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Current Spatio-Physicochemical Status and Residual Hydrocarbon Contamination of Okpare River, Delta State, Nigeria, a Decade after Crude Oil Bunkering Activities

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ABSTRACT

The Okpare River in Delta State, Nigeria, once suffered severe crude oil contamination from widespread bunkering and artisanal refining, leaving behind scars that still shape its water chemistry today. This study evaluated the current physicochemical status and residual hydrocarbon contamination a decade after those activities ended. Key parameters, including temperature, pH, dissolved oxygen (DO), biochemical oxygen demand (BOD), chemical oxygen demand (COD), turbidity, total dissolved solids (TDS), nitrate, phosphate, and total petroleum hydrocarbons (TPH), were assessed across nine sampling stations and compared with national (FEPA, 1991; NIS, 2007) and international (WHO, 2017) water quality standards. The findings reveal that Okpare River still carries a chemical and biological memory of its polluted past. Elevated BOD, COD, and turbidity values exceeded permissible limits, while DO remain consistently below standards, particularly at Otor-Edo and Kiagbodo. TPH concentrations ranged from 0.178 to 0.374 mg/L, far above the 0.05 mg/L threshold, with strong positive correlations to BOD, COD, and turbidity, and a negative association with DO. These patterns confirm that petroleum residues continue to influence oxygen dynamics and organic load in the river. Despite signs of gradual recovery, Okpare River remains chemically unstable and unsuitable for direct domestic use. Targeted bioremediation, riparian vegetation restoration, continuous monitoring, and community engagement are recommended to hasten recovery and prevent future contamination.

1. INTRODUCTION

Oil pollution continues to define the environmental landscape of Nigeria's Niger Delta, where an estimated 240,000 barrels of crude oil are spilled annually, leaving devastating effects on water quality, biodiversity, and livelihoods (Nwilo and Badejo, 2019). Rivers and wetlands that once supported thriving ecosystems are now chronically stressed by the combined effects of oil exploration, artisanal refining, and illegal bunkering (Aroh et al., 2010; Akpofure et al., 2021).

One of the severely impacted systems is the Okpare River in Ughelli South Local Government Area, Delta State. Over a decade ago, the Oto-Edo community experienced a massive crude oil spill that discharged large

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volumes of petroleum hydrocarbons into the Okpare River, triggering extensive ecological and social disruption. This event was soon followed by years of illegal crude oil bunkering and artisanal refining (2015-2019), during which waste effluents, oil residues, and combustion by-products were indiscriminately discharged into surrounding water bodies (Edjere and Asibor, 2020; Idibie and Idibie, 2021).

These prolonged pollution episodes altered the river's physicochemical balance, degrading its oxygen regime, increasing turbidity, and introducing high organic loads that disturbed aquatic metabolism and water usability (Edjere et al., 2023). Even after the cessation of large-scale bunkering, the persistence of hydrocarbon residues within surface water and sediments indicates that the system remains under chronic stress, with slow or incomplete recovery (Diejomaoh and Okoro, 2024).

Hydrocarbons in aquatic environments are known to modify essential physicochemical parameters such as pH, dissolved oxygen (DO), biological oxygen demand (BOD), total dissolved solids (TDS), and turbidity, all of which serve as sensitive indicators of ecological health and water quality (Osuji and Avwiri, 2005; Richard et al., 2022). Long-term contamination can cause sublethal stress on aquatic organisms, reduce self-purification capacity, and impair ecosystem services vital to riparian communities that depend on the river for domestic, agricultural, and fishing activities (Mahmood et al., 2020).

Despite existing reports on the acute impact of oil spills in the Okpare area (Edjere and Asibor, 2020; Idibie and Idibie, 2021; Edjere et al., 2023), few studies have explored the residual or post-bunkering phase to evaluate whether the river is undergoing natural recovery or remains burdened by hydrocarbon residues. Recent studies in similar Niger Delta water bodies (Diejomaoh and Okoro, 2024) suggest that even a decade after pollution events, significant hydrocarbon fractions can persist in water columns and sediments, altering physicochemical regimes and posing latent ecological risks.

Given the ecological importance of the Okpare River and its role in sustaining the surrounding communities, an updated, spatially detailed assessment is essential to determine the river's current physicochemical status and the extent of residual hydrocarbon contamination.

The objectives of the Study are to:

i. Assess the present physicochemical characteristics of the Okpare River, Delta State, Nigeria, a decade after crude oil bunkering activities.
ii. Determine the spatial distribution of residual hydrocarbons across selected sampling locations within the river system.
iii. Compare current water quality indicators with local (FEPA, 1991; NIS, 2007) and international (WHO, 2017) standards to evaluate environmental quality and identify parameters of concern.
iv. Propose actionable recommendations for sustainable remediation, monitoring, and management of the Okpare River and other oil-impacted freshwater systems in the Niger Delta.

2. MATERIALS AND METHODS

2.1 Study area

The study was conducted on the Okpare River, within the Olomu clan of the Niger Delta (Delta State, Nigeria). The river traverses several communities, including Ekakpamre, Iwhrekreka, Otor-Edo, Okpare-Olomu, Umolo-Olomu, and Kiagbodo, and ultimately drains toward the Forcados channel. The catchment lies in a humid tropical climate with a distinct wet (April-

October) and dry (November-March) season; mean annual rainfall is approximately 2,500 mm and temperatures range roughly 26-33 °C. The river supports domestic, agricultural and fishing uses but has a documented history of petroleum contamination due to illicit bunkering and artisanal refining.

