

Spatial and Vertical Variability of Petroleum Hydrocarbon Contamination in Depth-Stratified Soils Following a Sabotage-Induced Pipeline Spill: A Case Study from the Niger Delta, Rivers State, Nigeria

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Abstract- Accurate understanding of the spatial and vertical distribution of petroleum hydrocarbons in post-spill soils is very important to develop effective intervention strategies, assess the processes of natural attenuation of spill impacts, and conduct risk assessment according to regulatory requirements. This study examined the spatial variability and vertical distribution of total hydrocarbon content (THC) and associated physicochemical properties in soils impacted by a sabotage incident that ruptured a pipeline at Obele-Ibaa, Emohua Local Government Area, Rivers State, Nigeria, on April 14, 2015. Soils were sampled approximately 1 year post-spill from three paired topsoil and subsoil locations at depths of 0-15 cm and 15-30 cm, respectively, and one uncontaminated control site. The total hydrocarbon content was determined using n-hexane as a solvent and ultraviolet spectrophotometry as the analytical method. Spatial variability was characterized using contamination factors (CF), coefficient of variation (CV), and vertical distribution ratios (VDR = subsoil THC/topsoil THC). The THC values ranged from 1,302.2 to 1,860.7 mg/kg with a mean of 1,495.6 mg/kg and a coefficient of variation of 17.3 % in the topsoil samples, indicating moderate uniformity of surface contamination. In contrast, the THC values ranged from 769.6 to 4,443.6 mg/kg with a mean of 2,021.2 mg/kg and a coefficient of variation of 84.8 % in the subsoil samples, indicating high spatial variability with vertical distribution ratios ranging from 0.59 to 2.39. This study has shown that there is a two-tier contamination architecture with a uniform surface layer formed by initial spill impacts and a spatially heterogeneous subsoil layer that is governed by preferential flow through macropores and structural discontinuities in the soils. Position P3 was identified as a sub-surface hotspot with high THC values of 4,443.6 mg/kg and a high vertical distribution ratio of 2.39, indicating preferential vertical flow through a high permeability path. All the contamination factors were above the Department of Petroleum Resources (DPR) threshold of 50 mg/kg by 15 to 2,020-fold. This study has shown that spatially uniform intervention strategies are inappropriate for spill impacts of this class and that sub-surface hotspots need to be targeted during cleanup operations. A spatial remediation prioritization framework based on Tier I, Tier II, and Tier III is proposed based on contamination factor values and vertical distribution ratio values.

Keywords: spatial variability; depth-stratified contamination; total hydrocarbon content; Niger Delta; preferential flow; subsurface hotspot; contamination factor; vertical distribution ratio; remediation prioritization; pipeline spill

I. INTRODUCTION

Oil spills resulting from pipeline infrastructure are the leading mode of release of petroleum hydrocarbons in the Niger Delta, Nigeria—one of the most extensively exploited petroliferous provinces in the world. The Niger Delta pipeline infrastructure includes more than 5,000 km of operational crude oil and gas transmission infrastructure that is prone to deterioration, corrosion, and intentional third-party-related damage over more than six decades of operation (National Oil Spill Detection and Response Agency [NOSDRA], 2015; Tuttle et al., 1999). NOSDRA statistics consistently demonstrate that pipeline-related spills account for 50-60% of the total spills by volume released annually, with those resulting from sabotage-related damage being the most critical and concentrated spills as a result of their intentional nature and the attendant delay in detection and response to spills (NOSDRA, 2015).

Whereas the spreading of the discharged crude oil from the point of a pipeline rupture follows a complex set of physical and chemical processes involving gravity vertical percolation, capillary displacement of water, lateral spreading under gradients of surface tension, preferential flow along macropores and structural discontinuities, and distribution among non-aqueous phase liquid, water, vapor, and sorbed phases (Ekundayo & Obuekwe, 1997; Osuji et al., 2006), the three-dimensional distribution of petroleum hydrocarbons within the soil profile is rarely uniform and often exhibits considerable spatial variability or heterogeneity, especially with respect to the vertical dimension, with differences in subsoil contamination patterns over lateral distances of only a few meters being as great as one order of magnitude (Okop & Ekpo, 2012).

This spatial and vertical heterogeneity also has important practical implications. Remediation strategies that assume a uniform level of contamination, as implicitly assumed by most regulatory-mandated Remediation by Enhanced Natural Attenuation (RENA) programs, will systematically under-treat subsurface hotspots while over-treating areas with lower levels of

contamination, leading to inefficient allocation of remediation resources and failure to attain regulatory compliance within designated time frames (Marmioli & McCutcheon, 2003). Quantification of the spatial heterogeneity of contamination through the calculation of the coefficient of variation (CV), contamination factor (CF), and depth distribution ratio provides the empirical basis for the spatial targeting of remediation design (Osuji et al., 2004).

