Communication in Physical Sciences, 2025, 12(8):2537-2562

Multivariate Assessment of Water Quality Parameters and Health Risk of Toxic Metals in Surface Water of Crude Oil Impacted Mangrove-Creek in Southern Nigeria

Gabriel C. C. Ndinwa and Florence Amiewalan
Received: 27 July 2025/Accepted: 04 December 2025/Published: 13 December 2025
https://doi.org/10.4314/cps.v12i8.28

Abstract: *Surface water pollution within the Niger Delta area is a threat to aquatic ecosystems. This study determined the physicochemical characteristics, toxic metal contamination, and human health risk of surface water from Goi Creek in Rivers State, Nigeria. Water samples were collected monthly from four sampling stations for a period of ten months and analysed using standard procedures. Samples were determined for physicochemical parameters and heavy metals. One-way ANOVA was used to determine the spatial significance between the stations whereas Pearson correlation, principal component analysis (PCA) and hierarchical cluster analysis (HCA) were used to assess the relationships and inferred the likely contamination sources. WQI, HPI, MI and PI were used to assess the water quality status and level of metal contaminations, while ingestion-related chronic intake, HI and CR were used to estimate the likely related non carcinogenic and carcinogenic risk. The results show that there was significant difference in the concentrations of physicochemical parameters and heavy metals analysed between the stations (p <0 .05). Station 4 had the highest mean concentrations of the contaminants. The mean concentration of metals were ranked as Fe > Zn > Mn > Cu > Ni > Cr > Pb > As ≈ V > Cd > Hg. Most of the metals recorded concentrations that surpassed the guidelines used in this study. PCA and HCA results revealed positive associations between THC and most metals, indicating that petroleum-related activities were the likely source of contamination. The water samples were rated unsuitable for drinking (WQI =175.71), relatively polluted (HPI=176.05) and severely contaminated by metals (MI=65.81). Hazard index values were 2.03 for adults and 4.75 for children. The study revealed that the non-carcinogenic risk for children was higher than adult and the risk of cancer from As, Cd and Cr was above the acceptable range. The findings show that the creek has been severely impacted and recommend the provision of alternative water supply to the surrounding communities, improve pollution control strategies and continuous environmental monitoring.*

Keywords: *Heavy metals, Cancer risk, Niger Delta, Water Quality, Mangrove creek*

Gabriel C. C. Ndinwa
Department of Environmental Management and Toxicology
University of Delta, Agbor, Delta State
Email: gc.ndinwa@unidel.edu.ng
https://orcid.org/0000-0002-3136-948X

Florence Amiewalan
Department of Geology
University of Delta, Agbor, Delta State
Email: florence.amiewalan@unidel.edu.ng
https://orcid.org/0009-0005-2081-0582

1.0 Introduction

Crude oil, a complex blend of hydrocarbons and non-hydrogen chemicals, including harmful heavy metals, is perhaps the world's most economically useful natural resource (Orajiaka-Uchegbu *et al*., 2020). However, despite its economic advantages, the exploration and production of crude oil is closely associated with the degradation and contamination of both biotic and abiotic environments. In oil-producing regions, there have been reports of large-scale contamination of groundwater, surface water and soil as a result of oil spills, poor waste management, malfunction of equipment as well as vandalism of pipelines (Nriagu *et al*., 2016). In Nigeria, the Niger Delta region is particularly vulnerable to these dangers having been the center of hydrocarbon exploitation for more than 60 years (Davies and Abowei, 2009). Particularly concerning is the discharge of cadmium, arsenic, mercury, lead and other heavy metals into surface waters. Since these metals are non-biodegradable, can persist in aquatic systems and bioaccumulate in many species including fishes, they are a significant threat to the environment and public health (Kpomah and Orororo, 2023; Orajiaka-Uchegbu *et al*., 2020; Osioma and Iniaghe 2019). Orororo *et al*. (2024) proved that exposure to cadmium causes kidney dysfunction, while Hassan *et al*. (2021) and El Hammari *et al*. (2022) showed that exposure to arsenic and mercury can bring about skin and lung malignancies as well as cardiovascular and reproductive health issues.

Water from rivers and creeks aids human growth and provides support and sustenance for different living things (Bhardwaj *et al.* 2017). It is the natural source of drinkable water in places where groundwater sources are unavailable or not sufficient (Seiyaboh *et al*. 2017). The term 'water quality' refers to the biological, physical, chemical as well as radiological properties of water (Kondum *et al*. 2021) and maintaining water quality is very important to humanity given the fact that water is perhaps the most essential resource for the survival of life (Kumar et al. 2018). Reports indicate that during the past few decades, pollution of aquatic bodies by harmful chemical products has increased as a result of the surge in human activity around the aquatic bodies (Efekemo *et al*., 2024a; Alam *et al*., 2009).

Water quality assessment, as a research area, has been of interest to many Nigerian researchers (Akhionbare *et al*., 2019; Efekemo *et al*., 2024b). For example, Oboh and Agbala (2017) and Egun and Ogiesoba-Eguakun (2018) reported that Siluko and Okhuaile Rivers in Edo State, Nigeria, have excellent water quality. Egun and Oboh (2021), reported that the Ikpoba reservoir was severely contaminated by heavy metals like Cd, Pb, and Fe, which accounted for the water's declining water quality (Akpakpan *et al*., 2024). According to Atalawei *et al.* (2020), who carried out a study on the Olugbobiri and Ogboinbiri creeks in the Niger Delta area, water from the creeks are not good for human consumption due to the high concentrations of iron and polycyclic aromatic hydrocarbons they content. Because pollution immediately affects water supplies and food chains, communities in the Niger Delta, where farming and fishing are major sources of income, are especially vulnerable. While a number of studies have documented heavy metal contamination and hydrocarbon pollution in certain areas of the Niger Delta (Nduka and Orisakwe, 2011; Orajiaka-Uchegbu *et al.*, 2020), the majority of assessments have been either limited to particular metals, localized to particular spill sites, or have not integrated physicochemical and toxicological parameters. The spatiotemporal variations in heavy metal concentrations and water quality across Delta State's oil-producing communities have not been exhaustively studied. As a result, trustworthy baseline data are still needed, which will aid assessment of ecological threats, adherence to to water quality regulations, and implementation of evidence-based policy.

Crude oil spills have affected Ogoniland communities in a number of ways. According to FEI (2019), between 1976 and 1991, Ogoniland experienced about 2976 distinct oil leaks totaling more than two million barrels of oil. These are the consequences of leaks from pipelines, wellheads, and flow stations, as well as spills related to the transportation of stolen crude oil, illicit well tapping, local product refining, and vandalism (Lindén and Pålsson, 2013). The physical, chemical, and biological conditions of the creek have been negatively impacted by the numerous oil leak episodes, and the Goi community has been barred from human occupancy while the spills are cleaned up (Iruoma and Olurounbi 2020). Crude oil spills inject pollutants into the aquatic ecosystem, such as heavy metals, oil and grease, short-chain alkanes, and polyaromatic hydrocarbons (Kumar *et al*., 2019; Setia *et al*., 2020).

Environmental quality evaluation indices are effective tools for informing local managers and decision-makers about potential contamination risks, which is necessary for the development of effective protection and management plans for surface water ecosystems (Haque *et al*., 2020). For managers, technicians, decision-makers, and the general public, environmental quality evaluation indices are crucial instruments for managing, evaluating, and communicating unprocessed environmental data (Kumar *et al*., 2019). Thus this study determined some physicochemical properties and metal concentrations of surface water from Goi Creek in order to offer information on the quality status, reasons of contamination, and risk to humans. By comparing water quality to national and international standards, the study provides baseline data required for environmental monitoring, community health protection, and sustainable water resource management.

2.0 Materials and Methods

2.1 Area of Study

The study area is Goi Creek in Goi Community, Gokana Local Government Area, River State (Fig. 1). The town is one of the most impacted by Ogoniland's oil drilling operations (Nnoli *et al*., 2021), situated between latitude 4º42’45.631” N and longitude 7º14’8.1025” E at an elevation of 13 meters above sea level (Table 1). The watercourse is replenished by Kpor watercourse, Bodo Creek, and Goi Spring. The people's only supply of fresh water is the spring, even though they can get it from the stream during low tide. The tide goes westward and then returns toward the eastern part of the stream as it recedes. Because the area is an intertidal zone with unidirectional water flow, there are discernible differences in low and high tides. Tidal regimes have caused oil scum to spread rapidly along Goi Creek and the network of adjacent Creeks. It has two different seasons, just like the rest of Nigeria: the dry season, which runs from October to March, and the rainy season, which runs from April to September (Vincent-Akpu *et al*., 2015). The dry season, which lasts from October to March, is when the Hamattan from northern Nigeria arrive.

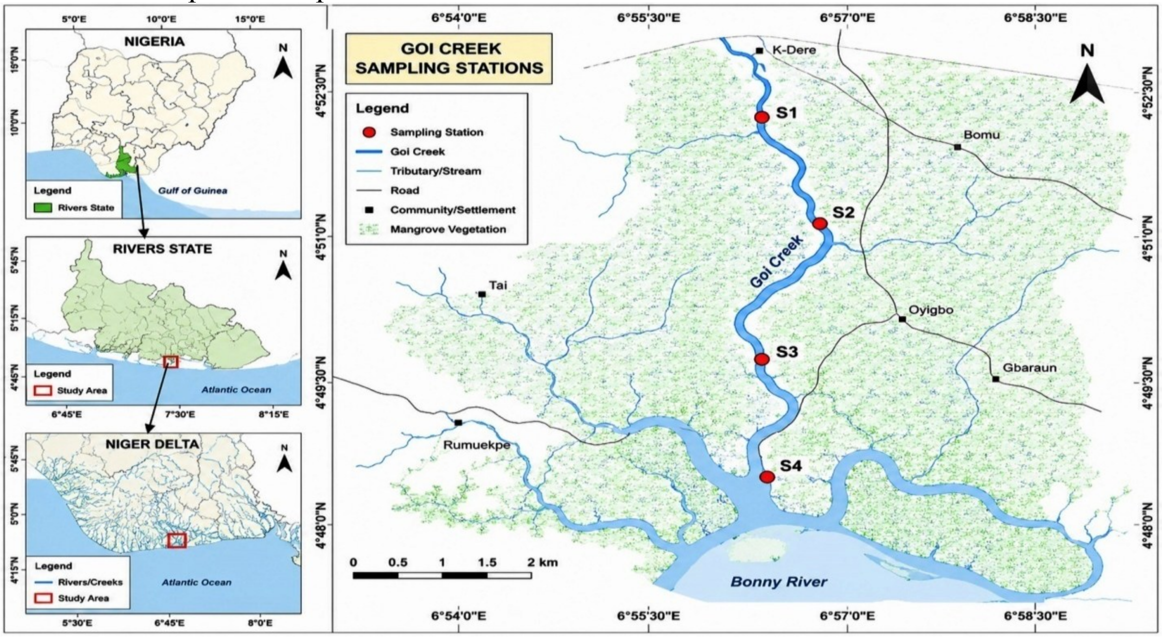
Table 1: Coordinates of Goi Community and the Sampling Points

Location	Latitude	Longitude	Elevation
Goi Community	N4º38’46.869”	E7º16’48.502”	13M
Sampling Station One	N4º37’17854”	E7º16’11415”	9M
Sampling Station Two	N4º33’40.167”	E7º15’25.867”	4M
Sampling Station Three	N4º38’26.330”	E7º9’39.317”	10M
Sampling Station Four	N4º30’15.179”	E7º18’43.954”	13M

2.2 Sample Stations

For this experiment, three specific locations were chosen downstream from the creek's source. Station 1 was located around 128 kilometers from the creek source, whereas Stations 2, 3, and 4 were about 1.5 kilometers distant (Fig. 1).

