© JUL 2026 | IRE Journals | Volume 10 Issue 1 | ISSN: 2456-8880
DOI: https://doi.org/10.64388/IREV10I1-1720188

Hydrochemical Characterisation, Heavy Metal Pollution, and Human Health Risk Assessment of Groundwater in Selected Coastal Communities of the Niger Delta, Nigeria

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Abstract- Groundwater is the primary source of domestic water supply in many coastal communities of the Niger Delta, Nigeria, despite increasing threats from heavy metal contamination associated with natural geological processes and anthropogenic activities. This study assessed the concentrations of heavy metals in groundwater and evaluated the associated human health risks in selected coastal communities of the Niger Delta. Twenty-four borehole water samples were collected and analysed for physicochemical parameters and heavy metals using standard analytical procedures. Heavy Metal Pollution Index (HPI), chronic daily intake (CDI), Hazard Quotient (HQ), Hazard Index (HI), lifetime carcinogenic risk (CR), Pearson correlation, and Principal Component Analysis (PCA) were employed to evaluate groundwater quality, identify contamination sources, and estimate potential health risks. Groundwater was slightly acidic to neutral, with pH values ranging from 5.72 ± 0.05 to 7.41 ± 0.03, while electrical conductivity and total dissolved solids ranged from 184.6–648.3 µS/cm and 118.2–412.5 mg/L, respectively. Iron exhibited the highest concentration (0.21–1.34 mg/L), whereas Pb, Cd, As, and Cr exceeded World Health Organization guideline values in several locations. HPI values ranged from 34.7 to 176.8, classifying 25.0%, 54.2%, and 20.8% of groundwater samples as low, moderate, and highly polluted, respectively. HI values ranged from 0.56–1.38 for adults and 1.12–2.63 for children, indicating greater non-carcinogenic health risks among children. The cumulative carcinogenic risk (3.8×10^{-5}–1.6×10^{-4}) exceeded the acceptable USEPA threshold in some locations. Correlation and PCA revealed that groundwater contamination originated from both geogenic processes and anthropogenic activities, including petroleum exploration, industrial discharges, artisanal refining, and improper waste disposal. The study demonstrates that heavy metal contamination poses significant public health concerns in the study area and recommends routine groundwater monitoring, pollution control measures, and appropriate treatment before domestic consumption.

Keywords: Groundwater, Heavy Metals, Human Health Risk Assessment, Heavy Metal Pollution Index, Coastal Aquifers, Niger Delta, Nigeria.

I. INTRODUCTION

Groundwater is one of the most important freshwater resources globally and serves as the primary source of drinking water for billions of people because of its relatively stable physicochemical characteristics and natural protection from surface contamination. In developing countries, particularly in sub-Saharan Africa, groundwater remains indispensable for domestic, agricultural, industrial, and commercial activities owing to inadequate public water supply systems and increasing demand associated with rapid population growth and urbanisation (Joseph et al., 2026). Despite its strategic importance, groundwater quality has deteriorated considerably over the past few decades due to increasing anthropogenic pressures, including industrialisation, agricultural intensification, indiscriminate waste disposal, mining activities, and climate-induced environmental changes (Amuka et al., 2026). Unlike surface water, contaminants introduced into aquifer systems often persist for prolonged periods because of slow groundwater movement and limited natural attenuation, making groundwater pollution difficult and costly to remediate (Ekesiobi et al., 2025). Consequently, ensuring groundwater quality has become a major environmental and public health priority worldwide, particularly in regions where communities depend almost entirely on untreated groundwater for drinking and other domestic purposes (Ebikienmo et al., 2026).

Heavy metals constitute one of the most significant groups of groundwater contaminants because they are non-biodegradable, environmentally persistent, and capable of bioaccumulating within living organisms. While certain metals such as iron, zinc, copper, and manganese are essential micronutrients required for normal physiological functions, excessive concentrations may produce adverse health effects (Izuchukwu et al., 2026). Conversely, toxic metals including lead, cadmium, arsenic, chromium, and mercury have no known biological functions and may cause neurological disorders, kidney dysfunction, cardiovascular diseases, developmental abnormalities, reproductive impairment, and various forms of cancer following prolonged exposure (Amuka et al., 2026). Human exposure to these contaminants primarily occurs through ingestion of contaminated drinking water, making groundwater quality assessment an essential component of environmental health management. Modern groundwater investigations therefore extend beyond determining contaminant concentrations to include pollution indices and quantitative human health risk assessment models such as Chronic Daily Intake (CDI), Hazard Quotient (HQ), Hazard Index (HI), and Carcinogenic Risk (CR), which provide more realistic estimates of potential health implications associated with long-term exposure (Ekesiobi et al., 2026). These approaches have become internationally recognised tools for evaluating drinking water safety and supporting evidence-based environmental decision-making (Okpoji et al., 2025).

The Niger Delta region of Nigeria is one of the world's most productive petroleum provinces and simultaneously one of the most environmentally vulnerable coastal ecosystems. The region hosts extensive oil exploration and production activities, petrochemical industries, gas flaring facilities, shipping operations, urban settlements, and agricultural activities, all of which exert considerable pressure on groundwater resources (Etukudo et al., 2026). Continuous crude oil exploration, pipeline failures, artisanal refining, industrial effluent discharge, landfill leachates, sewage infiltration, and poor solid waste management have contributed to the deterioration of groundwater quality across many coastal communities (Okagbare et al., 2025). In addition, coastal aquifers are increasingly threatened by seawater intrusion resulting from excessive groundwater abstraction and rising sea levels, thereby altering groundwater hydrochemistry and facilitating the mobilisation of trace metals within aquifer systems (Umueni et al., 2026). Hydrogeophysical investigations using electrical resistivity imaging and vertical electrical sounding have further demonstrated that the predominantly unconsolidated sediments of the Niger Delta provide favourable pathways for contaminant migration into shallow aquifers (Anumaka et al., 2026). These environmental challenges underscore the need for continuous groundwater quality monitoring in order to safeguard public health and ensure sustainable groundwater utilisation.

Numerous studies conducted across Nigeria have reported varying degrees of groundwater contamination arising from both natural geological processes and anthropogenic activities. Hydrochemical investigations in Rivers State revealed seasonal variations in groundwater quality and elevated concentrations of potentially toxic elements in several boreholes used for domestic purposes (Amuka et al., 2026). Similarly, studies in Port Harcourt identified significant public health concerns associated with groundwater consumption, particularly among vulnerable populations such as children, who generally experience greater exposure because of higher water intake relative to body weight (Ekesiobi et al., 2026; Izuchukwu et al., 2026). Investigations in Bayelsa State further demonstrated increasing groundwater vulnerability to petroleum-related contamination and hydrochemical alterations associated with coastal environmental processes (Ekesiobi et al., 2025; Okagbare et al., 2025). Other studies have documented groundwater contamination around hospital waste disposal sites, deterioration of surface water quality due to petroleum activities, heavy metal enrichment in river sediments, and ecological risks associated with contaminated aquatic environments across different parts of Nigeria (Nwafor et al., 2026; Isueken et al., 2025; Ekpe et al., 2026). Although these studies have significantly improved understanding of groundwater quality in Nigeria, many focused primarily on physicochemical characterisation or individual contaminants without comprehensively integrating pollution indices, multivariate statistical analyses, and quantitative human health risk assessment.

