 Ωm, while aquifer thickness varied from approximately 7.0 to 20.57 m, suggesting the predominance of sandy to sandy-clayey formations characteristic of the Niger Delta sedimentary sequence. Transverse resistance values ranged from 3,258 to 26,979 Ωm², with VES2 exhibiting the highest value and consequently representing the most favourable groundwater prospect, followed by VES3. VES4 and VES5 were identified as moderate prospects, whereas VES1 showed the lowest groundwater potential based on transverse resistance. Longitudinal conductance values ranged from 0.00478 to 0.01865 mho, placing all investigated locations within the poor protective-capacity category. This indicates that the aquifers are inadequately protected by the overlying materials and are potentially vulnerable to contamination from surface-derived pollutants. Estimated hydraulic conductivity values ranged from 0.372 to 1.386 m/day, indicating moderate permeability, while transmissivity values of 3.03–10.80 m²/day suggest generally low groundwater-transmitting capacity. Although the relatively high aquifer resistivity values suggest predominantly sandy formations and potentially favourable freshwater conditions, groundwater quality and salinity cannot be conclusively established from resistivity data alone and require hydrochemical validation. VES2 and VES3 are recommended for further groundwater exploration, subject to borehole logging and pumping tests. The poor protective capacity highlights the need for proper borehole construction, sanitary protection, and groundwater monitoring in Amassoma–Tombia.

Keywords
Afokpella, Basement Complex Rock, Geochemistry, Petrography, Charnockite

1. Introduction

Groundwater is one of the principal freshwater resources supporting domestic, agricultural, and industrial activities throughout the Niger Delta region of Nigeria. Its importance is particularly evident in communities where surface-water resources are constrained by seasonal variations, increasing population, urban expansion, inadequate sanitation, industrial activities, and environmental degradation associated with petroleum exploration and other anthropogenic activities. The hydrogeological setting of the Niger Delta is complex, reflecting the deposition of thick sequences of unconsolidated to semi-consolidated sediments consisting predominantly of interbedded sands, gravels, clays, sandy clays, and shales. The basin is principally underlain by the Akata, Agbada, and Benin Formations, with the Benin Formation and associated deltaic sediments constituting major groundwater-bearing units. The alternation of permeable sandy horizons with relatively impermeable clayey materials produces multilayered aquifer systems whose depth, thickness, hydraulic properties, degree of confinement, and groundwater potential vary considerably across relatively short distances.

The Benin Formation, commonly referred to as the Coastal Plain Sands, is particularly important to groundwater development because of its extensive distribution and dominance of permeable sands and gravels. However, the presence of clay and sandy-clay intercalations within the formation introduces considerable heterogeneity into the aquifer system and influences groundwater storage, movement, and natural protection. Hydrogeological investigations within the Niger Delta have demonstrated that aquifer architecture varies substantially from one locality to another. Some areas are characterised by relatively shallow unconfined aquifers, whereas others contain multiple aquifer units separated by clayey aquitards.

Consequently, regional hydrogeological characteristics cannot always be directly applied to individual communities, making detailed local-scale investigations essential for reliable groundwater exploration and management. The groundwater resources of the Niger Delta are further subjected to increasing anthropogenic pressures arising from rapid population growth, settlement expansion, agricultural activities, indiscriminate waste disposal, industrialisation, and petroleum-related operations. In coastal parts of the basin, the proximity of groundwater systems to the Atlantic Ocean, tidal channels, creeks, and saline wetlands also introduces the potential for saline-water intrusion. Recent investigations have continued to demonstrate that although the sandy and gravelly aquifers of the Niger Delta constitute important freshwater resources, they may be vulnerable to both surface-derived contamination and saline influences depending on local geological and hydrogeological conditions.

A recent study of coastal aquifers in the Niger Delta, for example, emphasised the importance of integrated geoelectrical and hydrogeological investigations for understanding aquifer vulnerability, hydraulic yield potential, and subsurface heterogeneity in rapidly developing coastal environments.

Within this context, the assessment of aquifer geometry, hydraulic properties, groundwater potential, and protective capacity is essential for sustainable groundwater-resource development. Electrical resistivity methods, particularly Vertical Electrical Sounding (VES), have become widely applied by researchers in the Niger Delta because they provide a relatively rapid and non-invasive means of investigating subsurface lithology and delineating potential aquifer units. VES data can be used to estimate the resistivity and thickness of subsurface layers and to identify probable groundwater-bearing formations. In addition, the derivation of Dar-Zarrouk parameters, particularly transverse resistance (TR) and longitudinal conductance (S), provides useful information for evaluating aquifer potential and vulnerability. Transverse resistance reflects the combined influence of aquifer resistivity and thickness and is therefore useful in assessing the relative groundwater potential of aquifer units, whereas longitudinal conductance provides an indication of the protective capacity of the overburden against downward migration of contaminants.

Previous investigations across the Niger Delta have demonstrated the effectiveness of VES and related geophysical techniques in groundwater exploration and aquifer characterisation. Mgbolu et al. (2019), for example, integrated geological, VES, borehole-log, and pumping-test information to investigate groundwater potential, aquifer hydraulic characteristics, and vulnerability in parts of Ndokwa, Niger Delta Basin. Their results showed that the subsurface is predominantly sandstone intercalated with clay, sandy clay, and clayey sand. Aquifer resistivity ranged from 470.84 to 2,697.70 Ωm, with an average value of approximately 1,289 Ωm, while aquifer thickness ranged from 4.7 to 149.7 m, with an average thickness of 42.52 m. The study also reported calculated hydraulic conductivity values of 25.69–28.92 m/day and transmissivity values of 129.54–4,181.31 m^2/day.

Importantly, longitudinal conductance values ranged from 0.006 to 0.137, indicating predominantly poor to weak protective capacity and suggesting that parts of the aquifer system were susceptible to contamination from infiltrating pollutants. The relevance of this regional research becomes more apparent when considering investigations conducted within Bayelsa State, particularly in areas geographically close to the present study. Bunonyo, Adanya, and Omamode investigated the groundwater potential of Tantua–Amassoma in Bayelsa State using geoelectrical and hydrochemical techniques. Their study employed electrical resistivity measurements together with groundwater sampling and trace-element analysis to identify areas suitable for borehole development and to assess groundwater quality.

The geographical proximity of their investigation to Amassoma–Tombia makes their findings particularly relevant to the present research and provides an important local benchmark for interpreting the geoelectrical and hydrogeological conditions of the study area. Similarly, Oki and Didei (2024) investigated aquifer protective capacity at the Federal University Otuoke in Ogbia Local Government Area of Bayelsa State using ten Vertical Electrical Soundings. Their study demonstrated the usefulness of longitudinal conductance derived from VES data for assessing the ability of overburden materials to protect shallow aquifers from contamination. The findings are particularly relevant to the present study because both investigations occur within the Bayelsa sector of the Niger Delta and address the relationship between geoelectrical properties and aquifer vulnerability.

More recent research has further reinforced the environmental significance of groundwater vulnerability in the Niger Delta. An investigation in Yenagoa, Bayelsa State, combined twelve VES surveys with hydrochemical analysis to assess groundwater vulnerability to petroleum-related pollution. The study demonstrates the continuing need to integrate geophysical and hydrochemical information when evaluating groundwater resources in areas exposed to petroleum activities. This is particularly relevant to Amassoma–Tombia because the study area occurs within the same broader Niger Delta environmental setting, where groundwater systems may be influenced by anthropogenic activities and petroleum-related environmental pressures.

Research conducted elsewhere in Delta State provides further evidence of the spatial variability and vulnerability of Niger Delta aquifers. For example, a recent study of the FUPRE campus and Agbarho axis in Delta State used VES and Dar-Zarrouk parameters to investigate groundwater potential and aquifer vulnerability. The study identified areas with relatively high transverse resistance and promising groundwater potential but also reported generally poor aquifer protective capacity based on low longitudinal conductance values. The authors consequently emphasised the importance of combining groundwater-potential assessment with vulnerability evaluation rather than relying solely on aquifer productivity.

Recent investigations in Delta North have produced similar observations. A 2025 hydrogeophysical study used VES to investigate aquifer geometry, groundwater potential, and vulnerability and reported considerable spatial variations in aquifer thickness, longitudinal conductance, transverse resistance, hydraulic conductivity, and transmissivity. The study identified areas of relatively favourable groundwater potential while also indicating susceptibility to contamination. Such findings reinforce the understanding that aquifer productivity and aquifer protection are separate but complementary considerations in groundwater-resource assessment within the Niger Delta.

A further recent investigation in Delta North District employed VES together with borehole lithological information to characterise aquifer units and assess groundwater vulnerability. The study identified a heterogeneous subsurface consisting of clayey sand, lateritic clayey sand, coarse sand, medium-to-coarse sand, and fine-to-medium sand, with deeper sandy aquifers occurring at varying depths. Although moderate-to-good groundwater prospects were identified, the aquifers were also considered moderately to highly vulnerable to surface contamination. The researchers recommended deeper aquifer development and improved waste-management practices. These findings provide additional regional evidence that groundwater development in the Niger Delta must consider both aquifer productivity and environmental vulnerability. The vulnerability of Niger Delta groundwater is not restricted to geoelectrical evidence. Chinemelu and Adeoye (2022), using the DRASTIC model and GIS techniques in Osubi Metropolis, Delta State, demonstrated considerable spatial variability in groundwater vulnerability, with moderate, high, and very-high vulnerability zones associated partly with waste dumpsites, septic systems, and other potential pollution sources. Their findings demonstrate that anthropogenic land-use activities can significantly influence groundwater vulnerability and reinforce the need for effective groundwater-protection measures in rapidly developing Niger Delta communities.