Despite the obvious importance of spatial heterogeneity to the effective remediation of contamination in the Niger Delta, few published studies from the region specifically report spatial variability metrics along with the typical contamination concentration data. Most published research reports only means from a small number of sample locations, effectively losing the spatial information contained within the dataset (Adeniyi & Afolabi, 2002; Onianwa, 1995). This analytical omission is especially concerning for sabotage spills, as they are assumed to be more spatially localized with greater vertical extent of contamination compared to the gradual corrosion seepage spills (Eneogwe & Ekundayo, 2003).

This research addresses the information gap by using quantitative spatial variability analysis on a depth-stratified THC data set obtained from the Obele-Ibaa sabotage-induced pipeline spill site in Rivers State, Nigeria, approximately 12 months post-spill event. Specific objectives include: (i) quantifying spatial variability in THC at the site using CV and CF values; (ii) determining VDR values to describe the pattern of vertical contamination distribution at three spatial positions; (iii) determining subsurface hotspot positions and their geotechnical implications; (iv) comparing spatial variability patterns at the Obele-Ibaa spill site with published data from other spill sites in the Niger Delta Basin; and (v) developing a spatial remediation prioritization framework using quantitative variability values applicable to other spill sites in the Niger Delta Basin.

II. MATERIALS AND METHODS

Study Site and Spill Event

The study site at Obele-Ibaa is located approximately at 4°56'N and 6°48'E in the Emohua Local Government Area of Rivers State, Nigeria, in the freshwater swamp/lowland rain forest ecological zone of the Niger Delta Basin. Terrain types at the site include flat to undulating topography with seasonal water courses, sandy terraces, and waterlogged depressions typical of distal fluvial-deltaic plains. On April 14, 2015, the Shell Petroleum Development Company's 4-inch crude oil pipeline at Obele-Ibaa was intentionally ruptured by a third party in an act of sabotage resulting in a documented spill of 87 barrels covering 0.497 ha. Figure 1 presents the geographical context of the spill site.

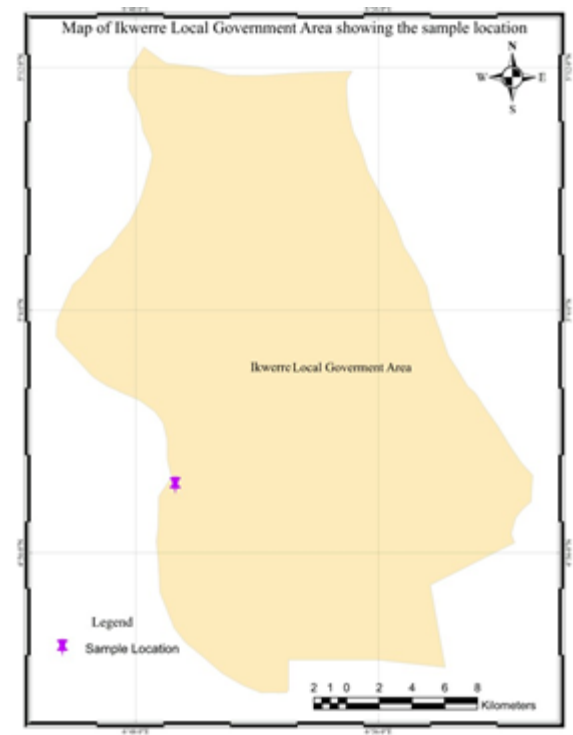


Figure 1. Geographic location of the Obele-Ibaa oil spill study site within Emohua Local Government Area, Rivers State, Nigeria (4°56'N, 6°48'E). Three paired topsoil–subsoil sampling positions (P1, P2, P3) were located within the visible oil-affected zone; the control was collected 100 m north of the spill

boundary. Map produced from field GPS survey data (2016).

Soil Sampling Design

A stratified replicated depth sampling design was adopted to account for the spatial and vertical distribution of the contaminant. Three positions, P1, P2, P3, were marked along the visible oil spill. At each position, paired samples of topsoil (0-15 cm, sample numbers 1A, 2A, 3A) and subsoil (15-30 cm, sample numbers 1B, 2B, 3B) were obtained using a stainless-steel hand auger, which was cleaned with deionized water. A control sample, C, was obtained at a point 100m away from the spill boundary at the topsoil depth from an area with similar parent material and land use history. Sample positions were determined using a GPS with an accuracy of ±3m. Approximately 500g of each sample was placed in a sealed HDPE bag, labeled, and stored at 4°C before transportation to the laboratory.

