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Impact evaluation of crude oil spills on surface water, sediment and fish in oil-producing communities of the Niger Delta, Nigeria

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Abstract

Crude oil spills remain frequent in the Niger Delta, yet post-spill studies rarely rate contamination to prioritise clean-up. This study evaluated surface water, sediment and fish at ten spill-affected stations in Delta, Bayelsa and Rivers States, Nigeria, with the Agbarho River as reference. Water was analysed in triplicate for physicochemical parameters, total petroleum hydrocarbons (TPH) by gas chromatography, and Pb, Cu, Cr, Fe and Zn by flame atomic absorption spectrophotometry; TPH was also determined in sediment and in dead African catfish (*Clarias gariepinus*). Contamination was scored on a five-point impact-magnitude scale from the departure of mean TPH from regulatory limits. Surface-water TPH ranged from < 0.001 to 97.6 mg/L and exceeded the 10 mg/L benchmark only at Okerenkoko and Santa Barbara, where crude oil was visible. Sediment TPH reached 21,550 mg/kg at Okerenkoko, over four times the national intervention value of 5,000 mg/kg, and 1,740 mg/kg at Santa Barbara, but was within the 50 mg/kg target elsewhere. Fish from Okerenkoko contained 58,334 mg/kg TPH, against 0.39–0.43 mg/kg at two other stations. Dissolved oxygen (1.40–5.80 mg/L) declined as TPH increased (Spearman $\rho = -0.73$, $p = 0.017$). Iron and chromium exceeded their limits at several stations and at the reference river without correlating with TPH, pointing to catchment-wide sources. Impact evaluation rated surface water high at Okerenkoko and medium at Santa Barbara, and sediment severe at both; all other stations were within limits. Both stations need active remediation of water and sediment; all stations need continued monitoring.

1 Introduction

The Niger Delta holds most of Nigeria's oil wealth and extensive mangrove forests. The mangrove area fell to about 802,000 ha by 2017, 12% less than a decade earlier, and oil pollution is among the major causes of mangrove degradation and loss [1, 2]. Oil still dominates the national economy; crude oil alone made up about 69% of the value of exports in the fourth quarter of 2024 [3]. The communities that host the oil industry depend on creeks, rivers and swamps for fishing, farming, drinking water and transport, so pollution of these waters translates directly into lost livelihoods and health risks [2, 4].

Oil spills are frequent in the region and concentrated in a few states. Bayelsa, Delta and Rivers States account for more than 85% of the spills recorded by the National Oil Spill Detection and Response Agency (NOSDRA) between 1994 and 2021 [5], and the Federal Ministry of Environment reported 4,919 spills between 2015 and March 2021 [6]. Response is often slow; Shell, for example, reached spill sites within the required 24 hours in only 26% of cases [2, 7].

The resulting damage is severe and long-lasting. The United Nations assessment of Ogoniland found widespread, long-standing contamination of land and water and estimated that a full clean-up could take 25 to 30 years [8]. Two large spills in Ogoniland killed about 393 km^2 of vegetation, mostly mangrove, and placed more than one million people in the impact zone [9]. Oil spills near a mother's home before conception have also been linked to a doubling of neonatal mortality [10].

Once spilled, crude oil spreads, partly evaporates, dissolves and disperses in the water, and a large part binds to particles and sinks; sediments thus become long-term stores of oil, in which buried oil degrades slowly because oxygen is scarce [11]. Because crude oil is a complex mixture, it is commonly measured as

total petroleum hydrocarbons (TPH), a single measure of the whole mixture; the aromatic fractions in particular are toxic to aquatic life and to people [12]. Crude oil and oil-field discharges also carry potentially toxic metals [13], which persist and accumulate in sediments and living organisms [14]. Fish take up metals through their gills and food and suffer stress and damage to the gills, liver and kidneys [15]. Contaminated fish are a direct route of human exposure, and oil-derived toxins have entered the region's food chain [2].

Many studies have documented this pollution in the Niger Delta. Severe TPH contamination has been reported in the water and sediment of the Kporghor estuary [16], and TPH and metals above drinking-water guidelines in the water of the Bille mangrove [17]; monthly sampling has shown that contaminant levels change with the seasons [18]. Other work has detected petroleum hydrocarbons in seafood from oil-impacted creeks [19]. Methods have also been proposed for ranking contaminated sites so that the worst can be cleaned up first [20], and for remediation that restores the land while creating local jobs [4, 21].

Three gaps remain. Most studies have covered a single site, estuary or state, which limits comparison across the region; few go beyond reporting concentrations to rate how serious the contamination is, the information decision-makers need to prioritise clean-up when resources are limited [20]; and water, sediment and fish from the same spill events are rarely examined together. This study addresses these gaps by comparing ten stations across Delta, Bayelsa and Rivers States with one set of methods and a common reference river, converting TPH concentrations into a severity rating for each station, and relating these ratings to the condition of the water, sediment and fish in the same communities.

The aim of this study was therefore to evaluate the impact of crude oil spills on surface water, sediment and fish at ten stations in spill-affected communities of Delta, Bayelsa and Rivers States. The specific objectives were to: (i) determine TPH in surface water and sediment; (ii) determine TPH in the African catfish, *Clarias gariepinus*; (iii) determine Pb, Cu, Cr, Fe and Zn in surface water; (iv) describe the physicochemical quality of the water; and (v) rate the significance of TPH contamination in water and sediment through impact evaluation, in order to identify the stations that most need remediation.