The increasing relevance of integrated approaches is also demonstrated by recent studies combining geophysical and hydrochemical techniques. A 2026 investigation in the Niger Delta integrated VES, groundwater chemistry, and borehole lithological information to evaluate groundwater quality, aquifer vulnerability, and suitability for domestic and irrigation purposes. The study identified heterogeneous sandy aquifer units, predominantly poor protective capacity, and variable groundwater vulnerability. The predominance of NaCl-type groundwater was attributed to both natural geochemical processes and anthropogenic influences. Such findings demonstrate the importance of combining geophysical characterisation with groundwater-quality assessment when evaluating the sustainability of Niger Delta aquifer systems. The body of research described above demonstrates that the Niger Delta aquifer system cannot be treated as hydrogeologically homogeneous.

Significant differences have been documented between Ndokwa, Yenagoa, Amassoma, Otuoke, Delta North, and other parts of the basin with respect to aquifer resistivity, thickness, depth, hydraulic conductivity, transmissivity, protective capacity, and vulnerability. These variations are controlled by differences in sedimentary facies, grain size, clay content, aquifer geometry, groundwater chemistry, recharge conditions, and anthropogenic influences. Therefore, information obtained from one locality provides a useful regional comparison but should not be assumed to represent groundwater conditions at another locality without site-specific investigation. The Amassoma–Tombia area consequently requires detailed investigation to establish the characteristics of its aquifer system and determine how its groundwater conditions compare with those documented elsewhere in the Niger Delta.

The present study addresses this need through the interpretation of five Vertical Electrical Sounding locations (VES1–VES5). The investigation focuses on key geoelectrical and hydrogeological parameters, including aquifer resistivity, aquifer thickness, transverse resistance (TR), longitudinal conductance (S), hydraulic conductivity, and transmissivity. The integration of these parameters provides a basis for determining the relative groundwater potential of the investigated locations, evaluating aquifer protective capacity, and identifying areas that may be suitable for future groundwater development.

The significance of the present research to Niger Delta groundwater studies therefore lies in its provision of additional site-specific information on the relationship between aquifer electrical properties, groundwater potential, hydraulic characteristics, and vulnerability. The study is particularly valuable because it contributes data from the Amassoma–Tombia environment, an area for which detailed geoelectrical information can complement existing investigations from nearby Tantua–Amassoma and other parts of Bayelsa State. By comparing the results obtained in Amassoma–Tombia with findings from other Niger Delta locations, the research contributes to a broader understanding of spatial variations in aquifer characteristics across the basin.

Furthermore, the study demonstrates the importance of evaluating groundwater potential and aquifer vulnerability simultaneously. A location may possess a relatively favourable aquifer in terms of resistivity and thickness but may nevertheless have poor protective capacity and therefore remain susceptible to contamination. This distinction is especially important in the Niger Delta, where increasing population; urbanisation, petroleum activities, agriculture, waste disposal, and industrial development continue to place pressure on groundwater resources. Consequently, groundwater exploration and development should be accompanied by appropriate borehole construction, sanitary protection, groundwater-quality monitoring, and proper management of potentially contaminating activities.

2. Description of the Study Area

2.1. Location and Accessibility

The study area covers Amassoma and Opuma communities in Bayelsa State, Southern Nigeria, located between latitudes E4°52′ to E5°02′ and longitudes E6°19′ to E6°25′. The area is accessible via the Yenagoa–Amassoma road and several interconnected rural roads (Fig. 1). The climate is humid tropical with mean annual rainfall exceeding 2500 mm. Drainage is controlled by the Nun River and its tributaries, characteristic of the Niger Delta's low-lying swampy terrain.

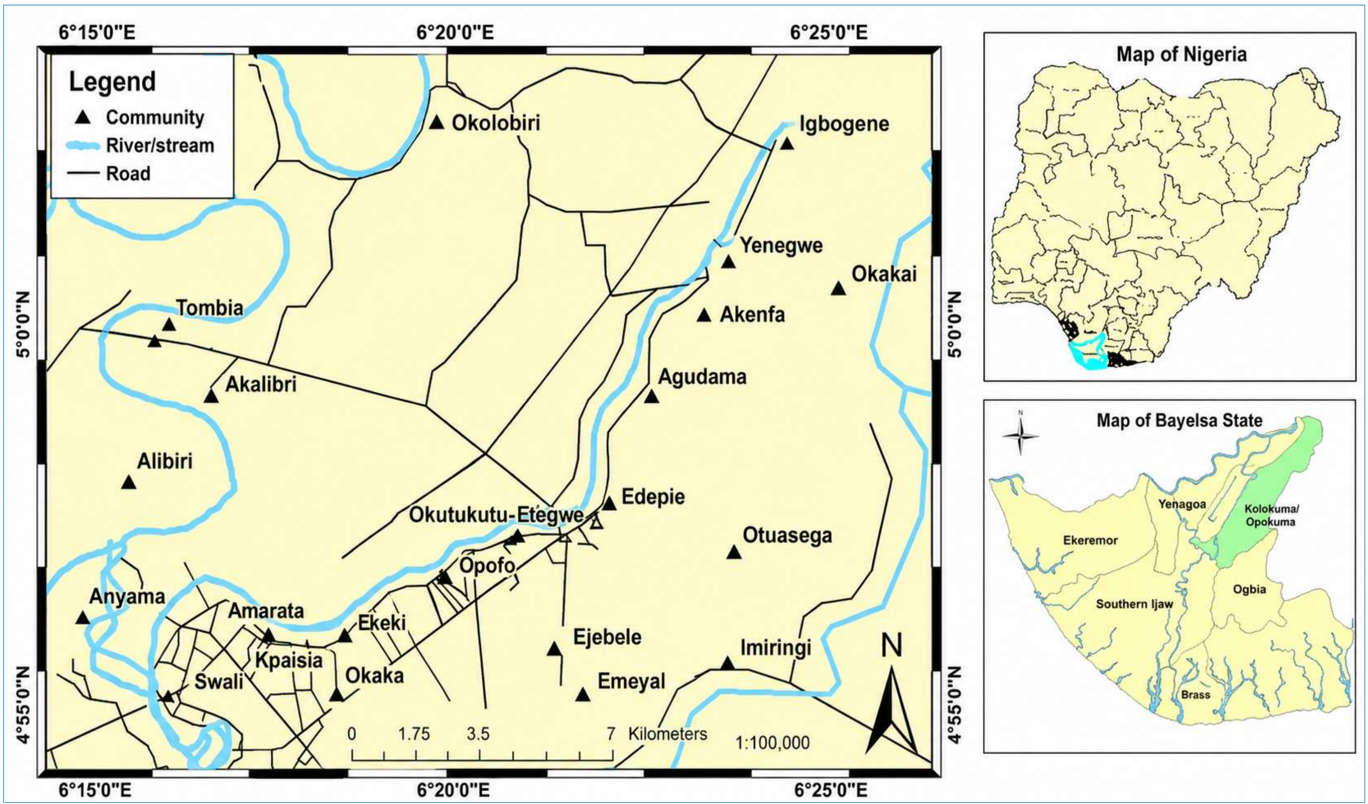

Fig. 1. Map of the study area

3. Geology of the Study Area

Geologically, the study area lies within the Niger Delta Basin and is predominantly underlain by the Benin Formation (Miocene–Recent), which is characterized by fluvial to alluvial sediments. These deposits consist mainly of soft, compressible clays, silts, and sands, frequently interbedded with peaty materials, and are indicative of a typical freshwater swamp depositional environment. Soils are generally fine-grained, highly plastic, with variable compaction, requiring careful geotechnical assessment for construction, but deeper layers offer greater strength, crucial for infrastructure support. This formation consists mainly of unconsolidated sands, gravels, intercalated clay lenses, and lateritic overburden. The near-surface stratigraphy is marked by alternating sandy and clayey sequences, which exert significant control on groundwater storage, movement, and aquifer protection (Short and Stauble, 1967; Reyment, 1965).

4. Materials and Methods

4.1. Data Acquisition

Five VES stations (VES 1–VES 5) were conducted using the Schlumberger electrode array configuration. Measurements were taken along accessible road corridors close to existing and proposed borehole locations at Amassoma–Tombia and along Imiringi Road in Bayelsa State. The total spread length for the VES was 200 m. The VES station was positioned along the tarred road near the borehole location. The survey employed a maximum current electrode half-spacing (AB/2) of 100 m on both sides, resulting in a total current electrode separation (AB) of 200 m. The potential electrode half-spacing (MN/2) varied between 0.3 m and 25 m during the measurements. The investigation employed the electrical resistivity method, which introduces an artificial electric current into the subsurface through current electrodes while the resulting potential difference is measured using potential electrodes. The apparent resistivity of the subsurface is obtained by multiplying the measured resistance by the geometric factor of the electrode array. The method is based on the principle that the earth conducts electricity through ionic or electrolytic processes, primarily due to the presence of pore fluids in the subsurface. Consequently, Ohm's law provides the theoretical foundation for the electrical resistivity technique.

$$\text{Ohm's law: } R=\Delta V/I \quad (1)$$

Where; R = Resistance, ΔV = potential and I = current.

4.2. Data Processing and Interpretation

Field resistance values were converted to apparent resistivity using appropriate geometric factors. Initial curve matching was performed manually, followed by computer-assisted inversion using INTERPEX 1-D software. The 1-D inversion was performed by transforming the measured apparent-resistivity data into a layered-earth model consisting of discrete geoelectric layers defined by resistivity and thickness. An initial model was generated from the observed apparent-resistivity curve and the characteristic changes in slope associated with variations in subsurface resistivity. Forward modelling was subsequently used to calculate theoretical apparent-resistivity values for the initial model. The calculated response was compared with the measured field data, and the layer resistivities and thicknesses were iteratively adjusted to minimize the data misfit. The inversion was terminated when the RMS error reached an acceptable level and successive iterations produced insignificant changes in both the model parameters and misfit. The quality of the inversion was assessed from the final RMS error and the agreement between the observed and calculated apparent-resistivity curves. Model uncertainty was evaluated by considering parameter sensitivity, resolution, and the possibility of alternative layer configurations producing comparable data fits. The final inverted model was then correlated with the available lithological and geological information to identify the likely subsurface materials and groundwater-bearing units.