Total Hydrocarbon Content Determination

THC was determined using the n-hexane solvent extraction method combined with UV spectrophotometry. This method was based on the work of Bales (1954) as modified by Osuji et al. (2006). Air-dried, sieved (<1µm) soil (5.000±0.001g) was extracted with HPLC-grade n-hexane (2 x 10mL) containing 5g activated silica gel (mesh size 80-100) using a wrist-action shaker for 30 minutes. The combined solvent extracts were made up to 25mL, and the absorbance read at 425nm using a Genesis 10 UV spectrophotometer after blanketing with HPLC-grade n-hexane. THC was calculated from:

$$\text{THC (mg/kg)} = [A \times V(\text{hexane}) \times G \times 100] / W(\text{soil}) \dots (\text{Equation 1})$$

where A = absorbance at 425 nm, V(hexane) = total extraction volume (mL), G = calibration gradient (mg mL⁻¹ per absorbance unit), W(soil) = soil mass (g).

Spatial Variability Metrics

➤ Contamination Factor (CF)

The contamination factor for each sample and depth interval:

$$CF(i) = C(i) / C(\text{control}) \dots (\text{Equation 2})$$

where C(i) = THC of sample i (mg/kg) and C(control) = THC of the uncontaminated control (mg/kg). CF

interpretation: < 1 = below background; 1–2 = minor; 2–5 = moderate; 5–20 = considerable; > 20 = very high contamination (adapted from Hakanson, 1980).

➤ **Coefficient of Variation (CV)**

CV quantifies spatial variability within each depth interval:

$$CV (\%) = (S.D. / \text{Mean}) \times 100 \quad \dots \text{(Equation 3)}$$

CV < 20% = low (homogeneous); 20–50% = moderate; > 50% = high spatial variability (heterogeneous).

➤ **Vertical Distribution Ratio (VDR)**

VDR characterizes the vertical partitioning of THC at each position:

$$VDR(j) = \text{THC}(\text{subsoil}, j) / \text{THC}(\text{topsoil}, j) \quad \dots \text{(Equation 4)}$$

VDR > 1 = net downward migration (subsoil-dominant); VDR < 1 = surface-dominant; VDR > 1.5 = subsurface preferential flow hotspot designation.

➤ **Depth Attenuation Coefficient (DAC)**

DAC is the proportional change in THC per unit depth from the topsoil to the subsoil:

$$DAC(j) = [\text{THC}(\text{subsoil}, j) - \text{THC}(\text{topsoil}, j)] / \Delta z \quad \dots \text{(Equation 5)}$$

Δz = depth interval = 15 cm. Negative DAC implies attenuation of contaminants with depth; positive DAC implies increasing contaminants with depth.

III. RESULTS

THC by Sampling Position and Depth

Table 1 lists the entire dataset of THC values along with the calculated CF, VDR, and DAC values. Figure 2 illustrates the extent of the visually observable contaminants at the study site.

Table 1

Total hydrocarbon content (THC, mg/kg), contamination factor (CF), vertical distribution ratio (VDR), and depth attenuation coefficient (DAC) by sampling position and depth, Obele-Ibaa, Rivers State, Nigeria (2016).

Position	Sample ID	Depth (cm)	THC (mg/kg)	CF	VDR	DAC (mg kg ⁻¹ cm ⁻¹)
P1	1A (top)	0–15	1,324.0	602	0.64	-31.6
P1	1B (sub)	15–30	850.5	387	—	—
P2	2A (top)	0–15	1,302.2	592	0.59	-35.5
P2	2B (sub)	15–30	769.6	350	—	—
P3	3A (top)	0–15	1,860.7	846	2.39	+171.3
P3	3B (sub)	15–30	4,443.6	2,020	—	—
Control	C (top)	0–15	2.20	1.00	—	—

Note. CF = sample THC ÷ control THC (2.20 mg/kg). VDR = subsoil THC ÷ topsoil THC at same position. DAC = (subsoil THC – topsoil THC) ÷ 15 cm. VDR > 1.5 = subsurface preferential flow hotspot. DPR agricultural threshold = 50 mg/kg. All THC values in mg/kg (dry weight).

Spatial Variability Statistics by Depth

Table 2 lists the calculated statistics for the THC values at each depth interval along with the regulatory comparators.

Table 2

Summary statistics and spatial variability metrics for total hydrocarbon content (THC) at topsoil (0–15 cm) and subsoil (15–30 cm) depth intervals, Obele-Ibaa (2016).

