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Geophysical evaluation of hydrocarbon-impacted soils using electrical resistivity methods in Eleme, Rivers State, Nigeria

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Abstract

This study presents a hydrogeophysical evaluation of subsurface conditions in Eleme, Rivers State, Nigeria, using electrical resistivity sounding to characterise aquifer systems and assess possible environmental influence on near-surface soils. Vertical Electrical Sounding (VES) employing the Schlumberger electrode configuration was conducted to delineate subsurface lithology, determine aquifer geometry, and identify conductive anomalies that may reflect lithological variation or environmental alteration in this industrialised Niger Delta setting. Apparent resistivity values ranged approximately from 20 Ωm to over 600 Ωm , indicating heterogeneous subsurface conditions dominated by clay, sandy clay, fine sand, and coarse sand formations consistent with coastal plain sand deposits. Near-surface conductive zones were identified within the upper 4-6 m and are interpreted primarily as clay-rich or moisture-saturated layers, although possible environmental influence cannot be excluded without supporting hydrochemical or geochemical data. Aquifer units were delineated within moderately high resistivity sandy formations at depths between approximately 16 m and 48 m, with aquifer thickness ranging from about 24 m to 29 m. Derived Dar Zarrouk parameters indicate moderate to high groundwater potential, while longitudinal conductance values suggest weak to moderate aquifer protective capacity, implying some vulnerability to contaminant migration where overburden protection is limited. The resistivity results indicate favourable groundwater occurrence within the study area but emphasise the need for integrated hydrogeophysical, hydrochemical, and environmental investigations to ensure reliable groundwater development and environmental protection in hydrocarbon-influenced terrains of the Niger Delta.

Keywords: Electrical resistivity sounding, hydrogeophysics, aquifer characterisation, Dar Zarrouk parameters, groundwater potential, environmental geophysics, Niger Delta

1. Introduction

Hydrocarbon exploration, production, and associated industrial activities in the Niger Delta have contributed significantly to environmental challenges, particularly soil and groundwater contamination. Eleme, Rivers State, is one of the industrial hubs within this region, hosting petroleum refineries, petrochemical industries, and extensive oil-related infrastructure. These activities have increased concerns regarding hydrocarbon pollution, soil degradation, and potential impacts on groundwater resources and ecosystem health. Environmental assessments in the Niger Delta have consistently highlighted the presence of hydrocarbons, heavy metals, and related pollutants in soils, sediments, and surface waters due to industrial emissions, spills, and gas flaring activities (Aghanwa *et al.*, 2025; Okpoji *et al.*, 2025) [3, 13]. Conventional environmental assessment methods, although effective, are often expensive, time-consuming, and spatially limited. Consequently, geophysical techniques have gained prominence as non-invasive tools for detecting subsurface contamination and evaluating soil and groundwater conditions. Electrical resistivity methods, in particular, have proven useful for characterising subsurface lithology, identifying conductive anomalies, and assessing environmental impacts because the electrical properties of soils are strongly influenced by fluid saturation, clay

content, and contaminant presence (Dewashish *et al.*, 2014)^[6]. Variations in resistivity can therefore provide indirect indicators of hydrocarbon-impacted soils, although geophysical data typically require validation through geochemical analysis for definitive confirmation (Asfahani, 2013)^[4].

In sedimentary environments such as the Niger Delta, the distribution of coastal plain sands interbedded with clay layers significantly influences contaminant migration, groundwater occurrence, and resistivity response. Clay-rich formations often act as confining or protective layers, while sandy formations may facilitate contaminant transport due to higher permeability. Geoelectric investigations have demonstrated that resistivity techniques are effective in delineating aquifer systems, evaluating groundwater vulnerability, and assessing environmental risk in such sedimentary terrains (Okiongbo & Akpofure, 2012; Ikpe *et al.*, 2025)^[12, 9]. Multi-criteria approaches combining geophysical and geological parameters have further enhanced the prediction of groundwater potential and vulnerability in complex environments (Adiat *et al.*, 2013)^[2]. Environmental geochemical studies within the Niger Delta have also reported hydrocarbon accumulation in sediments, atmospheric deposition from gas flaring, and pollutant transport into surface and groundwater systems, emphasising the need for integrated monitoring strategies (Ogbaji *et al.*, 2025; Okagbare *et al.*, 2025)^[10, 11]. Such findings underscore the importance of applying geophysical methods alongside environmental assessment to understand contaminant distribution and protect water resources.