4.3. Hydraulic Parameter Estimation

Dar Zarrouk parameters, namely longitudinal conductance (S) and transverse resistance (TR), were computed for the identified aquifer layers using standard formulations (Maillet, 1947). Hydraulic conductivity was estimated based on the empirical relationship proposed by Heigold et al. (1979), while transmissivity was determined as the product of hydraulic conductivity and aquifer thickness.

5. Presentation of Results

5.1. Geoelectric Layer Characterizations

The interpretation of VES 1 indicates the presence of eight (8) distinct geoelectric layers, with apparent resistivity values ranging from 67.144 Ωm to 2245.1 Ωm. The overburden thickness varies between 0.86164 m and 1.3832 m, corresponding to depths of 0.86164 m to 2.5512 m. The near-surface materials are composed of organic-rich topsoil or a thin sandy–lateritic layer, characterized by moderate to high resistivity resulting from oxidation, partial drying, and the presence of unsaturated sandy lenses. This unit is generally suitable for light shallow foundations and provides good drainage, although excavation or compaction may be required prior to construction.

Table 1. Apparent Resistivity Parameters of VES 1 with natural lithological identification

VES 1, LAT: 4 58 57.342 LONG: 6 19 27.077						
AB/2 (m)	**MN/2 (m)**	**Resistance**	**Geometric factor**	**Calculated apparent resistivity**	**Adjusted apparent resistivity**	**Interpreted Lithology**
1	0.3	20.131	4.76	95.823	85.82	Topsoil
1.5	0.3	7.88	10.84	85.419	105.42	Lateritic Soil
2	0.3	0.6946	23.3	16.184	126.18	Clayey Silt
3	0.3	3.8671	51.8	200.315	180.32	Clayey Sand
5	0.3	1.7570	112	196.786	220.79	Clayey Sand
7	0.3	1.3939	242	337.316		Clayey Sand
7	1	2.1471	71.3	153.088	227.32	Clayey Sand
10	1	1.1662	156	181.927	201.93	Clayey Sand
15	1	0.3547	338	119.889	139.89	Clayey Sand
15	9	1.0430	73.6	76.765		Silt
20	9	1.4932	73.6	109.901	119.9	Silty Clay
25	9	1.2875	97.8	125.917	105.92	Clayey Silt
30	9	0.8705	97.8	85.135	95.13	Silt
40	9	0.6671	89.9	59.972	99.97	Silt
45	9	0.6706	141	94.555	108.55	Silt
50	9	0.8926	122	108.902	118.9	Silty Clay
55	9	1.0087	122	123.058	123.06	Clayey Sand
60	9	0.2375	481	114.237	114.24	Clayey Sand
70	9	0.4737	713	337.748	127.75	Sand
80	9	0.4713	868	409.088	129.09	Sand
90	9	0.1534	868	133.151	133.15	Clayey Sand
90	25	0.2902	314	91.123		Silt
100	25	0.1443	589	84.993	124.99	Silt

Table 2. Apparent Resistivity and Resistivity Model VES 1

VES 1 DATA					Resistivity model		
S/N	AB/2 (m)	MN/2 (m)	Calculated Apparent Resistivity (Ωm)	Adjusted Resistivity (Ωm)	Resistivity (Ωm)	Thickness (m)	Depth (m)
1	1	0.3	95.823	85.82	67.144	0.86164	0.86164
2	1.5	0.3	85.419	105.42	2245.1	0.30640	1.1680
3	2	0.3	16.184	126.18	503.55	1.3832	2.5512
4	3	0.3	200.315	180.32	50.637	11.761	14.312
5	5	0.3	196.786	220.79	170.98	6.8168	21.129
6	7	0.3	227.32	227.32	418.60	7.7963	28.925
7	10	1	201.93	201.93	344.60	9.7058	38.631
8	15	1	139.89	139.89	69.998	Undetermined	Undetermined
9	20	9	109.901	119.9			
10	25	9	125.917	105.92			
11	30	9	85.135	95.13			
12	40	9	59.972	99.97			
13	45	9	94.555	108.55			
14	50	9	108.902	118.9			
15	55	9	123.058	123.06			
17	60	9	114.237	114.24			
18	70	9	337.748	127.75			
19	80	9	409.088	129.09			
20	90	9	133.151	133.15			
21	100	25	84.993	124.99			

Interpretation further indicates that the fourth geoelectric layer consists of clayey silt (water-saturated fine-grained sediments), with a thickness of 11.761 m occurring at an approximate depth of 14.312 m. This layer acts as an aquitard, restricting vertical groundwater flow and potentially giving rise to perched water table conditions. The fifth, sixth, and seventh layers are identified as clayey sand, coarse sand, and saturated sand, respectively. These units have thicknesses ranging from 6.8168 m to 9.7058 m and resistivity values of 170.98 Ωm, 418.60 Ωm, and 344.60 Ωm, occurring at depths between 21.129 m and 38.631 m. The relatively high resistivity of these coarse-grained units reflects low clay content and good sorting. When saturated, they constitute high-quality aquifer zones with excellent transmissivity and strong potential for groundwater development, provided lateral continuity exists. The eighth geoelectric layer exhibits a resistivity of 69.998 Ωm; however, its thickness and depth extent could not be determined as shown in Tables 1-2 and Figs. 2-3.

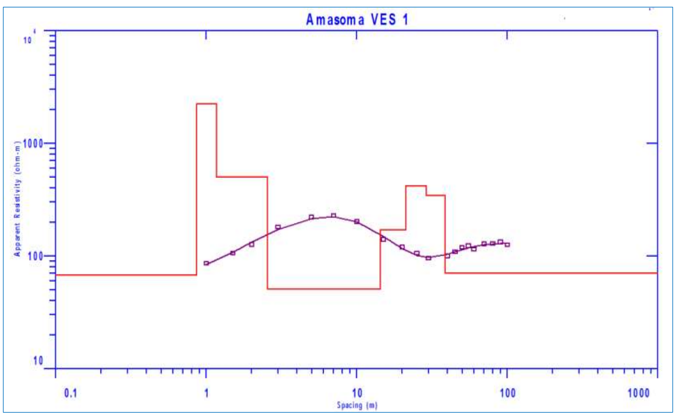

Fig. 2. Typical Hydrogeophysical Sounding Curve of VES 1

The modelling results for VES 2 similarly delineate eight (8) geoelectric layers, with apparent resistivity values ranging from 67.144 Ωm to 2245.1 Ωm. The overburden is relatively thin, with thicknesses between 0.19169 m and 0.51380 m, corresponding to depths of 0.19169 m to 0.70549 m. The surface layer comprises a lateritic cap or dry sandy laterite, forming a hard, cemented horizon typical of ferricrete or indurated laterite. The third geoelectric layer is interpreted as coarse sand, with a thickness of 3.6974 m and a high resistivity of 1323.2 Ωm, encountered at a depth of 4.4029 m.

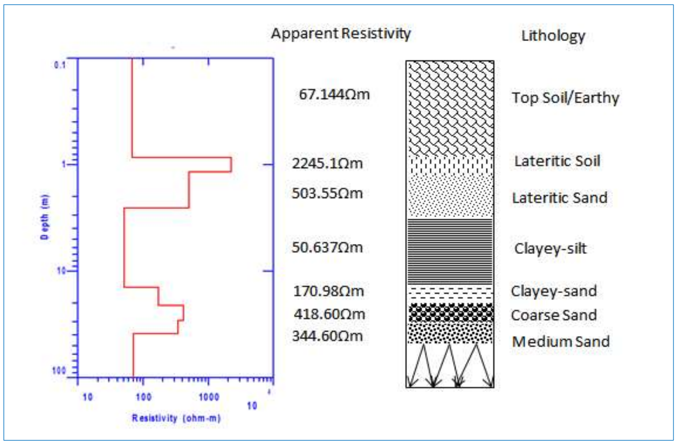

Fig. 3. Layered Inversion Model of VES 1

This high resistivity suggests very dry, coarse sand or gravel with high permeability when saturated, though currently containing minimal moisture. The fourth layer consists of clayey silt, with a thickness of 5.2925 m and a resistivity of 78.097 Ωm at a depth of 9.6953 m. This unit marks an increase in moisture and clay content and represents the first moderately conductive horizon, but it is unsuitable as an aquifer.

The fifth layer, identified as clayey sand, has a thickness of 4.8063 m and a resistivity of 228.61 Ωm at a depth of 14.502 m and may function as a perched aquifer under localized saturation conditions. The sixth and seventh layers comprise medium to coarse sand, with thicknesses ranging from 9.4831 m to 20.568 m and resistivity values between 847.74 Ωm and 1311.7 Ωm, occurring at depths of 23.985 m to 44.553 m.

These clean, coarse-grained units are potentially water-bearing and, when saturated, represent excellent aquifer zones with high transmissivity and strong groundwater development potential. The eighth layer has an apparent resistivity of 249.26 Ωm, though its thickness and depth extent remain undetermined as shown in Tables 3-4 and Figs. 4-5.

VES 3 interpretation identifies six (6) geoelectric layers, with apparent resistivity values ranging from 78.576 Ωm to 2516.2 Ωm. The overburden thickness varies between 0.49794 m and 0.83267 m, corresponding to depths of 0.49794 m to 1.3306 m. This upper layer consists of organic-rich topsoil or a thin sandy soil cover, typical of shallow overburden conditions. The third and fourth layers are interpreted as silt, with a combined thickness of 2.1253 m and resistivity values decreasing from 30.585 Ωm to 23.946 Ωm, encountered between depths of 3.4559 m and 5.5483 m. These low resistivity values are indicative of fine-grained, water-saturated silt or silty clay with low permeability, functioning as an aquitard or semi-confining layer. From an engineering perspective, these materials are highly compressible and unsuitable for shallow foundations. The fifth layer consists of coarse sand with a thickness of 10.228 m and a high resistivity of 1710.3 Ωm at a depth of 15.776 m, suggesting clean, well-sorted sand that likely represents the main productive aquifer. The sixth layer exhibits a very high resistivity of 2516.2 Ωm, although its thickness and depth extent remain undefined as shown in Tables 5-6 and Figs 6-7.