Metric	Tops oil Mean	Top S.D.	Top CV (%)	Subs oil Mean	Sub S.D.	Sub CV (%)
THC (mg/kg)	1,495.6	258.3	17.3	2,021.2	1,713.2	84.8
Mean CF	680	—	—	919	—	—
Control THC (mg/kg)	2.20	—	—	2.20	—	—
DPR Threshold (mg/kg)	50	—	—	50	—	—
Exceedance factor (mean / threshold)	~30x	—	—	~40x	—	—

Note. CV = (S.D./Mean) × 100. CF = mean THC ÷ control. DPR = Department of Petroleum Resources (1991) EGASPIN agricultural threshold. S.D. = standard deviation across n = 3 positions per depth.

Vertical Distribution Ratios and Depth Attenuation

Table 3 lists the calculated VDR and DAC values for each position along with the qualitative interpretation of the vertical architecture of the contaminants.

Table 3 Vertical Distribution Ratio (VDR) and Depth Attenuation Coefficient (DAC) by sampling position,

with qualitative vertical contamination classification, Obele-Ibaa (2016).

Pos.	Top THC (mg/kg)	Sub THC (mg/kg)	VDR	DAC (mg kg ⁻¹ cm ⁻¹)	CF (sub)	Vertical Pattern Classification
P1	1,324.0	850.5	0.64	-31.6	387	Surface-dominant; moderate attenuation with depth
P2	1,302.2	769.6	0.59	-35.5	350	Surface-dominant; moderate attenuation with depth
P3	1,860.7	4,443.6	2.39	+171.3	2,020	SUBSURFACE HOTSPOT — strong preferential downward migration
Mean	1,495.6	2,021.2	1.35	—	919	Net subsoil-dominant when P3 hotspot included

Note. VDR = subsoil THC ÷ topsoil THC. VDR > 1.5 = subsurface hotspot designation. DAC positive = THC increasing with depth; negative = decreasing with depth. CF referenced to control = 2.20 mg/kg.

Comparative Summary: Obele-Ibaa vs. Published Niger Delta Spill Data

Table 4 lists the comparative study of the calculated THC values along with the available spatial statistics for the study site with published data from other Niger Delta spill investigations.

Table 4 Comparative summary of THC values, depth profiles, and coefficient of variation data at Obele-Ibaa versus selected Niger Delta spill sites from the published literature.

Study / Site	Time Post-Spill	THC Topsoil (mg/kg)	THC Subsoil (mg/kg)	Top CV (%)	Key Interpretive Finding
Obele-Ibaa [This Study]	~12 months	1,302–1,861	770–4,444	17.3	Low top variability; extreme sub heterogeneity; P3 hotspot (VDR = 2.39)
Isiokpo/Eneka (Osuji, 1998)	~15 months	1.9–2.5	2.25–3.18	n/r	Near-background; rapid natural attenuation; low spill volume
Ikot Ada Udo (Okop & Ekpo, 2012)	3 months	9–289	8–318	High (est.)	High variability at both depths; 3-depth profile; GC-FID method
Makaraba (Don-Pedro et al., 1992)	~24 months	1.7–4.6 mg/100 g	n/r	n/r	Low 2-year residual; effective natural attenuation documented
Lagos urban soils (Adeniyi & Afolabi, 2002)	Chronic	30.8–162.4	n/r	High (est.)	Diffuse multi-source contamination; no depth profile available

Note. n/r = not reported in source. CV estimates are derived from published concentration ranges where S.D. was not explicitly stated. All THC in mg/kg unless stated.



Figure 2. Crude oil-contaminated site at Obele-Ibaa, Emohua LGA, Rivers State, Nigeria. The uniform extent of surface oil contamination visible in the photograph is consistent with the low coefficient of variation (CV = 17.3%) documented in topsoil THC across the three sampling positions, while the photograph also shows locally deeper oil penetration in lower-lying areas consistent with the subsurface heterogeneity captured in the VDR analysis. Photograph taken approximately 12 months post-spill during the 2016 site investigation.

IV. DISCUSSION

The Two-Tier Contamination Architecture

The most striking structural observation of this study is the contrast between the spatial variability of THC values measured in the topsoil (CV = 17.3%) and subsoil (CV = 84.8%) samples (Table 2). This

observation provides direct empirical evidence of the existence of a two-tier contamination architecture with a spatially uniform surface contamination layer overlying a spatially heterogeneous subsoil plume.

