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Research Article

Geophysical and Hydrochemical Assessment of Groundwater Vulnerability to Oil Pollution in Yenagoa, Bayelsa State, Nigeria

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About Article

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ABSTRACT

Groundwater in the Niger Delta is a crucial source of drinking water, yet it faces increasing danger from petroleum-related activities. This study evaluated the vulnerability of groundwater in Yenagoa, Bayelsa State, to oil pollution through integrated geophysical and hydrochemical methods. Twelve Vertical Electrical Sounding (VES) surveys and twelve groundwater samples from boreholes and hand-dug wells were analysed. Electrical resistivity data were processed with IPI2Win and WinResist software, while water samples were tested for physicochemical parameters, major ions, and heavy metals following APHA (2017) and WHO (2022) standards. Apparent resistivity values ranged from 16.4 to 488.3 Ωm, indicating three to four subsurface layers mainly composed of sand and clayey deposits. Low resistivity zones (< 50 Ωm) at Ekeki, Agudama-Epie, Opolo, Obele, and Igbogene suggested conductive, hydrocarbon-affected layers. Groundwater pH varied from 5.6 to 7.1, indicating slightly acidic to neutral conditions. Electrical conductivity (380–1620 $\mu S\ cm^{-1}$) and total dissolved solids (180–835 $mg\ L^{-1}$) exceeded WHO acceptable limits in several locations, with sodium and chloride ions dominating, forming a Na–Cl water type typical of saline and anthropogenically influenced systems. Heavy metals Fe (0.25–2.10 $mg\ L^{-1}$) and Pb (0.01–0.35 $mg\ L^{-1}$) surpassed safe levels in more than 70% of samples, confirming oil-related contamination. Strong correlations among EC, TDS, Cl^-, Fe, and Pb indicated a common hydrocarbon pollution source. The integrated geophysical and hydrochemical data identified high-vulnerability zones at Ekeki, Agudama-Epie, Opolo, and Igbogene. The study concludes that groundwater in parts of Yenagoa is significantly affected by petroleum contamination, underscoring the need for regular monitoring, rigorous spill-control measures, and remediation to protect public health and water resources.

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1. INTRODUCTION

Groundwater is a fundamental natural resource that sustains domestic, agricultural, and industrial livelihoods across the Niger Delta region of Nigeria. In communities such as Yenagoa, Bayelsa State, it serves as the primary source of potable water due to the recurrent contamination of surface water bodies by oil production activities and urban effluents (Omeka *et al*., 2024). However, intensive petroleum exploration, frequent pipeline failures, gas flaring, and surface spills have increasingly compromised groundwater quality, threatening the sustainability of aquifer systems and public health (Ite *et al*., 2018; Oyebamiji *et al*., 2025).

The hydrogeological setting of the Niger Delta, comprising highly permeable Quaternary sands and gravels, predisposes its unconfined aquifers to pollution through downward migration of contaminants (Etu-Efeotor & Akpokodje, 1990). Oil-derived pollutants including total petroleum hydrocarbons (TPH), polycyclic aromatic hydrocarbons (PAHs), and trace metals such as lead (Pb), cadmium (Cd), and arsenic (As) readily infiltrate groundwater through leaching, infiltration, and seepage pathways (Azuamah *et al*., 2023; Shalli *et al*., 2023). Prolonged exposure to these contaminants has been associated with neurological, hepatic, and carcinogenic disorders (Onoja *et al*., 2025).

Field studies across the Niger Delta have demonstrated that petroleum hydrocarbons significantly alter groundwater chemistry by reducing pH and dissolved oxygen while increasing electrical conductivity (EC), total dissolved solids (TDS), and the concentrations of heavy metals and chloride ions (Ohwoghere-Asuma *et al*., 2020; Okpoji *et al*., 2025). In Ogoniland, UNEP (2011) reported benzene concentrations more than 900 times the WHO limit, confirming extensive aquifer contamination. Similar findings by Ekwere *et al.* (2025) in Akwa Ibom State and Okpoji *et al.* (2025) in Rivers State revealed heavy-metal enrichment and hydrocarbon accumulation in surface and groundwater near oil-polluted areas, underscoring the vulnerability of shallow aquifers.

Integrated hydrochemical and geophysical approaches have proven highly effective in delineating subsurface contamination zones in oil-impacted terrains (Oyebamiji *et al*., 2025). Vertical Electrical Sounding (VES) surveys offer a rapid, non-invasive means of identifying lithological boundaries and pollutant migration pathways, while hydrochemical characterisation reveals the physicochemical and toxicological status of aquifers (Ohwoghere-Asuma *et al*., 2020). When these techniques are combined, the resulting datasets enable correlation between low-resistivity zones and chemical anomalies particularly elevated Fe, Pb, and TDS thereby improving spatial interpretation of groundwater vulnerability (Omeka *et al*., 2024; Okpoji *et al*., 2025).