Table 3. Apparent Resistivity Parameters of VES 2 with natural lithological identification

VES 2, LAT: 4 58 51.942 LONG: 6 19 30.39						
AB/2 (m)	**MN/2 (m)**	**Resistance**	**Geometric factor**	**Calculated Apparent Resistivity**	**Adjusted Apparent Resistivity**	**Interpreted Lithology**
1	0.3	196.3677	4.76	934.7103	1034.71	Top soil
1.5	0.3	149.1511	10.84	1616.798	1316.8	Lateritic soil
2	0.3	97.1726	23.3	2264.122	1564.12	Sand
3	0.3	40.9308	51.8	2120.215	1720.22	Sand
5	0.3	14.1897	112	1589.246	1589.25	Sand
7	0.3	5.8236	242	1409.311	1309.31	Sand
7	1	16.6377	71.3	1186.268		Sand
10	1	5.5016	156	858.2496	858.25	Sand
15	1	1.4926	338	504.4988	467.00	Sand
15	3	1.043	17.5	18.2525		Silt
20	3	0.2704	161	43.5344	273.53	Silt
25	3	0.265	290	76.85	256.85	Silt
30	3	0.257	518	133.126	258.13	Clayey Sand
40	3	0.6671	518	345.5578	315.56	Clayey Sand
45	3	0.3473	928	322.3168	332.32	Clayey Sand
50	3	0.2369	1123	266.0387	366.04	Clayey Sand
55	3	0.189	1660	313.74	353.74	Clayey Sand
60	3	0.2375	1660	394.25	394.25	Clayey Sand
70	3	0.4737	2424	1148.249	390.25	Sand
80	3	0.4713	2942	1386.565	426.56	Sand
90	3	0.1534	2942	451.3028		Sand
90	5	0.2902	1760	510.752	451.3	Sand
100	5	0.1443	3134	452.2362	452.24	Sand

Table 4. Apparent Resistivity and Resistivity Model VES 2

VES 2 DATA					Resistivity model		
S/N	**AB/2 (m)**	**MN/2 (m)**	**Calculated Apparent Resistivity (Ωm)**	**Adjusted Resistivity (Ωm)**	**Resistivity (Ωm)**	**Thickness (m)**	**Depth (m)**
1	1	0.3	934.7103	1034.71	250.98	0.19169	0.19169
2	1.5	0.3	1616.798	1316.8	6555.8	0.51380	0.70549
3	2	0.3	2264.122	1564.12	1323.2	3.6974	4.4029
4	3	0.3	2120.215	1720.22	78.097	5.2925	9.6953
5	5	0.3	1589.246	1589.25	228.61	4.8063	14.502
6	7	0.3	1409.311	1309.31	847.74	9.4831	23.985
7	10	1	858.2496	858.25	1311.7	20.568	44.553
8	15	1	504.4988	467.00	249.26	Undetermined	Undetermined
9	20	9	43.5344	273.53			
10	25	9	76.85	256.85			
11	30	9	133.126	258.13			
12	40	9	345.5578	315.56			
13	45	9	322.3168	332.32			
14	50	9	266.0387	366.04			
15	55	9	313.74	353.74			
17	60	9	394.25	394.25			
18	70	9	1148.249	390.25			
19	80	9	1386.565	426.56			
20	90	9	510.752	451.3			
21	100	25	452.2362	452.24			

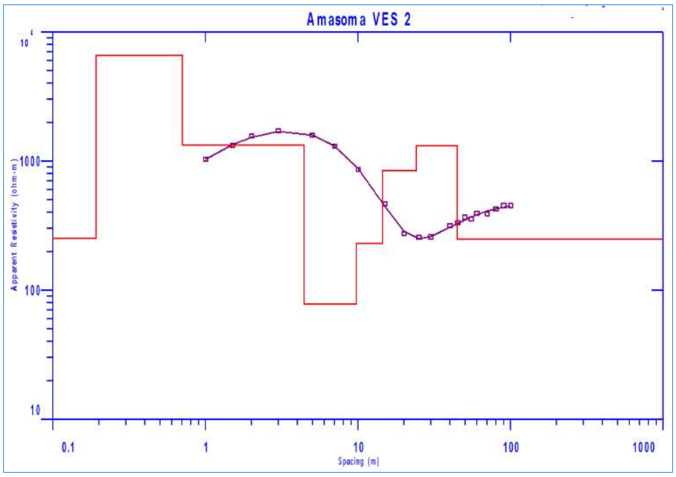

Fig. 4. Typical Hydrogeophysical Sounding Curve of VES 2

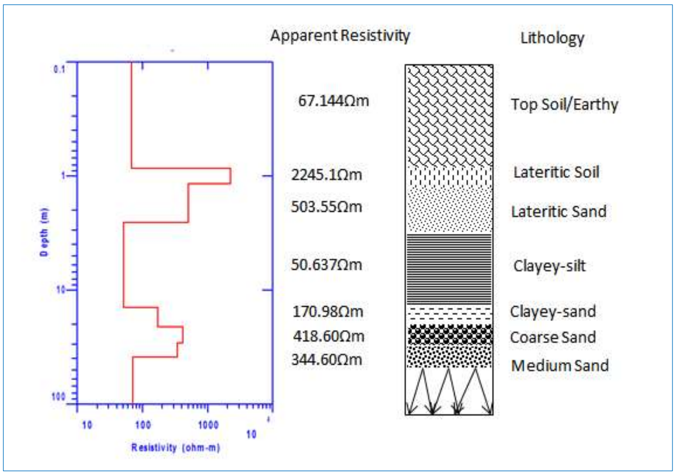

Fig. 5. Layered Inversion Model of VES 2

The interpretation of VES 4 indicates the presence of six (6) distinct geoelectric layers, characterized by apparent resistivity values ranging from 108.77 Ωm to 1518.3 Ωm. The overburden thickness varies from 0.53977 m to 2.1996 m, corresponding to depths of 2.1996 m to 2.7394 m. This zone is characterized by lateritic, ferruginous topsoil that is generally well-drained and unsaturated. Beneath this lies a highly conductive wet clay layer with very poor bearing capacity, functioning as an aquitard. The third and fourth layers consist of silt or clayey sand, forming a thick clay sequence with thicknesses ranging from 2.4911 to 4.6233 m. Apparent resistivity values decrease sharply from 69.544 Ωm to 6.3761 Ωm at depths between 5.2305 m and 9.8538 m, confirming the presence of a substantial, nearly impermeable clay unit that significantly restricts downward groundwater movement. The fifth layer comprises coarse sand with a thickness of 7.7336 m and a resistivity of 1518.3 Ωm at a depth of 17.589 m, representing the upper part of the aquifer system suitable for groundwater abstraction. The sixth layer shows an extremely high resistivity of 23,879 Ωm, though its thickness and depth extent remain undetermined as shown in Tables 7-8 and Figs. 8-9.

Table 5. Apparent Resistivity Parameters of VES 3 with natural lithological identification

VES 3 HALF SCHLUMBERGER , LOCATION: LAT.: 5 2 0.14 LONG.: 6 24 9.64						
AB/2 (m)	**MN/2 (m)**	**Resistance**	**Geometric factor**	**Calculated apparent resistivity**	**Adjusted apparent resistivity**	**Interpreted lithology**
1	0.3	10.58	4.76	50.3608	50.36	Topsoil
1.5	0.3	3.393	10.84	36.78012	36.78	Lateritic soil
2	0.3	1.4799	23.3	34.48167	30.48	Silt
3	0.3	0.3141	51.8	16.27038	28.27	Silt
5	0.3	0.0777	112	8.7024	32.7	Silt
7	0.3	0.0378	242	9.1476		Silt
7	1	1.1596	71.3	82.67948	38.68	Clay
10	1	0.0324	156	5.0544	45.05	Clay
15	1	0.0438	338	14.8044		Silt
15	3	3.3081	17.5	57.89175	67.89	Clay
20	3	1.7315	161	278.7715	98.77	Clayey Sand
25	3	3.6879	290	1069.491	119.49	Sand
30	3	0.657	518	340.326	139.33	Sand
40	3	6.1125	518	3166.275	186.27	Sand

Table 6. Apparent Resistivity and Resistivity Model VES 3

VES 3 DATA					Resistivity model		
S/N	**AB/2 (m)**	**S/N**	**AB/2 (m)**	**S/N**	**AB/2 (m)**	**S/N**	**AB/2 (m)**
1	1	0.3	50.361	50.36	78.576	0.49794	0.49794
2	1.5	0.3	36.780	36.78	20.460	0.83267	1.3306
3	2	0.3	34.482	30.48	30.585	2.1253	3.4559
4	3	0.3	16.270	28.27	23.946	2.0924	5.5483
5	5	0.3	8.702	32.7	1710.3	10.228	15.776
6	7	0.3	82.679	38.68	2516.2	Undetermined	Undetermined
7	10	1	5.054	45.05			
8	15	1	57.892	67.89			
9	20	9	278.771	98.77			
10	25	9	1069.491	119.49			
11	30	9	340.326	139.33			
12	40	9	3166.275	186.27			