In the surface layer of the soil column, the spilled crude oil has spread laterally under the influence of gravity according to film flow processes. The relatively low viscosity of fresh Niger Delta crude oils (1 to 10 cP at room temperature for medium-gravity Agbada Formation crudes) allows rapid spreading before absorption or weathering can reduce mobility significantly (Tissot & Welte, 1984; Doust, 1990). This leads to the formation of a spatially extensive but relatively uniform surface contamination layer, as evidenced by the narrow THC concentration range measured in the topsoil samples (1,302 to 1,861 mg/kg) and the low CV calculated over the three sampling positions.

Vertical percolation of crude oil into the subsoil is, by contrast, strongly controlled by soil structural properties that vary at centimetre scales: earthworm burrows, root channels (particularly abundant under the oil palm and tropical forest cover at this site), structural cracks in shrink-swell clay minerals, and hydraulic conductivity contrasts between sandy and clay-silt laminae characteristic of Quaternary fluvio-deltaic sediments (Eneogwe & Ekundayo, 2003; Tissot & Welte, 1984). Each of these mechanisms generates spatially concentrated preferential flow paths that can carry dense NAPL to depths substantially below the surface layer with little lateral dispersion. The resulting spatial patterns of subsoil contamination vary by an order of magnitude over lateral distances of only a few metres, as directly observed between positions P1/P2 (subsoil THC 770–851 mg/kg; VDR 0.59–0.64) and position P3 (subsoil THC 4,444 mg/kg; VDR 2.39) (Ekundayo & Obuekwe, 1997).

The two-tier architecture documented here has not, to the authors' knowledge, been explicitly demonstrated and quantified using VDR and DAC metrics in the peer-reviewed Niger Delta literature. The conceptually related "high-permeability layer" model of petroleum migration in heterogeneous

soils is well-established in international NAPL contaminant hydrogeology (Osuji et al., 2006), but its direct empirical documentation through within-site VDR analysis at a specific spill event contributes a methodologically novel characterization of Niger Delta spill contamination architecture.

Position P3 as a Subsurface Preferential Flow Hotspot

The VDR of 2.39 at position P3, combined with its DAC of $+171.3 \text{ mg kg}^{-1} \text{ cm}^{-1}$ and subsoil CF of 2,020, collectively designate P3 as a subsurface preferential flow hotspot substantially exceeding the proposed threshold ($\text{VDR} > 1.5$). The subsoil THC at P3 (4,443.6 mg/kg) is approximately 5.2 times the subsoil values at P1 and P2 (850.5 and 769.6 mg/kg), despite the topsoil THC at P3 (1,860.7 mg/kg) being only 1.4–1.5 times higher than at the other positions (Table 1). This proportionally much larger subsoil enhancement compared with that of the topsoil at P3 is the defining feature of preferential flow: whereas the surface contamination at P3 was only moderately enhanced compared with the contamination at the other positions, the vertical migration of crude oil was concentrated at precisely this position because of the presence of a high permeability flow path.

In the geological setting of the Niger Delta, such preferential flow paths would most commonly correspond to structural breaches in the clay barrier layer, where a connecting sandy interlayer connects the surface contamination zone to a lower-lying oil pool that forms beneath an impermeable horizon (Eneogwe & Ekundayo, 2003). Without subsurface investigation below a depth of 30 cm, the full vertical extent of the P3 hotspot plume cannot be determined from the present dataset. If the plume has reached the shallow water table, which would be at depths of 1–3 m in the Niger Delta alluvial zone, then dissolved-phase and NAPL-phase petroleum hydrocarbons may be entering the groundwater system, which has the potential to contaminate the shallow hand-dug wells utilized for domestic water supply for the Obele-Ibaa population. This is especially true given the persistence of the PAH compounds, which are classified as Group 1 or Group 2A human carcinogens by the International Agency

for Research on Cancer (IARC), present at these concentrations in the residual THC fraction (Osuji et al., 2004; Yunker et al., 2011).

The values of the DAC at P1 and P2 of $-31.6 \text{ mg kg}^{-1} \text{ cm}^{-1}$ and $-35.5 \text{ mg kg}^{-1} \text{ cm}^{-1}$ respectively point to a dominant surface contamination pattern with depth attenuation consistent with sorption to organic matter and clay minerals during downward percolation of the contaminants, as well as partial loss of the lighter fractions to volatilization and aerobic biodegradation in the topsoil. The strongly contrasting positive value of the DAC at P3 of $+171.3 \text{ mg kg}^{-1} \text{ cm}^{-1}$ is only directly interpretable as providing evidence of the occurrence of active downward preferential flow that dominated the sorption and biodegradation processes that caused attenuation of the contaminants at P1 and P2.