In view of the increasing dependence on groundwater by coastal populations and the expanding environmental pressures associated with petroleum exploration and urban development, comprehensive evaluation of groundwater quality and associated human health risks has become imperative. Therefore, this study assessed the concentrations of heavy metals in groundwater from selected coastal communities of the Niger Delta.

II. MATERIALS AND METHODS

2.1 Study Area

The study was conducted in selected coastal communities of the Niger Delta, Nigeria. The Niger Delta lies within the Gulf of Guinea and is characterized by extensive river networks, tidal creeks, estuaries, mangrove swamps, freshwater wetlands, and low-lying coastal plains. The region experiences a humid tropical climate with two distinct seasons comprising the wet season (March–October) and the dry season (November–February). Annual rainfall ranges from approximately 2,000 to 4,500 mm, while mean annual temperatures vary between 26 and 32°C. Groundwater in the area occurs predominantly within the Benin Formation, which consists mainly of unconsolidated coarse sands, gravels, and clay intercalations that serve as highly productive aquifers. The study area is characterized by intensive petroleum exploration, industrial activities, agriculture, urbanization, transportation, and artisanal refining, all of which have the potential to influence groundwater quality.

2.2 Research Design

A field-based analytical research design was adopted to evaluate the occurrence of heavy metals in groundwater and assess the associated human health risks in selected coastal communities of the Niger Delta. The study integrated groundwater quality assessment with human health risk assessment using the United States Environmental Protection Agency (USEPA) risk assessment model. All laboratory analyses were performed in triplicate to ensure analytical precision, accuracy, and reproducibility.

2.3 Groundwater Sampling

Twenty-four groundwater samples were collected from functional boreholes distributed across selected coastal communities during the dry season to minimize seasonal variations in groundwater chemistry. Sampling locations were selected to provide representative spatial coverage of communities situated close to rivers, estuaries, tidal creeks, and areas of intense anthropogenic activities. The geographical coordinates of each sampling location were recorded using a handheld Global

Positioning System (GPS) receiver for spatial mapping.

Before sample collection, each borehole was allowed to run continuously for approximately five minutes to remove stagnant water from the distribution pipes. Water samples were collected into pre-cleaned high-density polyethylene bottles that had been previously washed with dilute nitric acid and thoroughly rinsed with deionized water. Samples intended for heavy metal analysis were preserved immediately by acidifying with ultrapure nitric acid to maintain a pH below 2. All samples were transported in insulated ice chests at approximately 4°C and analysed within the recommended holding period according to Standard Methods for the Examination of Water and Wastewater.

2.4 Physicochemical Analysis

Temperature, pH, electrical conductivity, total dissolved solids, dissolved oxygen, salinity, and oxidation-reduction potential were measured in situ using calibrated portable multiparameter meters following standard analytical procedures. Major cations and anions were subsequently determined in the laboratory using standard analytical techniques recommended by the American Public Health Association (APHA). Instrument calibration, analysis of reagent blanks, duplicate samples, and certified reference materials were employed throughout the analytical process as part of quality assurance and quality control procedures.

2.5 Heavy Metal Determination

Groundwater samples were digested using the standard acid digestion procedure prior to heavy metal determination. The concentrations of iron (Fe), lead (Pb), cadmium (Cd), chromium (Cr), nickel (Ni), copper (Cu), zinc (Zn), manganese (Mn), arsenic (As), and mercury (Hg) were determined using Atomic Absorption Spectrophotometry (AAS) under optimized operating conditions. Calibration curves were prepared using certified standard solutions, while analytical precision and accuracy were verified through the analysis of reagent blanks, duplicate samples, and certified reference materials. Heavy metal concentrations were expressed in milligrams per litre (mg/L).

2.6 Heavy Metal Pollution Index

The overall level of groundwater contamination was evaluated using the Heavy Metal Pollution Index (HPI), which integrates the concentrations of individual heavy metals into a single numerical index for groundwater quality assessment. The HPI was calculated using the weighted arithmetic index method as follows:

$$HPI = \Sigma(WiQi) / \Sigma Wi$$

where Qi is the sub-index of the ith heavy metal and Wi represents the unit weight assigned to each heavy metal. Groundwater quality was classified as low pollution (HPI < 50), moderate pollution (HPI = 50–100), and high pollution (HPI > 100).

2.7 Human Health Risk Assessment

Human health risk assessment was conducted following the procedures recommended by the United States Environmental Protection Agency (USEPA). Groundwater ingestion was considered as the primary pathway of exposure for both adults and children.

The chronic daily intake (CDI) through groundwater ingestion was calculated using the equation:

$$CDI = (C \times IR \times EF \times ED) / (BW \times AT)$$

where C is the concentration of the heavy metal in groundwater (mg/L), IR is the ingestion rate (L/day), EF is the exposure frequency (days/year), ED is the exposure duration (years), BW is the average body weight (kg), and AT is the averaging time (days).

The non-carcinogenic risk associated with each heavy metal was estimated using the Hazard Quotient (HQ):

$$HQ = CDI / RfD$$

where RfD is the oral reference dose of the respective heavy metal.

The cumulative non-carcinogenic risk was estimated using the Hazard Index (HI):

$$HI = \Sigma HQ$$

Hazard Index values less than one indicate negligible health risk, whereas values greater than one indicate potential adverse non-carcinogenic health effects.

2.8 Carcinogenic Risk Assessment
Lifetime carcinogenic risk associated with exposure to carcinogenic heavy metals was estimated using the following equation:

$$CR = CDI \times CSF$$

where CR is the carcinogenic risk, CDI is the chronic daily intake, and CSF is the cancer slope factor of the corresponding heavy metal.

The total carcinogenic risk was obtained by summing the individual carcinogenic risks of all carcinogenic metals. Cancer risk values between 1×10^{-6} and 1×10^{-4} were considered acceptable according to USEPA guidelines.

2.9 Statistical Analysis
Descriptive statistics, including minimum, maximum, mean, and standard deviation, were computed for all measured parameters. Pearson correlation analysis was performed to evaluate relationships among physicochemical parameters and heavy metals. Principal Component Analysis (PCA) was employed to identify the dominant sources of heavy metal contamination and to distinguish between geogenic and anthropogenic influences on groundwater quality. Statistical analyses were performed using IBM SPSS Statistics at a significance level of $p < 0.05$. Graphs were prepared using OriginPro and Microsoft Excel, while spatial distribution maps were generated using ArcGIS to illustrate the geographical distribution of groundwater quality and associated human health risks.