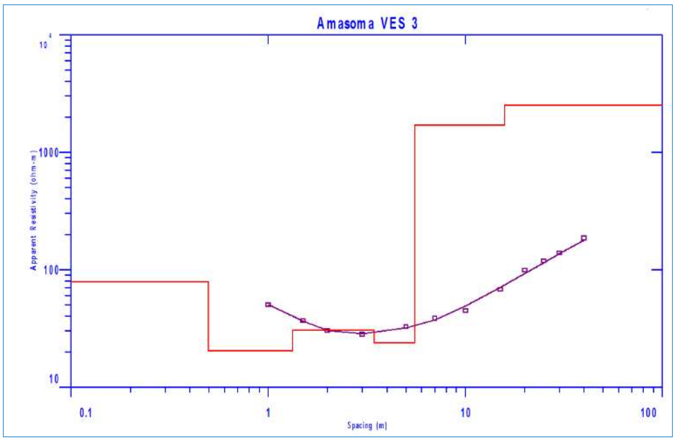

Fig. 6. Typical Hydrogeophysical Sounding Curve of VES 3

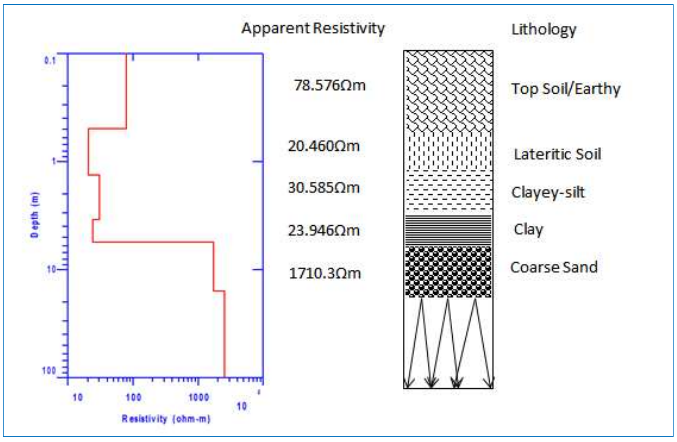

Fig. 7. Layered Inversion Model of VES 3

Table 7. Apparent Resistivity Parameters of VES 4 with natural lithological identification

VES 4, LOCATION: LAT.: 4 56 43.03 LONG.:6 21 27.88						
AB/2 (m)	AB/2 (m)	AB/2 (m)	AB/2 (m)	AB/2 (m)	AB/2 (m)	AB/2 (m)
1	0.3	20.133	4.76	95.83308	105.83	Top soil
1.5	0.3	8.9729	10.84	97.26624	101.27	Lateritic soil
2	0.3	4.3559	23.3	101.4925	99.49	Clayey-Silt
3	0.3	1.4164	51.8	73.36952	85.37	Clayey-Silt
5	0.3	0.2677	112	29.9824	59.98	Silt
7	0.3	0.1074	242	25.9908		Silt
7	1	0.4122	71.3	29.38986	42.39	Silt
10	1	0.2308	156	36.0048	36	Silt
15	1	0.0324	338	10.9512		Silt
15	3	3.3081	17.5	57.89175	27.89	Silt
20	3	0.1125	161	18.1125	29.11	Silt
25	3	0.0829	290	24.041	31.04	Silt
30	3	0.0646	518	33.4628	33.46	Silt
40	3	0.0401	518	20.7718	45.77	Silt
45	3	0.0435	928	40.368	49.37	Silt
50	3	0.0449	1123	50.4227	60.42	Silt
55	3	0.0242	1660	40.172	65.17	Silt
60	3	0.0298	1660	49.468	69.47	Silt
70	3	0.0426	2424	103.2624	83.26	Clayey-Silt
80	3	0.4713	2942	1386.565	97.56	Coarse Sand
90	3	0.1534	2942	451.3028		Clayey-Sand
90	5	0.2902	1760	510.752	110.75	Clayey-Sand
100	5	0.1443	3134	452.2362	118.24	Clayey-Sand

Table 8. Apparent Resistivity and Resistivity Model VES 4

VES 4 DATA					Resistivity model		
S/N	AB/2 (m)	MN/2 (m)	Calculated Apparent Resistivity (Ωm)	Adjusted Resistivity (Ωm)	Resistivity (Ωm)	Thickness (m)	Depth (m)
1	1	0.3	95.83308	105.83	108.77	2.1996	2.1996
2	1.5	0.3	97.26624	101.27	6.8462	0.53977	2.7394
3	2	0.3	101.4925	99.49	69.544	2.4911	5.2305
4	3	0.3	73.36952	85.37	6.3761	4.6233	9.8538
5	5	0.3	29.9824	59.98	1518.3	7.7336	17.589
6	7	0.3	29.38986	42.39	23879	Undetermined	Undetermined
7	10	1	36.0048	36			
8	15	1	10.9512	27.89			
9	20	9	18.1125	29.11			
10	25	9	24.041	31.04			
11	30	9	33.4628	33.46			
12	40	9	20.7718	45.77			
13	45	9	40.368	49.37			
14	50	9	50.4227	60.42			
15	55	9	40.172	65.17			
17	60	9	49.468	69.47			
18	70	9	103.2624	83.26			
19	80	9	1386.565	97.56			
20	90	9	510.752	110.75			
21	100	25	452.2362	118.24			

The modelling of VES 5 reveals the presence of six (6) geoelectric layers, with resistivity values ranging from 6.0169 Ωm to 18,644 Ωm. The overburden thickness varies between 0.74828 m and 1.5876 m, extending to depths of approximately 1.5876 m to 2.3358 m. The near-surface layer is interpreted as lateritic sandy topsoil or slightly compacted reddish-brown soil. It has moderately high resistivity values, indicating dry conditions and low clay content. The resistivity response suggests that the layer is predominantly sandy and relatively well drained, with limited moisture retention and a minor proportion of fine-grained materials. The third layer is identified as medium to coarse-grained sand, occurring at a depth of about 18.375 m, with a thickness of 82.855 m and a corresponding resistivity value of approximately 82.855 Ωm.vThe modelling of VES 5 reveals the presence of six (6) geoelectric layers, with resistivity values ranging from 6.0169 Ωm to 18,644 Ωm. The overburden thickness varies between 0.74828 m and 1.5876 m, extending to depths of approximately 1.5876 to 2.3358 m.

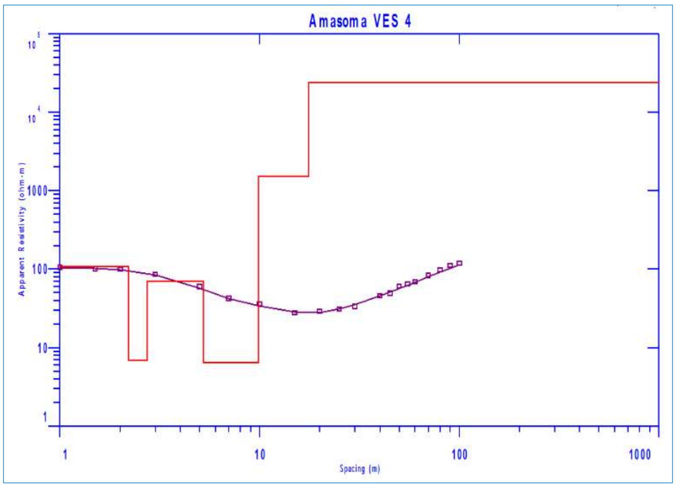

Fig. 8. Typical Hydrogeophysical Sounding Curve of VES 4

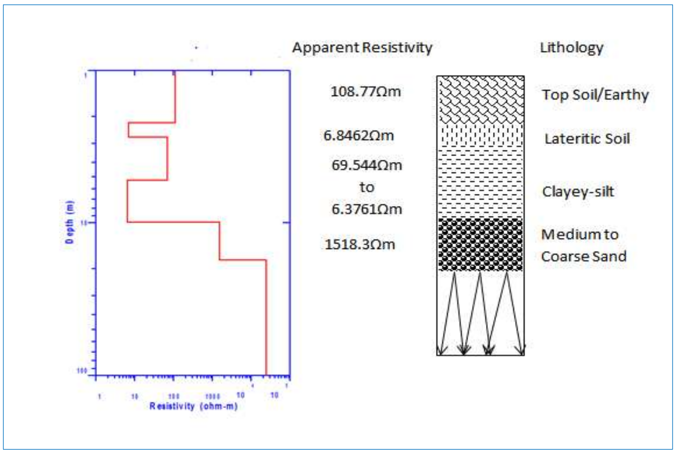

Fig. 9. Layered Inversion Model of VES 4

This near-surface layer is interpreted as lateritic sandy topsoil or slightly compacted reddish-brown soil, characterized by moderately high resistivity values suggesting relatively dry conditions and low clay content. The third layer is interpreted as medium- to coarse-grained sand, occurring at an approximate depth of 18.375 m. This layer has a considerable thickness of about 82.855 m and is associated with a resistivity value of approximately 82.855 Ωm. The relatively high resistivity and substantial thickness of this sandy unit may indicate a predominantly granular formation with good drainage characteristics and limited clay content. Overall, the geoelectric response suggests a transition from the relatively dry, lateritic near-surface material to a thick sandy subsurface unit. This resistivity suggests sand with minor fines and likely represents the first major aquifer unit. The fourth layer is interpreted as clayey silt with a thickness of 3.8373 m and a low resistivity of 13.056 Ωm at a depth of 22.212 m, acting as an aquitard separating upper and lower aquifer systems. The fifth layer comprises coarse sand with a thickness of 7.7158 m and a high resistivity of 1613.0 Ωm at a depth of 29.928 m.