2 Materials and methods

2.1 Study area and sampling stations

Sampling covered ten stations in four spill-affected areas of the Niger Delta (Table 1; Fig. 1): the Okerenkoko area of Gbaramatu Kingdom and nearby creeks in Delta State, Egbebiri in Biseni Kingdom and Santa Barbara in Nembe in Bayelsa State, and Afam in Rivers State. The Agbarho River in Delta State, a non-industrial river away from oil installations, served as the reference station. The stations lie among mangrove and freshwater swamps drained by creeks and rivers that host oilfields, flow stations, wellheads and pipelines, and fishing is the main occupation of the surrounding communities.

Several stations have recent spill histories. A wellhead rupture at Idu Well 11 in Egbebiri on 7 May 2021 was attributed to equipment failure [22], and a blowout at the Santa Barbara wellhead on Oil Mining Lease (OML) 29 in Nembe began on 5 November 2021 and was shut in on 8 December 2021 [23]. At Okerenkoko and Santa Barbara, crude oil was visible on the water surface during sampling.

Table 1
Sampling stations, locations and samples collected

Station	State (LGA)	Coordinates	Samples
Okerenkoko	Delta (Warri South West)	5°26'18"N, 5°27'37"E	W, S, F
Egwa	Delta (Warri South West)	5°37'19"N, 5°26'13"E	W, S, F
Odidi	Delta (Warri South West)	5°32'53"N, 5°27'22"E	W, S, F
Beniboye	Delta (Burutu)	5°19'02"N, 5°19'45"E	W, S
Odimodi	Delta (Burutu)	5°17'31"N, 5°22'18"E	W, S
Ebibode	Delta (Burutu)	5°16'N, 5°25'E	W, S
Egbebiri-Biseni	Bayelsa (Yenagoa)	5°15'N, 6°33'E	W, S
Santa Barbara	Bayelsa (Nembe)	4°20'47"N, 6°36'52"E	W, S
Afam 1	Rivers (Oyigbo)	4°49'N, 7°19'E	W, S
Afam 2	Rivers (Oyigbo)	4°49'N, 7°19'E	W, S
Agbarho River (reference)	Delta (Ughelli North)	5°35'17"N, 5°51'59"E	W, S

W = surface water; S = sediment; F = fish (*Clarias gariepinus*). Coordinates mark the community or oil-field location (Afam 1 and Afam 2 share the Afam coordinate); the Ebibode coordinate is approximate. LGA, local government area.

2.2 Sample collection and preservation

Surface water was collected in triplicate at each of the ten stations and at the reference station during January and February 2022, in the dry season. Water for metals was collected in 1 L polyethylene bottles, acidified with 1–2 mL of 1:1 HNO_3 and stored at 4°C; water for TPH was collected in glass bottles and preserved with 1 mL of 1:1 H_2SO_4; and water for physicochemical analysis was collected in plastic containers and cooled to 4°C [24]. Surface sediment was collected with a hand-held van Veen grab into solvent-rinsed glass jars and stored at 4°C. Dead African catfish (*C. gariepinus*) were collected at Okerenkoko, Egwa and Odidi and placed in Teflon bags, kept on ice, frozen at − 20°C within 6 h of collection and analysed as whole-body homogenates.

2.3 Physicochemical analysis

Temperature, pH, electrical conductivity (EC) and total dissolved solids (TDS) were measured with a PCSTestr 35 multiparameter tester after 3–5 min of equilibration. Turbidity was measured with a Micro TPI turbidimeter calibrated against 0 and 10 NTU standards. Total suspended solids (TSS) were determined gravimetrically by filtering 100 mL of sample through a filter pre-dried to constant weight at 105°C and drying the residue to constant weight at the same temperature.

Phosphate was determined by the ascorbic acid method, reading absorbance at 880 nm on a Hach DR 2800 spectrophotometer against a calibration curve. Total alkalinity was determined by titrating 100 mL of sample with 0.02 N H_2SO_4 to a mixed-indicator end point, and bicarbonate was calculated from it. Dissolved oxygen (DO) was measured by the azide modification of the Winkler iodometric method (4500-O C). All procedures followed Standard Methods [24].

2.4 Metals in water

A 100 mL aliquot of each water sample was digested with 5 mL of concentrated HNO_3 on a hot plate to 15–20 mL, filtered and made up to 50 mL with distilled water [24], so results represent total recoverable metals. Pb, Cu, Cr, Fe and Zn were determined by flame atomic absorption spectrophotometry (Shimadzu AA-6701F). Concentrations below the detection limit are reported as < 0.001 mg/L.

2.5 Total petroleum hydrocarbons

Water samples (750 mL) were extracted in a separatory funnel with 75 mL of dichloromethane–n-hexane (1:1, v/v), of which 50 mL was first used to rinse the sample bottle. The funnel was shaken for 10–15 min with periodic venting, 5 g of anhydrous Na_2SO_4 was added, and the organic phase was collected and cleaned on a silica-gel column packed with glass wool and anhydrous Na_2SO_4.