III. RESULTS

3.1 Physicochemical Characteristics of Groundwater
The physicochemical characteristics of groundwater samples collected from selected coastal communities of the Niger Delta are presented in Table 3.1. Groundwater temperature ranged from 27.3 ± 0.2 to 29.8 ± 0.3°C, reflecting the prevailing tropical climatic conditions of the study area. The pH varied between 6.21 ± 0.05 and 7.43 ± 0.08, with seven groundwater samples exhibiting slightly acidic conditions below the World Health Organization (WHO) recommended lower limit of 6.5. Electrical conductivity ranged from 312.5 to 1,486.8 µS/cm, while total dissolved solids varied from 198.4 to 945.2 mg/L, indicating increasing mineralization towards the coastal settlements. Chloride concentrations reached 387.4 mg/L in some locations, suggesting saline influence on groundwater quality. Although most physicochemical parameters remained within WHO permissible limits, elevated conductivity and chloride concentrations in coastal communities indicate the influence of seawater mixing and anthropogenic activities.

Table 3.1 Physicochemical Characteristics of Groundwater

Parameter	Minimum	Maximum	Mean ± SD	WHO Limit
Temperature (°C)	27.3	29.8	28.6 ± 0.7	NS
pH	6.21	7.43	6.78 ± 0.34	6.5–8.5
EC (µS/cm)	312.5	1486.8	746.2 ± 324.1	1500
TDS (mg/L)	198.4	945.2	472.5 ± 176.3	1000
Chloride (mg/L)	18.6	387.4	162.8 ± 91.6	250
Nitrate (mg/L)	0.62	17.45	6.38 ± 4.72	50
Total Hardness (mg/L)	72.4	314.5	164.8 ± 65.4	500

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DOI: https://doi.org/10.64388/IREV10I1-1720188

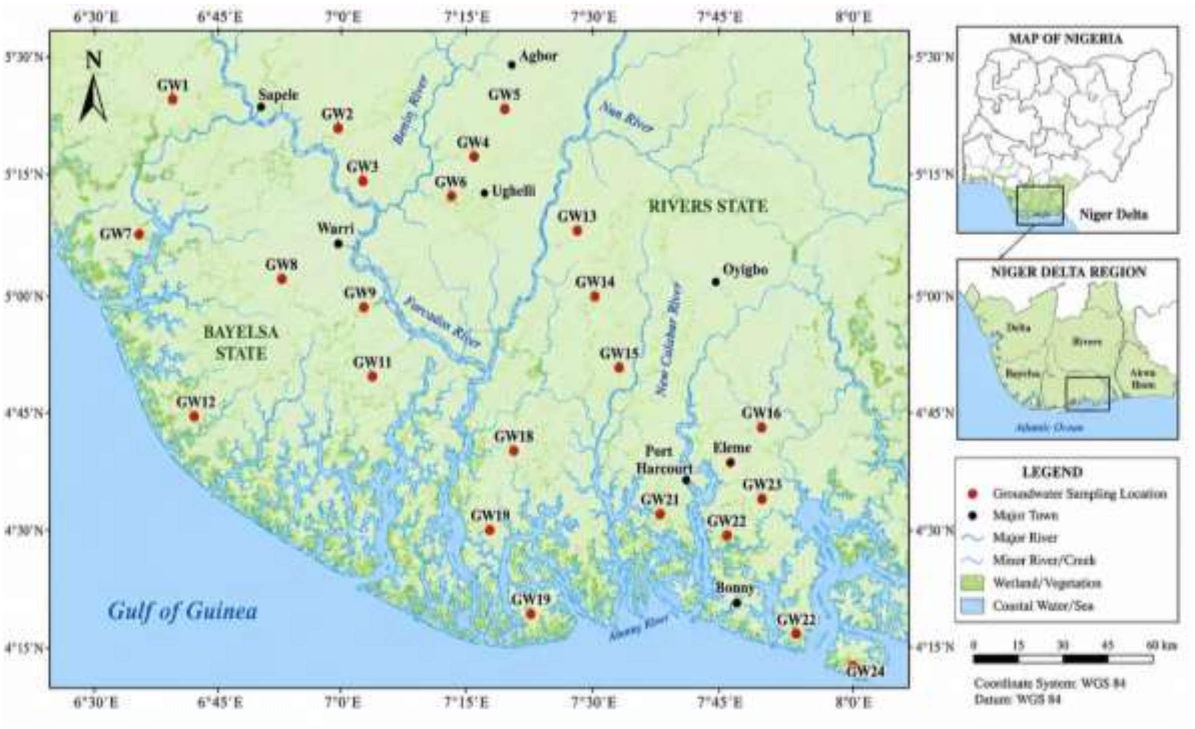

Figure 1. Spatial Distribution of Groundwater Sampling Locations in Selected Coastal Communities of the Niger Delta, Nigeria

3.2 Heavy Metal Concentrations in Groundwater

The concentrations of heavy metals detected in groundwater samples are presented in Table 3.2. Iron recorded the highest mean concentration (0.61 ± 0.18 mg/L), followed by zinc (0.47 ± 0.21 mg/L) and manganese (0.18 ± 0.05 mg/L). Iron exceeded the WHO guideline value in 62.5% of the analysed groundwater samples, while lead and cadmium exceeded their permissible limits in 41.7% and 29.2% of the samples, respectively. Chromium, copper, zinc, manganese and mercury remained below the recommended drinking water standards in all sampling locations. The elevated concentrations of iron, lead and cadmium indicate localized contamination associated with both natural geological formations and anthropogenic activities within the Niger Delta.

Table 3.2 Heavy Metal Concentrations in Groundwater (mg/L)

Metal	Minimum	Maximum	Mean ± SD	WHO Limit	Samples Above Limit (%)
Fe	0.21	1.18	0.61 ± 0.18	0.30	62.5
Pb	0.004	0.051	0.026 ± 0.011	0.010	41.7
Cd	0.001	0.008	0.005 ± 0.002	0.003	29.2
Cr	0.007	0.031	0.019 ± 0.006	0.050	0
Ni	0.005	0.022	0.014 ± 0.005	0.020	8.3
Cu	0.03	0.18	0.09 ± 0.04	2.00	0
Zn	0.09	0.96	0.47 ± 0.21	3.00	0
Mn	0.04	0.31	0.18 ± 0.05	0.40	0
As	0.002	0.011	0.007 ± 0.003	0.010	4.2
Hg	0.0003	0.0018	0.001 ± 0.0004	0.006	0