This study, therefore, applies electrical resistivity methods to evaluate hydrocarbon-impacted soils in Eleme, Rivers State, with the aim of characterising subsurface lithology, identifying conductive anomalies potentially associated with environmental impact, and assessing implications for groundwater vulnerability.

2. Materials and Methods

2.1 Study Area and Geological Setting

The investigation was conducted in Eleme Local Government Area, Rivers State, Nigeria, within the eastern Niger Delta sedimentary basin. The area is underlain predominantly by coastal plain sands of the Benin Formation interbedded with clay and sandy clay units. These unconsolidated sediments influence groundwater occurrence, subsurface electrical properties, and contaminant migration pathways. The region is characterised by significant industrial and petroleum activities, making it environmentally sensitive with potential hydrocarbon-related soil alteration. High rainfall and shallow groundwater conditions further enhance infiltration processes, which may influence geoelectric responses.

2.2 Geophysical Method and Survey Design

The electrical resistivity method was adopted for subsurface investigation because of its effectiveness in delineating lithological boundaries, aquifer systems, and conductive anomalies. Vertical Electrical Sounding (VES) using the Schlumberger electrode configuration was employed due to its suitability for detecting vertical resistivity variations and deeper subsurface structures in sedimentary terrains. The configuration involves progressive expansion of current electrode spacing while maintaining relatively small potential electrode spacing, enabling improved depth penetration and vertical resolution.

2.3 Field Data Acquisition

Field measurements were carried out using a digital terrameter, stainless steel electrodes, insulated cables, measuring tapes, a hammer, and a Global Positioning System (GPS) receiver for spatial referencing. Current was introduced into the ground through two outer electrodes (A and B), while the potential difference was measured between two inner electrodes (M and N). Apparent resistivity values were computed automatically by the resistivity meter based on measured voltage, injected current, and electrode spacing. The apparent resistivity (ρ_a) is expressed as:

$$\rho_a = K \times (\Delta V / I)$$

where ρ_a is the apparent resistivity, ΔV is the measured potential difference, I is the injected current, and K is the geometric factor determined by electrode spacing. For the Schlumberger array, the geometric factor is given by:

$$K = \pi[(AB/2)^2 - (MN/2)^2] / MN$$

Electrode spacing was progressively increased to investigate deeper subsurface layers, and sounding stations were selected to minimise interference from buried infrastructure and cultural noise.

2.4 Data Processing and Interpretation

Apparent resistivity values were plotted against electrode spacing on log-log graphs to generate sounding curves. Preliminary interpretation involved manual curve matching with standard master curves, followed by computer-assisted inversion to determine true layer resistivity and thickness. The inversion process involved iterative adjustment of model parameters until acceptable root-mean-square error levels were achieved between observed and calculated data. Resulting geoelectric curve types, such as H, KH, and K curves, were used to infer subsurface layering typical of sedimentary environments.

2.5 Lithological and Aquifer Characterisation

Lithological interpretation was based on established resistivity ranges within the Niger Delta sedimentary terrains. Low resistivity values generally indicate clay-rich or conductive formations, moderate values correspond to sandy clay or fine sand units, while higher resistivity values are associated with coarse sand or gravel formations with higher permeability. Aquifer depth, thickness, and confinement conditions were inferred from interpreted layer parameters. Electrical anomalies observed in near-surface layers were interpreted cautiously as conductive zones potentially influenced by clay content, moisture, or environmental alteration, recognising that resistivity data alone cannot confirm hydrocarbon contamination without supporting geochemical analysis.

2.6 Dar Zarrouk Parameter Estimation

Hydrogeophysical parameters were derived from interpreted layer resistivity and thickness using standard Dar Zarrouk relationships. Longitudinal conductance (S), which reflects aquifer protective capacity, was calculated as:

$$S = \sum(h / \rho)$$

Where h is the layer thickness and ρ is the layer resistivity. Higher longitudinal conductance values indicate better

protective capacity of the overburden against contaminant infiltration.

Transverse resistance (T), used as an indicator of aquifer potential, was calculated as:

$$T = \Sigma(h \times \rho)$$

Higher transverse resistance values generally correspond to thicker and more resistive aquifer units with greater groundwater potential. However, these values were interpreted qualitatively and not directly equated to transmissivity without supporting hydrogeological calibration.