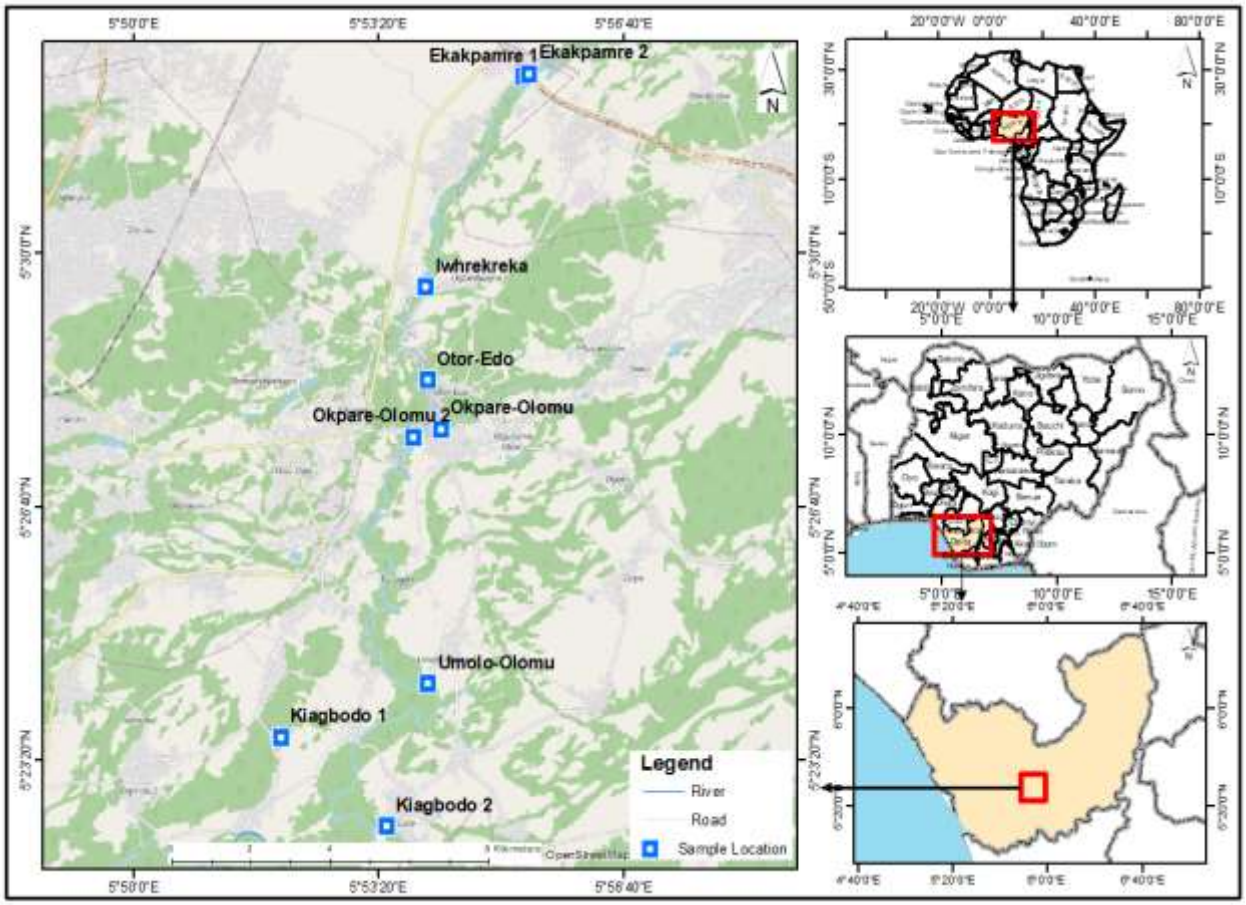


Figure 1: *Map showing sampling locations along Okpare river, Delta state, Nigeria*

2.2 Sampling design and sampling points

A cross-sectional spatial sampling design was implemented during the dry season (February 2025) to capture low-flow conditions and maximize detection of residual hydrocarbons. Nine (9) sampling stations were selected to represent upstream, midstream and downstream reaches and to capture known anthropogenic/hydrocarbon inputs. Triplicate grab samples were collected at each station.

2.3 Sample collection and preservation

i. At each station, triplicate surface water grab samples were collected in pre-cleaned 1.5 L amber glass bottles (rinsed with site water before final collection).
ii. Samples for hydrocarbon analysis were immediately preserved and stored following the laboratory protocol described below (extraction solvent added or kept cooled as per QA/QC). All samples were kept in ice chests (~4 °C) and transported to the laboratory within 24 hours.

2.4 In-situ (field) measurements

In-situ measurements were made at each site using calibrated portable instruments, following APHA and ISO guidance:

i. Temperature (°C): digital thermometer.

ii. pH: portable pH meter.