One microlitre of extract was injected into a calibrated gas chromatograph with flame ionisation detection (GC-FID; Agilent 7890B; HP-5 capillary column, 30 m × 0.32 mm i.d., 0.25 µm film; oven at 60°C for 2 min, then 10°C/min to 300°C held for 10 min; nitrogen carrier gas at 1.5 mL/min; injector 280°C; detector 320°C; TPH reported as C8–C40), and TPH was quantified from integrated peak areas against external calibration standards. Sediment was air-dried, homogenised and sieved to 2 mm, and 10 g was extracted with 50 mL of dichloromethane–n-hexane (1:1, v/v) on a mechanical shaker for 30 min. Whole fish were homogenised, and 10 g of homogenate was mixed with anhydrous Na_2SO_4 and extracted with 50 mL of the same solvent mixture. Both extracts were dried over anhydrous Na_2SO_4 and cleaned on silica-gel columns before GC-FID as described for water. Sediment TPH is therefore reported on a dry-weight basis and fish TPH on a wet-weight basis.

2.6 Quality assurance and quality control

Instruments were calibrated with standard solutions before each analytical run, all determinations were made in triplicate, and results are reported as means of triplicates (Table 2) or, where replicate SDs were available, as means ± standard deviation (SD; Tables 3 and 4). Replicate precision, expressed as the coefficient of variation (CV = SD/mean × 100) at stations where TPH was quantified, was below 1% for water, 7.5–17.3% for sediment and 2.6–13.1% for fish. Procedural blanks were below the method detection limits (MDLs): 0.001 mg/L for water TPH and for each metal, 0.03 mg/kg for sediment TPH and 0.01 mg/kg for fish TPH.

2.7 Impact evaluation

The significance of TPH contamination was evaluated from the departure of each concentration from its regulatory limit, an exceedance measure in the tradition of the contamination factor of Håkanson [25]. For

each station and matrix, impact magnitude (IM) was calculated as the percentage departure of the mean concentration from its regulatory limit:

$$IM\ (\%) = \frac{C - L}{L} \times\ 100$$

1

where *C* is the mean TPH concentration and *L* is the limit: 50 mg/kg, the target value for mineral oil in soil/sediment in the Environmental Guidelines and Standards for the Petroleum Industry in Nigeria (EGASPIN, Part VIII-F) [26], and 10 mg/L for surface water, the EGASPIN limit for oil and grease in effluent discharged to inland waters (EGASPIN Table II-8). EGASPIN sets no TPH value for ambient surface water [16], so the 10 mg/L effluent limit was used only as a screening benchmark (Section 3.7).

IM was rated on a five-point scale: 1 (negligible, IM ≤ 0), 2 (low, 0 < IM ≤ 100%), 3 (medium, 100 < IM ≤ 500%), 4 (high, 500 < IM ≤ 1,000%) and 5 (severe, IM > 1,000%). Because IM = (CF − 1) × 100, where CF = *C*/*L* is the contamination factor of Håkanson [25] with the regulatory limit in place of the background concentration, the class boundaries correspond to CF = 1, 2, 6 and 11, and the high and severe classes subdivide Håkanson's "very high contamination" class (CF ≥ 6). Each station was then assigned an action: active remediation of water and sediment where both matrices exceeded their limits; prompt recovery of free-phase oil with follow-up sediment monitoring where only the water exceeded its limit; and routine monitoring where neither did; no station exceeded the sediment limit alone. Sediment above the EGASPIN intervention value of 5,000 mg/kg was flagged separately. EGASPIN, issued by the former Department of Petroleum Resources, is now administered by the Nigerian Upstream Petroleum Regulatory Commission (NUPRC) under the Petroleum Industry Act 2021 [27].

2.8 Statistical analysis

Differences in metal concentrations among stations were tested with Welch's one-way ANOVA, which does not assume equal variances, and each station was compared with the reference by Welch's t-test on the triplicate means and SDs (n = 3), with Holm–Bonferroni adjustment for multiple comparisons (α = 0.05). All station means were compared with the adopted limits. Associations of surface-water TPH with DO and with each metal were tested across the impacted stations with Spearman's rank correlation (two-tailed, α = 0.05; tied values given average ranks). The DO correlation addressed a single question, whereas the five metal correlations were treated as one family and adjusted by the Holm method. Values below detection were set to the detection limit, and the Santa Barbara chromium value, which was not available, was excluded (n = 9 for Cr). Analyses were run in Python 3 with SciPy.

3 Results and discussion

3.1 Physicochemical characteristics of surface water

Water at every spill-impacted station had higher conductivity and turbidity than at the reference station (Table 2). pH ranged from 6.36 to 7.80 and fell slightly below the lower limit of 6.5 at Egwa (6.36) and

Beniboye (6.47), while temperature varied little (27–29°C). EC ranged from 720 to 3,539 µS/cm, 9 to 45 times the reference value of 78 µS/cm, and TDS reached 1,876 mg/L at Afam 2 against 42 mg/L at the reference. TSS (7–320 mg/L) and turbidity (8–18 NTU) were likewise well above the reference values of 1.5 mg/L and 1 NTU.

Part of the EC and TDS contrast probably reflects natural differences between the inland freshwater reference river and the tidal creeks of the mangrove belt. The highest EC and TDS, however, occurred at the inland Afam stations (up to 3,539 µS/cm and 1,876 mg/L), pointing to additional dissolved inputs such as oil-field produced water, which carries dispersed oil, polycyclic aromatic hydrocarbons and metals [13]. Suspended solids peaked at Afam 2 (320 mg/L), where TPH was low, consistent with runoff or sediment resuspension.