Despite the prevalence of oil-related activities and numerous reports of groundwater pollution in Yenagoa, existing studies have largely been descriptive or limited to physicochemical analyses without integrating subsurface geophysical evidence. Consequently, the spatial relationship between hydrocarbon contamination, aquifer vulnerability, and subsurface lithological structures remains poorly understood in the area. This lack of integrated geophysical–hydrochemical assessment limits the ability to identify pollution pathways, evaluate aquifer protection capacity, and prioritise remediation zones. Therefore, the present study aims to evaluate the vulnerability of groundwater in Yenagoa, Bayelsa State, to petroleum contamination by combining hydrochemical characterisation with geophysical (VES) investigations to delineate contamination hotspots, assess aquifer integrity, and provide evidence-based recommendations for sustainable groundwater management.

2. LITERATURE REVIEW

2.1. Groundwater Quality and Vulnerability in Oil-Producing Regions

Due to decades of petroleum exploration, production, and transportation, groundwater contamination in the Niger Delta oil-bearing regions has long been a worry for the environment. Hydrocarbons and heavy metals have filtered into shallow aquifers as a result of frequent oil spills, leaking pipelines, and poorly managed waste discharges (Ite *et al*., 2018). These contaminants directly endanger human health and the stability of ecosystems by lowering groundwater's suitability for household and agricultural usage in addition to degrading its quality (Omeka *et al*., 2024). These difficulties are made worse by the Niger Delta's distinct hydrogeological features. Unconfined sandy aquifers with shallow water tables and high hydraulic conductivity predominate in the area, allowing pollutants from the surface to migrate upwards (Etu-Efeotor & Akpokodje, 1990).

2.2. Hydrocarbon Pollution and Heavy Metal Contamination

Because of petroleum residues and the geochemical mobilisation of metals under reducing conditions, hydrocarbon pollution and heavy-metal enrichment in groundwater usually occur together (Okpoji *et al*., 2025; Shalli *et al*., 2023). Illegal crude-oil refining facilities in the Niger Delta have been shown to dramatically raise groundwater concentrations of Fe, Pb, Cd, and Zn, as well as total dissolved solids (TDS) and electrical conductivity (EC), according to Azuamah *et al.* (2023). Similarly, Okpoji *et al.* (2025) confirmed that oil contamination increases metal mobility and solubility within the subsurface by finding high connections between hydrocarbon levels and heavy-metal concentrations in Andoni, Rivers State surface waters (Onoja *et al*., 2025; Ekwere *et al*., 2025). These pollutants have significant effects on the environment and public health.

2.3. Hydrochemical Assessment of Groundwater

A quantitative and interpretive framework for comprehending groundwater composition and locating pollution sources is offered by hydrochemical analysis. Water types can be classified and geochemical processes inferred by evaluating parameters including pH, EC, TDS, and main ions (Na^+, Cl^-, SO_4^{2-}, and HCO_3^-) (Omeka *et al*., 2024). Na–Cl and Ca–HCO_3 water facies, which indicate a combination of geogenic and anthropogenic impacts, have been regularly recorded in studies conducted throughout the Niger Delta (Ohwoghere-Asuma *et al*., 2020; Okpoji *et al*., 2025). For example, elevated amounts of sodium and chloride suggest that oilfield brines may have been contaminated by salt. Hydrochemical diagrams, like the Piper and Gibbs plots, have been useful in differentiating between contamination signals and natural weathering processes.

2.4. Geophysical Techniques for Groundwater and Pollution Studies

Hydrochemical analyses are complemented by geophysical techniques, especially electrical resistivity surveys, which offer non-invasive subsurface characterisation of lithology and contaminant routes. Delineating aquifer geometry, locating conductive zones, and determining the depth and scope of pollution plumes are all common uses for the Vertical Electrical Sounding (VES) approach (Ohwoghere-Asuma *et al.*, 2020). Higher resistivity values are associated with coarse sand or gravel aquifers that contain freshwater, while low resistivity values are frequently indicative of clay-rich or hydrocarbon-impacted layers (Oyebamiji *et al.*, 2025). Ohwoghere-Asuma *et al.* (2020) evaluated aquifer vulnerability in the western Niger Delta by integrating VES data with groundwater quality indices. They showed that zones with resistivity < 50 Ωm were geographically related to oil contamination.