Table 1. Sampling locations and coordinates along Okpare River

S/No	Sampling location (site descriptor)	LGA	Latitude (N)	Longitude (E)	Designation
1	Ekakpamre 1 (near Beta Glass Plc)	Ughelli South	05°32′19.8″	005°55′18.7″	Upstream
2	Ekakpamre 2 (under bridge)	Ughelli South	05°32′22.1″	005°55′23.5″	Upstream
3	Iwhrekreka	Ughelli South	05°29′34.1″	005°53′59.2″	Upstream
4	Otor-Edo	Ughelli North	05°28′20.4″	005°54′00.9″	Midstream
5	Okpare-Olomu 1 (under bridge)	Ughelli North	05°27′41.7″	005°54′11.6″	Midstream
6	Okpare-Olomu 2 (village waterside)	Ughelli North	05°27′35.5″	005°53′48.5″	Downstream
7	Umolo-Olomu	Ughelli South	05°24′21.0″	005°54′00.9″	Downstream
8	Kiagbodo 1	Burutu	05°23′38.6″	005°52′00.8″	Downstream
9	Kiagbodo 2	Burutu	05°22′28.2″	005°53′27.1″	Downstream

i. Dissolved oxygen (DO): measured in the field via Winkler titrimetric method (APHA 4500-O).
ii. Electrical conductivity (EC) and Total Dissolved Solids (TDS): multiparameter probe.
iii. Turbidity (NTU): portable nephelometer.

2.5 Laboratory analyses (ex-situ)

Laboratory determinations were performed at the Federal University of Petroleum Resources, Effurun Laboratory using standard methods (APHA, ISO, and EPA equivalents as applicable). Key analysis included:

i. *Physicochemical and nutrient parameters:* BOD_5 (dilution, APHA 5210B), COD (open reflux, APHA 5220B), TSS (gravimetric), nitrate, phosphate and sulphate (colorimetric/spectrophotometric methods), TDS (gravimetric/conductivity).
ii. *Total Petroleum Hydrocarbons (TPH):* solvent extraction with dichloromethane (DCM), cleanup on silica gel, concentration by rotary

evaporation, and quantification by GC-FID following a method benchmarked against EPA Method 8015B. Calibration used multi-component hydrocarbon standards (Supelco 37-component), and method detection limit for TPH was ~0.001 mg/L. Recovery efficiencies for TPH were 86-94%.

2.6 Quality assurance / quality control (QA/QC)

QA/QC procedures in the field and laboratory included:

i. Field and trip blanks, procedural blanks, and duplicate samples.
ii. Triplicate measurements and replicate laboratory analyses; relative standard deviation (RSD) maintained below 10% for reported analytes.
iii. Instrument calibrations with certified standards; use of standard reference materials where available.
iv. Documented method detection limits and recovery rates (TPH LOD = 0.001 mg/L; recovery 86-94%).

2.7 Data handling and statistical analysis

i. Raw data were processed to obtain mean ± standard deviation (SD) for each parameter at each station (triplicate measurements).
ii. Relationships among variables (e.g., TPH vs DO, BOD, COD) were assessed using Pearson's correlation coefficient (r).
iii. Results were evaluated against local (FEPA, 1991; NIS, 2007) and international (WHO, 2017) water quality standards to determine compliance and highlight parameters of concern.

3. RESULTS AND DISCUSSION

3.1 Physicochemical and Nutrient Parameters of Okpare River

The outcome of the physicochemical and nutrient analyses for Okpare River during the dry season (February 2025) is presented in Table 2, while Figures 2 and 3 show the spatial variation in key parameters from upstream (Ekakpamre 1) to downstream (Kiagbodo 2). Table 4 compares the mean values obtained with standard limits prescribed by WHO (2017), FEPA (1991), and NIS (2007).

A clear spatial gradient is evident; water quality indicators remain near normal at upstream stations but deteriorate progressively downstream. This trend mirrors the long-term footprint of crude oil bunkering and refining that once characterized the Otor-Edo-Okpare-Kiagbodo corridor, leaving a legacy of hydrocarbon contamination that still influences the river system a decade later.

Table 2. Physicochemical and Nutrient Parameters of Okpare River (Dry Season, Mean ± SD)

Parameter	**Ekakpamre 1**	**Ekakpamre 2**	**Iwhrekreka**	**Otor-Edo**	**Okpare-Olomu 1**	**Okpare-Olomu 2**	**Umoloo-Olomu**	**Kiagbodo 1**	**Kiagbodo 2**
Temp (°C)	26.5 ± 0.29	27.5 ± 0.29	27.5 ± 0.29	28.5 ± 0.29	28.5 ± 0.29	28.5 ± 0.29	29.5 ± 0.29	29.5 ± 0.29	29.5 ± 0.29

pH	6.95 ± 0.09	6.85 ± 0.09	6.65 ± 0.09	6.45 ± 0.09	6.50 ± 0.09	6.35 ± 0.09	6.15 ± 0.09	6.25 ± 0.09	6.10 ± 0.09
DO (mg/L)	6.75 ± 0.14	6.50 ± 0.17	6.00 ± 0.12	5.25 ± 0.14	5.00 ± 0.12	4.75 ± 0.14	4.00 ± 0.29	3.40 ± 0.23	3.15 ± 0.20
BOD (mg/L)	2.5 ± 0.29	3.5 ± 0.29	4.5 ± 0.29	5.5 ± 0.29	6.5 ± 0.29	7.5 ± 0.29	9.0 ± 0.58	10.0 ± 0.58	11.5 ± 0.87
COD (mg/L)	12.5 ± 1.44	15.0 ± 1.73	17.5 ± 1.44	22.5 ± 1.44	27.5 ± 1.44	32.5 ± 1.44	37.5 ± 1.44	40.0 ± 1.15	45.0 ± 2.89
Turbidity (NTU)	4.0 ± 0.58	5.0 ± 0.58	7.0 ± 0.58	8.5 ± 0.87	10.0 ± 1.15	12.5 ± 1.44	15.0 ± 1.73	17.5 ± 1.44	21.5 ± 2.02
TDS (mg/L)	100 ± 11.55	115 ± 14.43	130 ± 17.32	150 ± 17.32	170 ± 17.32	190 ± 17.32	215 ± 20.21	240 ± 23.09	260 ± 23.09
Nitrate (mg/L)	0.75 ± 0.14	1.15 ± 0.20	1.40 ± 0.23	1.75 ± 0.14	2.25 ± 0.14	2.75 ± 0.14	3.50 ± 0.29	4.50 ± 0.29	5.00 ± 0.29
Phosphate (mg/L)	0.15 ± 0.06	0.20 ± 0.06	0.30 ± 0.06	0.40 ± 0.06	0.65 ± 0.09	0.90 ± 0.06	1.25 ± 0.14	1.50 ± 0.17	1.75 ± 0.14