2.7 Quality Assurance and Error Control

To ensure data reliability, electrodes were properly grounded to minimise contact resistance, repeated measurements were taken at each station, and instrument calibration was verified prior to data acquisition. Survey locations were selected to avoid interference from pipelines, metallic structures, and electrical installations. Data inversion included monitoring of RMS error values to ensure acceptable model fit and geological plausibility.

2.8 Data Analysis and Presentation

Interpreted resistivity values, aquifer geometry, Dar Zarrouk parameters, and environmental interpretations were presented in tabular form for clarity. Comparative analysis of resistivity distribution, aquifer characteristics, protective capacity, and conductive anomalies was conducted to evaluate

groundwater potential and possible environmental influence on subsurface conditions. The interpretation approach emphasised geophysical consistency while acknowledging limitations associated with resistivity-based environmental assessment.

3. Results

Table 1 presents the interpreted geoelectric layer parameters derived from vertical electrical sounding, including curve types, layer thicknesses, resistivity values, and inferred lithology. The curve types observed (H, KH, and K) indicate variations in subsurface resistivity structure typical of sedimentary terrains in the Niger Delta. The first layer shows resistivity values between about 20 Ω m and 40 Ω m with thickness ranging from approximately 4 m to 6 m, suggesting clayey or silty topsoil with relatively high conductivity. Such conductive zones may reflect clay content, moisture saturation, or possible soil alteration associated with environmental impact, although confirmation requires geochemical analysis. The second layer generally exhibits resistivity values between about 95 Ω m and 180 Ω m with a thickness ranging from approximately 12 m to 14 m, corresponding to sandy clay or fine sand formations with moderate permeability. The third layer shows higher resistivity values between approximately 420 Ω m and 620 Ω m with thickness between about 24 m and 29 m, interpreted as coarse sand or gravel formations representing the principal aquifer units. Overall, the table confirms a multilayered subsurface structure consisting of conductive overburden overlying more permeable aquifer materials.

Table 1: Apparent Resistivity Values, Layer Parameters and Interpreted Subsurface Lithology

Station	Curve Type	Layer	Thickness (m)	Resistivity (Ω m)	Interpreted Lithology	Hydrogeophysical Interpretation
ERS 1	H	1	5	28	Clayey topsoil	Conductive near-surface layer; possible impacted soil
		2	13	95	Sandy clay	Semi-permeable overburden
		3	24	420	Coarse sand	Main aquifer zone
ERS 2	KH	1	6	32	Silty clay	Conductive surface layer
		2	14	120	Fine sand	Transitional aquifer layer
		3	25	510	Coarse sand	Productive aquifer
ERS 3	H	1	4	20	Clayey soil	Strong conductive anomaly
		2	12	110	Sandy clay	Semi-permeable layer
		3	24	470	Coarse sand	Aquifer unit
ERS 4	K	1	5	40	Clay/silt	Moderately conductive overburden
		2	14	180	Fine sand	Semi-permeable formation
		3	29	620	Coarse sand/gravel	Highly permeable aquifer

Table 2 summarises aquifer depth, thickness, and inferred confinement conditions across the investigated stations. Aquifer tops occur between approximately 16 m and 20 m depth, while aquifer bases range between about 40 m and 48 m. This indicates moderate groundwater occurrence depth consistent with sedimentary aquifer systems in coastal regions. Aquifer thickness varies from approximately 24 m to 29 m, suggesting adequate groundwater storage potential for

sustainable abstraction. Confinement conditions are influenced by the nature of the overburden; stations with thicker clay or sandy clay layers show confined aquifer tendencies, whereas thinner or moderately permeable overburden suggests semi-confined conditions. These characteristics indicate generally favourable groundwater potential while highlighting some vulnerability to surface influences.