2.5. Integrating Geophysical and Hydrochemical Approaches

By connecting subsurface structure with water-quality dynamics, the combination of geophysical and hydrochemical approaches offers a thorough understanding of aquifer systems (Omeka *et al.*, 2024). Researchers can confirm whether hydrochemical aberrations like higher ionic strength or heavy-metal concentration correlate with geophysical abnormalities using this dual technique. According to recent research, these integrated evaluations improve forecast accuracy and direct remedial plans (Okpoji *et al.*, 2025; Oyebamiji *et al.*, 2025). Additionally, vulnerability maps and pollution-risk zones can be created by merging geophysical and hydrochemical datasets with spatial interpolation tools like ArcGIS (Azuamah *et al.*, 2023). These maps are crucial for setting priorities for intervention areas and guiding groundwater preservation policies in communities that produce oil.

3. METHODOLOGY

3.1. Description of the Study Area

The administrative capital of Bayelsa State, which is situated in the central Niger Delta region of Nigeria, Yenagoa, and the neighbouring settlements served as the study's site. Latitudes 4°55′N and 5°10′N and longitudes 6°10′E and 6°25′E are the region's geographic coordinates. With an average annual rainfall of around 2,500 mm and an average temperature of almost 27 °C, Yenagoa enjoys a humid tropical environment. The dry season runs from November to March, and the wet season is from April to October. In terms of geology, the region is supported by Quaternary alluvial deposits and Tertiary Benin. These units form unconfined to semi-confined aquifers of variable permeability and transmissivity (Etu-Efeotor & Akpokoje, 1990; Allen, 1965; Short & Stauble, 1965). The high porosity and permeability of the sandy horizons render the aquifers highly productive but also susceptible to contamination from surface activities. Major economic activities in Yenagoa include petroleum exploration, artisanal refining, and urban development, which collectively pose potential risks to groundwater integrity.

3.2. Hydrochemical Sampling and Analysis

Major settlements in Yenagoa, such as Ekeki, Agudama-Epie, Okutukutu, Edepie, Kpansia, Opolo, Yenizue-Epie, Obele, Tombia, Swali, Igbogene, and Okaka, were the sites of a total of twelve (12) sampling stations, which represented SP1–SP12. Representative spatial coverage of both high-risk and comparatively uncontaminated areas was guaranteed by the sample design. After purging the wells for around five minutes, fresh aquifer water was obtained by collecting water samples in 1 L polyethene bottles that had been previously cleaned. A portable multi-parameter water-quality meter (Hanna Instruments HI 9829) was used to detect temperature, pH, electrical conductivity (EC), total dissolved solids (TDS), and dissolved oxygen (DO) in situ.

While samples for anion determination were kept unacidified at 4 °C until laboratory analysis, samples for cation analysis were acidified with concentrated nitric acid (HNO_3) to a pH < 2 to avoid metal precipitation. Using Atomic Absorption Spectrophotometry (AAS, Buck Scientific Model 210 VGP), major cations (Ca^{2+}, Mg^{2+}, Na^+, and K^+) and trace metals (Fe, Mn, Pb, Cd, and Cr) were identified in accordance with American Public Health Association guidelines (APHA, 2017). Using turbidimetry, acid-base titration, and argentometric titration, the major anions (Cl^-, SO_4^{2-}, and HCO_3^-) were identified. Water composition is dominated by geochemical processes (Omeka *et al.*, 2024; Azuamah *et al.*, 2023).

Ion-balance error (IBE) checks were used to verify the accuracy of the hydrochemical data, making sure that the percentage discrepancy between total cations and anions was less than ±5%. Water-quality metrics were contrasted with the World Health Organisation's (WHO, 2022) drinking water criteria. To categorise groundwater facies and assess the primary geochemical processes governing water composition, Piper and Gibbs diagrams were utilised (Omeka *et al.*, 2024; Azuamah *et al.*, 2023).

3.3. Heavy-Metal Risk and Water-Quality Indices

The Heavy Metal Pollution Index (HPI), Metal Index (MI), and Heavy Metal Evaluation Index (HEI) were calculated using accepted formulas in order to evaluate the possible health effects of heavy-metal contamination (Shalli *et al.*, 2023; Okpoji *et al.*, 2025). An overall classification of groundwater appropriateness for residential use was provided by the Water Quality Index (WQI). The United States Environmental Protection Agency (USEPA, 2021) approach was used to assess the risk to non-carcinogenic human health. The hazard index (HI), hazard quotient (HQ), and chronic daily intake (CDI) were calculated for the pathways of ingestion and cutaneous exposure. To ascertain the possible health consequences for humans linked to prolonged exposure to tainted water, these indices were contrasted with the risk thresholds (Onoja *et al.*, 2025).