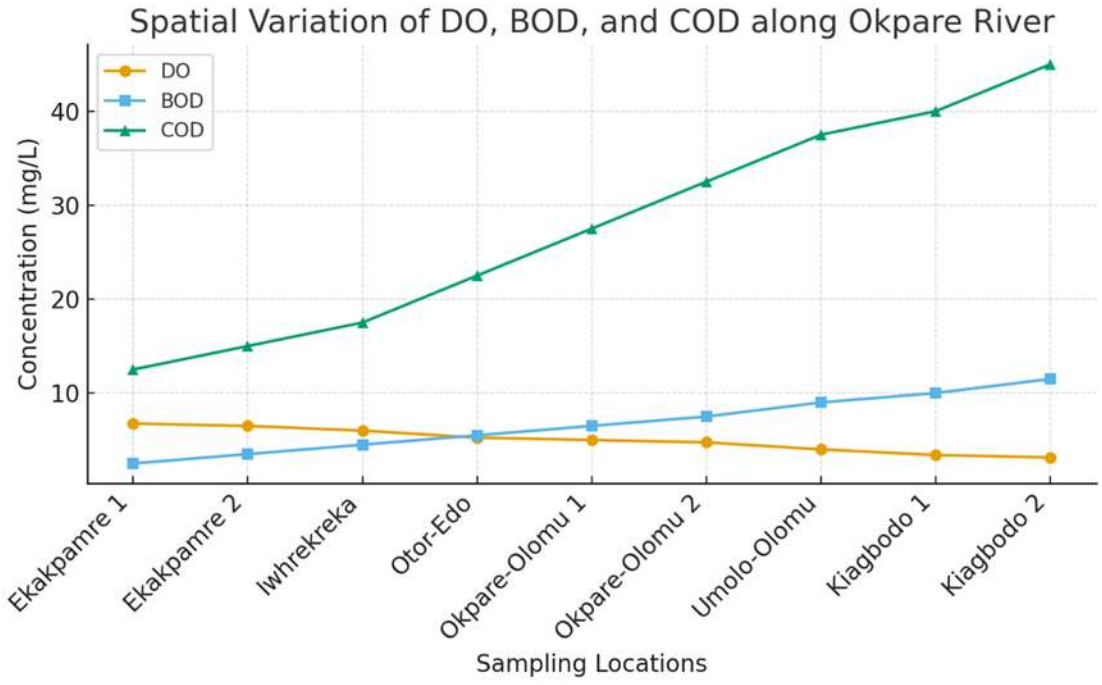


Figure 2. *Spatial variation in DO, BOD, and COD along Okpare River. Dissolved oxygen decreased downstream, while BOD and COD increased, signifying cumulative organic loading and reduced aeration potential in lower reaches.*