Table 9. Apparent Resistivity Parameters of VES 5 with natural lithological identification

VES 5, LOCATION: LAT.: 4 52 40.45 LONG.: 6 22 36.96						
AB/2 (m)	AB/2 (m)	AB/2 (m)	AB/2 (m)	AB/2 (m)	AB/2 (m)	AB/2 (m)
1	0.3	78.6581	4.76	374.4126	174.41	Top soil
1.5	0.3	21.0859	10.84	228.5712	168.57	Lateritic soil
2	0.3	7.9493	23.3	185.2187	145.22	Clayey-silt
3	0.3	1.8166	51.8	94.09988	88.1	Silt
5	0.3	0.302	112	33.824	52.82	Silt
7	0.3	0.1476	242	35.7192		Silt
7	1	0.5606	71.3	39.97078	40.97	Silt
10	1	0.2788	156	43.4928	43.49	Silt
15	1	0.1542	338	52.1196	52.12	Silt
15	3	0.5837	17.5	10.21475		Silt
20	3	0.2949	161	47.4789	59.48	Silt
25	3	0.2119	290	61.451	61.45	Silt
30	3	0.1676	518	86.8168	63.82	Clayey-Silt
40	3	0.1138	518	58.9484	78.95	Clayey-Silt
45	3	0.0952	928	88.3456	88.35	Clayey-Silt
50	3	0.0807	1123	90.6261	90.63	Clayey-Silt
55	3	0.0693	1660	115.038	96.04	Clayey-Silt
60	3	0.0617	1660	102.422	102.42	Clayey-Silt
70	3	0.0457	2424	110.7768	110.78	Clayey-Silt
80	3	0.0338	2942	99.4396	121.44	Clayey-Silt
90	3	0.0366	2942	107.6772	138.68	Clayey-Silt
90	5	0.3886	1760	683.936		Fine Sand
100	5	0.0526	3134	164.8484	164.85	Clayey-Silt

Table 10. Apparent Resistivity and Resistivity Model VES 5

VES5 4 DATA					Resistivity model		
S/N	**AB/2 (m)**	**MN/2 (m)**	**Calculated Apparent Resistivity (Ωm)**	**Adjusted Resistivity (Ωm)**	**Resistivity (Ωm)**	**Thickness (m)**	**Depth (m)**
1	1	0.3	374.4126	174.41	183.13	1.5876	1.5876
2	1.5	0.3	228.5712	168.57	6.0169	0.74828	2.3358
3	2	0.3	185.2187	145.22	82.855	16.039	18.375
4	3	0.3	94.09988	88.1	13.056	3.8373	22.212
5	5	0.3	33.824	52.82	1613.0	7.7158	29.928
6	7	0.3	39.97078	40.97	18644	Undetermined	Undetermined
7	10	1	43.4928	43.49			
8	15	1	52.1196	52.12			
9	20	9	47.4789	59.48			
10	25	9	61.451	61.45			
11	30	9	86.8168	63.82			
12	40	9	58.9484	78.95			
13	45	9	88.3456	88.35			
14	50	9	90.6261	90.63			
15	55	9	115.038	96.04			
17	60	9	102.422	102.42			
18	70	9	110.7768	110.78			
19	80	9	99.4396	121.44			
20	90	9	107.6772	138.68			
21	100	25	164.8484	164.85			

This extremely high resistivity suggests clean coarse sand, gravel, or partially cemented sandstone, representing a high-quality aquifer with excellent groundwater yield potential. The sixth layer has a resistivity of 18,644 Ωm, though its thickness and depth extent remain undefined as shown in Tables 9-10 and Figs. 10-11.

5.2. Hydrogeological Interpretation

The VES results indicate that the shallow subsurface is predominantly composed of clay and silt, resulting in low permeability and limited groundwater potential. The main aquifer units occur at greater depths and consist mainly of medium- to coarse-grained sands. VES3 contains the shallowest and potentially most productive aquifer, occurring at approximately 15–18 m, while VES1 and VES2 show more favourable aquifer zones from about 25–28 m downward. Clay-rich layers identified at VES4 and VES5 function as aquitards and provide some degree of protection to the underlying groundwater.

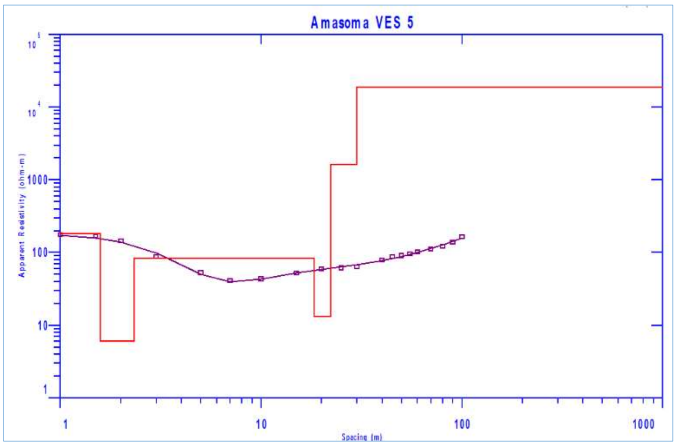

Fig. 10. Typical Hydrogeophysical Sounding Curve of VES 5

Overall, the most promising groundwater targets are the deeper sandy units, particularly those occurring below approximately 20–30 m. The identified aquifer system comprises a relatively shallow zone of medium sand and a deeper zone of coarse sand and gravel, with the deeper units showing greater groundwater potential and expected better water quality. Resistivity values of approximately 300–450 Ωm in the deeper formations are generally consistent with freshwater-bearing sands. However, resistivity interpretation alone cannot confirm groundwater quality; borehole drilling, pumping tests, and laboratory hydrochemical analyses are required for confirmation.

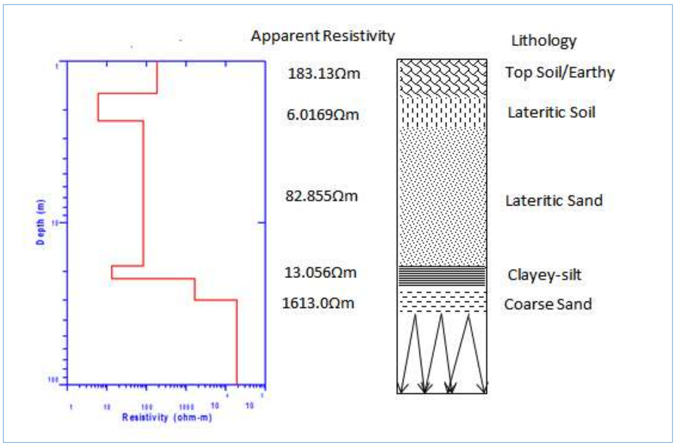

Fig. 11. Layered Inversion Model of VES 5

5.3. Geotechnical Interpretation

The upper 15–20 m of the study area is predominantly composed of highly compressible clay–silt formations characterized by low bearing capacity and high settlement potential under structural loads. Conversely, the presence of hard laterite and dry sand layers in the near-surface zone offers relatively superior bearing conditions. Consequently, shallow foundations at depths of approximately 1–2 m are feasible for light structures, contingent upon the implementation of adequate soil improvement and compaction techniques.

For heavy structures, pile foundations are recommended, with piles extending to approximately 25–40 m or deeper to reach dense sandy or gravelly formations and provide adequate load-bearing capacity. Seasonal groundwater fluctuations and perched water within clay layers should also be considered during foundation design. The heterogeneous nature of the Niger Delta sediments, together with possible tidal and salinity influences, may cause significant lateral variations in subsurface conditions. Overall, light structures may use improved shallow or raft foundations, whereas heavy structures should preferably be supported by deep piles terminating in competent dense sand or gravel layers.

Table 11. Summary of Resistivity Model

	Resistivity model			
VES No	**Resistivity (Ωm)**	**Thickness (m)**	**Depth (m)**	**Interpreted Lithology**
VES 1 DATA	67.144	0.86164	0.86164	Topsoil
	2245.1	0.3064	1.168	Lateritic soil
	503.55	1.3832	2.5512	Lateritic sand
	50.637	11.761	14.312	Silt
	170.98	6.8168	21.129	Clayey-Sand
	418.6	7.7963	28.925	Sand
	344.6	9.7058	38.631	Sand
	69.998	Undetermined	Undetermined	Clayey-Silt
VES 2 DATA	250.98	0.19169	0.19169	Topsoil
	6555.8	0.5138	0.70549	Lateritic soil
	1323.2	3.6974	4.4029	Lateritic Sand
	78.097	5.2925	9.6953	Silt
	228.61	4.8063	14.502	Clayey-Sand
	847.74	9.4831	23.985	Medium Sand
	1311.7	20.568	44.553	Coarse Sand
	249.26	Undetermined	Undetermined	Clayey-Sand
VES 3 DATA	78.576	0.49794	0.49794	Topsoil
	20.46	0.83267	1.3306	Silt
	30.585	2.1253	3.4559	Silt
	23.946	2.0924	5.5483	Silt
	1710.3	10.228	15.776	Coarse Sand
	2516.2	Undetermined	Undetermined	Coarse Sand
VES 4 DATA	108.77	2.1996	2.1996	Topsoil
	6.8462	0.53977	2.7394	Lateritic soil
	69.544	2.4911	5.2305	Silt
	6.3761	4.6233	9.8538	Silt
	1518.3	7.7336	17.589	Coarse Sand
	23879	Undetermined	Undetermined	Sandstone
VES 5 DATA	183.13	1.5876	1.5876	Topsoil
	6.0169	0.74828	2.3358	Lateritic soil
	82.855	16.039	18.375	Lateritic Sand
	13.056	3.8373	22.212	Clayey-Silt
	1613	7.7158	29.928	Coarse Sand
	18644	Undetermined	Undetermined	Sandstone

Table 12. Engineering/Geotechnical Summary

Depth Range	**Material**	**Suitability**
0–2 m	Lateritic topsoil	Suitable for shallow foundations
2–10 m	Thick clay	Poor bearing capacity; compressible
10–18 m	Coarse sand	Loose; compaction may be required
>18 m	Dense sand aquifer	Excellent bearing stratum for piles

5.4. Electrical Properties of Aquifer

5.4.1. Hydraulic Parameters

Electrical resistivity (ρ, Ωm) is a fundamental material property. Conductive media displaying low resistivity values include clays, saline/brackish water, and organic-rich wet sediments, whereas resistive media with high values encompass clean dry/coarse sands, gravels, and weathered bedrock. Longitudinal conductance (S = thickness × σ, Ω^{-1}) serves as a quantitative measure of overburden protective capacity; elevated S values typically signify a thicker or more conductive (clay-rich) protective layer that effectively attenuates the downward migration of contaminants, thereby enhancing the protection of the underlying aquifer.

Longitudinal conductance (S) quantifies the impermeability of a subsurface layer (Billing, 1972; Aladin, 2023).

The expressions for longitudinal conductance and transverse resistance are given as follows:

$$Si = h1/\rho 1 \quad (2)$$

$$Ti = \rho 1 \times h1 \quad (3)$$

For a sequence of horizontal, homogeneous and isotropic layers of resistivity ρ1 and thickness h1. *Equations 1* and *2* defined the Dar Zarrouk parameters (Maillet, 1947).