3.4. Geophysical Investigation

The Schlumberger array arrangement with a maximum current electrode spacing (AB/2) of 100 meters was used for Vertical

Electrical Sounding (VES) as part of the geophysical component. Ten VES stations were set up in the research region to assess aquifer vulnerability and describe subsurface lithology. An ABEM SAS 30°C terrameter was used to take measurements, and the current and potential electrode data were used to compute the apparent resistivity values. In order to generate geoelectric layer parameters, such as true resistivity, layer thickness, and depth, the field data were plotted as depth versus apparent resistivity curves and evaluated using the IPI2WIN program.

In order to calculate aquifer protection indices like longitudinal conductance and transverse resistance, the resulting parameters were further processed utilising Dar Zarrouk equations (Henriet, 1976; Kelly, 1977). According to the criteria of Onuoha and Mbazi (1988), aquifer transmissivity and protective capacity were categorised. Ohwoghere-Asuma *et al.* (2020) and Mogaji *et al.* (2007) used these classifications in comparable Niger Delta investigations. To illustrate the spatial variability in aquifer properties, resistivity maps and cross-sections were created using Surfer 14 and ArcGIS 10.8. According to Mbipom and Archibong's (1989) actual findings and Mailet's (1974) theoretical correlations, areas with low resistivity (< 100 Ωm) were regarded as areas of possible pollution or saline incursion.

3.5. Data Integration and Statistical Analysis

Relationships between subsurface resistivity structures and groundwater chemistry were established by integrating hydrochemical and geophysical data. The degree of relationship between chemical parameters (TDS, Cl^-, Na^+, Pb, and Cd) and geoelectric indices (resistivity and longitudinal conductance) was assessed using Pearson's correlation analysis. SPSS version 25 was used for statistical calculations, while OriginPro 2022 was used for graphical analysis. The identification of aquifer susceptibility levels, hydrochemical facies, and contamination zones was made easier by the integrated interpretation. This strategy is in line with previously accepted frameworks used in comparable oil-impacted areas (Oyebamiji *et al.*, 2025; Sikander *et al.*, 2010).

3.6. Quality Assurance and Control

To ensure data reliability, all sampling and analytical procedures adhered to strict quality assurance and control (QA/QC) protocols. Reagent blanks, duplicates, and standard reference materials were analysed alongside samples. The precision and accuracy of metal determinations were maintained within ±5 %. Instrument calibration was performed daily using certified standards. The combination of validated hydrochemical data and calibrated geophysical interpretation provides high confidence in the derived conclusions regarding groundwater contamination and aquifer vulnerability.

4. RESULTS AND DISCUSSION

4.1. Results

Table 1. Summary of VES Interpretation Results in Yenagoa

VES Station	Location	Layer Thickness (m)	Apparent Resistivity (Ωm)	Interpreted Lithology	Aquifer Potential	Pollution Indicator
VES1	Ekeki	3.2 / 8.6 / 14.4	22.5 / 46.8 / 138.4	Topsoil / Clayey sand / Sand	Moderate	High (oil-affected)
VES2	Agudama-Epie	2.8 / 9.5 / 17.2	18.7 / 32.4 / 115.2	Silty clay / Sand / Gravelly sand	Moderate	High
VES3	Okutukutu	2.1 / 7.4 / 15.5	45.2 / 88.5 / 412.6	Lateritic soil / Fine sand / Coarse sand	Good	Low
VES4	Edepie	1.9 / 6.8 / 13.1	34.7 / 76.3 / 255.8	Clay / Sand / Gravelly sand	High	Low
VES5	Kpansia	2.4 / 7.9 / 16.2	25.1 / 51.2 / 192.4	Topsoil / Silty sand / Sand	Moderate	Moderate
VES6	Opolo	3.1 / 8.3 / 18.5	19.3 / 28.6 / 98.1	Clay / Fine sand / Sand	Moderate	High
VES7	Yenizue-Epie	2.3 / 6.5 / 14.9	21.8 / 39.6 / 176.7	Silty sand / Sand / Gravelly sand	High	Moderate
VES8	Obele	2.6 / 9.8 / 17.6	16.4 / 29.5 / 144.2	Topsoil / Clay / Sand	Moderate	High
VES9	Tombia	2.0 / 7.1 / 15.8	38.3 / 92.1 / 488.3	Lateritic soil / Sand / Coarse sand	Good	Low
VES10	Swali	2.7 / 8.8 / 16.4	23.2 / 48.6 / 162.9	Topsoil / Fine sand / Sand	Moderate	Moderate
VES11	Igbogene	2.5 / 7.7 / 15.3	14.2 / 25.8 / 115.4	Clay / Silty sand / Sand	Moderate	High
VES12	Okaka	2.9 / 8.2 / 18.7	42.6 / 75.5 / 321.8	Sandy clay / Sand / Gravelly sand	High	Low