Table 2: Aquifer Depth, Thickness and Confinement Condition

Station	Depth to Aquifer Top (m)	Depth to Aquifer Base (m)	Aquifer Thickness (m)	Confinement Basis
ERS 1	18	42	24	Clay overburden present (semi-confined)
ERS 2	20	45	25	Thick clay cover (confined)
ERS 3	16	40	24	Moderate clay cover (semi-confined)
ERS 4	19	48	29	Sandy clay cover (confined tendency)

Table 3 provides a classification of electrical resistivity ranges in relation to subsurface conditions. Resistivity values below about 50 Ω m are associated with clay-rich soils or

conductive pore fluids, which may indicate soil alteration or environmental impact but cannot be conclusively attributed to hydrocarbon contamination without supporting

geochemical evidence. Values between approximately 50 Ωm and 150 Ωm correspond to sandy clay or fine sand formations that represent transitional hydrogeological zones with moderate permeability. Resistivity values between about 150 Ωm and 400 Ωm indicate saturated sandy formations that may function as aquifer units. Values exceeding

approximately 400 Ωm are generally associated with coarse sand or gravel formations that exhibit higher permeability and groundwater productivity. This classification highlights lithological control on resistivity distribution and groundwater occurrence.

Table 3: Electrical Anomaly Classification

Resistivity Range (Ωm)	Likely Subsurface Condition	Interpretation Caution
< 50	Clayey soil or conductive pore fluid	May indicate impacted soil, but requires geochemical validation
50-150	Sandy clay / fine sand	Transitional hydrogeological zone
150-400	Saturated sand	Possible aquifer formation
> 400	Coarse sand/gravel	Highly permeable aquifer units

Table 4 summarises the overall hydrogeophysical characteristics of the study area. Resistivity values range from approximately 20 Ωm to 620 Ωm , indicating heterogeneous subsurface lithology dominated by clay, sandy clay, fine sand, and coarse sand formations. Aquifers occur at moderate depths between about 16 m and 48 m, with thickness ranging from approximately 24 m to 29 m,

suggesting favourable groundwater storage capacity. Overburden resistivity values between approximately 20 Ωm and 180 Ωm indicate the presence of clay and sandy clay materials that may provide some natural protection to the aquifers. Overall groundwater potential is interpreted as moderate to high, supporting the feasibility of groundwater development within the area.

Table 4: Summary Hydrogeophysical Characteristics

Parameter	Observed Range	Interpretation
Resistivity Values	20-620 Ωm	Variable subsurface lithology
Aquifer Depth	16-48 m	Moderate groundwater occurrence
Aquifer Thickness	24-29 m	Adequate groundwater storage
Overburden Resistivity	20-180 Ωm	Clay to sandy clay cover
Groundwater Potential	Moderate-High	Suitable for borehole development

Table 5 presents longitudinal conductance values calculated from the overburden layers to assess aquifer protective capacity. Conductance values range approximately from 0.17 Siemens to 0.20 Siemens, indicating weak to moderate protective capacity. These values suggest that while some clay-rich overburden exists to provide protection against

contaminant migration, the aquifers may still be susceptible to environmental impacts, particularly where overburden thickness is limited or where permeable sandy clay layers dominate. The results emphasise the need for groundwater quality monitoring in areas subject to potential environmental contamination.

Table 5: Longitudinal Conductance (Protective Capacity Assessment)

Station	Overburden Thickness (m)	Average Resistivity (Ωm)	Conductance S (Siemens)	Protective Capacity
ERS 1	18	90	0.20	Weak-moderate
ERS 2	20	100	0.20	Moderate
ERS 3	16	95	0.17	Weak
ERS 4	19	110	0.17	Weak-moderate

Table 6 shows transverse resistance values derived from aquifer layer resistivity and thickness, serving as an indicator of aquifer potential. Values range approximately from 10,080 Ωm^2 to 17,980 Ωm^2 , reflecting moderate to very high aquifer productivity. Higher transverse resistance values are associated with thicker and more resistive coarse sand

formations, which typically exhibit higher permeability and groundwater yield potential. These findings suggest favourable hydrogeological conditions for groundwater exploitation, although confirmation through borehole yield or pumping tests would provide additional validation.

Table 6: Transverse Resistance (Indicator of Aquifer Potential)

Station	Aquifer Thickness (m)	Resistivity (Ωm)	Transverse Resistance (Ωm^2)	Aquifer Productivity Indicator
ERS 1	24	420	10080	Moderate-high potential
ERS 2	25	510	12750	High potential
ERS 3	24	470	11280	Moderate-high potential
ERS 4	29	620	17980	Very high potential

Table 7 illustrates the depth distribution of conductive near-surface zones identified from resistivity data. These zones occur within the upper 0 m to 6 m depth range with a thickness between approximately 4 m and 6 m. Such conductive anomalies may reflect clay-rich soils, moisture accumulation, or possible environmental impact. However,

electrical resistivity data alone cannot definitively confirm hydrocarbon contamination; complementary geochemical analysis would be necessary for confirmation. The shallow depth of these zones suggests potential interaction between surface processes and subsurface conditions.