The main channel of Bodo Creek is about 128 kilometers from Station 1. The bottom substrates at this site were mostly composed of sand and clay. The main activity at this station is fishing. The water velocity at this location is rather modest, with a mean of 0.25 m/s. The water is around three meters deep. The distance between Station 1 and Station 2 is roughly 1.5 kilometers. Here, the water velocity is about 0.40 m/s and the riverbed is composed of silt and sand. Human activities that occur here include the transportation of boats, the disposal of both organic and inorganic trash, the transportation of logs, the washing and laundering of boats, and the offloading and sale of goods and petroleum products. The water is around one meter deep. Stations 2 and 3 are roughly 1.5 kilometers apart. At these stations, the substratum is composed of sand and the main activities include fishing, gaming, and open defecation. The water velocity at this location is around 0.90 m/s and the water is around 1.50 meters deep. Near Kpor Creek is where station 4 is located and is about two kilometers apart from station 3. This creek is used as a fishing camp in Goi. The lowest substratum is composed of sand, clay, and decaying leaves. The main activity at this station is fishing. The water velocity at this location is rather modest, with a mean of 0.30 m/s. The water is around two meters deep.



3

Fig. 1 Map of Study area showing the sampling stations

2.2 Sampling and Sample Collection

Samples of surface water were taken from certain spots along the Creek. The sampling locations were selected to record geographical differences in water quality in connection to both community uses of the river and oil exploration and production activities. To reduce contamination, water samples were taken at each location in precisely cleaned polyethylene bottles that had been rinsed with river water. While samples for physicochemical analysis were kept in ice chests and brought to the lab for prompt examination, samples for heavy metal analysis were preserved with a few drops of strong nitric acid to avoid metal precipitation and adsorption onto container walls. From August 2023 to May 2024, monthly samplings were carried out.

2.3 Laboratory Analysis

A handheld digital pH meter (pHep, Hanna, USA) was used to measure the pH levels of the sample in-situ. Gravimetric measurements were used to determine total suspended solids (TSS) and total dissolved solids (TDS). Standard procedures were used to measure dissolved oxygen (DO), biochemical oxygen demand (BOD5), nitrate ($NO3^-$), hardness, and turbidity (APHA 2017). Samples were digested with nitric acid for the metals analysis, and atomic absorption spectrophotometry (PerkinElmer Model 3110) was used to quantify the results. Ten milliliters of 1 M nitric acid (90%, Sigma-Aldrich) were added to 100 milliliters of a water sample in a 250 milliliter conical flask. The mixture was reduced to around 25 mL by heating the flask in a digestion block at 150 °C. After that, it was taken out of the block, let to cool, filtered through Whatman No. 40 filter paper into a 100 mL volumetric flask, and then adjusted with 1 M nitric acid (Csuros and Csuros, 2002). Analytical standards for the corresponding metals were used to calibrate the apparatus. The working concentrations were obtained by serially diluting these standards (1000 mgL^{-1}). Following measurement, a calibration graph was created.

2.4 Quality control and statistical analysis

Analytical-grade acids were utilized in the analyses. The data were adjusted for any contaminants in the reagents or containers using procedural blanks. Every sample was examined three times, and the relative standard deviations (RSD) of each triplicate analysis were less than 10%. A spike recovery was used to validate the approach for metal analysis. The metal recovery percentages ranged from 89.2% to 101%. Analysed data are present in the mean ± standard deviation format. ANOVA was used to evaluate if the measure parameters were significantly different across the several sampled locations and time, with a p-value less than 0.05 ($p < 0.05$) taken as a statistically significant difference. Hierarchical cluster analysis, PCA and Pearson's correlation analysis were conducted to ascertain the interrelationships among the parameters investigated. This was done to offer dear insights on the possible sources and causes of pollution in Goi creek.

2.5 Water Quality Assessment

The overall water quality of Goi Creek was assessed using Water Quality Index, Metal Index, Heavy Metal Pollution Index as well as the Pollution Index. The weighted arithmetic water quality index approach (Eq. 1) as reported by Egun & Oboh (2021) was used to assess the WQI and compared with the reference standard set by SON (2017).

$$WQI = \frac{\sum_{i=1}^{n} W_i Q_i}{\sum_{i=1}^{n} W_i} \quad (1)$$

In equation 1 above, W_i represents the unit weight of the *i*th parameter, Qi stands for the quality rating scale of the *i*th parameter, while the number of parameters under consideration is denoted by *n*. The unit weight Wi is expressed in Eq. (2):

$$W_i = \frac{K}{S_i} \quad (2)$$

where S_i is the maximum allowable recommended standard for the *i*th parameter, and K is the proportionality constant, explained in equation 3,

$$K = \frac{1}{\sum(1/S_i)} \quad (3)$$

The quality rating, Qi, was obtained by using the expression given in equation 4

$$Q_i = \sum_{i=1}^{n} \frac{M_i - I_i}{S_i - 1_i} \times 100 \quad (4)$$

where M_i is the experimental value obtained for the *i*th parameter, Ii is the desirable/ideal value of the *i*th parameter in pure water (I_i = 0 for all parameters except pH with a value of 7.0) and dissolved oxygen (with a value of 14.6 mg L^{-1}), while Si represented the recommended standard value of the *i*th parameter. The quantity M_i–I_i is the numerical difference of the two values without regard to the algebraic sign.

WQI values are categorized into five classes based on the weighted arithmetic water quality index method (Tyagi *et al.* 2013) as follows: 0-25 (excellent water quality), 26-50 (good water quality), 51-75 (poor water quality), 76-100 (very poor water quality), and > 100 (water unsuitable for drinking).

The Heavy Metal Pollution Index (HPI) was calculated following the method of Prasad and Bose (2001) as described in equation 5:

$$HPI = \frac{\sum(Q_i W_i)}{\sum W_i} \quad (5)$$

where $HPI = \frac{M_i - I_i}{S_i - I_i} \times 100$, M_i represent the measured concentration, S_i is the WHO standard, and I the ideal value (0) for heavy metals and $W_i = \frac{I}{S_i}$. WHO (2022) drinking water standards were used for the statistical computation. Metal index (MI) of the analysed metals was calculated using equation 6

$$MI = \sum \frac{C_i}{MAC_i} \quad (6)$$

where C_i is the measured concentration of each metal (mg/L), and MAC denotes the maximum allowable concentration (WHO drinking water guideline). Pollution index (PI) of the individual heavy metals analyzed from the samples were calculated according to equation 7

$$PI = \frac{C_i}{S_i} \quad (7)$$

where C_i denotes the measured concentration (mg/L), and Si represents the permissible limit (mg/L) of the water quality guidelines.

2.5 Human health risk assessment of heavy metals in water

The non-cancer and cancer risk assessment from pollutants in water was evaluated as the hazard index and total cancer risk, respectively. The hazard index and total cancer risk were evaluated for ingestion exposure route. Chronic Daily Intake (CDI), Hazard Quotient (HQ), Hazard Index (HI), and Lifetime Cancer Risk (CR) were estimated separately for adults and children. The calculation was executed using equations 8, 9 and 10.

For the non-cancer risk,

$$HHI = \sum HQ \quad (8)$$

$$HQ = \frac{CDI_{nc}}{RfD} \quad (9)$$

$$CDI_{ing-nc} = \frac{C \times IngR \times EF \times ED}{BW \times AT_{nc}} \times 10^{-6} \quad (10)$$

For cancer risk

$$Risk_{ing} = \frac{C \times IngR \times EF \times ED \times CF \times SFO}{BW \times AT_{ca}} \times 10^{-6} \quad (11)$$

The computation of hazard index and total cancer risk was carried out using the parameters listed in Tables 2 and 3, respectively. A hazard index value less than 1 indicates that there is no adverse non-carcinogenic risk, while a hazard index value greater than 1 indicates the presence of adverse non-carcinogenic risks. A total cancer risk value less than 1×10^{-6} indicates no cancer risk but values greater than 1×10^{-6}, it indicates a cancer risk (USEPA, 2010). The criteria of risk for each of the model used are interpreted in Table 4.

Table 2: Human Health Risk Assessment Exposure Parameters

Parameter	Adult	Child
Body weight (BW)	70 kg	15 kg
Water ingestion rate (IR)	2.0 L/day	1.0 L/day
Exposure frequency (EF)	365 days/year	365 days/year
Exposure duration (ED)	30 years	6 years
Averaging time (AT, non-cancer)	ED × 365	ED × 365
Averaging time (AT, cancer)	70 × 365 days	70 × 365 days

Table 3: US EPA Oral Reference Doses (RfDs) and CSF

Metal	RfD (mg/kg/day)	CSF $(mg\ kg^{-1}\ day^{-1})^{-1}$
Fe	0.70	-
Zn	0.30	-
Mn	0.14	-
Cu	0.04	-
Ni	0.02	0.84
Cd	0.0005	6.1
Cr	0.003	0.5
Pb	0.0035	NA
Hg (Inorganic)	0.0003	NA
As (Inorganic)	0.0003	1.5

Table 4: Risk interpretation criteria

Index	Threshold	Interpretation
THQ/HI	< 1	No significant non-carcinogenic risk
THQ/HI	≥ 1	Potential health concern
CR	10^{-6}-10^{-4}	Acceptable/tolerable risk range
CR	> 10^{-4}	Unacceptable cancer risk
MPI	<2	Low
	2–5	Moderate
	5–10	High
	>10	Severe
HPI	<25	Excellent
	25–50	Good
	50–75	Poor
	75–100	Very Poor
	>100	Critical Pollution
MI	<0.3	Very Pure
	0.3–1.0	Pure
	1.0–2.0	Slightly Affected
	2.0–4.0	Moderately Affected
	4.0–6.0	Strongly Affected
	>6.0	Seriously Affected
PI	≤1	Low / No Pollution
	1–2	Moderate Pollution
	2–3	Considerable Pollution
	>3	High Pollution

3.0 Results and Discussion

3.1 Physicochemical characteristics of water samples collected from Goi Creek

The physicochemical characteristics of water samples collected from Goi Creek are presented in Table 5. Since temperature can either directly or indirectly affect other parameters and aquatic creatures, it is one of the most important parameter used in determining the quality of an aquatic environment (Kale 2016; Edori *et al.*, 2020). Elevated temperatures cause water to become more turbid, which inevitably slows down the rate of light penetration. This can skew the food chain by counteracting the photosynthetic process of primary producers. There was no discernible regional fluctuation in the water temperature, which varied from 21.10±5.02°C at Station 3 to 23.40±4.67°C at Station 1 ($p = 0.646$). When compared to the water temperature range of 28.30-29.80°C reported by George *et al.* (2009) in Okpoka Creek, Niger Delta, these readings were lower. This discrepancy may be the consequence of heat energy being transferred from the sun by tree leaves and other barriers. Similarly, pH readings (6.18-6.55) were generally within or near the WHO/USEPA-recommended range (6.5-8.5) and were statistically consistent across sites ($p = 0.173$). Several aquatic ecologists have previously indicated that Nigerian rivers are acidic (Ndinwa *et al.,* 2014; Omoigberale *et al.,* 2013). The amount of heavy metals likely present in water or sediment can be inferred from pH levels. Nnoli *et al*. (2021) found that Goi Creek in Ogoni land had a pH of 6.55. The average pH values found in this study are comparable to those found in Sagbama Creeks by Iyama *et al*. (2019), but they differ from those found in Bomadi Creek, Delta

State, by Iwegbue *et al*. (2023), who reported somewhat alkaline values (7.40-8.17).