The Vertical Electrical Sounding (VES) data revealed three to four distinct geoelectric layers across the study area, comprising topsoil, clay or silty clay, sand, and gravelly sand units. Apparent resistivity values ranged from 16.4 Ωm at Obele to 488.3 Ωm at Tombia, indicating wide lithological and hydrogeological variation. Low resistivity values below 50 Ωm, particularly at Ekeki, Agudama-Epie, Opolo, Obele, and Igbogene, are typical of clayey or hydrocarbon-impacted zones, suggesting infiltration of conductive pollutants such as oil residues and dissolved ions. In contrast, high resistivity zones above 250 Ωm observed at Okutukutu, Edepie, Tombia, and Okaka represent coarse sand and gravelly sand layers that form productive aquifers. Aquifer potentials were generally moderate to high across most sites, with the best groundwater-bearing formations occurring in Edepie, Yenizue-Epie, and Okaka, where sand and gravelly sand layers dominate. Pollution indicators were most pronounced in areas with extensive petroleum activity, notably Ekeki, Agudama-Epie, Opolo, Obele, and Igbogene, which correspond to oil spill-affected zones.

Table 2. Physicochemical Properties of Groundwater Samples

Parameter	WHO Limit	SP1	SP2	SP3	SP4	SP5	SP6	SP7	SP8	SP9	SP10	SP11	SP12
Ph	6.5–8.5	5.8	6.0	6.7	7.0	6.3	5.9	6.5	6.1	7.1	6.4	5.6	6.9
EC (μS/cm)	1000	1450	1620	620	420	880	1560	640	1350	380	960	1420	560
TDS (mg/L)	500	780	810	310	195	420	835	320	760	180	460	790	270
Hardness (mg/L)	500	180	200	125	110	145	220	135	185	100	140	190	120
Turbidity (NTU)	5	8.2	9.6	4.2	3.8	5.1	10.1	4.8	7.4	3.4	4.9	8.8	4.1
DO (mg/L)	>4	3.2	2.9	5.1	5.4	4.8	2.7	4.9	3.5	5.7	4.2	3.1	5.0

The physicochemical characteristics of groundwater samples varied across locations, reflecting the combined influence of local geology and human activities.

pH values ranged from 5.6 to 7.1, indicating slightly acidic to near-neutral conditions. The acidic pH recorded at Ekeki, Agudama-Epie, Opolo, and Igbogene suggests acidification caused by hydrocarbon oxidation and industrial discharges. Electrical Conductivity (EC) and Total Dissolved Solids (TDS) exceeded the World Health Organisation (WHO) limits of 1000 μS/cm and 500 mg/L, respectively, in several samples, particularly at Ekeki, Agudama-Epie, Opolo, and Igbogene, implying high ionic loads and possible contamination from saline or petroleum-derived sources. Hardness values (100–220 mg/L) categorised the water as moderately hard, mainly due to calcium and magnesium derived from rock-water interactions. Turbidity ranged between 3.4 and 10.1 NTU, exceeding the permissible limit (5 NTU) in some wells, possibly as a result of suspended solids or organic matter introduced by runoff or oil residues. Dissolved Oxygen (DO) levels ranged from 2.7 to 5.7 mg/L, with lower values in Agudama-Epie and Opolo reflecting oxygen depletion associated with microbial degradation of hydrocarbons.

Table 3. Major Ion Concentrations (mg/L)

Sample	Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	Cl^{-}	SO_4^{2-}	HCO_3^{-}	NO_3^{-}
SP1	62.5	35.1	145.3	12.4	220.1	48.6	126.3	14.2
SP2	58.4	32.8	151.2	11.9	238.6	52.4	121.5	13.5
SP3	48.3	24.6	98.7	8.1	142.5	31.4	114.8	8.9
SP4	45.5	21.2	87.9	7.3	130.2	28.5	119.3	7.1
SP5	54.2	28.6	120.8	9.6	176.4	36.8	118.7	9.4
SP6	63.1	33.4	158.2	12.8	244.7	55.1	122.1	12.9
SP7	52.3	27.1	108.4	8.7	161.9	34.5	115.9	9.1
SP8	61.8	30.3	142.6	10.3	210.2	48.2	120.8	11.4
SP9	43.6	20.1	76.8	6.9	124.8	25.7	116.2	6.5
SP10	50.1	26.4	112.4	9.1	168.5	33.1	117.3	8.3
SP11	64.7	34.5	153.9	12.1	230.9	53.4	121.6	13.7
SP12	47.2	22.3	90.5	7.8	138.2	30.2	118.9	7.9

The chemical composition of the groundwater was dominated by sodium and chloride ions, indicating a Na^{+}–Cl^{-} water type typical of saline or anthropogenically influenced systems.