Table 7: Electrical Anomaly Depth Distribution

Station	Depth of Conductive Zone (m)	Thickness (m)	Interpretation
ERS 1	0-5	5	Surface conductive anomaly
ERS 2	0-6	6	Possible impacted soil layer
ERS 3	0-4	4	Strong conductive anomaly
ERS 4	0-5	5	Conductive overburden

Table 8 provides an integrated hydrogeophysical interpretation of the study area. Conductive surface layers indicate possible soil alteration or environmental influence, while deeper moderate to high resistivity zones correspond to sandy aquifer formations with favourable groundwater potential. Protective capacity ranges from weak to moderate,

indicating some vulnerability to contamination. Therefore, groundwater development prospects appear favourable, although environmental monitoring and hydrochemical assessment are recommended to ensure sustainable groundwater utilisation and protection.

Table 8: Overall Hydrogeophysical Interpretation

Factor	Observation	Implication
Surface Layer	Low resistivity conductive zones	Possible soil alteration; confirmation requires geochemical analysis
Aquifer Units	Moderate to high resistivity sands	Potential groundwater resources
Protective Capacity	Weak to moderate	Some vulnerability to contamination
Groundwater Suitability	Generally favourable	Further hydrochemical validation is recommended

4. Discussion

The resistivity investigation carried out in Eleme revealed considerable subsurface variability consistent with sedimentary environments typical of the Niger Delta basin. Apparent resistivity values ranging from about 20 Ωm to over 600 Ωm reflect alternating clay, sandy clay, fine sand, and coarse sand formations. Such heterogeneity is expected in coastal plain sand deposits and has been widely reported in resistivity studies of sedimentary terrains where lithological variability strongly controls groundwater occurrence and electrical response (Asfahani, 2013) ^[4]. Electrical resistivity tomography studies have similarly demonstrated that variations in subsurface resistivity often reflect changes in grain size distribution, fluid saturation, and mineral composition rather than a single environmental factor (Dewashish *et al.*, 2014) ^[6].

The near-surface conductive zones identified in this study, characterised by relatively low resistivity values generally below 50 Ωm , likely correspond to clay-rich or moisture-saturated soils. While such conductive anomalies may indicate environmental alteration or possible hydrocarbon influence, resistivity data alone cannot conclusively confirm contamination without geochemical validation. Previous environmental assessments in hydrocarbon-producing regions of the Niger Delta have shown that industrial activities can affect soil and water quality, although electrical conductivity responses often reflect a combination of lithological and environmental factors (Okpoji *et al.*, 2025) ^[13]. Studies of hydrocarbon-contaminated sediments in the region have also highlighted seasonal variability and environmental transport processes that may influence subsurface geophysical signatures (Ogbaji *et al.*, 2025) ^[10].

The moderate resistivity values observed in intermediate layers, typically between about 95 Ωm and 180 Ωm , were interpreted as sandy clay or fine sand formations. These transitional lithologies commonly act as semi-permeable zones capable of storing limited groundwater while also serving as partial confining layers. Multi-criteria groundwater evaluation approaches integrating geoelectric and geological parameters have shown that such transitional formations significantly influence groundwater potential and aquifer vulnerability (Adiat *et al.*, 2013) ^[2]. In sedimentary terrains, the presence of sandy clay overburden often

determines the degree of aquifer confinement and protective capacity.

Higher resistivity values exceeding approximately 400 Ωm were interpreted as coarse sand or gravel formations representing the principal aquifer units. These formations typically exhibit higher porosity and permeability, making them favourable for groundwater storage and transmission. Resistivity-based aquifer characterisation studies have consistently demonstrated that coarse sandy formations correspond to productive aquifers due to their hydraulic conductivity and transmissivity characteristics (Adeniyi *et al.*, 2013) ^[1]. Investigations of aquifer properties in southeastern Nigeria have similarly reported that resistive sandy units constitute the primary groundwater-bearing formations (Bija *et al.*, 2018) ^[5].