DO ranged from 1.40 to 5.80 mg/L, against 5.90 mg/L at the reference, and declined as surface-water TPH increased (Spearman $\rho = -0.73$, $p = 0.017$; Fig. 2). The four lowest values, at Santa Barbara (1.40 mg/L), Okerenkoko (2.48 mg/L), Egwa and Odidi (2.98 mg/L each), occurred where TPH exceeded 1.4 mg/L, and at Santa Barbara and Okerenkoko DO was less than half the reference value; DO remained close to the reference at Egbebiri-Biseni (5.80 mg/L) and Afam 1 (5.30 mg/L) at comparable TPH. Microbial degradation of oil in surface waters is predominantly aerobic [28], so large oil inputs, together with decaying biota, create an oxygen demand that can exceed reaeration; surface slicks may also reduce gas exchange [28]. Phosphate (0.11–2.34 mg/L) and bicarbonate were highest at Okerenkoko, Egwa and Odidi, consistent with enhanced decomposition of organic matter.

Table 2
Physicochemical characteristics of surface water (means, n = 3)

Station	pH	Temp. (°C)	EC (µS/cm)	TDS (mg/L)	TSS (mg/L)	Turb. (NTU)	HCO_3^- (mg/L)	PO_4^{3-} (mg/L)	DO (mg/L)
Okerenkoko	6.50	27	1,198.3	802.86	8	10	15	2.34	2.48
Egwa	**6.36**	27	1,189	596	7	10	13	1.34	2.98
Odidi	6.50	28	1,178	602	9	8	13.7	1.24	2.98
Beniboye	**6.47**	27	1,400	402	18	11	0.04	0.47	3.90
Odimodi	6.50	27	2,603	603	40	14.1	0.09	0.11	3.98
Ebibode	6.58	29	802	42	35	18	0.03	0.14	5.50
Egbebiri-Biseni	6.78	28	1,247	63	45	16.5	0.05	0.12	5.80
Santa Barbara	7.80	27	720	78	90	16.8	2.14	0.53	1.40
Afam 1	6.78	28	2,603	1,372.57	40	10.2	0.01	0.41	5.30
Afam 2	6.50	27	3,539	1,875.67	320	8	0.01	0.57	5.80
Agbarho (reference)	6.80	27	78	42	1.5	1	2.4	0.04	5.90

Bold values fall outside the regulatory pH range of 6.5–8.5 [26]. EC, electrical conductivity; TDS, total dissolved solids; TSS, total suspended solids; Turb., turbidity; DO, dissolved oxygen.

3.2 Total petroleum hydrocarbons in surface water

Surface-water TPH ranged from below detection to 97.6 mg/L, a spread of five orders of magnitude (Fig. 3), and exceeded the 10 mg/L benchmark at two of the ten stations: Okerenkoko (97.6 mg/L, 9.8 times the benchmark) and Santa Barbara (27.0 mg/L, 2.7 times), where oil was visible on the water. TPH was 1.4–1.6 mg/L at Egwa, Afam 1, Odidi and Egbebiri-Biseni and 0.40 mg/L at Odimodi, and was below detection (< 0.001 mg/L) at Afam 2, Beniboye, Ebibode and the reference station.

The two highest values, 97.6 and 27.0 mg/L, were measured where oil was visible on the water; values of this magnitude approach or exceed the solubility of crude-oil hydrocarbons in water [12], so these samples probably included dispersed or free-phase oil, and the dissolved fraction to which aquatic organisms were exposed was likely smaller. All detected values fall within the span reported for other Niger Delta waters, from 0.18–57.66 mg/L in the Bille mangrove [17] to 10–620 mg/L in the chronically polluted Kporghor estuary [16].

3.3 Total petroleum hydrocarbons in sediment

Sediment TPH exceeded the EGASPIN target value of 50 mg/kg at two stations (Fig. 3; Table 3). At Okerenkoko it reached 21,550 ± 1,624 mg/kg, 4.3 times the intervention value of 5,000 mg/kg and comparable to the maximum of 20,600 mg/kg reported for surface sediments of the Kporghor estuary [16]; at Santa Barbara it reached 1,740 ± 167 mg/kg. Sediment at the other eight stations held 39 ± 5.0 mg/kg (Odimodi) or less, and the reference sediment was below 0.03 mg/kg. Moderately elevated TPH in water (1.4–1.6 mg/L) with low TPH in sediment (15 mg/kg or less) at Egwa, Odidi, Egbebiri-Biseni and Afam 1 suggests modest, ongoing or recent inputs whose oil had not settled into the sediment, whereas Okerenkoko and Santa Barbara combine fresh oil with an accumulated sediment burden. Because buried oil degrades slowly where oxygen is limited and can persist for a decade or more [11], sediments at these two stations are likely to act as long-term secondary sources of contamination.