The concentrations of dissolved oxygen (DO) ranged from 7.75±1.42 to 11.39±4.64 mg/L, staying over the minimum recommended level of 5 mg/L. Additionally, there were no significant variations between stations for alkalinity, chloride, sulphate, salt, or magnesium ($p > 0.05$). The concentration of dissolved oxygen (DO) in natural waterways is influenced by the water body's physical, chemical, and biological processes. Temperature, depth, flow velocity, salinity, and water body pressure all affect oxygen levels (Edori and Nna, 2018).

Table 5(a): Physicochemical Characteristics of Water Samples across the Four Stations

Parameter	Station 1	Station 2	Station 3	Station 4	*p*-value	STD*
Water temperature	23.40±4.67 (18.00-30.00)	21.80±4.64 (18.00-29.00)	21.10±5.02 (16.00-30.00)	23.10±3.98 (18.00-30.00)	0.646	-
Turbidity (NTU)	9.43±2.43 (7.55-13.89)	10.14±3.35 (7.33-16.39)	9.08±1.49 (7.75-12.52)	9.85±2.38 (7.99-15.21)	0.791	0.5-1.0 / <5.0
TDS (mg/L)	53.92±9.23 (35.50-64.50)	77.35±17.39 (52.00-102.13)	80.10±16.83 (43.00-108.50)	103.23±10.77 (88.50-120.50)	<0.001	500
TSS (mg/L)	17.56±7.51 (6.16-27.23)	25.35±5.38 (18.59-32.99)	21.69±6.27 (11.01-30.02)	25.34±6.90 (13.33-34.19)	0.035	500
pH	6.55±0.33 (5.98-6.95)	6.18±0.34 (5.55-6.53)	6.44±0.47 (5.59-6.99)	6.32±0.40 (5.44-6.75)	0.173	6.5-8.5
EC (μS/cm)	117.01±21.48 (91.26-164.52)	167.33±35.77 (128.31-218.94)	180.08±21.74 (149.74-217.10)	200.72±27.20 (162.51-241.27)	<0.001	1000
Alkalinity	31.94±5.77 (23.21-42.33)	34.85±4.88 (28.94-46.21)	30.07±3.92 (22.72-36.31)	35.24±5.04 (30.27-46.77)	0.078	100
DO (mg/L)	9.82±3.53 (6.53-15.58)	11.39±4.64 (7.21-19.68)	7.75±1.42 (5.74-10.74)	8.58±1.32 (7.51-11.56)	0.063	>5
BOD (mg/L)	4.65±1.54 (2.32-6.13)	5.83±2.23 (2.96-8.79)	6.21±1.72 (2.77-8.70)	4.49±2.77 (1.58-7.89)	0.202	3
Cl (mg/L)	114.42±46.18 (33.11-185.23)	119.17±44.85 (39.87-188.67)	125.91±40.92 (48.32-176.44)	136.00±45.57 (44.00-192.11)	0.723	250
SO_4^{2-} (mg/L)	22.15±23.30 (5.67-76.65)	30.21±27.41 (6.34-85.27)	25.19±14.58 (9.56-56.13)	40.02±28.10 (6.05-77.21)	0.375	250
NO_3^- (mg/L)	3.56±1.17 (2.01-5.12)	4.94±1.55 (1.78-6.68)	7.10±3.44 (1.03-11.28)	5.74±1.87 (1.67-7.71)	0.008	-
PO_4^{3-} (mg/L)	2.94±0.82 (1.32-4.11)	3.85±1.00 (2.17-5.16)	6.97±3.06 (1.25-10.85)	8.24±3.49 (1.05-12.05)	<0.001	10

It is a very useful indicator for assessing a water's purity and safety. According to WHO (2005) standards, a BOD of between 1.0 and 2.0 mg/L indicates clean water, a BOD of 3.0 mg/L shows fairly clean water, while a BOD of 5.0 mg/L shows unclean water. Water with BOD at 10.0 is highly contaminated. The BOD values obtained in this study are higher than those reported by Ayobahan *et al*. (2014) (2.78 to 3.58 mg/l). Increase human activity at the sampling locations in this study may be responsible for this discrepancy.

Excess calcium (Ca^{2+}) can harm the kidneys and affect water hardness, whereas too much magnesium in the water can make it hard and increase the risk of cardiovascular death (Nnoli *et al.,* 2021). With the exception of Mg concentration in station 3, the trends in K, Na, Ca, and Mg content in this study were noted to accumulate in station 4. In a portion of the Oji River and its surroundings in Enugu State, Oghenenyoreme and Njoku (2014) found lower levels of the minerals (4.2 mg/L for Ca, 3.5 mg/L for Mg, and 2.1 mg/L for K).

Table 5(b): Major Ions, Trace Metals and Total Hydrocarbon Concentrations across the Four Stations

Parameter	Station 1	Station 2	Station 3	Station 4	*p*-value	STD*
Na (mg/L)	12.96±11.05 (4.97-37.13)	16.70±16.17 (5.28-54.21)	21.95±10.87 (5.32-42.16)	22.45±27.42 (5.43-78.98)	0.586	200
K (mg/L)	14.77±5.35 (8.52-26.11)	19.01±6.25 (11.67-32.11)	25.98±8.46 (12.04-38.90)	16.15±14.33 (7.24-46.89)	0.049	-
Mg (mg/L)	2.91±1.28 (1.22-5.61)	3.65±1.76 (1.36-7.84)	4.06±2.24 (1.08-6.94)	3.78±2.35 (1.78-7.89)	0.597	-
Ca (mg/L)	31.16±13.87 (11.12-52.11)	45.25±10.60 (31.21-61.17)	29.94±7.68 (21.55-43.22)	48.68±8.01 (32.22-59.57)	<0.001	-
Fe (mg/L)	2.93±2.68 (0.78-7.44)	9.39±4.16 (1.06-13.24)	3.89±3.26 (0.95-9.70)	10.83±3.98 (2.21-14.70)	<0.001	0.3
Zn (mg/L)	2.54±1.53 (0.75-5.11)	4.24±3.75 (0.96-10.31)	2.25±1.83 (1.06-6.89)	4.75±3.84 (1.23-11.13)	0.171	3-5
Mn (mg/L)	2.17±1.29 (0.95-4.32)	2.75±1.61 (1.22-5.70)	1.12±0.44 (0.48-1.80)	2.90±1.04 (1.01-4.98)	0.007	0.5
Cu (mg/L)	1.93±0.93 (1.10-3.59)	2.10±0.77 (1.54-3.86)	1.61±0.52 (0.84-2.41)	2.73±1.07 (1.21-4.12)	0.041	1.3-2
Ni (mg/L)	1.79±1.04 (0.37-3.36)	2.39±1.51 (0.48-4.65)	0.90±0.48 (0.11-1.56)	2.88±0.96 (1.32-4.57)	0.001	0.02
Cd (mg/L)	0.85±0.38 (0.13-1.31)	1.19±0.63 (0.12-2.11)	0.37±0.42 (0.06-1.01)	1.31±0.77 (0.04-2.18)	0.004	0.003
V (mg/L)	1.08±0.53 (0.13-1.81)	1.07±0.49 (0.15-1.56)	1.29±0.33 (0.65-1.87)	1.25±0.66 (0.19-2.01)	0.680	0.005
Cr (mg/L)	1.43±0.55 (0.50-2.01)	1.91±1.04 (0.61-3.68)	1.33±0.32 (0.80-1.99)	2.49±1.16 (1.26-4.41)	0.015	0.1
Pb (mg/L)	0.86±0.42 (0.10-1.22)	1.62±1.03 (0.12-3.22)	0.85±0.44 (0.16-1.28)	1.71±0.83 (0.25-2.45)	0.013	0.01
Hg (mg/L)	0.05±0.03 (0.02-0.09)	0.06±0.03 (0.02-0.10)	0.07±0.02 (0.04-0.10)	0.08±0.02 (0.05-0.10)	0.061	0.001
As (mg/L)	0.83±0.37 (0.38-1.45)	1.45±0.51 (0.54-1.95)	0.90±0.60 (0.09-1.61)	1.51±0.49 (0.66-2.11)	0.005	0.01
Total hydrocarbons	52.66±16.40 (30.35-83.33)	62.88±21.47 (40.32-103.22)	33.51±10.35 (22.54-56.12)	68.73±22.28 (41.65-106.00)	<0.001	-

Note: STD* = USEPA/WHO 2004/2011

Numerous physicochemical characteristics showed notable geographical variations. Although all readings were considerably below the allowable limit of 500 mg/L, total dissolved solids (TDS) increased significantly from 53.92±9.23 mg/L at Station 1 to 103.23±10.77 mg/L at Station 4 ($p < 0.001$). Similar to other stations, electrical conductivity (EC) increased significantly (117.01-200.72 µS/cm; $p < 0.001$), but it was still below the suggested guideline limit of 1000 µS/cm. While Edori *et al*. (2019) and Anweting *et al.* (2024) found higher EC values of 26,567 µS/cm and 73.70 µS/cm in the surface water of the Silver River in Bayelsa and Idim Idaang Stream in Ibiono Ibom, Akwa Ibom State, Nigeria, Okorafor *et al.* (2014) found lower EC values of 12.15 and 11.65 µs/cm upstream and downstream of the Lower Qua Iboe River in Akwa Ibom State. According to Linden and Palsson (2013), electrical conductivity in their investigation was consistently poor and was directly impacted by the tides. The EC values of the sampled stations in this investigation varied significantly ($p>0.05$).

The substance in water that impacts the water's transparency or light scattering is called total suspended solids (TSS), and it is usually made up of organic compounds, plankton, fine clay or silt particles, or other microorganisms (Edori and Kpee, 2016). While nitrate ($p = 0.008$), phosphate ($p < 0.001$), potassium ($p = 0.049$), and calcium ($p < 0.001$) showed notable geographical fluctuations, the values obtained varied considerably between stations ($p = 0.035$). Despite the lack of significant differences ($p = 0.202$), biological oxygen demand (BOD) ranged from 4.49±2.77 to 6.21±1.72 mg/L, above the suggested limit of 3 mg/L at all locations. All stations had turbidity values (9.08-10.14 NTU) that were higher than WHO guidelines. High turbidity in a water body usually results from increase amount of suspended as well as dissolved particles (Edori *et al*., 2019).