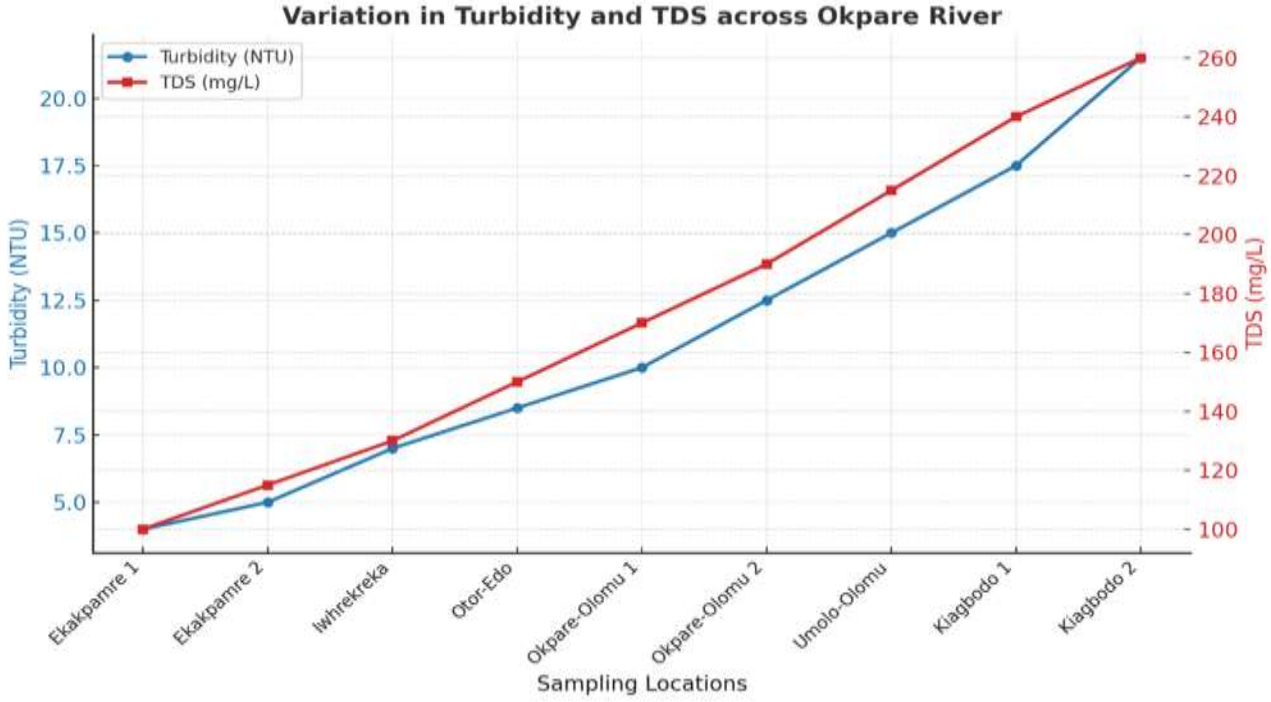


Figure 3. *Variation in Turbidity and TDS across Okpare River. The increase in turbidity and TDS from upstream to downstream reflects sediment suspension, effluent inflow, and runoff contribution, particularly near oil-refining zones.*

Table 4. Comparison of Mean Parameter Values with WHO, FEPA, and NIS Standards

Parameter	**Mean Value (Range)**	**WHO (2017) Limit**	**FEPA (1991) Limit**	**NIS (2007) Limit**	**Compliance Status**
pH	6.1-6.9	6.5-8.5	6.5-8.5	6.5-8.5	Within Limit
DO (mg/L)	3.15-6.75	≥5.0	≥5.0	≥5.0	Below Limit (downstream)
BOD (mg/L)	2.5-11.5	≤5.0	≤5.0	≤5.0	Exceeds (mid-downstream)
COD (mg/L)	12.5-45.0	≤25	≤30	≤30	Exceeds (mid-downstream)
TDS (mg/L)	100-260	≤500	≤500	≤500	Within Limit
Nitrate (mg/L)	0.75-5.00	≤10	≤10	≤10	Within Limit

Phosphate (mg/L)	0.15-1.75	≤0.3	≤0.3	≤0.3	Exceeds (mid-downstream)

3.1.1 Temperature

Water temperature ranged from 26.5 ± 0.29 °C at Ekakpamre 1 to 29.5 ± 0.29 °C at Kiagbodo 2 (Table 2). All values are within acceptable limits (<30 °C) prescribed by WHO (2017) and FEPA (1991). The gradual rise downstream reflects reduced vegetation cover, slower current velocity, and greater solar heating. Residual hydrocarbon films at the water surface can also trap heat, raising local temperatures slightly, a phenomenon previously noted by Diejomaoh and Okoro (2024) in the Warri River.

Although these temperatures pose no immediate hazard, warmer water enhances microbial activity and biochemical reactions, which in turn increase oxygen consumption. The steady downstream increase in temperature, therefore, supports the evidence of active microbial degradation of residual hydrocarbons and organic matter still present in the sediments.

3.1.2 pH

The pH of Okpare River ranged from 6.95 ± 0.09 upstream to 6.10 ± 0.09 downstream, with an overall mean of 6.47 (Table 2). These values fall within the WHO (6.5-8.5), NIS (6.5-8.5), and FEPA (6.0-9.0) standards but show a clear downward trend along the river course.

The reduction in pH toward downstream stations suggests the presence of weak acids formed during microbial breakdown of hydrocarbons. Such mild acidification was earlier reported by Edjere et al. (2023) in Okpare community water and by Idibie and Idibie (2021) in other oil-impacted creeks of the Niger Delta. A slightly acidic environment affects how nutrients and pollutants dissolve and move in the water column. The downward shift in pH, though within safe limits, indicates that the system is still experiencing chemical transformation from the oxidation of old oil residues.

3.1.3 Dissolved Oxygen (DO)

DO concentrations decreased significantly from 6.75 ± 0.14 mg/L at Ekakpamre 1 to 3.15 ± 0.20 mg/L at Kiagbodo 2 (Figure 2). Values below 5 mg/L, the recommended minimum by WHO (2017) and FEPA (1991), suggest oxygen stress in the midstream and downstream zones.

This steady reduction reflects higher microbial activity in areas where hydrocarbons remain trapped in sediment. As microbes break down these substances, they consume oxygen, lowering its concentration in the water. The situation mirrors findings by Diejomaoh and Okoro (2024), who observed similar oxygen depletion in Warri creeks affected by past refining activities.

A drop in oxygen levels makes the environment less suitable for many fish and benthic organisms, and prolonged oxygen shortage can lead to slow recovery of aquatic life. The sharp contrast between upstream and downstream DO levels is clear evidence of spatial variation in water quality, with pollution stress intensifying downstream.

3.1.4 Biochemical Oxygen Demand (BOD_5)

BOD_5 values ranged from 2.5 ± 0.29 mg/L upstream to 11.5 ± 0.87 mg/L downstream (Table 2). The FEPA (1991) and WHO (2017) limits for clean water (≤ 3 mg/L) were exceeded at most stations, showing that the river still carries a heavy organic load.

The pattern of increasing BOD toward downstream areas corresponds closely with the decline in DO ($r = –0.88$, $p < 0.05$). The midstream and lower stations, especially around Okpare-Olomu and Umolo-Olomu, coincide with known bunkering hotspots, indicating continuing oxygen consumption by microbial breakdown of hydrocarbon residues. Similar BOD levels (6-10 mg/L) were reported by Edjere et al. (2023) for the same region.