3.4 Total petroleum hydrocarbons in fish

Catfish from Okerenkoko contained 58,334 ± 7,631 mg/kg TPH (Table 3), more than five orders of magnitude above fish from Egwa (0.39 ± 0.01 mg/kg) and Odidi (0.43 ± 0.02 mg/kg), even though surface-water TPH at Egwa and Odidi (1.5–1.6 mg/L) was among the highest recorded after Okerenkoko and Santa Barbara. The specimens were dead fish recovered at spill sites, and the Okerenkoko value, about 6% of sample mass, probably includes oil coating the fish or held in its gut. Fish metabolise petroleum aromatics [29], consistent with the low residues at Egwa and Odidi, which are of the same order as the 1.2 mg/kg reported in periwinkles from oil-impacted creeks in Rivers State [19]. Because oil-derived toxins have entered the region's food chain [2], consumption of fish from actively oiled waters should be avoided as a precaution until residues in live fish have been assessed.

Table 3
Total petroleum hydrocarbons in sediment and fish

Station	TPH	CV (%)
Sediment (dry weight)		
Okerenkoko	**21,550 ± 1,624**	7.5
Santa Barbara	**1,740 ± 167**	9.6
Odimodi	39 ± 5.0	12.8
Beniboye	17.5 ± 2.7	15.4
Egwa	15 ± 2.6	17.3
Odidi	15 ± 2.0	13.3
Fish, *C. gariepinus* (wet weight)		
Okerenkoko	58,334 ± 7,631	13.1
Egwa	0.39 ± 0.01	2.6
Odidi	0.43 ± 0.02	4.7

Bold values exceed the EGASPIN sediment target of 50 mg/kg [26]; Okerenkoko sediment also exceeds the intervention value of 5,000 mg/kg. Sediment TPH was at or near the detection limit (0.03 mg/kg) at Egbebiri-Biseni, Afam 1, Afam 2 and Ebibode and below it at the reference station; fish were collected only at Okerenkoko, Egwa and Odidi. CV, coefficient of variation (SD/mean × 100).

3.5 Metals in surface water

Zn (0.013–0.93 mg/L) and Cu (0.004–0.041 mg/L) were within their limits at every station (Table 4). Fe exceeded 1.0 mg/L at Okerenkoko, Egwa, Odidi and Odimodi (2.01–2.96 mg/L), and Cr exceeded 0.03 mg/L at seven of the nine stations with chromium data, reaching 0.34 mg/L at Egwa. Pb exceeded its 0.05 mg/L limit only at Afam 1 (0.184 mg/L).

Metal concentrations did not separate impacted from reference waters (Fig. 4). Fe and Cr exceeded their limits at the reference station (Fe 2.62 mg/L; Cr 0.323 mg/L), where TPH was below detection. Fe, Zn, Cr and Cu each differed among stations (Welch's ANOVA, all $p < 0.001$), with differences from the reference in both directions (Table 4): Fe was significantly higher than at the reference at Okerenkoko, Egwa and Odidi and significantly lower at the other seven stations, including Santa Barbara, which had the second-highest TPH; Cr was significantly lower at five stations and did not differ at the other four; and Zn and Cu were significantly higher at seven and four stations, respectively, while remaining within their limits. No metal correlated significantly with TPH (Fe $\rho = 0.37$; Cr $\rho = 0.50$; Zn $\rho = -0.45$; Cu $\rho = 0.28$; Pb $\rho = 0.11$; all $p > 0.16$; Holm-adjusted $p \geq 0.84$), in contrast to the strong TPH–metal correlations ($r > 0.88$) reported for the Bille mangrove [17]. These patterns suggest that elevated Fe and Cr derive mainly from catchment-wide natural or diffuse sources.

Pb at Afam 1, more than three times the adopted limit and 18 times the World Health Organization drinking-water guideline of 0.01 mg/L [30], points to a localised source that warrants investigation where river water is used for drinking or cooking. Cr concentrations above 0.2 mg/L at five impacted stations also warrant monitoring, because metals persist, accumulate in fish [15] and harm human health at elevated exposure [31].

Table 4
Metals in surface water

Station	Fe	Zn	Cr	Cu	Pb
Okerenkoko	**2.955 ± 0.001***	0.181 ± 0.001*	**0.327 ± 0.002**	0.041 ± 0.0015*	< 0.001
Egwa	**2.95 ± 0.015***	0.19 ± 0.02*	**0.34 ± 0.01**	0.04 ± 0.003*	< 0.001
Odidi	**2.96 ± 0.01***	0.16 ± 0.01*	**0.33 ± 0.03**	0.03 ± 0.03	< 0.001
Beniboye	0.318 ± 0.001*	0.37 ± 0.01*	0.001 ± 0.001*	0.024 ± 0.0015*	< 0.001
Odimodi	**2.014 ± 0.002***	0.013 ± 0.013*	**0.031 ± 0.002***	0.04 ± 0.01	0.001
Ebibode	0.764 ± 0.001*	0.93 ± 0.025*	**0.214 ± 0.0021***	0.019 ± 0.001*	< 0.001
Egbebiri-Biseni	0.698 ± 0.0021*	0.78 ± 0.01*	**0.33 ± 0.015**	0.03 ± 0.01	0.02
Santa Barbara	0.398 ± 0.001*	0.036 ± 0.0021*	–	0.004 ± 0.004	< 0.001
Afam 1	0.596 ± 0.002*	0.085 ± 0.001*	0.014 ± 0.0015*	0.016 ± 0.002	**0.184**
Afam 2	0.493 ± 0.0025*	0.184 ± 0.001*	**0.141 ± 0.001***	0.007 ± 0.002	< 0.001
Agbarho (reference)	**2.620 ± 0.01**	0.098 ± 0.001	**0.323 ± 0.001**	0.011 ± 0.001	< 0.001
Limit [26]	1.00	1.00	0.03	1.50	0.05
Welch's ANOVA, p	< 0.001	< 0.001	< 0.001	< 0.001	n.t.