In this study, station 2 recorded a higher turbidity value than the other stations. Increase in particulate matter accompanying runoffs during the rainy season, with corresponding increase in suspended solids could be the reason for this observation (Okorafor *et al*., 2014). In a similar study carried out in the Silver River in Bayelsa State, Edori *et al*. (2019) reported lower values (15.57 NTU) and attributed their findings to the increased amount of dissolved organic and inorganic solids in the river. High turbidity do not only decrease the appearance of surface water, but also blocks the penetration of light, which in turn hinders photosynthesis and leads to the destruction of aquatic life (Gupta *et al*., 2017). The parameter that accounts for the amount of organic and inorganic materials in water bodies is known as total dissolved solids (TDS) (Edori *et al*., 2019). For stations 1, 2, 3, and 4, the average mean TDS levels were 53.92, 77.35, 80.10, and 103.23 (mg/L), respectively. While Akhionbare *et al*., (2019) reported higher TDS values (142-352 mg/L) for Forcados River in Delta State; Edori *et al.* (2019) found lower values (13.250 mg/L) in surface water of Silver River in Bayelsa State.

Concentrations of heavy metals showed that the watercourse was heavily contaminated. Iron concentrations (2.93-10.83 mg/L) substantially above the allowable limit of 0.3 mg/L and varied significantly between sites ($p < 0.001$). The levels of manganese ($p = 0.007$), copper ($p = 0.041$), nickel ($p = 0.001$), cadmium ($p = 0.004$), chromium ($p = 0.015$), lead ($p = 0.013$), and arsenic ($p = 0.005$) varied considerably between stations and were higher than the corresponding WHO/USEPA guideline values. Although observed amounts of vanadium and mercury remained significantly above suggested limits, there were no significant geographical differences ($p > 0.05$). Zinc concentrations did not significantly vary between stations and were either within or near the allowable range ($p = 0.171$). The total concentration of heavy metals in the water at each sampling point was as follows: Fe > Zn > Mn > Cu > Ni > Cr > Pb > As ≈ V > Cd > Hg. Mercury was found at the lowest concentrations (0.05±0.03-0.08±0.02 mg/L), while iron was the most prevalent metal at every location, with concentrations ranging from 2.93±2.68 to 10.83±3.98 mg/L. Although there is some fluctuation in the order of occurrence, this trend is consistent with reports from other rivers in the Niger Delta. For example, Wogu and Okaka (2011) discovered Fe > Mn > Zn > Cu > Ni > V > Cr > Cd > Pb in the Warri River, whereas Oribhabor and Ogbeibu (2009) reported Mg > Ca > Fe > Zn > Ni > Cr > Pb > Cd in a Niger Delta mangrove creek.

Anweting *et al.* (2024) found Zn > Fe > Cu > Mn > Cd > Pb > Cr > Ni > Co > Hg = As in surface water from Idim Idaang Stream in Ibiono Ibom, Akwa Ibom State, Nigeria, while Adewuyi and Olowu (2012) found Cu > Zn > Pb > Cd > Ni > Cr in surface waters close to the NNPC oil depot in Ibadan. In practically every study conducted to date, the concentration level of iron (Fe) in the environment has remained at the top when compared to the concentration levels of other heavy metals in surface water. According to Enuneku *et al.* (2017), this may be mostly caused by the effluents the river receives from numerous iron-based companies situated along its banks as well as Fe, which is present throughout our surroundings. Given that iron is the fourth most common metal in the earth's crust, its dominance may also have come from the bedrock (Wright and Welbourn., 2002). The concentrations of total hydrocarbons (THC) differed substantially between sampling sites ($p < 0.001$), with Station 4 having the greatest concentration (68.73 ± 22.28 mg/L) and Station 3 having the lowest (33.51 ± 10.35 mg/L). In comparison to the other sampling locations, Station 4 consistently showed higher amounts of several physicochemical parameters, heavy metals, and hydrocarbons, indicating a higher level of anthropogenic contamination. The THC levels found in this study were lower than those found by Wokoma (2014) in a contaminated tidal creek of the Bonny River and greater than those found by Howard *et al.* (2009) in an oil-polluted mangrove wetland in the Niger Delta. Conversely, the THC levels found in the current study are much lower than the mean value of 149 mg/L reported by Eja and Orji (2003) in the coastal regions of South Eastern Nigeria. Ogoniland's frequent crude oil spills are most likely the cause of the high THC levels in the water tests (FEI 2019). Long-term or chronic exposure to petroleum hydrocarbons has been linked to health impacts such as reduced immunological function, severe kidney, central nervous system/respiratory depression, cardiac arrhythmias, and liver damage (Fowzia and Fakhruddin, 2018; Kuppusamy *et al,.* 2020). Aquatic plants and animals are adversely affected by high THC concentrations (Edori *et al.,* 2019). High THC concentrations in surface water prevent oxygen from diffusing into the water, which lowers oxygen concentrations. Furthermore, because the oil covers the surface of their respiratory organs, fish and other aquatic species find it difficult to use the dissolved oxygen in their surroundings. High THC concentrations in water inhibit the growth of aquatic plants, which has an impact on the value and overall production of phytoplankton.

3.2 Spatial variation of water quality parameters across sampling stations

To determine whether water quality differed significantly among the four sampling stations (S1-S4), a one-way Analysis of Variance (ANOVA) was performed for each measured parameter and the result is shown in Table 6.

The strongest spatial differences were observed for TDS, electrical conductivity, iron, phosphate, and total hydrocarbon content, indicating that contamination is not uniformly distributed across Goi Creek. Total dissolved solids exhibited the greatest spatial variation ($F = 20.67$, $p < 0.001$), with concentrations increasing progressively from Station 1 to Station 4. Electrical conductivity also differed significantly among stations ($F = 17.18$, $p < 0.001$), indicating spatial differences in ionic composition.

The spatial heterogeneity of iron was higher compared to the other heavy metals assessed ($F = 12.14$, $p < 0.001$). Its mean concentrations at Stations 2 and 4 were considerably higher than those at Station 1. A similar pattern was observed for Phosphate and calcium. For Total hydrocarbon, significant difference ($F = 7.17$, $p < 0.001$) was observed between the stations and the values content increased downstream, which suggests localized hydrocarbon inputs. Noteworthy differences across the sampling stations were also recorded for cadmium, nickel, manganese, and arsenic, showcasing different degrees of contamination all through the creek.

In all, the highest level of many of the contaminants assessed were recorded in Station 4. In contrast, Station 1 recorded the lowest values.

The meaningful variability of measured parameters across the sampling stations show that the input of pollutants in the Creek is not evenly distributed but rather localized. Furthermore, the increase levels of cadmium, arsenic, iron, nickel and total hydrocarbons at stations located downstream are in consonance with the effects of oil production activities and surface runoffs, which are recognized hydrocarbon residue sources in the Niger Delta.

Table 6: Summary of One-way ANOVA for Selected Water Quality Parameters

Parameter	Mean (S1)	Mean (S2)	Mean (S3)	Mean (S4)	F-value	p-value
TDS (mg/L)	53.92	77.35	80.10	103.23	20.67	<0.001
EU (µS/cm)	117.01	167.33	171.50	200.72	17.18	<0.001
Iron (Fe, mg/L)	2.93	9.39	8.06	10.83	12.14	<0.001
Phosphate (mg/L)	2.94	3.85	5.62	8.24	10.87	<0.001
Calcium (mg/L)	31.16	45.25	43.94	48.68	8.60	<0.001
Total Hydrocarbon Content (mg/L)	52.66	62.88	64.79	68.73	7.17	<0.001
Nickel (mg/L)	1.79	2.39	2.43	2.88	6.39	0.001
Cadmium (mg/L)	0.85	1.19	1.11	1.31	5.38	0.004
Arsenic (mg/L)	0.83	1.45	1.19	1.51	5.13	0.005
Manganese (mg/L)	2.17	2.75	2.49	2.90	4.72	0.007

3.3 Seasonal variation in physicochemical parameters and heavy metals in Goi Creek

The result of the seasonal variation of measure parameters from water samples of Goi Creek is presented in Table 7. There was a significantly higher water temperature in the dry season compared to the rainy season ($p < 0.001$). Conversely, turbidity increase significantly in the wet season and this reflects increase surface runoff and the transportation of rainfall-associated sediments. It is widely reported that in tropical region, turbidity of water bodies usually increases in the wet season as a result of increase in rainfall intensity. pH was slightly acidic in the two seasons, but was significantly reduced in the wet season compared to the dry ($p < 0.05$). This indicates increased dilution by acidic runoff and the organic matter decomposition.

The concentrations of chromium, iron, lead, cadmium, and total hydrocarbon content were higher during the wet season, but not significantly different from the values recorded in the dry season ($p > 0.05$). thus, the concentration of heavy metals was fairly consistent all through the year with very little fluctuations due to the seasons.

Table 7: Seasonal variation in physicochemical parameters and heavy metals in Goi Creek

Parameter	Wet Season (Mean ± SD)	Dry Season (Mean ± SD)	t-value	p-value
Temperature (°C)	20.9±2.8	25.6±3.6	4.11	<0.001
pH	6.18±0.31	6.46±0.42	2.21	0.033
Turbidity (NTU)	11.84±2.56	8.68±1.79	4.58	<0.001
TDS (mg/L)	70.82±20.17	82.01±22.91	1.63	0.111
EC (µS/cm)	149.37±32.10	171.84±38.77	2.02	0.051
DO (mg/L)	Higher	Lower	-	<0.05
BOD (mg/L)	Higher	Lower	-	<0.05
Fe (mg/L)	8.72±2.91	7.41±3.08	1.39	0.173
Pb (mg/L)	1.62±0.54	1.39±0.47	1.44	0.158
Cd (mg/L)	1.02±0.33	0.86±0.27	1.71	0.096
Cr (mg/L)	2.08±0.64	1.81±0.52	1.47	0.149
THC (mg/L)	69.47±13.62	60.85±15.93	1.88	0.068

The correlation among measured parameters in water from Goi Creek is presented in Table 8. There was a strong negative correlation between TSS and pH ($r = -0.850$), which can be interpreted to mean that increasing acidity of the water was associated with increasing particular matter. For the heavy metals, the strongest positive relationship was seen between manganese and nickel (r = 0.860). Strong positive correlation was also observed between cadmium whereas Zinc has a strong correlation total hydrocarbon content (r = 0.860) and between Zinc and chromium (r = 0.840). Also, nickel had a strong positive correlation with total hydrocarbon content (r = 0.829).

The result show that most of the metals originated from a common pollution event and share similar transportation mechanisms. Heavy metals in oil-producing regions such as the Niger Delta, Nigeria have been commonly correlated as they are associated with oil production and exploration activities.

3.4 Principal Component Analysis

The result of Principal component analysis is shown in Table 9. Five principal components which accounts for 76.49% of the total variance in the water quality dataset were extracted. The first principal component (PC1) (40.51%) was dominated by total hydrocarbon content, zinc, chromium, lead, nickel, cadmium, manganese, iron, and copper. This suggests that these variables are closely associated and most likely have a common source.