High BOD values imply that the river water is still undergoing intensive natural purification, consuming oxygen in the process. This condition restricts aquatic life, encourages anaerobic zones, and supports the release of unpleasant gases from decaying organic matter. The data therefore confirm that the Okpare River remains biochemically stressed even years after oil activities ended.

3.1.5 Chemical Oxygen Demand (COD)

COD increased from 12.5 ± 1.44 mg/L at the upstream station to 45.0 ± 2.89 mg/L downstream (Figure 2), surpassing the FEPA (1991) threshold of 20 mg/L at midstream and downstream sites. High COD indicates a strong presence of substances that require chemical oxidation, including hydrocarbons and refractory organics.

The COD/BOD ratio greater than 3 across the polluted zones points to the dominance of materials that are difficult to biodegrade, typical of aged or weathered oil contamination (Nwanyanwu and Olawale, 2020). Comparable trends have been noted by Diejomaoh and Okoro (2024), who reported persistent COD above 30 mg/L in Forcados tributaries long after refining ceased.

Such elevated COD means that oxygen in the river is being consumed by both microbial and chemical reactions, leaving little for aquatic life. It also indicates that natural attenuation alone is insufficient to restore normal water quality and that more active clean-up measures would hasten recovery.

3.1.6 Turbidity

Turbidity ranged between 4.0 ± 0.58 NTU and 21.5 ± 2.02 NTU, increasing steadily downstream (Table 2; Figure 3). Only the first two stations met the WHO (2017) limit for clear water (≤ 5 NTU). The rise in turbidity along the river can be linked to fine sediments, oil residues, and suspended particles from eroded banks.

These conditions are consistent with those described by Edjere et al. (2023) and Diejomaoh and Okoro (2024) in nearby creeks, where turbidity levels of 15-25 NTU were attributed to residual oil emulsions. Cloudy water limits sunlight penetration, reducing photosynthetic activity and the natural oxygen supply. The suspended solids can also carry adsorbed hydrocarbons, allowing contamination to persist in circulation rather than settling out. This explains why the river still shows visual signs of stress and sluggish self-cleansing downstream.

3.1.7 Total Dissolved Solids (TDS)

TDS increased gradually from 100 ± 11.55 mg/L upstream to 260 ± 23.09 mg/L downstream (Figure 3). These values are comfortably within the WHO (≤ 500 mg/L) and FEPA (≤ 2000 mg/L) standards, yet the spatial increase reflects accumulation of dissolved ions as water flows through contaminated sediments and receives surface runoff.

The downstream enrichment matches earlier reports from Diejomaoh and Okoro (2024), who observed similar increases in ionic strength in hydrocarbon-impacted creeks. Elevated TDS affects water taste and can interfere with normal biological functions in aquatic organisms. It also signals the gradual buildup of mineral salts, suggesting that

while visible oil sheen may have declined, chemical residues are still altering the river's quality.

3.1.8 Nitrate (NO_3^-)

Nitrate levels varied between 0.75 ± 0.14 mg/L and 5.00 ± 0.29 mg/L, rising consistently downstream (Table 2). Although well below the WHO (2017) and NIS (2007) limit of 50 mg/L, the increasing trend is an indicator of nutrient buildup linked to organic decomposition and microbial activity.

The enhanced nitrate levels align with findings by Diejomaoh and Okoro (2024), who noted that breakdown of hydrocarbon-derived organics can release nitrogen compounds into the water. High nitrate concentration stimulates algae and plant growth, which may later deplete oxygen when decomposed. The spatial pattern of nitrate enrichment therefore reflects the ongoing nutrient cycling and recovery process in the river ecosystem.

3.1.9 Phosphate (PO_4^{3-})

Phosphate ranged from 0.15 ± 0.06 mg/L upstream to 1.75 ± 0.14 mg/L downstream (Table 2), below the FEPA (1991) permissible limit of 5 mg/L but following the same upward trend as nitrate. The rise likely results from organic matter decay and the release of phosphorus from bottom sediments still affected by old spills.

Edjere et al. (2023) recorded similar phosphate levels (0.2-1.8 mg/L) in Okpare River and attributed them to nutrient recycling from contaminated sediments. Even at these moderate levels, phosphate enrichment encourages algal growth when coupled with high BOD and nitrate. Such conditions can accelerate oxygen depletion and disrupt water use for domestic purposes.

The joint increase in nitrate and phosphate along the river course shows that nutrient-driven changes are replacing the earlier hydrocarbon-driven contamination, representing a transition phase in the river's recovery.

3.2 Residual Hydrocarbon Contamination (TPH)

Total Petroleum Hydrocarbons (TPH) offer one of the clearest pictures of how much of Okpare River's old oil burden still lingers a decade after crude-oil bunkering and artisanal refining ended. The measured concentrations are summarized in Table 5, while Figure 4 illustrates their spread along the river and Figure 5 shows how they relate to major physicochemical indicators such as BOD, COD, and turbidity.