Bold values exceed the adopted limit. Values below the detection limit are shown as < 0.001; –, not available; Pb values are shown without SD. * Significantly different from the reference (Welch's t-test with Holm adjustment, $p < 0.05$). The last row gives the overall Welch's ANOVA result; n.t., not tested (most Pb values were below detection).

3.6 Impact evaluation and remediation priorities

Impact evaluation rated surface water high at Okerenkoko (IM 876%) and medium at Santa Barbara (IM 170%), and sediment severe at both stations (IM 43,000% and 3,380%; Table 5). At the other eight stations, water TPH was below the 10 mg/L benchmark (IM − 84% to − 100%) and sediment TPH below the 50 mg/kg target (IM − 22% to − 100%), so all of these rated negligible. Okerenkoko and Santa Barbara were thus the only stations where both matrices exceeded their limits, and Okerenkoko sediment also exceeded the EGASPIN intervention value. These ratings were robust to replicate variability: water SDs were below 1% of

the means, the Okerenkoko and Santa Barbara sediment ratings stayed severe at the mean minus one SD (19,926 and 1,573 mg/kg), and sediment at the other stations stayed below the target at the mean plus one SD, Odimodi coming closest (44 mg/kg; Table 3).

The ratings turn these concentrations into a ranking that can guide action (Fig. 5). Okerenkoko and Santa Barbara combine impacts in water and sediment, and Okerenkoko sediment exceeds the intervention value; both are priorities for active remediation of both matrices. At the remaining eight stations neither matrix exceeded its limit, so they fall to routine monitoring; the depressed dissolved oxygen at Egwa and Odidi, the moderately elevated water TPH (1.4–1.6 mg/L) at Egwa, Odidi, Egbebiri-Biseni and Afam 1, and the sediment TPH close to the target at Odimodi nevertheless justify closer observation within that programme.

For the remediation itself, approaches based on enhanced natural attenuation have performed poorly in the Delta's dynamic wetlands, and bioremediation is now favoured for its low cost and small environmental footprint [21]; designed well, it can also create local employment [4].

Table 5
Impact evaluation of TPH in surface water and sediment, sorted by surface-water impact magnitude

Station	Water IM (%)	Water rating	Sediment IM (%)	Sediment rating	Recommended action
Okerenkoko	876	4, high	43,000[a]	5, severe	Active remediation of water and sediment
Santa Barbara	170	3, medium	3,380	5, severe	Active remediation of water and sediment
Egwa	−84	1, negligible	−70	1, negligible	Routine monitoring
Afam 1	−84	1, negligible	−100	1, negligible	Routine monitoring
Odidi	−85	1, negligible	−70	1, negligible	Routine monitoring
Egbebiri-Biseni	−86	1, negligible	−100	1, negligible	Routine monitoring
Odimodi	−96	1, negligible	−22	1, negligible	Routine monitoring
Afam 2	−100	1, negligible	−100	1, negligible	Routine monitoring
Beniboye	−100	1, negligible	−65	1, negligible	Routine monitoring
Ebibode	−100	1, negligible	−100	1, negligible	Routine monitoring

IM, impact magnitude from Eq. (1), with L = 10 mg/L for water and 50 mg/kg for sediment. Values of − 100 correspond to concentrations at or near the detection limit. Actions follow the decision rule in Section 2.7. [a]

Sediment TPH (21,550 ± 1,624 mg/kg) also exceeds the EGASPIN intervention value of 5,000 mg/kg.

3.7 Limitations

The study rests on a single sampling campaign, and contaminant levels in Niger Delta waters vary seasonally [18]. The freshwater reference river cannot fully represent the brackish creeks among the impacted stations, and because it exceeded the Fe and Cr limits it represents regional background rather than uncontaminated conditions. The 10 mg/L water benchmark is an effluent limit for oil and grease, a method-defined parameter that is not strictly equivalent to TPH measured by GC-FID. The impact evaluation compares each concentration with a single limit and does not weigh exposure pathways, ecological sensitivity or the number of people affected, which multi-criteria prioritisation incorporates [20]; it serves as a first screen within risk-based site management [32], and no human health risk assessment was attempted. TPH was measured in bulk, without fractionation, polycyclic aromatic hydrocarbons or diagnostic ratios, so petrogenic and biogenic hydrocarbons were not distinguished; DO was measured on a single visit to each station, without biochemical oxygen demand; fish were dead specimens from three stations; and metals were not measured in sediment or fish. Future work should sample across seasons, use reference sites matched for salinity, apply hydrocarbon fingerprinting, quantify polycyclic aromatic hydrocarbons and metals in sediment and biota, and pair tissue residues with biomarkers in live fish.