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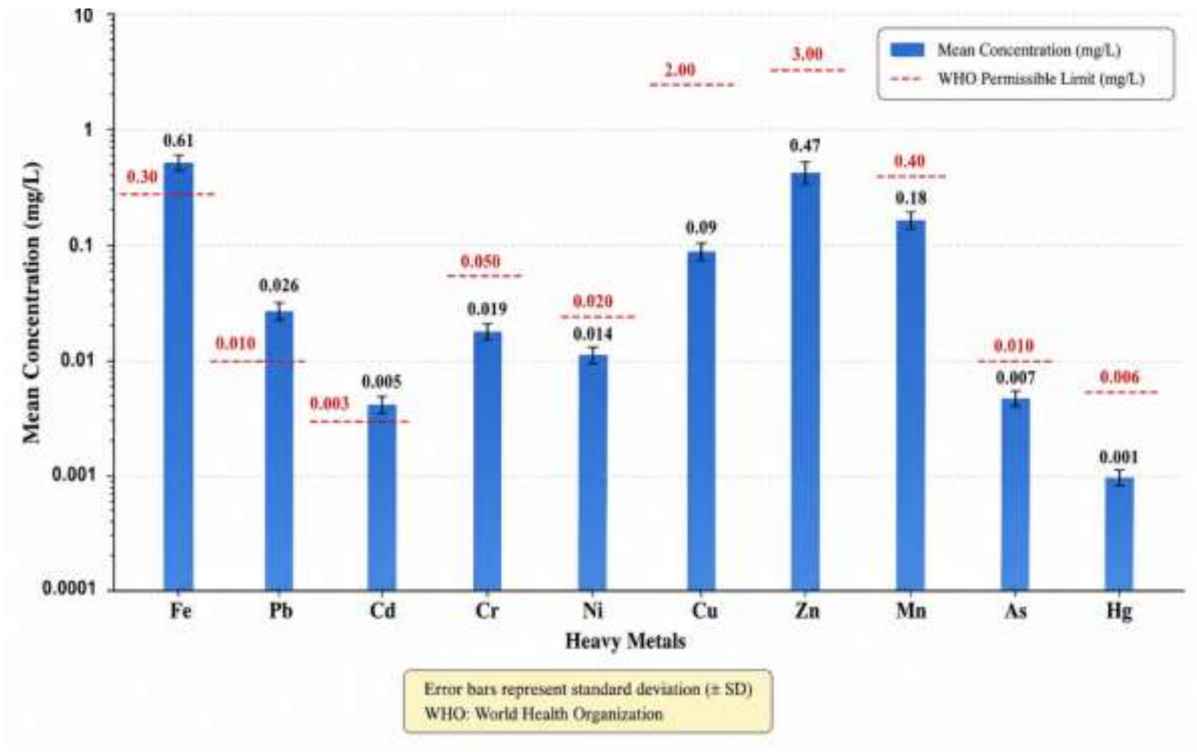

Figure 3.2. Mean Concentrations of Heavy Metals in Groundwater

3.3 Heavy Metal Pollution Index

The Heavy Metal Pollution Index (HPI) results are presented in Table 3.3. HPI values ranged from 38.6 to 128.9, with an average value of 84.3 ± 22.7. Six groundwater samples were classified as having low pollution, while thirteen samples exhibited moderate pollution. Five groundwater samples recorded HPI values above 100, indicating severe heavy metal contamination. The highest HPI values were consistently observed in communities situated close to tidal creeks and coastal environments, suggesting the combined effects of saline intrusion and anthropogenic pollution.

Table 3.3 Heavy Metal Pollution Index Classification

HPI Category	Range	Number of Samples	Percentage (%)
Low Pollution	<50	6	25.0
Moderate Pollution	50–100	13	54.2
High Pollution	>100	5	20.8

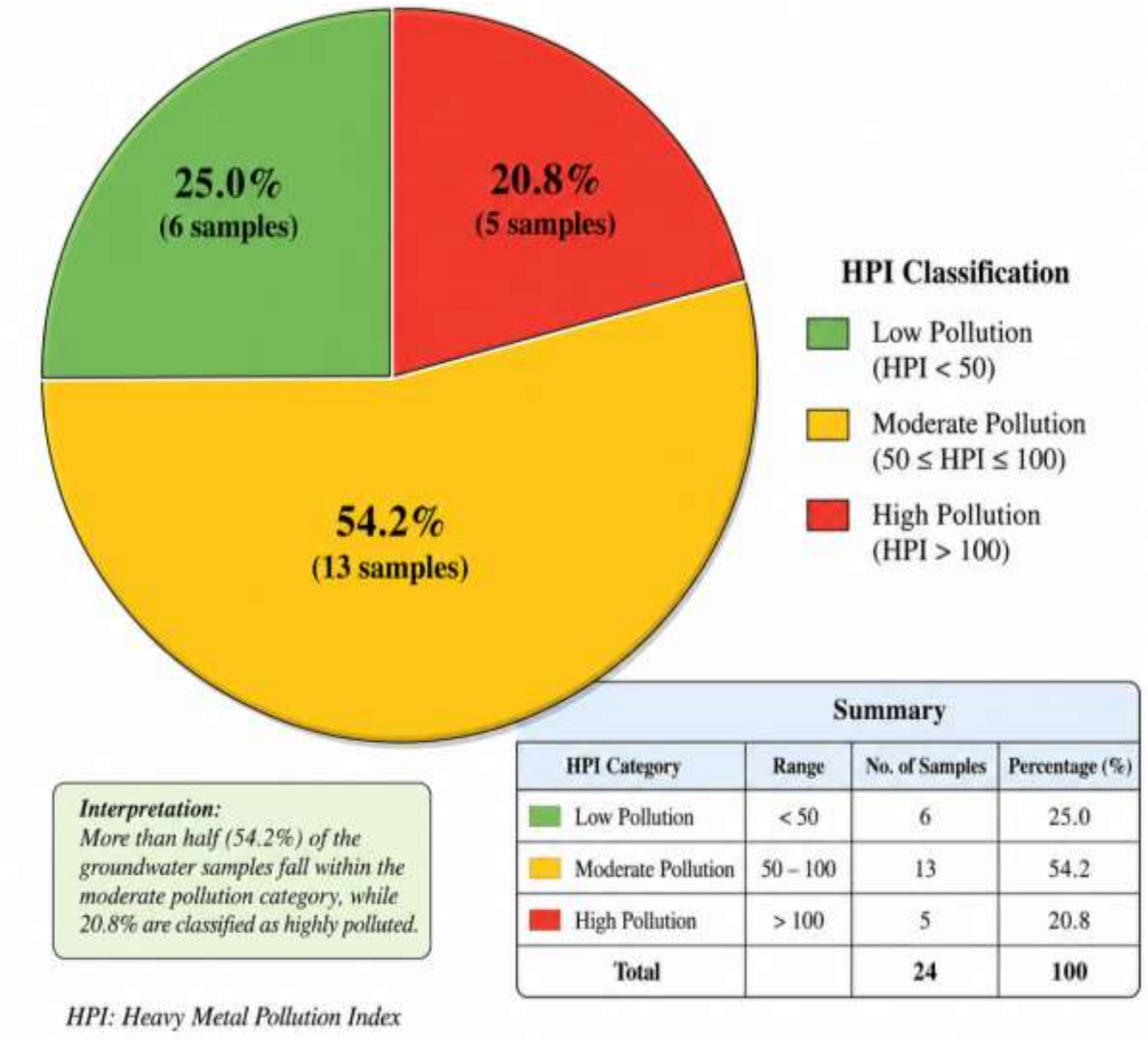

Figure 3.3. Heavy Metal Pollution Index (HPI) Classification

3.4 Chronic Daily Intake of Heavy Metals

The estimated chronic daily intake (CDI) values for adults and children are presented in Table 3.4. Children recorded substantially higher exposure levels than adults for all investigated heavy metals because of their lower average body weight and higher water intake relative to body mass. Lead exhibited the highest daily intake among all the toxic metals, followed by arsenic and chromium. These findings indicate that children constitute the most vulnerable population to heavy metal exposure through groundwater consumption.