Implications for Contamination Factor Classification and Remediation

Classification and Remediation

The range of the CF values for the contaminated samples at Obele-Ibaa is from 350 to 2,020. This is an approximately six-fold range of values for the samples in the single category of “very high contamination” for the CF values of all the samples. This range has significant implications for the resource allocation for the remediation of the contaminants. The subsoil at P3 has a CF value of 2,020, which is of a different qualitative order of magnitude from the subsoil samples from P1 with a CF value of 387 or the subsoil sample from P2 with a CF value of 350. Yet all three positions would be treated in the same way under a flat regulatory system where all of them would be classified as “severely contaminated.” The proposed three-tier spatial prioritization framework (Table 5) seeks to address this limitation by translating the quantified variability data into a decision matrix that differentiates the strategies based on severity and vertical architecture.

The comparison with published spill sites in Table 4 lends further credence to the exceptional severity of the contamination at Obele-Ibaa. The rapid rate of near-background attenuation reported by Osuji

(1998) at Isiokpo and Eneka after just 15 months confirms the potential for natural attenuation to achieve compliance, but the results at Obele-Ibaa after 12 months demonstrate that this cannot be assumed. Moreover, the fact that the THC at the Obele-Ibaa spill is higher than that at the Ikot Ada Udo spill (Okop & Ekpo, 2012) at a later time point post-spill indicates that the non-linear interaction of elapsed time, spill type, soil type, and response effectiveness is critical to the persistence of the contamination, such that time-based remediation strategies need to be supplemented with quantified monitoring data.

Proposed Spatial Remediation Prioritization Framework

Table 5 formalizes the three-tier framework for spatial remediation prioritization derived from the CF and VDR metrics. The framework is intended to be applied during the site assessment phase of remediation planning and updated iteratively as monitoring data are collected.

Table 5
Proposed three-tier spatial remediation prioritization framework based on contamination factor (CF) and vertical distribution ratio (VDR), with recommended intervention strategies for each tier.

Tier	CF Range	VDR	Obele-Ibaa Position	Rationale	Recommended Intervention
I Critical	> 1,000	> 1.5	P3 subsoil	Subsurface hotspot; extreme THC; preferential flow pathway; greatest groundwater and PAH risk	Targeted subsurface excavation and ex-situ treatment; bioaugmentation with enriched indigenous cultures; installation of subsurface monitoring wells
II High	100–1,000	< 1.0	P1, P2 (both); P3 topsoil	Severe but moderately uniform; surface-dominant profile; significant PAH loading	Intensified RENA: biostimulation with N and P amendments; increased windrow frequency; phytoremediation establishment; quarterly THC monitoring
III Elevated	< 100	Any	Peripheral zones	Approaching DPR threshold zone; residual PAH persistence risk	Passive RENA with monitoring; pH amendment; phytoremediation planting; 6-monthly THC monitoring

Note. CF and VDR thresholds are based on quantitative metrics from the present study and the contamination factor classification of Hakanson (1980) as adapted for petroleum hydrocarbons. Tier assignments should be updated iteratively as post-intervention monitoring data are collected.

Limitations and Future Research Directions

The sample size of three positions per depth provides sufficient data for CV, VDR, and DAC computation but is inadequate for formal geostatistical analysis (variogram modelling, kriging). A minimum of 20–30 positions on a systematic grid would be required for reliable spatial interpolation of the contamination field. Future studies should additionally: (i) employ GC-FID or GC-MS to achieve compound-specific THC fractionation and PAH profiling rather than total-extractable UV spectrophotometry; (ii) collect samples below 30 cm depth to determine whether the P3 hotspot plume has reached the water table; (iii) install temporary piezometers and collect groundwater samples for dissolved-phase hydrocarbon analysis; and (iv) measure soil texture and hydraulic conductivity at each position to enable quantitative modelling of the relationship between soil physical properties and THC spatial variability. Such incorporation of these measurements into a coupled NAPL migration model would significantly enhance the predictive and prescriptive value of pre-remediation spatial assessments at Niger Delta spill sites.



Figure 3. Windrow standing operations at the Obele-Ibaa RENA remediation site (2016). The spatial prioritization framework (Table 5) designates P1 and P2 positions (and P3 topsoil) as Tier II High priority zones for intensified windrow aeration combined with biostimulation. The P3 subsoil hotspot (Tier I Critical) requires targeted excavation in preference to surface landfarming alone. Photograph taken during the 2016 site investigation.