4 Conclusion

Surface-water TPH exceeded the 10 mg/L screening benchmark, and sediment TPH the 50 mg/kg target, only at Okerenkoko and Santa Barbara, the two stations where crude oil was visible on the water. These are the most affected stations: water TPH reached 97.6 and 27.0 mg/L, and Okerenkoko also had sediment TPH 4.3 times the EGASPIN intervention value and heavily oiled fish. At the other eight stations, water and sediment TPH remained within their limits. Dissolved oxygen declined as TPH increased and, at the two most affected stations, fell below half the reference value, to levels that are stressful for most aquatic life.

Iron and chromium exceeded their limits at the reference river as well as at impacted stations and did not correlate with TPH, pointing to catchment-wide sources; the lead exceedance at Afam 1 indicates a separate, localised source that warrants investigation.

A concentration-based impact evaluation converted the analytical results into a severity rating for each station, separating the two acutely oiled stations from those within limits and identifying the stations most in need of clean-up.

The results support prioritising Okerenkoko and Santa Barbara for active remediation of water and sediment, for example with bioremediation-based methods suited to wetlands, with recovery verified against the EGASPIN intervention value. The depressed dissolved oxygen at Egwa and Odidi, the moderately elevated water TPH there and at Egbebiri-Biseni and Afam 1, and the sediment TPH close to the target at Odimodi justify continued monitoring even though concentrations were within their limits. Regulators (NUPRC and NOSDRA) should require routine post-spill monitoring of TPH, dissolved oxygen and metals in water, sediment and fish, and an ambient surface-water TPH standard would strengthen

EGASPIN. As a precaution, communities should be advised not to eat fish from actively oiled waters until clean-up is achieved and residues in live fish have been assessed. Applied after significant spills, this approach can help direct limited clean-up resources to the communities that need them most.

Declarations

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Author contributions

DFO: conceptualisation, methodology, supervision, writing – review and editing. PDC: investigation, formal analysis, data curation, visualisation, writing – original draft. NAN: investigation, validation, writing – review and editing. All authors read and approved the final manuscript.

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Data availability

The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request

Ethics approval and consent to participate

Not applicable

Consent for publication

Not applicable

Ai Tool Declaration

The authors declare that generative artificial intelligence (AI) tools was used only language editing and improving readability during manuscript preparation

Competing interests

The authors declare no competing interests.