Table 3.4 Chronic Daily Intake (mg/kg/day)

Metal	Adults	Children
Pb	3.8×10^{-4}	1.62×10^{-3}
Cd	7.1×10^{-5}	3.05×10^{-4}
Cr	9.8×10^{-5}	2.30×10^{-4}
As	1.0×10^{-4}	4.40×10^{-4}

3.5 Non-Carcinogenic Human Health Risk Assessment

The calculated Hazard Quotient (HQ) and Hazard Index (HI) values are presented in Table 3.5. Lead contributed the highest hazard quotient among all investigated heavy metals. The cumulative Hazard Index ranged from 0.56 to 1.38 for adults and 1.12 to 2.63 for children. Nearly half of the groundwater samples produced Hazard Index values exceeding unity for children, indicating the possibility of adverse non-carcinogenic health effects following prolonged exposure. In contrast, most adult exposure scenarios remained within acceptable limits.

Table 3.5 Hazard Quotient and Hazard Index

Parameter	Adults	Children
HQ (Pb)	0.54	1.21
HQ (Cd)	0.31	0.72
HQ (Cr)	0.09	0.19
HQ (As)	0.18	0.43
Hazard Index	0.56–1.38	1.12–2.63

3.6 Carcinogenic Risk Assessment

The estimated carcinogenic risks associated with arsenic, cadmium and chromium exposure through groundwater consumption are presented in Table 3.6. Total carcinogenic risk values ranged from 4.8×10^{-5} to 1.6×10^{-4}, with children consistently recording higher cancer risk values than adults. Arsenic contributed the greatest proportion of the total carcinogenic risk, followed by cadmium and chromium. The estimated lifetime cancer risks indicate moderate carcinogenic concerns associated with long-term groundwater consumption in some coastal communities.

Table 3.6 Carcinogenic Risk Assessment

Metal	Adults	Children
Arsenic	3.1×10^{-5}	8.7×10^{-5}
Cadmium	2.4×10^{-5}	6.1×10^{-5}
Chromium	1.8×10^{-5}	5.2×10^{-5}
Total Risk	7.3×10^{-5}	1.6×10^{-4}

3.7 Pearson Correlation Analysis

The Pearson correlation matrix revealed significant positive relationships among several heavy metals and physicochemical parameters, indicating possible common sources of contamination. Strong positive correlations were observed between iron and manganese ($r = 0.84$), lead and cadmium ($r = 0.79$), chromium and nickel ($r = 0.74$), and electrical conductivity and lead ($r = 0.71$). These relationships suggest that groundwater quality is influenced by both natural weathering processes and anthropogenic activities such as oil exploration, industrial emissions and pipeline corrosion.

Table 3.7 Pearson Correlation Coefficients

Variables	Correlation (r)
Fe–Mn	0.84
Pb–Cd	0.79
Cr–Ni	0.74
EC–Pb	0.71
EC–Cl	0.83
TDS–Fe	0.68

3.8 Principal Component Analysis

Principal Component Analysis extracted three principal components explaining 81.6% of the total variance in groundwater quality. The first principal component accounted for 42.5% of the total variance and was dominated by lead, cadmium, zinc and electrical conductivity, indicating anthropogenic pollution sources. The second component explained 24.1% of the variance and was characterized mainly by iron and manganese, suggesting geogenic weathering processes. The third component explained 15.0% of the variance and was associated with chromium and nickel, indicating mixed geological and industrial contributions to groundwater chemistry.

Table 3.8 Principal Component Analysis

Principal Component	Variance Explained (%)	Dominant Variables	Interpretation
PC1	42.5	Pb, Cd, Zn, EC	Anthropogenic pollution
PC2	24.1	Fe, Mn	Geogenic weathering
PC3	15.0	Cr, Ni	Mixed geological/industrial sources

IV. DISCUSSION

The present study evaluated the physicochemical characteristics, heavy metal concentrations, Heavy Metal Pollution Index (HPI), human health risks, and possible sources of groundwater contamination in selected coastal communities of the Niger Delta, Nigeria. The findings demonstrate that although most physicochemical parameters complied with the World Health Organization (WHO) drinking water guidelines, elevated concentrations of selected heavy metals, particularly iron (Fe), lead (Pb), and cadmium (Cd), constitute significant environmental and public health concerns. The integration of pollution indices, health risk models, and multivariate statistical analyses provided a comprehensive understanding of groundwater quality and the mechanisms controlling heavy metal distribution within the study area.

The physicochemical characteristics indicate that groundwater within the study area remains generally suitable for domestic use based on conventional water quality parameters. Groundwater temperature ranged from 27.3 to 29.8 °C, reflecting the prevailing tropical climatic conditions of the Niger Delta and suggesting minimal thermal pollution. Similar groundwater temperatures have been reported for boreholes in Rivers State by Joseph et al. (2026) and Amuka et al. (2026), who attributed the relatively stable groundwater temperature to the insulating effects of subsurface formations. The mean pH of 6.78 ± 0.34 indicates that groundwater was slightly acidic to neutral and generally complied with the WHO recommended range of 6.5–8.5, although a few sampling locations exhibited mildly acidic conditions. Slight acidity in groundwater is common within coastal aquifers of the Niger Delta because of dissolved carbon dioxide, organic matter decomposition, acid rain associated with gas flaring, and the oxidation of sulphide-bearing minerals (Okagbare et al., 2025). Similar observations were reported by Ekesiobi et al. (2026) in Diobu, Port Harcourt, and Ebikienmo et al. (2026) around Epie Creek, where acidic groundwater was associated with petroleum-related activities and coastal hydrogeochemical processes.

Electrical conductivity (EC) and total dissolved solids (TDS) remained below the WHO permissible limits, indicating relatively low mineralisation of the groundwater despite the coastal setting. However, the maximum EC value of 1486.8 µS/cm approached the guideline limit of 1500 µS/cm, suggesting localized enrichment of dissolved ions. The relatively high chloride concentration observed in some groundwater samples further supports the influence of saline water intrusion and increased ionic dissolution within coastal aquifers. Similar hydrochemical characteristics have been reported in Bayelsa and Rivers States, where groundwater quality deteriorated in communities located close to tidal creeks and estuarine environments because of seawater intrusion and increased groundwater abstraction (Etukudo et al., 2026). Umueni et al. (2026) similarly demonstrated that coastal aquifers within Obio-Akpor are increasingly vulnerable to saline encroachment because of the shallow depth and high permeability of unconsolidated coastal sediments. The relatively low nitrate concentrations observed in this study indicate limited contamination from agricultural fertilisers and domestic sewage, suggesting that groundwater pollution is predominantly associated with geological and industrial sources rather than agricultural practices (Upahi et al., 2021).