PC2, accounting for 12.52% of the total variance, was primarily associated with copper, lead, zinc, manganese, and alkalinity, indicating additional geochemical controls on the mobility of the metals. PC1 and PC2 accounted for 53.03% of the variability of the entire dataset and suggests that a fairly small number of petroleum-related activities factors are responsible Goi Creek's water quality. The grouping of total hydrocarbon content with Zn, Cd, Cr, Pb, Ni, Fe, Mn, and Cu signposts that these pollutants are introduced concurrently into the water, a phenomenon that is typical of oil-producing regions as a result of oil spills, artisanal refining and industrial wastes (Figs. 2 and 3).

3.5 Hierarchical cluster analysis

Fig. 4 shows the hierarchical cluster analysis result. The four sampling stations were grouped into two main clusters, Cluster one (Stations 1 and 2) and Cluster two (Stations 3 and 4), arising from similarities in water quality features. The clustering pattern shows that contamination is getting worse as it moves downstream.Three separate groups were also identified by cluster analysis of the measured variables. Heavy metals and overall hydrocarbon content made up the majority of the first cluster, indicating a shared human origin. Hydrochemical processes were reflected in the second cluster, which included dissolved ions and conductivity-related metrics. Physicochemical variables related to organic matter dynamics and environmental factors were included in the third cluster. The high correlation between Pb, Cd, Cr, Ni, Fe, Zn, Cu, Mn, and THC indicates that the main cause of contamination in Goi Creek is petroleum-related activity.

Table 10: PC1 (Dominant pollution factor)

Variable	Loading
Zn	0.260
THC	0.260
Cr	0.256
Ni	0.246
Alkalinity	0.244
Pb	0.244
Mn	0.232
Cu	0.231
Cd	0.221
Fe	0.213

Similar clustering patterns have been seen in oil-producing areas where hydrocarbons and trace metals are introduced into aquatic environments via pipeline leaks, drilling waste, and crude oil residues.

Table 8: Correlation of physicochemical parameters and heavy metals in water sampled from Goi Creek

Parameters	*Water temperature*	*Turbidity (NTU)*	*TDS (mg/L)*	*TSS (mg/L)*	*pH*	*EC (us/cm)*	*Alkalinity*	*DO (mg/L)*	*BOD (mg/L)*	*Cl (mg/L)*	*SO (mg/L)*	*NO (mg/L)*	*PO (mg/L)*	*Na (mg/L)*
Water temperature	1													
Turbidity (NTU)	0.2388	1												
TDS (mg/L)	-0.1315	0.3156	1											
TSS (mg/L)	-0.2993	0.6777	0.834	1										
pH	0.3256	-0.821	-0.55	-0.921	1									
EC (us/cm)	0.7384	-0.132	0.958	0.133	0.419	1								
Alkalinity	0.4013	0.9487	0.502	0.703	-0.733	0.202	1							
DO (mg/L)	0.154	0.7488	-0.37	0.148	-0.499	-0.64	0.533	1						
BOD (mg/L)	-0.9785	-0.233	-0.06	0.177	-0.278	-0.83	-0.446	-0.014	1					
Cl (mg/L)	0.724	-0.153	0.952	0.112	0.438	1	0.181	-0.654	-0.813	1				
SO (mg/L)	0.203	0.5957	0.915	0.824	-0.612	0.747	0.785	-0.086	-0.364	0.733	1			
NO (mg/L)	-0.7361	-0.352	0.635	0.447	-0.2	0.237	-0.285	-0.678	0.586	0.258	0.271	1		
PO (mg/L)	-0.1911	-0.152	0.888	0.52	-0.151	0.931	0.08	-0.756	-0.014	0.938	0.68	0.7968	1	
Na (mg/L)	-0.4194	-0.133	0.882	0.609	-0.283	0.836	0.038	-0.69	0.223	0.848	0.622	0.9065	0.969	1
K (mg/L)	-0.9426	-0.518	0.148	0.129	-0.055	-0.41	-0.606	-0.461	0.893	-0.39	-0.25	0.8415	0.353	0.535
Mg (mg/L)	-0.7463	-0.073	0.744	0.676	-0.472	0.179	-0.033	-0.47	0.595	0.2	0.436	0.958	0.771	0.905
Ca (mg/L)	0.2215	0.885	0.708	0.856	-0.812	0.303	0.963	0.354	-0.313	0.283	0.901	-0.015	0.318	0.301
Fe (mg/L)	0.0916	0.8337	0.787	0.921	-0.849	0.327	0.912	0.269	-0.201	0.307	0.923	0.134	0.418	0.424
Zn (mg/L)	0.2698	0.8864	0.691	0.83	-0.785	0.324	0.971	0.358	-0.358	0.304	0.899	-0.052	0.303	0.275
Mn (mg/L)	0.5866	0.9177	0.321	0.51	-0.573	0.21	0.97	0.597	-0.599	0.189	0.667	-0.498	-0.082	-0.163
Cu (mg/L)	0.5914	0.6714	0.666	0.577	-0.429	0.668	0.871	0.098	-0.701	0.652	0.903	-0.147	0.406	0.272
Ni (mg/L)	0.5767	0.8724	0.479	0.584	-0.572	0.367	0.976	0.439	-0.628	0.347	0.79	-0.361	0.107	0.012
Cd (mg/L)	0.5531	0.918	0.399	0.57	-0.607	0.25	0.984	0.548	-0.582	0.23	0.727	-0.425	-0.002	-0.08
V (mg/L)	-0.3496	-0.511	0.653	0.229	0.132	0.674	-0.312	-0.925	0.171	0.69	0.343	0.8764	0.922	0.911
Cr (mg/L)	0.3797	0.7281	0.787	0.759	-0.611	0.612	0.898	0.108	-0.506	0.596	0.969	0.0268	0.491	0.41
Pb (mg/L)	0.152	0.8971	0.701	0.884	-0.856	0.229	0.953	0.384	-0.239	0.208	0.88	0.0127	0.3	0.303
Hg (mg/L)	-0.1904	0.0554	0.965	0.685	-0.349	0.991	0.269	-0.6	-0.015	0.993	0.802	0.758	0.977	0.962
As (mg/L)	0.0701	0.8701	0.741	0.922	-0.882	0.223	0.923	0.342	-0.166	0.202	0.887	0.0971	0.35	0.369
Total hydrocarbon	0.6038	0.8943	0.379	0.526	-0.556	0.287	0.972	0.529	-0.631	0.267	0.715	-0.456	-0.008	-0.101

Table 8: Correlation of physicochemical parameters and heavy metals in water sampled from Goi Creek (condt.)

Parameters	*K (mg/L)*	*Mg (mg/L)*	*Ca (mg/L)*	*Fe (mg/L)*	*Zn (mg/L)*	*Mn (mg/L)*	*Cu (mg/L)*	*Ni (mg/L)*	*Cd (mg/L)*	*V (mg/L)*	*Cr (mg/L)*	*Pb (mg/L)*	*Hg (mg/L)*	*As (mg/L)*	*Total hydrocarbon*
K (mg/L)															
Mg (mg/L)	1														
Ca (mg/L)	0.764	1													
Fe (mg/L)	-0.401	0.2334	1												
Zn (mg/L)	-0.262	0.3777	0.988	1											
Mn (mg/L)	-0.444	0.192	0.999	0.981	1										
Cu (mg/L)	-0.778	-0.271	0.872	0.789	0.892	1									
Ni (mg/L)	-0.638	0.0076	0.875	0.832	0.894	0.856	1								
Cd (mg/L)	-0.728	-0.146	0.919	0.852	0.937	0.981	0.937	1							
V (mg/L)	-0.738	-0.195	0.908	0.834	0.925	0.996	0.886	0.992	1						
Cr (mg/L)	0.581	0.7559	-0.07	0.047	-0.09	-0.46	0.043	-0.28	-0.39	1					
Pb (mg/L)	-0.463	0.2159	0.95	0.936	0.957	0.827	0.97	0.916	0.87	0.117	1				
Hg (mg/L)	-0.349	0.2699	0.997	0.992	0.992	0.852	0.833	0.893	0.888	-0.08	0.925	1			
As (mg/L)	0.287	0.7944	0.501	0.598	0.485	0.09	0.523	0.27	0.172	0.828	0.632	0.49	1		
Total hydrocarbon	-0.264	0.353	0.988	0.996	0.979	0.802	0.801	0.851	0.843	-0.02	0.911	0.996	0.539	1	
Water temperature	-0.774	-0.238	0.887	0.808	0.907	0.997	0.896	0.993	0.998	-0.39	0.865	0.863	0.157	0.814	1

Table 9: Principal Component Analysis

Principal Component	Variance Explained (%)	Cumulative (%)
PC1	40.51	40.51
PC2	12.52	53.03
PC3	9.08	62.11
PC4	7.72	69.83
PC5	6.66	76.49

Major loadings

Natural hydrochemical controls, such as weathering processes and tidal impacts, are reflected in the clustering of conductivity, TDS, sodium, chloride, and sulphate. The spatial heterogeneity of pollution is demonstrated by the distance between Stations 3 and 4 and Stations 1 and 2. Because of their close proximity to oil exploration infrastructure and areas impacted by persistent petroleum contamination, stations 3 and 4 seem to receive higher pollutant loads. Strong multivariate evidence that the observed contamination patterns are primarily manmade rather than naturally occurring is provided by the strong agreement between HCA, PCA, Pearson correlation, and ANOVA.

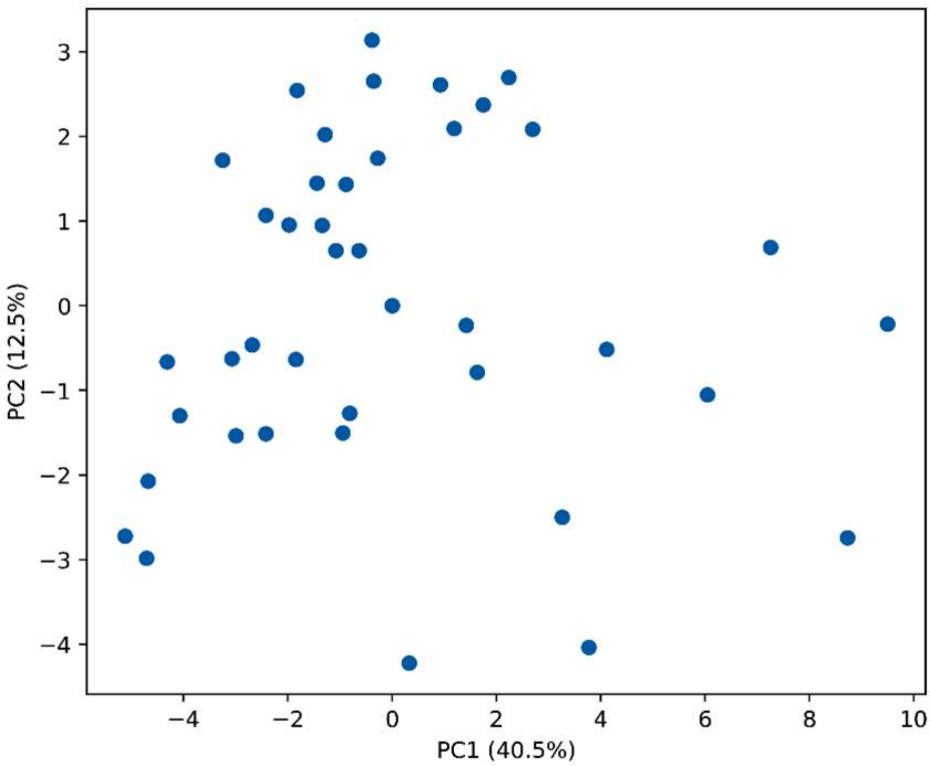


Fig. 2: PCA score plot (PC1 vs. PC2).