Figure 4. Bulking and backfilling operations at Obele-Ibaa (2016). Mechanical soil mixing enhances aeration and distribution of biostimulation amendments across Tier II priority zones. For the Tier I P3 hotspot, subsurface excavation to below 30 cm and ex-situ thermal or bioaugmentation treatment is recommended as a necessary supplement to surface landfarming. Photograph taken during the 2016 site investigation.

V. CONCLUSIONS

This study has applied quantitative spatial variability analysis—CF, CV, VDR, and DAC—to depth-stratified THC data from the Obele-Ibaa sabotage-induced pipeline spill site, Rivers State, Nigeria, 12 months post-spill. The principal conclusions are:

- Topsoil THC exhibited low spatial variability (CV = 17.3%; mean $1,495.6 \pm 258.3$ mg/kg), consistent with relatively uniform lateral oil spreading at the soil surface. All topsoil positions exceeded the DPR (1991) agricultural threshold by approximately 30-fold.
- Subsoil THC exhibited high spatial variability (CV = 84.8%; mean $2,021.2 \pm 1,713.2$ mg/kg), directly attributable to preferential vertical flow through a spatially heterogeneous soil matrix. All subsoil positions exceeded the DPR threshold by 15–88-fold.
- Position P3 was identified as a subsurface preferential flow hotspot based on VDR = 2.39, DAC = $+171.3$ mg kg⁻¹ cm⁻¹, and subsoil CF = 2,020. These values indicate a concentrated downward oil migration through a structural breach within the subsurface soil matrix.

- The characteristic contamination architecture for this particular event of point-source sabotage spill into the groundwater system consisted of a two-tier structure with a uniform surface layer (low CV) and a heterogeneous subsoil plume (high CV).
- Comparison with published spill data from the Niger Delta region verifies that the Obele-Ibaa THC values after 12 months post-spill rank among the highest recorded to date, with natural attenuation far from sufficient, indicating the need for intensified spatial remediation.
- The proposed three-tier spatial remediation prioritization framework (Tier I Critical: excavation and ex-situ treatment; Tier II High: intensified RENA with biostimulation; Tier III Elevated: passive RENA with monitoring) provides a quantitatively defensible decision framework applicable to analogous spill sites across the Niger Delta.

The VDR, DAC, and two-tier architecture concepts introduced in this study advance the methodological toolkit for quantitative spatial assessment of petroleum hydrocarbon contamination in Niger Delta soils and provide a template for risk-based remediation prioritization at analogous pipeline spill sites throughout the region.

Contributions to Existing Knowledge

This study contributes: (i) the first explicit application of Vertical Distribution Ratio and Depth Attenuation Coefficient as spatial variability metrics to a Niger Delta spill site THC dataset; (ii) the first published quantification of the two-tier uniform-surface / heterogeneous-subsoil contamination architecture for a sabotage-induced Niger Delta pipeline spill; (iii) the first identification and designation of a P3-class subsurface preferential flow hotspot using these metrics at an Emohua LGA spill site; and (iv) a three-tier spatial remediation prioritization framework grounded in quantitative field metrics and adaptable to regulatory use across the Niger Delta.

Author Contributions

E.I.E.: Conceptualization, field sampling, laboratory analysis, spatial metric development, writing—

original draft. A.D.O.: methodology review, writing—
review and editing.

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Data Availability Statement

The raw THC data supporting the conclusions of this article are available from the corresponding author upon reasonable request.

Conflicts of Interest

The authors declare no conflicts of interest.