Longitudinal conductance (S):

$$S = \frac{h1}{p1} + \frac{h2}{p2} + \frac{h3}{p3} \dots\dots\dots\dots\dots\dots\dots\dots\dots \sum_{i=0}^{n} \frac{hi}{pi} \qquad (4)$$

Transverse resistance is proxy for aquifer potential: large TR often indicates a thick, resistive layer (clean sand/gravel) that can be a good aquifer when saturated.

For Transverse Resistance (TR):

$$TR = h1p1 + h2p2 + h3p3 \dots\dots\dots\dots\dots.. \sum_{i=0}^{n} hipi \qquad (5)$$

It illustrates the relationship between aquifer transmissivity and longitudinal conductance, as proposed by Todd (1980).

$$Tr = K\delta TR = Kh \qquad (6)$$

Where, Tr: aquifer transmissivity, K: hydraulic conductivity, σ: electrical conductivity (reciprocal of resistivity), TR: traverse resistance, S: longitudinal conductance and h: Aquifer thickness. The hydraulic conductivity (K) was determined using the equation given by Heigold et al. (1979).

$$K = 386.40Rrw^{0.93283} \qquad (7)$$

Where; K is the hydraulic conductivity and R_{rw} is the aquifer resistivity (Resistivity of the inferred aquiferous layer dervied from the interpreted curves).

VES1 shows the highest conductivity (δ) and highest longitudinal conductance (S = 0.01865) of the five points. That suggests a more conductive overburden (more clay/silt or saline influence) i.e., better near-surface attenuation/protective cover but less favourable as a coarse clean aquifer. Its TR is the lowest (≈3.3×10^3), so it has the weakest aquifer potential of the five locations (thin or less resistive aquifer material). VES2 has the largest TR (~2.7×10^4) and a very large thickness (20.568 m).

That combination (substantial thickness × moderate–high resistivity) points to the best aquifer prospect among the five a thick resistive body (likely clean sand/gravel) that would yield well if saturated. VES3 also has a large TR (~1.75×10^4) and very high resistivity (1710 Ωm). Although its thickness is smaller than VES2, the high resistivity suggests clean, well-sorted sand/gravel and therefore a good aquifer target (productive if saturated). VES4 and VES5 show moderate TR (1.17–1.24×10^4).

They likely represent reasonable aquifer units (coarse sand or gravel) but are less promising than VES2 and VES3 on the basis of TR and thickness. Longitudinal conductance S is relatively low at VES3–VES5 (≈0.0048–0.0060), indicating a thin or non-protective overburden at those sites i.e., aquifers there could be more vulnerable to surface contamination if present. VES1 and VES2 have higher S (0.0187 and 0.0157) and thus relatively better protective cover. VES2 (best overall: thick, high TR) and VES3 (high resistivity & good TR). They are the prime targets for test drilling and well development. VES4 and VES5 are acceptable but expect lower yields than VES2; consider them if VES2/3 are not accessible. VES1 for high-yield freshwater supply, it shows more conductive material near surface and a low TR (poor aquifer potential).

Table 13. Summary of Aquifer Electric Properties

Points	Resistivity (ρ, Ωm)	Thickness (m)	Conductivity (δ, Ωm^{-1})	Longitudinal Conductance (S, Ω^{-1})	Transverse Resistance (TR, Ωm^2)	Hydraulic Conductivity (K)	Transmissivity (Tr, m^2/day)
VES 1	418	7.7963	0.002392	0.01865	3258.853	1.386517	10.8097
VES 2	1311.7	20.568	0.000762	0.01568	26979.04	0.47712	9.813402
VES 3	1710.3	10.228	0.000585	0.00598	17492.95	0.372503	3.809965
VES 4	1518.3	7.7336	0.000659	0.00509	11741.92	0.416266	3.219238
VES 5	1613	7.7158	0.000620	0.00478	12445.58	0.393423	3.035572

Table 14. Aquifer protective capacity based on longitudinal conductance (after Oladapo and Akintorinwa, 2007) and aquifer classification according to transmissivity values (Offodile, 1983; Aladin, 2023).

S/N	Longitudinal Conductance (Ω^{-1})	Protective Capacity Rating	Transmissivity (m^2/day)	Classification of well
1	>10	Excellent	>500	High potential
2	5–10	Very good	50–500	Moderate potential
3	0.7–4.9	Good	5–50	Low potential
4	0.2–0.69	Moderate	0.5–5	Very low potential
5	0.1–0.19	Weak	<0.5	Negligible potential
6	<0.1	Poor		

Table 15. Estimated Aquifer Status of the study area

Resistivity	Thickness (m)	Longitudinal conductance S (Ω^{-1})	Protective Capacity Rating	Transmissivity Tr (m^2/day)	Classification of well
2758.6	40.873	0.014817	Poor	9.747561	Very Low potential
1267.9	42.554	0.033563	Poor	20.95688	Low potential
4199.9	29.241	0.006962	Poor	4.711545	Very Low potential
7215.6	18.349	0.002543	Poor	1.784585	Very Low potential
1823.1	73.345	0.040231	Poor	25.74102	Low Potential

However, VES1's higher S suggests the subsurface there is more clayey/saline and might provide some protection to deeper units but do not expect good yields without going much deeper or targeting lateral continuity with better units. Because S is low at VES3 to VES5, those aquifers may be less protected from surface infiltration, implement good sanitary borehole design (casing/ grouting) and test for water quality (salinity, organics) after drilling as shown in Table 13.

5.4.2. Aquifer Electric Properties

High resistivity (418–1710 Ωm) across VES 1–5 indicates coarse-grained sandy formations with low clay content. The layer thickness (7–20 m) suggests a significant saturated zone, though thickness varies across locations. All VES points likely represent unconfined to semi-confined sandy aquifers. Conductivity values range from 0.000585–0.002392 Ωm^{-1}. These values are typical for freshwater-bearing sands and confirm low salinity.

The aquifers contain fresh groundwater with minimal ionic concentration. The VES Longitudinal Conductance (S) values range from 0.00478 to 0.01865 Ω^{-1}, which indicates that S is very low in the study area. This falls into the Poor Protective Capacity category. This indicates that the aquifers lack thick clayey protective layers and are therefore highly vulnerable to contamination, especially from surface pollutants, septic systems, and industrial activities.

The TR values range from 3,258 to 26,979 Ωm^2, which indicates that high TR indicates thick, resistive, water-bearing sands with good groundwater movement. VES 2 > VES 3 > VES 5 > VES 4 > VES, it shows increasing aquifer potential, with VES 2 having the best groundwater storage capacity. The hydraulic conductivity (K) ranges from 0.372 – 1.386 m/day. These values indicate medium permeability, typical of fine to medium sands. This indicates that the groundwater movement is moderate, not extremely fast, which is good for yield but increases contamination risk due to poor protective capacity. Transmissivity varies from 3.03 – 10.80 m^2/day, its aquifer productivity is classified as low to good. The best groundwater yield is at VES 1 and VES 2, while VES 3–5 have lower groundwater productivity as shown in Tables 13, 14 and 15.

6. Discussion

The geoelectrical parameters obtained from VES1–VES5 demonstrate noticeable spatial variations in the electrical and hydraulic properties of the aquifer system beneath Amassoma–Tombia. The interpreted aquifer resistivity values range from approximately 418 to 1,710 Ωm, while aquifer thickness varies between about 7.0 and 20.57 m. The relatively high resistivity values generally indicate the presence of predominantly sandy and coarse-grained formations with limited clay content. Comparable resistivity characteristics have been reported in other parts of the Niger Delta. For example, Mgbolu et al. (2019) recorded aquifer resistivity values ranging from 470.84 to 2,697.70 Ωm, with an average of approximately 1,289 Ωm, in parts of Ndokwa, Delta State. The similarity between the reported values and those obtained in Amassoma–Tombia suggests that the aquifer materials in the study area are broadly consistent with the sandy to sandy-clayey sediments characteristic of the Benin Formation and related Niger Delta deposits.

The aquifer thicknesses determined in the present investigation, ranging from approximately 7.0 to 20.57 m, are generally smaller than the average thickness of 42.52 m reported by Mgbolu et al. (2019) in Ndokwa. The relatively thinner aquifer units in Amassoma–Tombia may limit groundwater storage and potential yield at some locations. However, the combined consideration of aquifer resistivity and thickness reveals the presence of locally favourable groundwater-bearing formations, particularly at VES2 and VES3.

TR values across the study area range from approximately 3,258 to 26,979 Ωm^2. VES2 records the highest TR value of approximately 26,979 Ωm^2, resulting from the combined effect of its relatively high resistivity and substantial aquifer thickness. On this basis, VES2 represents the most favourable groundwater prospect among the investigated locations. VES3, with a TR value of approximately 17,500 Ωm^2 and an aquifer resistivity of about 1,710 Ωm, constitutes the second most favourable prospect. VES4 and VES5 display intermediate

TR values and may therefore be regarded as moderately favourable groundwater targets, whereas VES1, with the lowest TR value of approximately 3,258 Ωm^2, represents the least favourable location based on this parameter. The variation in TR highlights differences in the potential storage and transmissive characteristics of the aquifer units and supports its use as an important indicator of groundwater potential in sedimentary environments. The longitudinal conductance (S) values range from approximately 0.00478 to 0.01865 mho. All five VES locations fall within the poor protective-capacity class because their values are substantially lower than the 0.10 mho threshold. This indicates that the overlying materials may be insufficiently thick or lack continuous clay-rich layers capable of effectively restricting the downward movement of contaminants into the aquifer. The result is consistent with previous investigations within the Niger Delta. Akana et al. (2016), in Yenagoa, Bayelsa State, reported poor protective capacity in 33.3% of their study area and weak protective capacity in 53.3%.

Similarly, Oki and Didei (2024), in Ogbia Local Government Area of Bayelsa State, identified areas of poor aquifer protective capacity and emphasised the vulnerability of shallow groundwater systems to surface-derived contaminants. Mgbolu et al. (2019) also reported predominantly poor to weak protective capacity in parts of Ndokwa, Delta State. Although VES1 exhibits the highest longitudinal conductance value of 0.01865 mho among the five locations, this should not be interpreted as evidence of adequate protective capacity. Rather, it represents relatively greater conductance within the investigated area. Since the value remains substantially below 0.10 mho, VES1 is still classified as having poor protective capacity. Its comparatively higher conductance may indicate a greater contribution from conductive or clay-rich materials within the overburden, but the magnitude is insufficient to provide effective protection against contaminant migration into the underlying aquifer.