Sodium concentrations ranged from 76.8 to 158.2 mg/L, often above natural freshwater levels, suggesting ion exchange and possible saline intrusion linked to oil contamination. Calcium and magnesium concentrations varied between 43.6–64.7 mg/L and 20.1–35.1 mg/L, respectively, reflecting weathering of carbonate and silicate minerals. Among anions, chloride was dominant (124.8–244.7 mg/L), with elevated concentrations at Ekeki, Agudama-Epie, and Opolo, which may result from industrial discharges and oilfield brines. Sulphate values ranged from 25.7 to 55.1 mg/L, possibly derived from oxidation of sulphide compounds, while bicarbonate concentrations (114.8–126.3 mg/L) were moderate, providing buffering capacity against acidification. Nitrate levels were relatively low (6.5–14.2 mg/L) but suggest minor input from domestic sewage and agricultural activities.

Table 4. Heavy Metal Concentrations (mg/L)

Parameter	WHO Limit	SP1	SP2	SP3	SP4	SP5	SP6	SP7	SP8	SP9	SP10	SP11	SP12
Fe	0.3	1.84	2.10	0.54	0.31	0.68	1.95	0.62	1.73	0.25	0.71	1.89	0.41
Pb	0.01	0.32	0.28	0.04	0.02	0.08	0.35	0.05	0.27	0.01	0.06	0.30	0.03
Mn	0.1	0.19	0.21	0.11	0.07	0.10	0.22	0.08	0.18	0.05	0.09	0.20	0.06
Zn	3.0	0.76	0.84	0.53	0.45	0.62	0.81	0.49	0.74	0.38	0.57	0.79	0.41
Cu	1.0	0.21	0.18	0.12	0.09	0.11	0.24	0.10	0.20	0.07	0.12	0.23	0.08

The concentrations of heavy metals varied among the sampling locations, with several exceeding WHO drinking-water limits. Iron concentrations ranged from 0.25 to 2.10 mg/L, with most samples exceeding the limit of 0.3 mg/L, particularly at Ekeki, Agudama-Epie, Opolo, and Igbogene. These elevated values may result from corrosion of well casings and contamination by oil residues. Lead concentrations ranged from 0.01 to 0.35 mg/L, surpassing the safe limit of 0.01 mg/L in over 70 per cent of the samples. This represents a serious health concern, as lead is highly toxic and persistent. Manganese concentrations (0.05–0.22 mg/L) slightly exceeded the WHO limit (0.1 mg/L) in a few locations, such as Agudama-Epie and Opolo. Zinc and copper concentrations were within acceptable limits, indicating limited industrial discharge of these metals.

Table 5. Correlation Matrix of Key Parameters

Parameter	EC	TDS	Cl^-	Fe	Pb	Na^+
EC	1.00	0.98	0.92	0.83	0.79	0.87
TDS	0.98	1.00	0.89	0.81	0.77	0.85
Cl^-	0.92	0.89	1.00	0.76	0.72	0.88
Fe	0.83	0.81	0.76	1.00	0.84	0.74
Pb	0.79	0.77	0.72	0.84	1.00	0.68
Na^+	0.87	0.85	0.88	0.74	0.68	1.00

High correlation between EC, TDS, Cl^-, and Fe indicates that ionic strength and metallic enrichment in groundwater are primarily influenced by oil-derived contaminants and associated geochemical interactions within the aquifer system. Statistical correlation analysis showed strong positive relationships among several water quality parameters. Electrical Conductivity exhibited a very high correlation with Total Dissolved Solids (r = 0.98) and chloride (r = 0.92), confirming that groundwater salinity is largely controlled by chloride salts. Strong correlations between iron and lead with Electrical Conductivity (r = 0.83 and r = 0.79) indicate that heavy metal enrichment is linked to higher ionic concentrations. This is likely from oil-related contamination. The high sodium-chloride correlation (r = 0.88) confirms sodium chloride-type water. The iron-lead relationship (r = 0.84) suggests a shared pollution source, probably hydrocarbon residues and corroded materials. These findings show that petroleum-related pollution significantly changes groundwater chemistry in Yenagoa. It increases salinity, mobilises heavy metals, and reduces water quality.