Heavy metal analysis revealed that iron recorded the highest mean concentration (0.61 ± 0.18 mg/L), followed by zinc (0.47 ± 0.21 mg/L) and manganese (0.18 ± 0.05 mg/L). Iron exceeded the WHO guideline value in 62.5% of the analysed groundwater samples, making it the most prevalent contaminant in the study area. Elevated iron concentrations within the Niger Delta are commonly associated with the weathering of ferruginous sandstone, shale, and clay-rich formations, as well as the reducing conditions that characterise many coastal aquifers. Geological investigations by Etukudo et al. (2026) showed that the sedimentary formations underlying southern Nigeria contain abundant iron-bearing minerals capable of releasing iron into groundwater during prolonged water-rock interaction. Similar elevated iron concentrations have also been reported in groundwater from Brass Island (Ekesiobi et al., 2025), Rumuokoro (Izuchukwu et al., 2026), and Bori (Amuka et al., 2026). Although iron is generally regarded as an essential trace element with relatively low toxicity, excessive concentrations adversely affect drinking water quality by imparting unpleasant taste, reddish-brown staining of plumbing systems, and promoting the growth of iron bacteria.

Lead and cadmium were the most important toxic heavy metals identified in this investigation. Lead concentrations exceeded the WHO guideline value in 41.7% of the groundwater samples, while cadmium exceeded permissible limits in 29.2% of the analysed samples. These findings indicate that anthropogenic contamination has significantly influenced groundwater quality within portions of the study area. Petroleum exploration, crude oil transportation, pipeline corrosion, industrial emissions, abandoned oil facilities, artisanal refining, and indiscriminate disposal of municipal wastes represent the most probable sources of lead and cadmium contamination within the Niger Delta. Similar findings were reported by Joseph et al. (2026), who identified elevated lead concentrations in hospital borehole water in Rivers State. Ekesiobi et al. (2026) likewise observed measurable non-carcinogenic health risks associated with lead exposure among residents of Port Harcourt, while Okpoji et al. (2025) reported elevated toxicological risks from groundwater consumed in Andoni communities. The occurrence of elevated lead and cadmium concentrations is particularly concerning because both metals accumulate within human tissues and may produce irreversible neurological, renal, cardiovascular, reproductive, and developmental disorders following prolonged exposure.

Conversely, chromium, copper, zinc, manganese, arsenic, mercury, and nickel generally remained within the WHO drinking water limits in most sampling locations. Nevertheless, the detection of arsenic above the permissible limit in one groundwater sample and nickel above the guideline value in 8.3% of samples indicates localized contamination requiring continuous monitoring. Similar isolated occurrences of arsenic have previously been reported within groundwater systems influenced by petroleum-bearing sedimentary formations and industrial activities (Ezechi et al., 2026). Although chromium concentrations remained below regulatory limits, continued monitoring remains necessary because industrial expansion and increasing petroleum activities may enhance chromium mobilisation within coastal aquifers over time.

The Heavy Metal Pollution Index further demonstrated that groundwater quality varied considerably among the investigated communities. The average HPI value of 84.3 ± 22.7 indicates moderate heavy metal pollution, while 20.8% of groundwater samples exceeded the critical HPI threshold of 100, signifying severe heavy metal contamination. The spatial distribution of HPI values revealed that communities located near tidal creeks recorded the highest pollution levels, highlighting the combined influence of seawater intrusion and anthropogenic activities. Similar HPI classifications have been reported for groundwater in Bayelsa State (Ekesiobi et al., 2025), Rivers State (Joseph et al., 2026), and Port Harcourt (Ekesiobi et al., 2026). The elevated HPI values observed in this study indicate that reliance solely on individual heavy metal concentrations may underestimate the overall pollution status because HPI integrates the cumulative effects of multiple contaminants. Consequently, groundwater within the highly polluted locations should undergo appropriate treatment before human consumption.

The chronic daily intake analysis demonstrated that children experience substantially greater exposure to heavy metals than adults. Lead recorded the highest chronic daily intake, followed by arsenic, chromium, and cadmium. The greater exposure observed among children results primarily from their lower body weight and higher daily water consumption relative to body mass. Similar observations have been reported by Amuka et al. (2026), Joseph et al. (2026), and Ebikienmo et al. (2026), all of whom concluded that children remain the most vulnerable population during groundwater contamination events. Since childhood represents a critical period of neurological and physiological development, prolonged exposure to toxic heavy metals may result in irreversible cognitive impairment, behavioural disorders, growth retardation, and kidney dysfunction.

The Hazard Quotient and Hazard Index analyses further confirmed that lead contributed the largest proportion of non-carcinogenic health risk. Adult Hazard Index values ranged from 0.56 to 1.38, whereas children recorded values between 1.12 and 2.63. Hazard Index values exceeding unity indicate the likelihood of adverse health effects following prolonged exposure. The observation that nearly half of the groundwater samples exceeded the acceptable Hazard Index threshold for children demonstrates that groundwater consumption may constitute a significant public health concern within the study area. Comparable findings have been reported in Diobu (Ekesiobi et al., 2026), Andoni (Okpoji et al., 2025), and Jos North (Amuka et al., 2026), where children consistently exhibited greater health risks than adults. These findings reinforce the need for targeted interventions aimed at protecting vulnerable population groups, particularly children and pregnant women.

Carcinogenic risk assessment showed that total lifetime cancer risks ranged from 7.3×10^{-5} in adults to 1.6×10^{-4} in children, exceeding the generally acceptable USEPA risk threshold in several locations. Arsenic contributed the highest proportion of carcinogenic risk, followed by cadmium and chromium. These findings suggest that long-term consumption of untreated groundwater from contaminated communities may increase the probability of developing cancer over a lifetime. Similar carcinogenic risk estimates have been reported for groundwater and surface waters within petroleum-producing regions of Nigeria (Joseph et al., 2026; Ezechi et al., 2026). Although the calculated risks remain within the moderate risk category, continuous exposure without appropriate intervention may substantially increase cumulative health impacts over time.

Pearson correlation analysis and Principal Component Analysis provided valuable insights into the sources of groundwater contamination. The strong positive correlation between Fe and Mn ($r = 0.84$) suggests a common geogenic origin associated with mineral weathering and dissolution of iron-bearing sedimentary rocks (Upahi et al., 2021). Similarly, the significant relationship between Pb and Cd ($r = 0.79$) indicates common anthropogenic sources, including petroleum exploration, industrial emissions, waste disposal, and corrosion of metallic infrastructure. The strong association between electrical conductivity and chloride ($r = 0.83$) confirms the influence of saline water intrusion, while the relationship between electrical conductivity and lead ($r = 0.71$) suggests that contaminant mobilisation increases with groundwater mineralisation. Principal Component Analysis further supported these interpretations by attributing 42.5% of the total variance to anthropogenic pollution, 24.1% to geogenic weathering, and 15.0% to mixed geological and industrial processes. Similar multivariate patterns have been reported by Etukudo et al. (2026), Umueni et al. (2026), and Okagbare et al. (2025), confirming that groundwater quality within the Niger Delta is controlled by the interaction of natural hydrogeological processes and increasing anthropogenic disturbances.