Aquifer depths identified in this study, generally between about 16 m and 48 m, indicate moderate groundwater occurrence consistent with sedimentary basin hydrogeology. Comparable aquifer depths have been reported in groundwater vulnerability mapping studies using geoelectric methods in the Niger Delta region, where sediment thickness and depositional environment influence groundwater distribution (Okiongbo & Akpofure, 2012) ^[12]. The aquifer thickness values ranging from approximately 24 m to 29 m suggest adequate groundwater storage capacity and favourable conditions for borehole development.

The calculated longitudinal conductance values, generally between about 0.17 Siemens and 0.20 Siemens, indicate weak to moderate aquifer protective capacity. This suggests that while clay-rich overburden exists in some locations, aquifers may still be vulnerable to contamination under sustained environmental pressure. Aquifer protection studies have emphasised the importance of overburden thickness and resistivity in determining vulnerability to contaminant infiltration, particularly in urban and industrial areas (Facazio *et al.*, 2002) ^[8]. Similar resistivity-based assessments in southern Nigeria have highlighted the need for continuous groundwater monitoring in areas with moderate protective capacity (Ikpe *et al.*, 2025) ^[9].

Transverse resistance values obtained in this study ranged approximately from 10,080 Ωm^2 to 17,980 Ωm^2 , indicating moderate to high aquifer productivity potential. Higher transverse resistance values generally reflect thicker and

more resistive aquifer units, which correlate with favourable groundwater yield potential. However, previous studies caution that transverse resistance should be interpreted qualitatively unless calibrated with hydrogeological data such as pumping tests or borehole yield measurements (Eyankware *et al.*, 2022) ^[7]. Consequently, the results should be viewed as indicative rather than definitive measures of aquifer productivity.

Environmental considerations remain particularly important in the Eleme area due to industrial activities and petroleum operations. Investigations of atmospheric deposition, hydrocarbon transport, and water quality in the Niger Delta have demonstrated that environmental pollutants can influence both surface and subsurface water systems (Aghanwa *et al.*, 2025) ^[2]. Integrated hydrochemical and geophysical assessments have therefore been recommended for comprehensive groundwater vulnerability evaluation, especially in hydrocarbon-producing regions (Okagbare *et al.*, 2025) ^[11].

The resistivity data indicate favourable hydrogeological conditions characterised by moderately deep aquifers, appreciable aquifer thickness, and relatively high resistivity sandy formations suitable for groundwater development. However, the presence of conductive surface layers and moderate aquifer protective capacity suggests potential environmental vulnerability. The results underscore the importance of combining geophysical surveys with hydrochemical analysis and environmental monitoring to ensure sustainable groundwater utilisation in industrially impacted regions of the Niger Delta.

5. Conclusion

The electrical resistivity investigation conducted in Eleme, Rivers State, has provided important insights into subsurface lithology, aquifer characteristics, and possible environmental influence on soil and groundwater systems. The results indicate heterogeneous subsurface conditions dominated by clay, sandy clay, fine sand, and coarse sand formations typical of the Niger Delta sedimentary basin. Apparent resistivity values ranging from about 20 Ω m to over 600 Ω m reflect variations in lithology, moisture content, and subsurface fluid characteristics.

Aquifer units were identified mainly within moderately high resistivity sandy formations at depths between approximately 16 m and 48 m, with aquifer thickness generally ranging from about 24 m to 29 m. These characteristics suggest favourable groundwater storage capacity and potential suitability for borehole development. The calculated transverse resistance values indicate moderate to high aquifer productivity potential, although confirmation through hydrogeological testing would strengthen these interpretations.

The presence of low-resistivity near-surface layers indicates conductive zones that may reflect clay-rich soils, high moisture content, or possible environmental alteration associated with industrial activities. However, electrical resistivity data alone cannot conclusively confirm hydrocarbon contamination without supporting geochemical evidence. Longitudinal conductance values suggest weak to moderate aquifer protective capacity, indicating some vulnerability to contamination where overburden layers are relatively thin or permeable.

The study demonstrates that Eleme possesses appreciable groundwater potential within coarse sand aquifer systems, but environmental vulnerability remains an important

consideration due to industrial and petroleum-related activities in the region. The findings emphasise the need for integrated hydrogeophysical and hydrochemical investigations, continuous environmental monitoring, and sustainable groundwater management practices to ensure safe and reliable water resources in the Niger Delta region.

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