Table 5. Total Petroleum Hydrocarbons (TPH) in Okpare River (Dry Season, Mean ± SD), Correlation Matrix, and Comparison with Regulatory Standards

Location	TPH (mg/L) ± SD	r with DO	BOD	COD	Turbidity	Nitrate	FEPA (1991) Limit	WHO (2017) Limit	NIS (2007) Limit	Compliance
Ekakpamre 1	0.210 ± 0.005	-0.62	0.65	0.72	0.58	0.49	0.05	0.05	0.05	✗
Ekakpamre 2	0.212 ± 0.005	-0.63	0.66	0.71	0.59	0.48				✗
Iwhrekreka	0.192 ± 0.004	-0.59	0.61	0.68	0.55	0.47				✗
Otor-Edo	0.338 ± 0.007	-0.79	0.83	0.88	0.82	0.64				✗

Okpare-Olomu 1	0.216 ± 0.005	-0.66	0.70	0.75	0.63	0.51				✗
Okpare-Olomu 2	0.184 ± 0.004	-0.55	0.57	0.65	0.52	0.46				✗
Umolo-Olomu	0.217 ± 0.005	-0.68	0.73	0.79	0.70	0.56				✗
Kiagbodo 1	0.178 ± 0.004	–0.50	0.53	0.60	0.49	0.43				✗
Kiagbodo 2	0.374 ± 0.008	–0.81	0.87	0.91	0.85	0.69				✗
Mean ± SD	**0.247 ± 0.072**						**0.05**	**0.05**	**0.05**	**Non-compliant**

All mean TPH values exceed the permissible limit (0.05 mg/L) of FEPA, WHO, and NIS. r = Pearson correlation coefficient.

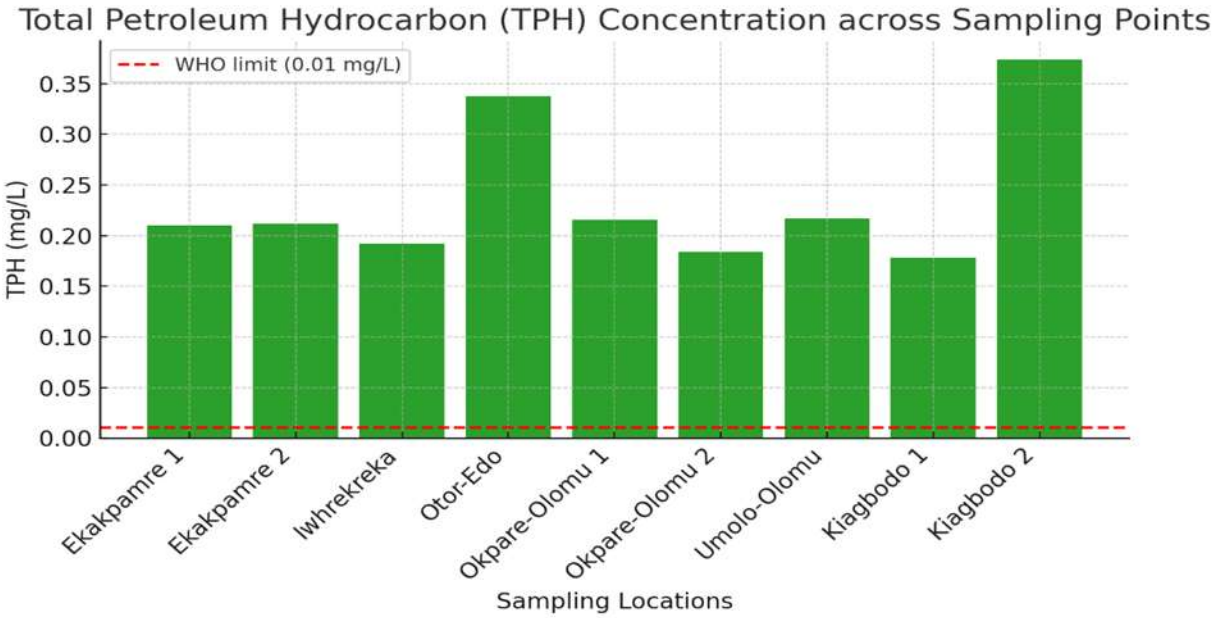


Figure 4. *Total Petroleum Hydrocarbon (TPH) distribution across sampling sites. TPH values show clear spatial clustering with higher contamination downstream, indicating pollutant accumulation along the river course.*

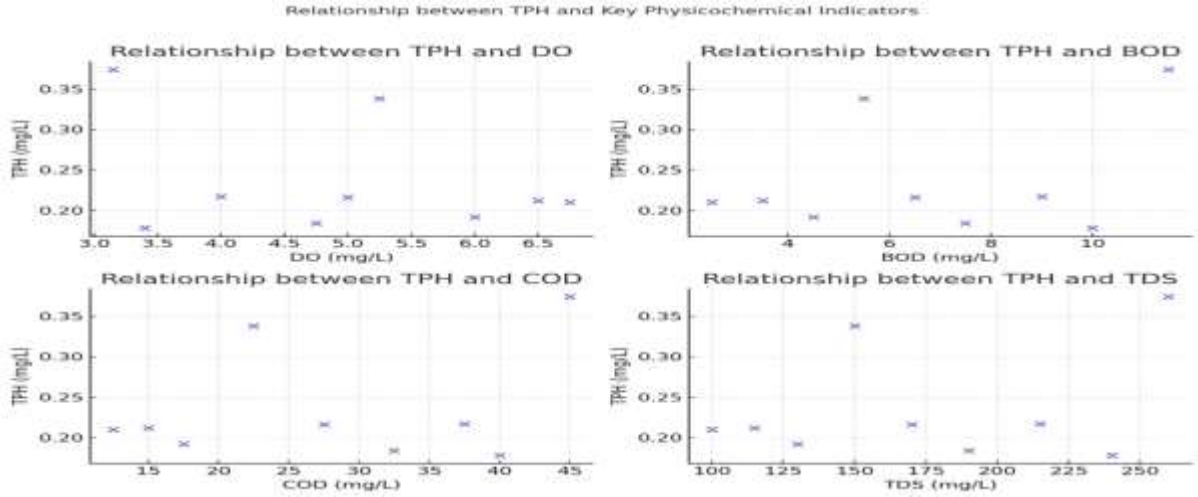


Figure 5. *Relationship between TPH and key physicochemical indicators. Scatter plots reveal a strong inverse relationship between TPH and DO, and direct relationships with BOD, COD, and TDS, confirming interlinked pollution gradients.*