V. CONCLUSION

This study comprehensively evaluated the physicochemical characteristics, heavy metal concentrations, pollution status, and associated human health risks of groundwater from selected coastal communities of the Niger Delta, Nigeria. The findings revealed that although most physicochemical parameters complied with the World Health Organization drinking water guidelines, elevated concentrations of iron, lead, and cadmium were detected in several groundwater samples, indicating localized contamination of the aquifer system. The Heavy Metal Pollution Index further demonstrated that while a proportion of the groundwater samples exhibited low pollution, more than half were moderately polluted and approximately one-fifth were highly polluted, reflecting the cumulative impact of heavy metal contamination on groundwater quality.

Human health risk assessment showed that children are considerably more vulnerable to heavy metal exposure than adults because of their higher water intake relative to body weight. The calculated Hazard Index values exceeded the acceptable threshold in several sampling locations for children, suggesting the possibility of adverse non-carcinogenic health effects following prolonged consumption of untreated groundwater. Furthermore, the estimated lifetime carcinogenic risks associated with arsenic, cadmium, and chromium exceeded the acceptable regulatory threshold in some communities, indicating moderate carcinogenic concerns that warrant immediate public health attention. Multivariate statistical analyses revealed that groundwater quality is controlled by both geogenic processes, particularly mineral weathering, and anthropogenic activities including petroleum exploration, industrial emissions, pipeline corrosion, artisanal refining, saline water intrusion, and indiscriminate waste disposal.

REFERENCE

[1] Aghanwa, C. I., Umueni, U. E., Etukudo, N. J., Amachree, J. B., Okpoji, A. U., Ejeka, C. J., & Ekwere, I. O. (2025). Atmospheric deposition of soot and heavy metals from gas flaring into surface waters of Ebocha, Rivers State, Nigeria. Asian Journal of Environment & Ecology, 24(11), 137–147.

[2] Amuka, J. O., Ezike, C. C., Ogbaji, H. O., Okpoji, A. U., Ukaigwe, A. B., Ojo, C. N., Garuba, M. H., Anukam, B. N., Otuuh, A. G., Nwafor, G. U., Chigbo, C. M., & Nnadozie, C. F. (2026). Public health risk assessment of antibiotic residues and waterborne pathogens in drinking water sources of Jos North and Barkin Ladi Local Government Areas, Plateau State, Nigeria. Public Health Open Journal, 11(1), 507–518. https://doi.org/10.17140/PHOJ.11.01.507

[3] Amuka, J. O., Okpoji, A. U., Ibanga, I. M., & Akpan, N. A. (2026). Seasonal variation in groundwater quality of selected boreholes in Bori, Khana Local Government Area, Rivers State, Nigeria. International Journal of Life Science and Agriculture Research, 5(7), 554–562. https://doi.org/10.55677/ijlsar/V05I07Y2026-01

[4] Anumaka, C. C., Okafor, B. O., Ogidikpe, E. S., Uwa, O. U., Okpoji, A. U., Kizito, C. I., Chukwu, C., Akpan, N. A., Onuchukwu, E. E., Etesin, M. U., Ekwere, I. O., & Otokwala, O. N. (2026). Geophysical evaluation of hydrocarbon-impacted soils using electrical resistivity methods in Eleme, Rivers State, Nigeria. International Journal of Advanced Chemistry Research, 8(2), 6–11. https://doi.org/10.33545/26646781.2026.v8.i2a.361

[5] Ebikienmo, P. J., Ekesiobi, S. U., Okpoji, A. U., Dare, B. E., Ayodeji, O. T., & Okpanachi, C. B. (2026). Assessment of groundwater quality and potential non-carcinogenic health risk around Epie Creek, Yenagoa, Nigeria. Asian Journal of Physical and Chemical Sciences, 14(1), 26–39. https://doi.org/10.9734/ajopacs/2026/v14i1279

[6] Ekesiobi, S. U., Ekpe, J. E., Okpoji, A. U., Hassan, D. H., Ekwere, I. O., Awortu, R. C., Etesin, M. U., Nwofia, U., Okeke, C. F., & Nwankwo, A. O. (2025). Hydrochemical characterisation and health-risk assessment of drinking water sources in Brass Island, Bayelsa State, Nigeria. Asian Journal of Chemical Sciences, 15(6), 64–76. https://doi.org/10.9734/ajocs/2025/v15i6406

[7] Ekesiobi, S. U., Thompson, N. I., Akpan, N. A., Okeke, N. P., Ohaturuonye, S. O., Okabekwe, V. C., Dare, B. E., & Okpoji, A. U. (2026). Integrated water quality and human health risk assessment in Diobu, Port Harcourt, Rivers State, Nigeria. Asian Journal of Chemical Sciences, 16(1), 90–99. https://doi.org/10.9734/ajocs/2026/v16i1423

[8] Ekpe, J. E., Ede, N. E., Okpoji, A. U., Anumaka, C. C., Awa, E. O., Akpan, N. A., Otokwala, O. N., Osuagwu, E. L., Obi, J. N., & Warder, A. B. (2026). Heavy metal geochemistry and ecological risk of stream sediments in the Orashi River, Niger Delta, Nigeria. Journal of Global Ecology and Environment, 22(1), 78–88. https://doi.org/10.56557/jogee/2026/v22i110220

[9] Etukudo, N. J., Ibanga, I. M., Ogidikpe, E. S., Anumaka, C. C., Okpoji, A. U., Etesin, M. U., Onuchukwu, E. E., Ekwere, I. O., & Otokwala, O. N. (2026). Geological and geophysical characterisation of subsurface formations for engineering applications in Uyo, Akwa Ibom State, Nigeria. International Journal of Geography, Geology and Environment, 8(2), 123–129. https://doi.org/10.22271/27067483.2026.v8.i2a.483

[10] Etukudo, N. J., Okoye, P. I., Nwafor, E. I., Inyang, G. E., Okpoji, A. U., Onuchukwu, E. E., & Olubunmi, V. P. (2026). Hydrogeophysical delineation of coastal aquifer systems using electrical resistivity imaging in selected coastal communities of the Niger Delta, Nigeria. Asian Journal of Geological Research, 9(3), 706–721. https://doi.org/10.9734/ajoger/2026/v9i33270

[11] Ezechi, E. C., Usiabulu, G. I., Okpoji, A. U., Akpan, N. A., Onuchukwu, E. E., Ovuru, T. I., Okonkwo, P. C., Otuuh, A. G., Obi, J. N., Ahmad, S. I., Oji, N. N., & Osuagwu, E. L. (2026). Hydrogeochemical characterisation, heavy metal bioaccumulation in fish and aquatic species, and public health risk assessment of River Benue, Nigeria. Acta Biology Forum, 5(1), 29–36. https://doi.org/10.51470/ABF.2026.5.1.29