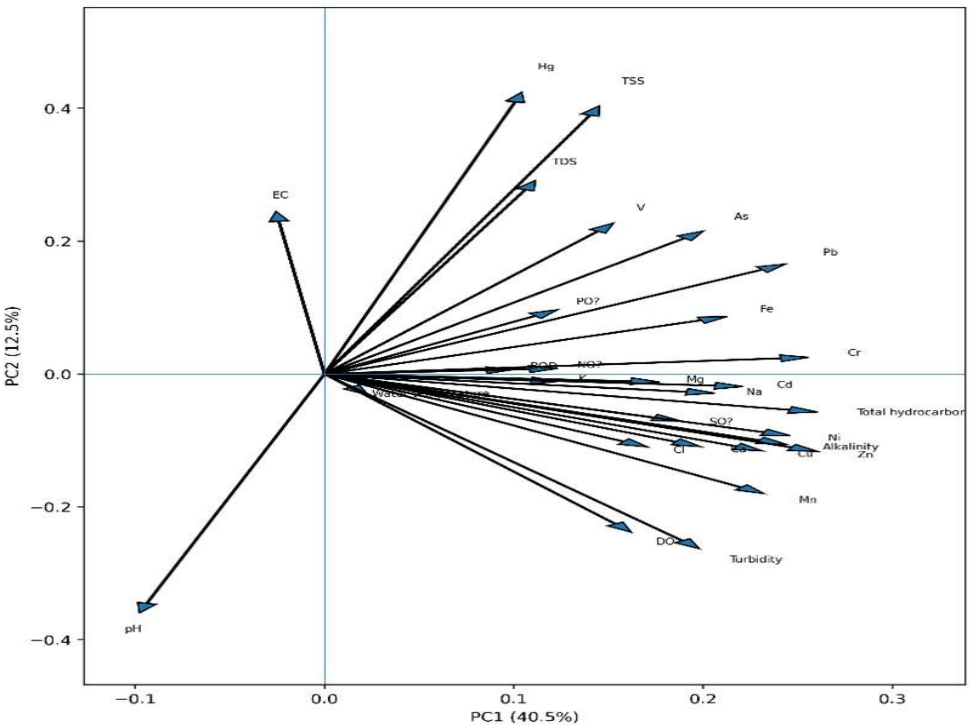


Fig. 3: PCA loading biplot

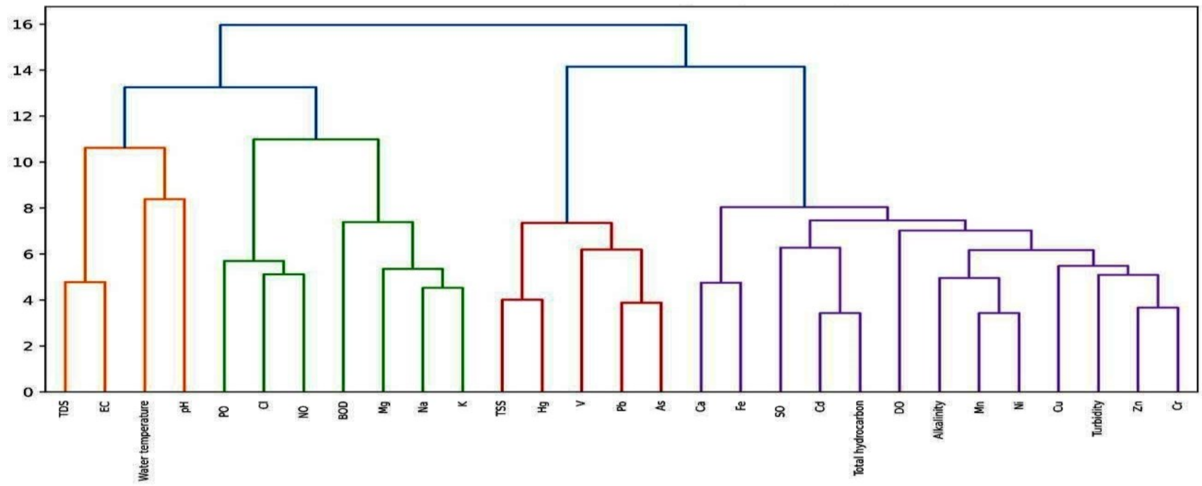


Fig. 4: Hierarchical clustering of sampling stations

3.6 Water Quality Assessment

The water quality was deemed unfit for human consumption due to the computed Water Quality Index (WQI) of 175.71, which was significantly above the threshold of 100. The cumulative effect of higher concentrations of multiple heavy metals, especially cadmium, lead, arsenic, chromium, nickel, and mercury, which significantly exceeded the World Health Organization (WHO) guideline values, is reflected in the calculated WQI. Iwegbue *et al*. (2023), who examined a water sample from Bomadi Creek in Delta State, found similar results. Nigeria. The creek was severely contaminated with heavy metals, as evidenced by the Heavy Metal Pollution Index (HPI), which was 176.05, well above the critical pollution threshold of 100. Cadmium, lead, arsenic, chromium, nickel, and mercury had a significant impact on the HPI, indicating significant human inputs into the aquatic ecosystem.

Table 10a. Calculated WQI values of water samples collected across the sampling stations along the Goi Creek, Rivers State, Nigeria (Physicochemical parameters)

Parameter	Mean Concentration	WHO Standard	Relative Weight (W_i)	Quality Rating (Q_i)	Sub-index (SI_i)
Temperature (°C)	22.35	-	-	-	-
Turbidity (NTU)	9.63	5	0.00059	192.54	0.11
TDS (mg/L)	78.65	500	0.000006	15.73	0.00
pH	6.37	8.5	0.00035	74.97	0.03
EC (µS/cm)	166.28	1000	0.000003	16.63	0.00
DO (mg/L)	9.39	5	0.00059	187.72	0.11
Chloride (mg/L)	123.88	250	0.000012	49.55	0.00
Sulphate (mg/L)	29.39	250	0.000012	11.76	0.00
Nitrate (mg/L)	5.34	50	0.000059	10.67	0.00
Sodium (mg/L)	18.51	200	0.000015	9.26	0.00

Note: WQI = Water Quality Index; TDS = total dissolved solids; WHO = World Health Organization; W_i = relative weight; Q_i = quality rating; SI_i = sub-index.

Table 10b. Calculated WQI values of water samples collected across the sampling stations along the Goi Creek, Rivers State, Nigeria (heavy metal)

Parameter	Mean Concentration	WHO Standard	Relative Weight (W_i)	Quality Rating (Q_i)	Sub-index (SI_i)
Fe (mg/L)	6.76	0.30	0.00983	2252.50	22.14
Zn (mg/L)	3.45	3.00	0.00098	114.88	0.11
Mn (mg/L)	2.24	0.40	0.00737	558.94	4.12
Cu (mg/L)	2.09	2.00	0.00147	104.65	0.15
Ni (mg/L)	1.99	0.07	0.04214	2846.43	119.95
Cd (mg/L)	0.928	0.003	0.98339	30,933.33	30,419.96
Cr (mg/L)	1.79	0.05	0.05899	3582.00	211.30
Pb (mg/L)	1.263	0.01	0.29498	12,630.00	3725.57
Hg (mg/L)	0.0627	0.006	0.49170	1044.58	513.65
As (mg/L)	1.175	0.01	0.29498	11,750.00	3466.87

Note: WQI = Water Quality Index; TDS = total dissolved solids; WHO = World Health Organization; W_i = relative weight; Q_i = quality rating; SI_i = sub-index.

Goi Creek is severely impacted by heavy metal pollution and is unfit for human consumption, according to the Metal Index (MI) (Table 11), which was determined to be 65.81, far higher than the crucial limit of 6.0. Lead, arsenic, chromium, nickel, and cadmium made up the biggest share of the total metal burden. Iron (22.53), manganese (5.59), nickel (28.46), cadmium (309.33), chromium (35.82), lead (126.30), mercury (10.45), and arsenic (117.50) all showed high pollution levels (PI > 3), according to the Pollution Index (PI) (Table 12). Conversely, copper (1.05) and zinc (1.15) were categorized as moderately contaminated. After lead and arsenic, cadmium had the highest contamination index, surpassing the WHO permitted limit by more than 300 times.

Goi Creek water's Metal Index (MI) was determined to be 65.88, significantly above the critical threshold of 6.0, suggesting serious heavy metal contamination. About 47.0% of the total MI came from cadmium, with lead coming in second at 19.2% and arsenic at 17.9%. While zinc and copper contributed very little, chromium and nickel were also significant contributors. These results show that the main cause of the decline in water quality in the research region is harmful trace metals.

Goi Creek is severely contaminated by heavy metals, as indicated by the computed HPI, which is significantly higher than the critical threshold of 100. Cadmium, lead, arsenic, mercury, chromium, and nickel, all of which significantly surpass WHO recommended levels, dominate the index. Due to their extremely low allowable limits and high concentrations, these metals contributed the highest weighted scores. In keeping with the long-term effects of petroleum exploration, oil spills, artisanal refining, pipeline corrosion, and related industrial operations throughout the Niger Delta, the remarkably high HPI strongly supports chronic anthropogenic contamination. Such contamination shows that the water is unfit for drinking without significant treatment and presents a major ecological risk. When taken as a whole, the four water quality indices consistently show that Goi Creek is highly contaminated with hazardous metals and should not be consumed without proper treatment. Strong evidence that heavy metal contamination is the primary cause of the decline in water quality in the study area is provided by the agreement between the WQI, HPI, MI, and PI.