REFERENCES

1. Adeniyi, A. A., & Afolabi, J. A. (2002). Determination of total petroleum hydrocarbons and heavy metals in soils within the vicinity of facilities handling refined petroleum products in Lagos metropolis. *Environment International*, 28(1–2), 79–82. [https://doi.org/10.1016/S0160-4120\(01\)00099-0](https://doi.org/10.1016/S0160-4120(01)00099-0)
2. ASTM International. (2015). Standard guide for risk-based corrective action applied at petroleum release sites (ASTM E1739-95). ASTM International. <https://doi.org/10.1520/E1739-95R15>
3. Bales, R. G. (1954). Determination of total hydrocarbon content (Laboratory reference publication, pp. 7, 22–23).
4. Benka-Coker, M. O., & Ekundayo, J. A. (1994). Effects of an oil spill on physico-chemical properties of a spill site in the Niger Delta area of Nigeria. *Environmental Monitoring and Assessment*, 36(2), 93–104. <https://doi.org/10.1007/BF00546189>
5. Department of Petroleum Resources (DPR). (1991). Environmental guidelines and standards for the petroleum industry in Nigeria (EGASPIN). Ministry of Petroleum and Mineral Resources.
6. Don-Pedro, K. N., Asuquo, F. E., Osuji, L. C., & Nwankwo, J. N. (1992). Petroleum contamination of soil in the Niger Delta area of Nigeria. In *Proceedings of the Annual Conference of the Soil Science Society of Nigeria* (pp. 45–52).
7. Doust, H. (1990). Petroleum geology of the Niger Delta. *Geological Society Special Publication*, 50, 365–390. <https://doi.org/10.1144/GSL.SP.1990.050.01.22>
8. Ekundayo, E. O., & Obuekwe, C. O. (1997). Effects of an oil spill on soil physico-chemical properties of a spill site in a typical Ultisol of Midwestern Nigeria. *Environmental Monitoring and Assessment*, 45(3), 209–221. <https://doi.org/10.1023/A:1005776607693>
9. Eneogwe, C. I., & Ekundayo, O. (2003). Geochemical correlation of crude oils in the NW Niger Delta, Nigeria. *Journal of Petroleum Geology*, 26(1), 95–103. <https://doi.org/10.1111/j.1747-5457.2003.tb00018.x>
10. Federal Environmental Protection Agency (FEPA). (1991). Guidelines and standards for environmental pollution control in Nigeria. Federal Ministry of Environment.
11. Hakanson, L. (1980). An ecological risk index for aquatic pollution control: A sedimentological approach. *Water Research*, 14(8), 975–1001. [https://doi.org/10.1016/0043-1354\(80\)90143-8](https://doi.org/10.1016/0043-1354(80)90143-8)
12. Malallah, G., Afzal, M., Kurian, M., Gulshan, S., & Dharmi, M. S. I. (1998). Impact of oil pollution on some desert plants. *Environment International*, 24(8), 919–924. [https://doi.org/10.1016/S0160-4120\(98\)00083-6](https://doi.org/10.1016/S0160-4120(98)00083-6)
13. Marmiroli, N., & McCutcheon, S. C. (2003). Making phytoremediation a successful technology. In S. C. McCutcheon & J. L. Schnoor (Eds.), *Phytoremediation: Transformation and control of contaminants* (pp. 85–119). John Wiley & Sons. <https://doi.org/10.1002/047127304X.ch4>
14. National Oil Spill Detection and Response Agency (NOSDRA). (2015). Annual report on oil spill incidents in Nigeria. NOSDRA.
15. Okop, I. J., & Ekpo, S. C. (2012). Determination of total hydrocarbon content in soil after petroleum spill. *Proceedings of the World Congress on Engineering*, 3, 1513–1517.
16. Onianwa, P. C. (1995). Petroleum hydrocarbon pollution of urban topsoil in Ibadan city, Nigeria. *Environment International*, 21(3), 341–343. [https://doi.org/10.1016/0160-4120\(95\)00037-B](https://doi.org/10.1016/0160-4120(95)00037-B)
17. Osuji, L. C. (1998). Total hydrocarbon content of soil approximately 15 months after Isiokpo and

- Eneka spillages [Unpublished research report].
University of Port Harcourt.
18. Osuji, L. C. (2011). Petroleum chemistry and toxicology in theory and practice. Jesco International.
 19. Osuji, L. C., Adesiyun, S. O., & Obute, G. C. (2004). Post-impact assessment of oil pollution in Agbada West plain of Niger Delta, Nigeria. *Chemistry & Biodiversity*, 1(3), 208–218. <https://doi.org/10.1002/cbdv.200490021>
 20. Osuji, L. C., Idung, I. D., & Ojinnaka, C. M. (2006). Hydrocarbon speciation by fingerprinting technique and diagnostic vanadium/nickel ratio of Mgbede-20 oil-impacted site in the Niger Delta Basin. *Environmental Forensics*, 7(3), 259–265. <https://doi.org/10.1080/15275920600840924>
 21. Tissot, B. P., & Welte, D. H. (1984). Petroleum formation and occurrence: A new approach to oil and gas exploration (2nd ed.). Springer-Verlag.
 22. Tuttle, M. L. W., Charpentier, R. R., & Brownfield, M. E. (1999). The Niger Delta petroleum system: Niger Delta Province, Nigeria, Cameroon, and Equatorial Guinea, Africa (USGS Open-File Report 99-50-H). United States Geological Survey.
 23. Yunker, M. B., Macdonald, R. W., Snowdon, L. R., & Fowler, B. R. (2011). Alkane and PAH biomarkers as tracers of terrigenous organic carbon in Arctic Ocean sediments. *Organic Geochemistry*, 42(9), 1109–1146. <https://doi.org/10.1016/j.orggeochem.2011.06.007>