The estimated hydraulic conductivity values range from 0.372 to 1.386 m/day, indicating relatively moderate permeability within the investigated aquifer units. These values are generally compatible with fine- to medium-grained sands or heterogeneous sandy formations. However, they are considerably lower than the hydraulic conductivity values of approximately 25.69–28.92 m/day reported by Mgbolu et al. (2019) for parts of Ndokwa. This difference may be attributed to variations in grain size, sediment sorting, clay content, lithological heterogeneity, and other hydraulic characteristics that influence groundwater movement within the Amassoma–Tombia aquifer system.

The estimated transmissivity values range from approximately 3.03 to 10.80 m²/day, indicating relatively low groundwater-transmitting capacity when compared with values reported from some other parts of the Niger Delta. Mgbolu et al. (2019), for example, obtained transmissivity values ranging from 129.54 to 4,181.31 m²/day in parts of Ndokwa. The comparatively low transmissivity values obtained in Amassoma–Tombia suggest that, although favourable sandy aquifer units occur locally, their ability to transmit substantial volumes of groundwater may be limited.

An integrated evaluation of the geoelectrical parameters identifies VES2 as the most favourable location for exploratory borehole development. Its high ranking is supported by the combination of the highest TR value, considerable aquifer thickness, and relatively high aquifer resistivity. VES3 represents the second most promising location due to its high resistivity and relatively high TR. VES4 and VES5 constitute moderate groundwater prospects, whereas VES1 is considered the least favourable based primarily on its low TR value. However, these rankings represent geophysical estimates of relative groundwater potential and should not be regarded as definitive predictions of borehole yield. Further confirmation should be obtained through borehole lithological logging, pumping tests, and groundwater-quality analyses. The relatively high aquifer resistivity values suggest the dominance of sandy formations and may be indicative of favourable freshwater conditions. Nevertheless, resistivity measurements alone cannot conclusively establish groundwater salinity or potability because subsurface resistivity is influenced by several factors, including lithology, clay content, porosity, degree of saturation, and pore-water chemistry. Consequently, hydrochemical analysis of groundwater samples is required to establish the actual salinity, chemical composition, and suitability of the groundwater for domestic, agricultural, or other uses before extensive groundwater development.

The uniformly poor protective capacity identified at all five VES locations has important implications for groundwater management in Amassoma–Tombia. The shallow aquifer system is potentially vulnerable to contamination from septic systems, inadequately managed waste-disposal sites, agricultural activities, petroleum-related operations, and other anthropogenic sources. This finding agrees with previous Niger Delta investigations linking low longitudinal conductance with increased aquifer vulnerability to surface-derived contaminants. Accordingly, groundwater development within the study area should incorporate appropriate borehole-protection measures, including adequate casing, sanitary sealing, and proper grouting. Potential sources of contamination should also be appropriately separated from groundwater abstraction points, while periodic groundwater-quality monitoring should be implemented to identify and manage contamination risks at an early stage.

7. Conclusion

The findings of the study are consistent with previous investigations in Bayelsa State and the wider Niger Delta, confirming that groundwater-bearing formations are mainly medium- to coarse-grained sands interbedded with clay and silt. The Amassoma–Tombia aquifer system is heterogeneous, with aquifer resistivity ranging from 418–1,710 Ωm and thickness from 7.0–20.57 m. Based on transverse resistance, VES2 is the most favourable groundwater prospect, followed by VES3, while VES4 and VES5 have moderate potential and VES1 is the least favourable. All five VES locations have poor protective capacity, with longitudinal conductance values of 0.00478–0.01865 mho, indicating limited protection of the aquifers from surface-derived contaminants. The study therefore demonstrates that high groundwater potential does not necessarily imply low vulnerability, as favourable aquifer units may still lack adequate protective overburden. Overall, the research provides useful baseline information for groundwater exploration, borehole siting, aquifer vulnerability assessment, and environmental management in Amassoma–Tombia. It recommends integrating VES interpretation with borehole logging, pumping tests, hydrochemical analysis, proper borehole sealing, waste management, and regular groundwater monitoring to support sustainable groundwater development in the Niger Delta.

8. Recommendations

Based on the VES results, boreholes should generally be drilled to depths of about 45–70 m to penetrate productive aquifer units, with well screens installed within the identified high-resistivity sandy layers and away from clayey horizons. Proper casing and grouting are essential to protect the deeper aquifers from contamination, while pumping tests and water quality analyses should be carried out before full-scale development. The study area for VES 1 requires drilling to approximately 45–60 m, potentially extending to 70–80 m for greater yield assurance, whereas VES 2 should reach at least 30–45 m, preferably 50–70 m. For VES 3, a drilling depth of 45–70 m is recommended. Pilot boreholes should also be considered in areas containing thick and laterally continuous resistive sand units. Geotechnically, the shallow clay-dominated zone is unsuitable for heavy foundations, while the dense sands below about 15 m provide better bearing capacity, with pile foundations extending to approximately 18–20 m recommended for heavy structures.

References

Akana, T.S., George, G.C., and Oki, O.A., 2016. Aquifer vulnerability assessment in some towns of Yenagoa, South-

South Nigeria. Science and Technology 6 (1), 15-23. https://doi.org/10.5923/j.scit.20160601.03.

Atakpo, E.A., Ayolabi, E.A., 2009. Evaluation of aquifer vulnerability and the protective capacity in some oil producing communities of western Niger Delta. Environment Systems and Decisions 29 (3), 310-317. https://doi.org/10.1007/s10669-008-9191-3.

Babasola, O.V., Nmoka, G.I., 2025. Assessment of groundwater potential and vulnerability using electrical resistivity techniques: A case study of the FUPRE Campus and Agbarho Axis, Delta State, Nigeria. Hydrology 13 (1), 22-33. https://doi.org/10.11648/j.hyd.20251301.13.

Billing, M.P., 1972. Structural geology. Prentice Hall.

Bunonyo, T.Y., Adanya, J.G., Omamode, M.E., 2022. Geoelectrical and hydrochemical assessment of groundwater potential in Tantua-Amassoma, Bayelsa State, Nigeria. Water Resources 32, 68-73.

Chinemelu, E.S., Adeoye, S.O., 2022. Groundwater vulnerability assessment in Osubi Metropolis, Niger Delta, Nigeria using DRASTIC and GIS techniques. Journal of Geography. Environment and Earth Science International 26 (6), 1-10. https://doi.org/10.9734/jgeesi/2022/v26i630353.

Chinyem, F.I., Abriku, E.O., Ovwamuedo, G., Salami, S.A., Igili, C.O., Nwugha, V.N., Osieke, J.O., 2026. Hydrogeophysical investigation of groundwater potential, lithological strata and aquifer vulnerability in parts of Delta North District, Nigeria. FUDMA Journal of Sciences 10 (2), 375-389. https://doi.org/10.33003/fjs-2026-1002-4482.

Aladin, E.A., Salami, S., Akperi, O., 2023. Determination of groundwater status and characteristics of the subsurface layers using electrical vertical sounding (VES) and dipole–dipole configuration at Osasogie Road and environs, Southern Nigeria. International Journal of Earth Sciences Knowledge and Applications 5 (2), 282-292.

Eyankware, M.O., Osisanya, O.W., Akakuru, O.C., Odesa, G.E., Okanigbuan, P.N., Ukor, K.P., Esi, E.O., Chukwusa, F.O., 2025. Depiction of aquifer potential and vulnerability mapping: A case study of Delta North, Southern Nigeria, using geophysical approach. Discovery Nature 2 (4), e8dn3121. https://doi.org/10.54905/disssi.v2i4.e8dn3121.

Heigold, P.C., Gilkeson, R.H., Cartwright, K., Reed, P.C., 1979. Aquifer transmissivity from surface electrical methods. Ground Water 17 (4), 338-345.

Maillet, R., 1947. The fundamental equations of electrical prospecting. Geophysics 12 (4), 527-556.

Mgbolu, C.C., Obiadi, I.I., Obiadi, C.M., Okolo, C.M., Irumhe, P.E., 2019. Integrated groundwater potentials studies, aquifer hydraulic characterisation and vulnerability investigations of parts of Ndokwa, Niger Delta Basin, Nigeria. Solid Earth Sciences 4 (3), 102-112. https://doi.org/10.1016/j.sesci.2019.06.002.

Offodile, M.I., 1983. The occurrence and exploitation of groundwater in the Nigerian Basement Complex. Mining Geology 20 (3), 131-146.

Ogwu, D.A., Molua, O.C., Irunkwor, T.C., Ataman, J.O., Edobor, M., Ukpene, A.O., Egheneji, A.O., 2024. Geo-electrical assessment of groundwater potentials and vulnerability to contaminants for sustainable water management at Utue-Ogume, Delta State, Nigeria. Geology and Geophysics of Russian South 14 (2), 21-102. https://doi.org/10.46698/VNC.2024.47.37.006.

Oki, A.O., Didei, I.S., 2024. Investigation of aquifer protective capacity using electrical resistivity method in Federal University Otuoke Campus, Ogbia LGA of Bayelsa State, Nigeria. Pakistan Journal of Geology 8 (2), 135-140. https://doi.org/10.26480/pjg.02.2024.135.140.

Olorunfemi, M.O., Fasuyi, S.A., 1993. Aquifer types and the geoelectric/hydrogeologic characteristics of part of the central basement terrain of Nigeria. Journal of African Earth Sciences 16 (3), 309-317. https://doi.org/10.1016/0899-5362(93)90051-Q.

Reyment, R.A., 1965. Aspects of the geology of Nigeria. Ibadan University Press.

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

Todd, D.K., 1980. Groundwater hydrology. John Wiley & Sons.

Todd, D.K., 2004. Groundwater hydrology (2nd ed.). John Wiley & Sons, New York.