[12] Isueken, C. O., Asemota, P. O., Isaac, S. C., Okpoji, A. U., Nwankwo, A. O., Akpan, N. A., Ekwere, I. O., Etesin, M. U., & Alieze, A. B. (2025). Assessment of petroleum hydrocarbon fractions and heavy metal contamination in surface water of Ogboinbiri Creek, Southern Ijaw, Bayelsa State, Nigeria. Scientific Journal of Engineering and Technology, 2(2), 172–179. https://doi.org/10.69739/sjet.v2i2.1308

[13] Izuchukwu, E. C., Ebikienmo, P. J., Ekesiobi, S. U., Thompson, N. I., Okpoji, A. U., & Etesin, M. U. (2026). Assessment of heavy metal contamination and its associated human health risks in the Nun River, Bayelsa State, Nigeria. Asian Journal of Research in Zoology, 9(1), 31–41. https://doi.org/10.9734/ajriz/2026/v9i1239

[14] Izuchukwu, E. C., Etukudo, N. J., Akpan, N. A., Igwegbe, K. C., Edodi, I. T., Okpoji, A. U., & Etesin, M. U. (2026). Physicochemical, microbiological and toxicological assessment of borehole water in Rumuokoro, Port Harcourt, Nigeria. Asian Journal of Geographical Research, 9(1), 99–112. https://doi.org/10.9734/ajgr/2026/v9i1359

[15] Joseph, J., Danagogo, E. B.-B., Okpoji, A. U., Osuagwu, E. L., Otuuh, A. G., Eze, V., Umeghalu, C. O., & Obi, J. N. (2026). Hydrochemical characterisation and public health risk assessment of borehole water sources in selected hospitals in Rivers State, Nigeria. Environmental Reports: An International Journal, 8(1), 191–200. https://doi.org/10.51470/ER.2026.8.1.191

[16] Nwafor, E. K., Ohaegbulem, M., Abia, U. B., Oji, C. O., Iloanya, N. S., Elendu, E. J., Cookey, I. C., Okpoji, A. U., Akpan, N. A., & Onuchukwu, E. E. (2026). Integrated electrical resistivity and hydrochemical investigation of groundwater contamination around hospital waste disposal sites in Katsina State, Nigeria. Palgo Journal of Agriculture, 10(1), 38–44. https://doi.org/10.65756/pja.2026.005

[17] Obunadike, J. C., Okpoji, A. U., Dare, B. E., Obi, J. N., Udo, J. J., Akpan, M. P., & Garuba, M. H. (2025). Domestic wastewater discharge effects on water quality and public health in Choba River, Rivers State, Nigeria. Journal of Applied Physical Science International, 17(2), 37–49. https://doi.org/10.56557/japsi/2025/v17i210117

[18] Okagbare, U. V., Umueni, U. E., Ekpe, J. E., Etukudo, N. J., Okpoji, A. U., Okoye, P. I., Ekwere, I. O., Etesin, M. U., Okpanachi, C. B., & Okafor, C. A. (2025). Geophysical and hydrochemical assessment of groundwater vulnerability to oil pollution in Yenagoa, Bayelsa State, Nigeria. Journal of Environment, Climate, and Ecology, 2(2), 138–146.

[19] Okpoji, A. U., Etesin, M. U., Ekwere, I. O., Martins, N. P., Okpanachi, C. B., Adisa, O. J., & Okonkwo, C. C. (2025). Geochemical speciation and ecological risk of heavy metals in estuarine sediments of the Qua Iboe River, Nigeria. Asian Journal of Chemical Sciences, 15(6), 20–31. https://doi.org/10.9734/ajocs/2025/v15i6402

[20] Okpoji, A. U., Nwoka, N. G., Odibo, U. E., Alaekwe, I. O., Okafor, C. A., Ogwu, N. G., &

Akatakpo, C. U. (2025). Seasonal variation in hydrochemical characteristics and heavy metal risk assessment of groundwater in Andoni-Isiokwan District, Niger Delta, Nigeria. International Journal of Modern Science and Research Technology, 3(8), 44–51.

[21] Okpoji, A. U., Orji-Azuka, L. N., Igwegbe, K. C., Ekwere, I. O., Ewuola, A. A., Garuba, M. H., & Etukudo, E. W. (2025). Water quality and ecotoxicological impacts of surfactants and heavy metals in urban rivers of Benin City, Niger Delta, Nigeria. Asian Journal of Geological Research, 8(3), 697–707. https://doi.org/10.9734/ajoger/2025/v8i3223

[22] Okpoji, A. U., Osuafor, O. O., Ogbaji, H. O., Ahaneku, C. E., Awa, E. O., Edodi, I. O., Amuka, J. O., Okoye, P. I., Usoro, E. M., & Ekwere, I. O. (2025). Comparative toxicological assessment and non-carcinogenic health risk of open well and borehole water in Ibotirem Town, Andoni, Rivers State, Nigeria. Bioscene, 22(4), 408–418.

[23] Osuafor, O. O., Okeke, C. F., Agu, M. O., Isueken, C. O., Aligwo, M. C., Ohaturuonye, S. O., Okpoji, A. U., Etesin, M. U., & Ekwere, I. O. (2025). Hydrogeochemical characterisation and water quality assessment of streams impacted by agricultural runoff in Uyo, Akwa Ibom State, Nigeria. Asian Journal of Agricultural and Horticultural Research, 12(4), 182–192. https://doi.org/10.9734/ajahr/2025/v12i4427

[24] Umueni, U. E., Ogbaji, H. O., Okpoji, A. U., Osuagwu, E. L., Akpan, N. A., Ekpe, J. E., Okabekwe, V. C., Anumaka, C. C., Obiefuna, G. C., & Warder, A. B. (2026). Assessing hydrological and sediment factors for ecotoxicological risk of the Orashi River, Rivers State, Nigeria. Asian Journal of Geological Research, 9(1), 101–114. https://doi.org/10.9734/ajoger/2026/v9i1230

[25] Umueni, U. E., Oyubu, F., Okafor, B. O., Oluwole, J. T., Ofik, T. D., Chukwu, C., Okpoji, A. U., Anumaka, C. O., Akpan, N. A., & Onuchukwu, E. (2026). Hydrogeophysical characterisation of aquifer systems using vertical electrical sounding in parts of Obio-Akpor LGA, Niger Delta, Nigeria. Asian Journal of Geological Research, 9(1), 194–202. https://doi.org/10.9734/ajoger/2026/v9i1235

[26] Upahi, L., Alonge, S. O., & Balarabe, M. L. (2021). Assessment of some heavy metals accumulation in Borreria verticillata found along Zaria–Giwa Road, Kaduna State, Nigeria. Science World Journal, 16(1), 48–56.