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Figures

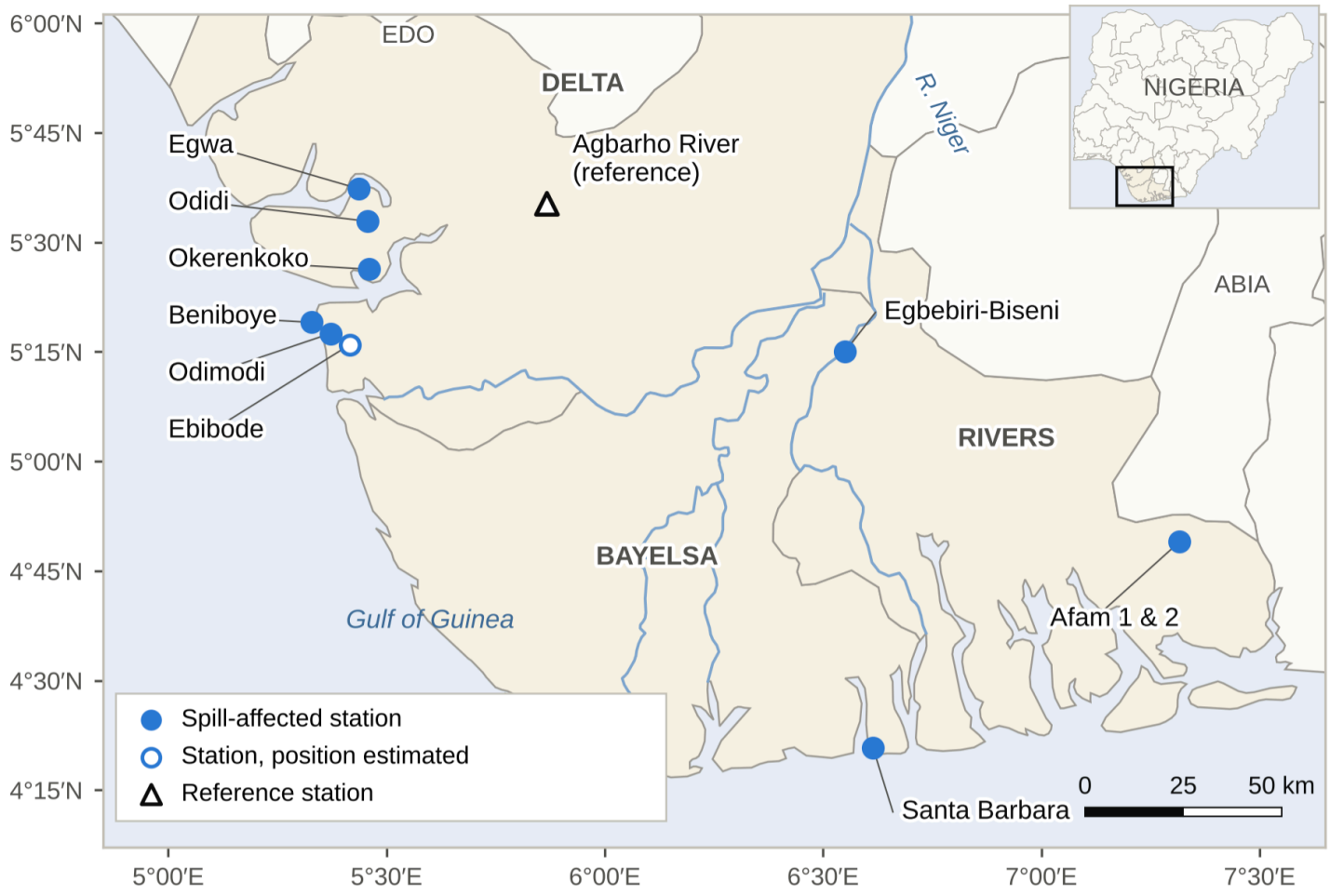


Figure 1

Map of the sampling stations in oil-producing communities of the Niger Delta, Nigeria, and the Agbarho River reference station. Coordinates are listed in Table 1; the Ebibode position is estimated (open circle). State boundaries and the River Niger are from Natural Earth (public domain)

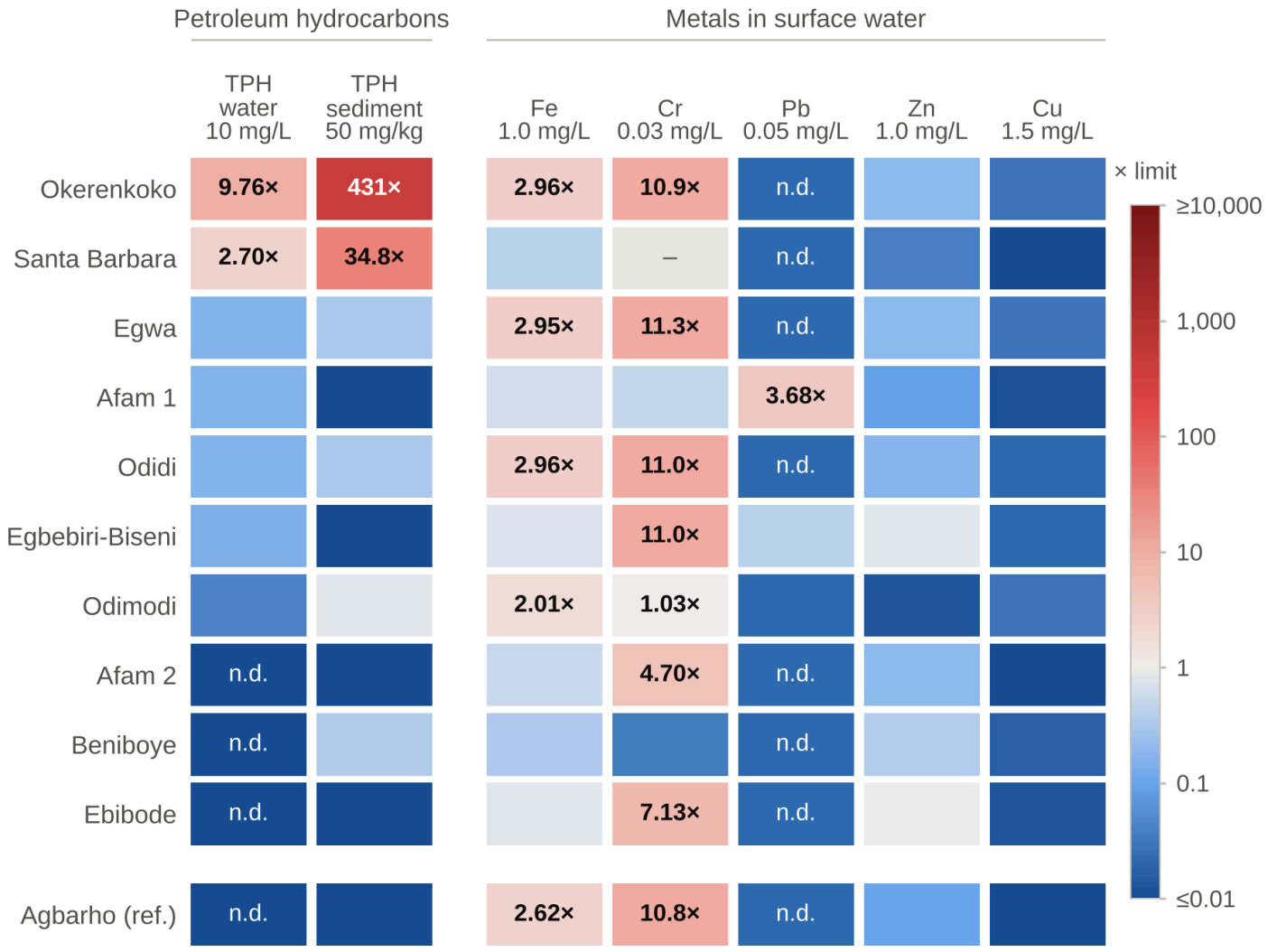


Figure 4

Exceedance of regulatory limits by TPH in surface water and sediment and by metals in surface water. Each cell is the station mean divided by its limit (shown under each column heading) on a logarithmic colour scale; red cells exceed the limit and are labelled with the exceedance factor, blue cells are below it; n.d., not detected; –, not available. Rows are sorted by surface-water TPH, with the reference station last