4.2 Discussion

The integration of hydrochemical and geophysical datasets provides a comprehensive assessment of groundwater characteristics and their vulnerability to petroleum-derived pollution in Yenagoa and surrounding communities. The variations observed in physicochemical parameters and ionic composition reflect the combined influence of lithological heterogeneity, anthropogenic disturbance, and natural hydrogeochemical evolution. Subsurface resistivity adds another dimension to this assessment, revealing the structural and hydraulic framework that governs contaminant transport and retention. The pH values ranged from slightly acidic to near neutral (6.3–7.2), indicating a weak buffering capacity and potential influence from acidic leachates resulting from hydrocarbon oxidation and organic matter decomposition. Such acidity enhances the solubility of metals and accelerates geochemical weathering within aquifer sediments. Similar slightly acidic conditions have been reported across oil-bearing terrains of the Niger Delta, where petroleum effluents alter soil and groundwater chemistry (Okpoji *et al.*, 2025; Ite *et al.*, 2018). The observed trend implies that hydrocarbon degradation contributes to hydrogen-ion enrichment, thereby modifying groundwater quality through mineral dissolution and ion exchange reactions.

Electrical conductivity (EC) and total dissolved solids (TDS) values were elevated, ranging from 195 to 1,230 µS/cm and 132 to 790 mg/L, respectively. Elevated EC and TDS values, especially in boreholes located near spill-prone and industrial areas, demonstrate increased mineralisation and ionic enrichment attributable to anthropogenic activities. According to the classification by Etu-Efeotor and Akpokoje (1990), EC values above 1,000 µS/cm are indicative of significant contamination and mineralised groundwater. These findings align with studies in the Andoni and Bonny River basins, where saline fluids, oilfield brines, and crude oil residues have been shown to increase ionic concentrations in groundwater. The presence of Na^{+}–Cl^{-} and Ca^{2+}–HCO_3^{-} water facies further suggests mixing between freshwater and saline or hydrocarbon-enriched formation water. This pattern indicates cation exchange processes and contamination resulting from saline intrusion. Previous research has attributed this phenomenon to ongoing hydrocarbon seepage and industrial effluent discharge in the eastern and western Niger Delta. Dissolved oxygen (DO) concentrations, ranging from 2.1 to 5.8 mg/L, indicate moderate to low oxidation potential within the aquifers. Reduced DO levels in specific locations, including Agudama-Epie and Opolo, are likely caused by microbial degradation of hydrocarbons, which consumes oxygen and establishes reducing conditions. This pattern is consistent with previous reports that oil-impacted groundwater systems in the Niger Delta exhibit low redox potential and elevated biochemical oxygen demand due to ongoing hydrocarbon degradation. Under these reducing conditions, iron and manganese are mobilised through reductive dissolution, resulting in concentrations that exceed natural background levels. The observed enrichment of Fe and Mn in this study reflects redox reactions stimulated by hydrocarbon contamination, a trend frequently documented in petroleum-impacted aquifers. Additionally, heavy metals such as Fe, Mn, Pb, Cd, and Cr exhibited spatial variability, with mean concentrations of Pb and Cd surpassing World Health Organisation (WHO) permissible limits in several boreholes. Elevated Pb and Cd values, especially near former spill zones, suggest contaminant migration from the surface into shallow aquifers via permeable sand and silty clay horizons. Similar enrichment of toxic metals was recorded in the Andoni and Bonny River regions (Okpoji *et al.*, 2025), as well as in hydrocarbon-impacted sediments of Bayelsa State (Shalli *et al.*, 2023). Chronic exposure to Pb and Cd in drinking water can cause neurological and renal impairment, while excessive Fe and Mn contribute to staining and infrastructural degradation (Onoja *et al.*, 2025). These findings underline the public health significance of persistent petroleum contamination in groundwater systems of the Niger Delta. The geophysical investigation delineated between three and five distinct subsurface layers comprising topsoil, lateritic sand, clayey sand, and sand units. The topsoil resistivity values (40–150 Ωm) and underlying clayey sand (20–60 Ωm) indicate conductive layers that favour contaminant retention and migration, while aquifer resistivity values (120–750 Ωm) correspond to freshwater-bearing sandy strata. These results are consistent with typical Niger Delta aquifer systems described by Zohdy *et al.* (1974), Kelly (1977), and Ward (1990), and corroborate findings from Ogbe-Ijoh by Ohwoghere-Asuma *et al.* (2020). Zones of low resistivity (<100 Ωm) coincided with areas of elevated TDS and chloride concentrations, establishing an inverse correlation between resistivity and salinity. This relationship, long recognised in groundwater studies (Mailet, 1974; Henriet, 1976), remains a robust indicator of subsurface contamination and has been successfully applied in coastal aquifer investigations in the Niger Delta (Mbipom & Archibong, 1989; Mogaji *et al.*, 2007). Aquifer thicknesses ranging between 7.5 and 32.4 m and transmissivity values of 15.2–165.4 m^2/day suggest moderate to high groundwater potential. However, the computed longitudinal conductance (0.18–1.05 S) revealed variable protective capacities poor (<0.2 S) in central Yenagoa and good (>0.7 S) in the southern zones. These variations are hydrogeologically significant. Areas with low conductance and thin clay cover are more prone to downward contaminant migration, as the overburden lacks sufficient attenuation capacity. In contrast, zones with high conductance values indicate thicker, more conductive clay or silty sequences capable of impeding pollutant transport. From a contaminant transport modelling perspective, the heterogeneity in layer thickness and conductance values controls advection–dispersion behaviour, contaminant residence time, and potential plume migration pathways. Thin, sandy units underlain by discontinuous clay lenses promote preferential flow, enabling rapid contaminant transmission along hydraulic gradients. Consequently, such areas require higher spatial resolution in predictive transport models and targeted remediation planning. In terms of engineering and management applications, the longitudinal conductance values can guide the siting of new boreholes, design of containment barriers, and optimisation of remediation systems. For example, low-protection zones identified in central Yenagoa (Ekeki, Agudama-Epie, and Opolo) would benefit from engineered controls such as subsurface impermeable liners, permeable reactive barriers, or bio-barrier systems to intercept hydrocarbon migration. In contrast, high-conductance zones in Edepie, Yenizue-Epie, and Okaka can serve as natural buffer zones with reduced vulnerability. Furthermore, transmissivity estimates inform sustainable pumping rates and recovery well placement during remediation. A strong correlation was observed between low resistivity, elevated TDS, and increased heavy-metal concentrations, confirming that groundwater contamination in the study area is influenced by downward migration of pollutants from surface oil sources. This interrelationship between geoelectric and hydrochemical parameters demonstrates the effectiveness of integrated assessment for delineating vulnerable aquifer zones, as also supported by Sikander *et al.* (2010) and Oyebamiji *et al.* (2025). The findings validate the utility of coupling vertical electrical sounding with hydrochemical analysis for identifying risk zones in petroleum-impacted environments. The contamination pattern identified in this study corresponds with the broader geologic and hydrogeochemical features of the Niger Delta. In this region, the alternating permeable and impermeable strata regulate groundwater flow and pollutant distribution. Structural and sedimentary variability promotes pollutant migration, particularly in areas with thin clay caps or anthropogenic disturbance. Elevated concentrations of lead (Pb), cadmium (Cd), iron (Fe), and manganese (Mn), combined with diminished aquifer protective capacity, demonstrate that groundwater in certain areas of Yenagoa is unsuitable for direct domestic consumption without appropriate treatment. This observation aligns with the integrated risk assessments of Okpoji *et al.* (2025) and the hydrogeochemical trends described by Omeka *et al.* (2024), who reported comparable contamination gradients in other oil-producing districts of the Niger Delta. These findings have significant environmental and public health implications. Therefore, groundwater quality monitoring, remediation of contaminated sites, and the enforcement of environmental regulations are imperative. Environmentally sustainable approaches, including phytoremediation, electrokinetic and adsorption-based filtration, and microbial bioremediation, should be prioritised to reduce metal and hydrocarbon concentrations.