Table 11: Metal index (MI) of water samples collected from Goi Creek

Heavy Metal	Mean Concentration (mg/L)	WHO MAC (mg/L)	Ci/MAC
Iron (Fe)	6.758	0.30	22.53
Zinc (Zn)	3.446	3.00	1.15
Manganese (Mn)	2.236	0.40	5.59
Copper (Cu)	2.093	2.00	1.05
Nickel (Ni)	1.992	0.07	28.46
Cadmium (Cd)	0.928	0.003	309.33
Chromium (Cr)	1.791	0.05	35.82
Lead (Pb)	1.263	0.01	126.30
Mercury (Hg)	0.0627	0.006	10.45
Arsenic (As)	1.175	0.01	117.50

Table 12: Heavy Metal Pollution Index

Metal	Mean Concentration (mg/L)	WHO Standard (mg/L)	Unit Weight (Wi = 1/Si)	Quality Rating (Qi)	Wi×Qi
Fe	6.758	0.30	3.333	2252.67	7508.90
Zn	3.446	3.00	0.333	114.87	38.29
Mn	2.236	0.40	2.500	559.00	1397.50
Cu	2.093	2.00	0.500	104.65	52.33
Ni	1.992	0.07	14.286	2845.71	40653.06
Cd	0.928	0.003	333.333	30933.33	10311110.00
Cr	1.791	0.05	20.000	3582.00	71640.00
Pb	1.263	0.01	100.000	12630.00	1263000.00
Hg	0.0627	0.006	166.667	1045.00	174166.67
As	1.175	0.01	100.000	11750.00	1175000.00

Table 13: Pollution index (PI) of individual heavy metals in Goi Creek water

Heavy Metal	Mean Concentration (mg/L)	WHO Standard (mg/L)	PI (Ci/Si)
Iron (Fe)	6.758	0.30	22.53
Zinc (Zn)	3.446	3.00	1.15
Manganese (Mn)	2.236	0.40	5.59
Copper (Cu)	2.093	2.00	1.05
Nickel (Ni)	1.992	0.07	28.46
Cadmium (Cd)	0.928	0.003	309.33
Chromium (Cr)	1.791	0.05	35.82
Lead (Pb)	1.263	0.01	126.30
Mercury (Hg)	0.0627	0.006	10.45
Arsenic (As)	1.175	0.01	117.50

3.6 Human Health Risk Assessment

Due to their lower body weight in relation to water consumption rate, children consistently had higher estimated chronic daily intake (CDI) values for all tested heavy metals than adults. Mercury had the lowest exposure levels, while iron had the highest CDI in both adults (0.1931 mg kg^{-1} day^{-1}) and children (0.4505 mg kg^{-1} day^{-1}) (Table 14). The non-carcinogenic risks linked to copper, nickel, cadmium, chromium, lead, mercury, and arsenic surpassed the acceptable level (HQ > 1) in both adults and children, according to the computed Hazard Quotients (HQ). The highest HQ values were found for arsenic (111.90 for adults and 261.10 for children), followed by chromium (17.06 and 39.80) and cadmium (53.02 and 123.73). On the other hand, manganese slightly surpassed the safety limit in children (HQ = 1.07), while iron, zinc, and manganese showed HQ values below unity in adults.

Long-term use of untreated stream water may provide serious non-carcinogenic health concerns, as indicated by the cumulative Hazard Index (HI) of 2.03 for adults and 4.75 for children, both of which significantly above the safety threshold of 1.0. Children were more vulnerable to heavy metal exposure than adults, as evidenced by their about 2.3-fold higher cumulative risk.

Table 14: Chronic Daily Intake (CDI) and Hazard Quotient (HQ) of Heavy Metals through Water Ingestion

Metals	Mean Conc. (mg/L)	CDI - Adults (mg/kg/day)	CDI - Children (mg/kg/day)	HQ (Adult)	HQ (Child)
Fe	6.7575	0.19307	0.45050	0.276	0.644
Zn	3.4463	0.09846	0.22975	0.328	0.766
Mn	2.2358	0.06388	0.14905	0.456	1.065
Cu	2.0930	0.05980	0.13953	1.495	3.488
Ni	1.9925	0.05693	0.13283	2.847	6.642
Cd	0.9280	0.02651	0.06187	53.02	123.73
Cr	1.7910	0.05117	0.11940	17.06	39.80
Pb	1.2630	0.03609	0.08420	10.31	24.06
Hg	0.06268	0.00179	0.00418	5.97	13.94
As	1.1750	0.03357	0.07833	111.90	261.10

Arsenic, cadmium, and chromium presented unacceptable carcinogenic hazards through the ingestion pathway, according to a lifetime cancer risk assessment. Adult cancer risks were predicted to be 5.04×10^{-2} (As), 1.67×10^{-1} (Cd), and 2.56×10^{-2} (Cr); equivalent values for children were 1.17×10^{-1}, 3.90×10^{-1}, and 5.97×10^{-2}. A possibly higher lifetime cancer risk, especially among adolescents, was indicated by all calculated cancer risks exceeding the US EPA tolerable risk level (10^{-0}-10^{-1}) (Table 15).

The results of the health risk assessment shows that drinking the water collected directly from the creek for an extended period of time may have significant non-carcinogenic and carcinogenic health impacts, with children being the most vulnerable group. The results revealed the need for carrying out cleanup of the water body as well as providing the populations that depend on the water body with safe alternative drinking water supply.

Table 15: Lifetime Cancer Risk (CR) through Ingestion of Water from Goi Creek

Metal	CDI (mg/kg/day)	CDI (mg/kg/day)	CSF	Cancer Risk (CR)	
	Adult	Child		(Adult)	(Child)
As	0.03357	0.07833	1.5	5.04×10^{-2}	1.17×10^{-1}
Cr(VI)	0.05117	0.11940	0.5	2.56×10^{-2}	5.97×10^{-2}
Cd	0.02651	0.06187	6.3	1.67×10^{-1}	3.90×10^{-1}
Ni	0.05693	0.13283	0.84	4.78×10^{-2}	1.12×10^{-1}

4.0 Conclusion

The results of this investigation show that the water quality of Goi Creek has been reduced by crude oil pollution and other human related-activities. Though many of the measured physicochemical parameters were within the WHO/USEPA permissible brackets, values recorded for turbidity and BOD were significantly higher that the recommended standards. The occurrence of heavy metals was in the order Fe > Zn > Mn > Cu > Ni > Cr > Pb > As ≈ V > Cd > Hg, and their values with exceeded permissible limits, most especially at Station 4, which had the highest levels of contamination. These results point to the fact that the Creek has significantly been impacted by petroleum-related activities and that it poses risk to the ecology and human health. The control of pollution, and effective remediation strategies as well as continuous environmental monitoring, are of great importance in order to protect public health and the aquatic ecosystem.

5.0 References

Akhionbare, S. M. O., Peretomode, M. & Ndinwa, G. C. C. (2019). Assessment of water quality of hand dug wells in a riverine community, Southern Nigeria. *World Journal of Innovative Research (WJIR)*, 7, 2, pp. 103–119.

Akpakpan, A. E., Udo, I. E., Uwanta, E. J., Akpanudo, N. W., Ikpe, E. E., Fatunla, O. K. & Etim, U. J. (2024). Influence of operating variables on the adsorption of Pb^{2+} and Cd^{2+} from wastewater using *Gmelina arborea* and its ester derivatives. *Journal of Natural and Applied Sciences, Pakistan*, 6, 2, pp. 1950–1968.

Alam, M. Z., Ahmad, S. & Malik, A. (2009). Genotoxic and mutagenic potential of agricultural soil irrigated with tannery effluents at Jajmau (Kanpur), India. *Archives of Environmental*

Contamination and Toxicology, 57, 3, pp. 463–476.

Anweting, I. B., Ebong, G. A., Okon, I. E., Etuk, H. S. & Etim, I. S. (2024). Physicochemical characteristics and heavy metals assessment of surface water and sediment from Idim Idaang Stream in Ibiono Ibom, Akwa Ibom State, Nigeria. *Journal of Material and Environmental Science*, 15, 1, pp. 72–83.

APHA (American Public Health Association). (2017). *Standard Methods for the Examination of Water and Wastewater*, 23rd Edition. Washington, USA.

Atalawei, E. S., Gobo, A. E. & Daka, E. R. (2020). Comparative assessment of surface water quality in Olugbobiri and Ogboinbiri Creeks, Bayelsa State, Nigeria. *IIARD International Journal of Geography and Environmental Management*, 6, 2, pp. 22–29.

Ayobahan, S. U., Ezenwa, I. M., Orogun, E. E., Uriri, J. E. & Wemimo, I. J. (2014). Assessment of anthropogenic activities on water quality of Benin River. *Journal of Applied Sciences and Environmental Management*, 18, pp. 629–636.

Bhardwaj, R., Gupta, A. & Garg, J. K. (2017). Evaluation of heavy metal contamination using environmetrics and indexing approach for River Yamuna, Delhi stretch, India. *Water Science*, 31, pp. 52–66.

Ndinwa, G. C. C., Peretomode, M. & Asiagbe, T. (2014). Distribution of trace metals in vertebrate and invertebrate species from Ubeji Creek, Southern Nigeria. *International Journal of Advances in Life Science and Technology*, 1, 1, pp. 16–24. doi: 10.18488/journal.72/2014.1.1/72.1.16.24.

Davies, O. A. & Abowei, J. F. N. (2009). Sediment quality of lower reaches of Okpoka Creek, Niger Delta, Nigeria. *European Journal of Scientific Research*, 26, 3, pp. 437–442.

Edori, O. S., Iyama, W. A. & Amadi, M. Q. C. (2020). Variation of some physicochemical parameters in surface water of Elelenwo River, Rivers State, Niger Delta, Nigeria. *International Journal of Research and Scientific Innovation*, 7, 5, pp. 230–235.

Edori, O. S. & Nna, P. J. (2018). Determination of physicochemical parameters of effluents at discharge points into the New Calabar River along Rumuolumeni axis, Niger Delta, Nigeria. *Journal of Environmental Analytical Chemistry and Toxicology*, 8, 3. doi: 10.4172/2161-0525.1000585.

Edori, O. S. & Kpee, F. (2016). Physicochemical and heavy metal assessment of water samples from boreholes near some abattoirs in Port Harcourt, Rivers State, Nigeria. *American Chemical Science Journal*, 14, pp. 1–8. doi: 10.9734/ACSJ/2016/22525.

Edori, O. S. & Marcus, A. C. (2019). Some sediment physicochemical parameters at effluents discharge points of New Calabar River along Rumuolumeni axis, Port Harcourt, Niger Delta, Nigeria. *Chemistry Research Journal*, 4, 1, pp. 67–73.

Efekemo, O., Davies, I. C. & Orororo, O. C. (2024a). Water quality assessment and heavy metal levels in mudskipper (*Periophthalmus papilio*), sediments and water of mangrove swamps, Rivers State, Nigeria. *African Journal of Environment and Natural Science Research*, 7, 1, pp. 128–145.

Efekemo, O., Orororo, O. C. & Davies, I. C. (2024b). Evaluation of water quality and heavy metal concentrations in shrimp (*P. monodon*), sediment and surrounding water of the mangrove swamps, Rivers State, Nigeria. *Scientia Africana*, 23, 2, pp. 251–262.

Egun, N. K. & Ogiesoba-Eguakun, C. U. (2018). Physico-chemical and water quality index analysis of the Okhuaihe River, Edo State, Nigeria. *African Journal of Aquatic Science*, 43, 4, pp. 345–351.

Egun, N. K. & Oboh, I. P. (2022). Surface water quality evaluation of Ikpoba reservoir, Edo State, Nigeria. *International Journal of Energy and Water Resources*, 6, pp. 509–519. doi: 10.1007/s42108-021-00139-z.

Eja, E. M. & Ogri, O. R. (2003). Evaluation of total hydrocarbon (THC) levels in oil polluted coastal areas of South Eastern Nigeria. *Global Journal of Environmental Science and Management*, 2, 1, pp. 1–9. doi: 10.4314/gjes.v2i1.2399.

El Hammari, L., Latifi, S., Saoiabi, S., Saoiabi, A., Azzaoui, K. *et al.* (2022). Toxic heavy metals removal from river water using a porous phospho-calcic hydroxyapatite. *Moroccan Journal of Chemistry*, 10, 1, pp. 62–72. doi: 10.48317/IMIST.PRSM/morjchem-v10i1.31752.