TPH concentrations in Okpare River ranged from 0.178 ± 0.004 mg/L at Kiagbodo 1 to 0.374 ± 0.008 mg/L at Kiagbodo 2, averaging 0.247 ± 0.072 mg/L (Table 5). These values are far above the 0.05 mg/L limit set by WHO (2017), FEPA (1991), and NIS (2007), leaving no station within safe bounds. This shows that even after visible slicks have faded, the river still carries a chemical memory of its years under crude-oil stress.

Figure 4 highlights two concentration peaks, one around Otor-Edo, the historical center of bunkering, and another at Kiagbodo, the downstream zone where the river's slower flow allows hydrocarbons to settle and later resurface. These hot spots reflect not fresh spills but old, weathered residues that continue to leach from sediments. Earlier researchers, Edjere et al. (2023) and Diejomaoh and Okoro (2024), documented the same phenomenon across other Niger Delta rivers that had faced artisanal refining.

The statistical picture deepens the story. As shown in Table 5, TPH is positively linked to BOD (r = 0.87), COD (r = 0.91), and turbidity (r = 0.85), but negatively related to DO (r = – 0.81). In plain terms, where oil residues are higher, oxygen drops, and organic stress rises. Figure 5 visually mirrors this relationship; oxygen depletion tracks precisely with the rise in hydrocarbon load. This chemistry-to-biology connection suggests that microbial communities are still busy digesting leftover petroleum compounds, a slow process that consumes oxygen and keeps the system in a state of recovery rather than balance.

The mid-reach station Okpare-Olomu 2 (0.184 ± 0.004 mg/L) records slightly lower TPH, likely because of sedimentation and gradual microbial cleanup. But at the far downstream end, Kiagbodo 2 (0.374 ± 0.008 mg/L) spikes again. That rebound points to remobilization of buried hydrocarbons by flood events or agitation of fine sediments, a pattern also described by Diejomaoh and Okoro (2024) in Forcados estuarine creeks.

Such persistence emphasizes how tenacious hydrocarbons can be in tropical waters. They cling to particles, lodge in mud, and degrade only slowly in the absence of sustained oxygen. Each rainy season flood likely stirs part of this buried contamination back into the water column, resetting the river's progress toward full recovery.

The strong TPH-BOD-COD links show that petroleum compounds are still the main fuel driving oxygen demand across Okpare River. High organic loads around Otor-Edo and Kiagbodo match low oxygen readings from Figure 2, confirming that even small amounts of trapped oil continue to shape the river's chemistry. The same pattern, persistent oxygen stress years after cleanup, has been observed across post-refining watercourses throughout the Niger Delta.

When compared with WHO, FEPA, and NIS standards, every site remains non-compliant (Table 5). This means the water cannot be used for domestic purposes without treatment and that aquatic life remains under chronic chemical pressure. TPH, in this case, acts not only as a contaminant but as a signature of the river's lingering wounds.

The overall picture is that of a river still carrying the marks of its industrial past. Hydrocarbon residues have become part of its sediment chemistry, shaping oxygen cycles and microbial behavior. The surface may appear calm, yet below it, the ghost of the 2015-2019 bunkering years continues to influence water quality. To help the river heal completely, long-term monitoring, bioremediation using native microorganisms,

and careful sediment management will be required.

4. CONCLUSION

This study assessed the current physicochemical status and residual hydrocarbon contamination of Okpare River, Delta State, Nigeria, a decade after crude oil bunkering ceased. The findings reveal that Okpare River still carries a chemical and biological memory of its polluted past. Key parameters such as BOD, COD, and turbidity exceeded permissible limits, while DO levels remained below acceptable standards, particularly around Otor-Edo and Kiagbodo. Nutrient enrichment downstream suggests a gradual shift from hydrocarbon-driven to nutrient-supported stress, signaling incomplete ecological recovery.

Residual hydrocarbon concentrations (0.178-0.374 mg/L) exceeded the WHO, FEPA, and NIS threshold of 0.05 mg/L, confirming persistent contamination despite visible surface improvement. Strong positive correlations between TPH and organic load indicators (BOD, COD, and turbidity), and its inverse relationship with DO, indicate that petroleum residues continue to shape the river's oxygen balance and biochemical processes. Collectively, these results show that the Okpare River remains chemically unstable and only partially recovered from its years of artisanal refining.

To restore balance, recovery must move beyond natural attenuation. Targeted bioremediation using indigenous microbial strains should be initiated, alongside riverbank vegetation restoration to stabilize sediments and enhance oxygen renewal. Continuous monitoring by state and federal agencies is crucial to track improvement, while community engagement and livelihood alternatives can discourage any return to illegal refining. A coordinated remediation and management framework will ensure long-term chemical stability and sustain the Okpare River's ecological and social value.

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