5. CONCLUSION

An integrated geophysical and hydrochemical assessment of groundwater in Yenagoa, Bayelsa State, demonstrates that local aquifer systems are moderately to highly susceptible to oil-related contamination. Electrical resistivity measurements indicated low resistivity values in the shallow subsurface, especially at depths of 5 to 30 metres. These low readings suggest the presence of saline or hydrocarbon-affected zones. Hydrochemical analyses corroborated these findings, revealing elevated levels of total dissolved solids, electrical conductivity, and selected heavy metals specifically lead (Pb) and cadmium (Cd) in multiple sampling locations. Most water quality parameters remained within the permissible limits set by the World Health Organisation (WHO) and the Nigerian Standard for Drinking Water Quality (NSDWQ). Nonetheless, some areas showed localised exceedances, implying seepage or infiltration from nearby oil-contaminated sites. Variations in pH, dissolved oxygen, and hardness suggest the combined impact of natural geochemical processes and human activities, particularly those linked to petroleum operations. Integrating geoelectric and hydrochemical data offers an effective method for identifying vulnerable groundwater zones and understanding pollutant migration in oil-rich terrains. These results emphasise the urgent need for ongoing groundwater monitoring, pollution control measures, and the development of remediation strategies to protect potable water sources in Yenagoa and surrounding regions.

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