Enuneku, A., Biose, E. & Ezemonye, L. (2017). Levels, distribution, characterization and ecological risk assessment of heavy metals in road side soils and earthworms from urban high traffic areas in Benin Metropolis, Southern Nigeria. *Journal of Environmental Chemical Engineering*, 5, 3, pp. 2773–2781. doi: 10.1016/j.jece.2017.05.019.

FEI. (2019). *A journey through the oil spills of Ogoniland*. Foei.org/new/olspill/ogoniland. Accessed 18 June 2020.

Fowzia, A. & Fakhruddin, A. N. M. (2018). A review on environmental contamination of petroleum hydrocarbons and its biodegradation. *International Journal of Environmental Sciences and Natural Resources*, 11, 3, 555811. doi: 10.19080/IJESNR.2018.11.555811.

George, A. D. I., Abowei, J. F. N. & Daka, E. R. (2009). Benthic macro invertebrate fauna and physico-chemical parameters in Okpoka Creek sediments, Niger Delta, Nigeria. *International Journal of Animal and Veterinary Advances*, 1, pp. 59–65.

Gupta, N., Pandey, P. & Hussain, J. (2017). Effect of physicochemical and biological parameters on the quality of river water of Narmada, Madhya Pradesh, India. *Water Science*, 31, pp. 11–23. doi: 10.1016/j.wsj.2017.03.002.

Haque, M. M., Niloy, N. M., Nayna, O. K., Fatema, K. J., Quraishi, S. B., Park, J. H., Kim, K. W. & Tareq, S. M. (2020). Variability of water quality and metal pollution index in the Ganges River, Bangladesh. *Environmental Science and Pollution Research*, 27, pp. 42582–42599. doi: 10.1007/s11356-020-10060-3.

Hassan, F. Y., Usman, B., Yalwa, I. R., Rilwanu, T. Y. & Abdulhamid, A. (2021). Comparative analysis of heavy metals in groundwater around Sharada and Bompai industrial areas, Kano Metropolis, Nigeria. *Journal of Material and Environmental Science*, 1, 1, pp. 66–77.

Howard, I. C., Gabriel, U. U. & Horsfall, M. (2009). Evaluation of total hydrocarbon levels in some aquatic media in an oil polluted mangrove wetland in the Niger Delta. *Applied Ecology and Environmental Research*, 7, 2, pp. 111–120. doi: 10.15666/aeer/0702_111120.

Iruoma, K. & Olurounbi, R. (2020). *Nigeria's silent killer: Welcome to Ogoniland*. The Africa Report. Accessed 18 June 2020.

Iwegbue, C. M. A., Faran, T. K., Iniaghe, P. O., Ikpefan, J. O., Tesi, G. O., Nwajei, G. E. & Martincigh, B. S. (2023). Water quality of Bomadi Creek in the Niger Delta of Nigeria: Assessment of some physicochemical properties, metal concentrations, and water quality index. *Applied Water Science*, 13, 36. doi: 10.1007/s13201-022-01804-2.

Iyama, W. A., Edori, O. S. & Ede, P. N. (2019). Physicochemical assessment of surface water quality around the Sagbama Creek water body, Bayelsa State, Nigeria. *Global Journal of Science Frontier Research B: Chemistry*, 18, 2, pp. 1–10. doi: 10.34257/GJSFR.

Kale, V. S. (2016). Consequence of temperature, pH, turbidity and dissolved oxygen water quality parameters. *International Advanced Research Journal in Science, Engineering and Technology*, 3, pp. 186–190. doi: 10.17148/IARJSET.2016.3834.

Kondum, F. A., Iwar, R. T. & Kon, E. T. (2021). A comparison of water quality indexes for an inland river. *Journal of Engineering Research and Reports*, 20, 4, pp. 1–14.

Kpomah, E. D. & Orororo, O. C. (2023). Evaluation of some heavy metals in selected canned sardine sold in Yenagoa Metropolis, Bayelsa State, Southern Nigeria. *Nigerian Journal of Science and Environment*, 21, 1, pp. 224–236.

Kumar, V., Parihar, R. D., Sharma, A., Bakshi, P., Singh-Sidhu, G. P., Bali, A. S., Karaouzas, I., Bhardwaj, R., Thukral, A. K., Gyasi, A. Y. & Rodrigo-Comino, J. (2019). Global evaluation of heavy metal content in surface water bodies: A meta-analysis using heavy metal pollution indices and multivariate statistical analyses. *Chemosphere*, 236, 124364. doi: 10.1016/j.chemosphere.2019.124364.

Kumar, V., Sharma, A., Kumar, R., Bhardwaj, R., Thukral, K. A. & Rodrigo-Comino, J. (2018a). Assessment of heavy-metal pollution in three different Indian water bodies by combination of multivariate analysis and water pollution indices. *Human and Ecological Risk Assessment: An International Journal*, 26, pp. 1–16. doi: 10.1080/10807039.2018.1497946.

Kuppusamy, S., Maddela, N. R., Megharaj, M. & Venkateswarlu, K. (2020). *Total Petroleum Hydrocarbons: Environmental Fate, Toxicity, and Remediation*. Springer Nature, Switzerland AG. doi: 10.1007/978-3-030-24035-6.

Linden, O. & Palsson, J. (2013). Oil contamination in Ogoniland, Niger Delta. *Ambio*, 1, 4, pp. 47–77. doi: 10.7901/2169-3358-2014.1.1706.

Nduka, J. K. & Orisakwe, O. E. (2011). Water-quality issues in the Niger Delta of Nigeria: A look at heavy metal levels and some physicochemical properties. *Environmental Science and Pollution Research*, 18, 2, pp. 237–246. doi: 10.1007/s11356-010-0366-3.

Nnoli, N. G., Olomukoro, J. O., Odii, E. C., Ubrei-Joe, M. M. & Ezenwa, I. M. (2021). Another insight into the contamination levels at Ogoniland in Niger Delta, Nigeria, with focus on Goi Creek. *Environmental Science and Pollution Research*, 1–17. doi: 10.1007/s11356-021-13117-z.

Nriagu, J., Udofia, E. A., Ekong, I. & Ebuk, G. (2016). Health risks associated with oil pollution in the Niger Delta, Nigeria. *International Journal of Environmental Research and Public Health*, 13, 3, 346. doi: 10.3390/ijerph13030346.

Oboh, I. P. & Agbala, C. S. (2017). Water quality assessment of the Siluko River, Southern Nigeria. *African Journal of Aquatic Science*, 42, 3, pp. 279–286. doi: 10.2988/16085914.2017.1371579.

Oghenenyoreme, E. M. & Njoku, O. P. (2014). Physicochemical analysis of water resources in selected part of Oji River and its environs, Enugu State, Southeastern Nigeria. *International Journal of Innovative Science and Research*, 10, pp. 171–178.

Okorafor, K. A., James, E. S. & Udoh, A. D. (2014). Assessment of macroinvertebrates and physico-chemical parameters of the lower Qua Iboe River, Akwa Ibom State, Nigeria. *ARPN Journal of Science and Technology*, 4, pp. 666–677.

Omoigberale, M. O., Ezenwa, I. M. & Okereka, E. E. (2013). Assessment of heavy metal concentrations in surface water and sediment of the Okhuiahe River, Edo State, Nigeria. *Nigerian Journal of Life Science*, 3, 2, pp. 140–147. doi: 10.52417/njls.v3i2.141.

Orajiaka-Uchegbu, C., Patrick-Iwuanyanwu, K. C., Ogbo, A. I. & Egbuna, C. (2020). Bioaccumulation of heavy metals and potential health risk through consumption of seafoods from selected creeks in Rivers State, Nigeria. *Egyptian Journal of Aquatic Biology and Fisheries*, 24, pp. 1033–1053. doi: 10.21608/ejabf.2020.133858.

Oribhabor, B. J. & Ogbeibu, A. E. (2009). Concentration of heavy metals in a Niger Delta mangrove creek, Nigeria. *Global Journal of Environmental Sciences*, 8, pp. 1–10. doi: 10.4314/gjes.v8i2.53776.

Orororo, O. C., Efekemo, O., Egbune, E. O., Awhin, E. P., Odeghe, O. B. & Okoro, E. O. (2024). Amelioration of cadmium toxicity in the liver and kidney of Wistar rats by combined *Citrus sinensis* and *Manihot esculenta* leaf extract. *International Journal of Biochemistry Research and Review*, 23, 6, pp. 71–79.

Osioma, E. & Iniaghe, P. O. (2019). Concentration of heavy metals in water, sediments and tissues of *Clarias gariepinus* from earthen ponds in Kolo Creek communities in Bayelsa State, Niger Delta, Nigeria. *Asian Journal of Water, Environment and Pollution*, 16, 4, pp. 97–106.

Seiyaboh, E. I., Izah, S. C. & Oweibi, S. (2017). Assessment of water quality from Sagbama Creek, Niger Delta, Nigeria. *Biotechnology Research*, 3, 1, pp. 20–24.

Setia, R., Dhaliwal, S. S., Kumar, V., Singh, R., Kukal, S. S. & Pateriya, B. (2020). Impact assessment of metal contamination in surface water of Sutlej River (India) on human health risks. *Environmental Pollution*, 265, 114907. doi: 10.1016/j.envpol.2020.114907.

Tyagi, S., Sharma, B., Singh, P. & Dobhal, R. (2013). Water quality assessment in terms of water quality index. *American Journal of Water Resources*, 1, 3, pp. 34–38.

United States Environmental Protection Agency (US EPA). (2011). *Regional Screening Level Table (RSL) for Chemical Contaminants at Superfund Sites*.

Vincent-Akpu, I. F., Tyler, A. N., Wilson, C. & Mackinnon, G. (2015). Assessment of physico-chemical properties and metal contents of water and sediments of Bodo Creek, Niger Delta, Nigeria. *Toxicology and Environmental Chemistry*, 97, 2, pp. 135–144. doi: 10.1080/02772248.2015.1041526.

WHO (World Health Organization). (2011). *Guidelines for Drinking-Water Quality*, 4th Edition. WHO Press, Switzerland.

Wogu, M. D. & Okaka, C. E. (2011). Pollution studies on Nigerian rivers: Heavy metals in surface water of Warri River, Delta State. *Journal of Biodiversity and Environmental Sciences*, 1, 3, pp. 7–12.

Wright, D. A. & Welbourn, P. (2002). *Environmental Toxicology*. Cambridge University Press, Cambridge. In: Wright, D. A. & Welbourn, P. (eds.) *Environmental Toxicology: Environmental Chemistry Series 11*. Cambridge University Press, Cambridge, pp. 249–348. doi: 10.1017/CBO9780511805998.

Declarations

Conflict of Interest

The authors declared no conflict of interest

Funding

No funding was obtained for this work

Ethical consideration

Has been declared in section 2.7

Data Availability

Data shall be made available upon request

Author Contributions

Gabriel C. C. Ndinwa contributed to study conceptualization, field sampling, laboratory analysis, statistical evaluation, and interpretation of physicochemical and heavy-metal data. He contributed to water-quality and health-risk assessments, including WQI, HPI, MI, PI, HI, and cancer-risk analyses. He also participated in manuscript preparation, critical revision, interpretation of findings, and final approval of the manuscript