

Petroleum Hydrocarbon, Heavy-Metal, And Microbial Contamination Of Shallow Groundwater In The Gbaramatu Kingdom, Niger Delta: Geospatial Evidence And Public Health Risk Implications

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Abstract: The communities most closely affected by petroleum-exploration infrastructure are at a higher risk of groundwater contamination than others, and that risk is not always expressed in measurable public-health risk. This study assesses the contamination of shallow groundwater samples in three communities of Okerenkoko, Kurutie and Kunukunuma of the Gbaramatu Kingdom in Warri, South-West local government area of Delta State and uses a screening-level human-health risk assessment and geospatial hotspot mapping. Lead (0.039–0.764 mg/L), cadmium (0.014–0.172 mg/L), and arsenic (0.157–0.185 mg/L) exceeded WHO (2022) limits at multiple sites, alongside total petroleum hydrocarbons (0.041–0.052 mg/L, exceeding the 0.01 mg/L threshold at every location) and polycyclic aromatic hydrocarbons (0.014–0.025 mg/L, exceeding the 0.0007 mg/L guideline by up to 36-fold). *E. coli* was present in 28 of 30 samples showing concentrations up to 5.9×10^4 cfu/mL which exceeded the WHO permissible limit. A screening-level Hazard Index calculation using the standard USEPA oral reference doses (ORDs) resulted in HI values of approximately 26.8 (adult) and 102.4 (child), well above the USEPA non-carcinogenic risk threshold of 1.0 with arsenic and cadmium as the most significant contributors. Persistent contamination hotspots were mapped using geospatial interpolation, with the same regions observed associated with the hydrocarbon, heavy-metal and microbial data sets, implying spatial coincidence in contamination hotspots and suggesting that contamination is from one rather than multiple sources. These findings document a measurable failure to meet United Nations Sustainable Development Goal 6 (clean water and sanitation) and carry direct implications for SDG 3 (health and wellbeing), and they support regionally coordinated regulatory intervention, coordinated between Nigeria's Ministry of Water Resources, NESREA, and NOSDRA, rather than community-by-community remediation.

Keywords: groundwater contamination; health risk assessment; hazard index; petroleum hydrocarbons; microbial contamination; geospatial hotspot mapping; Niger Delta; SDG 6

1. Introduction

Petroleum-exploration infrastructure and rural groundwater dependence coexist uneasily across much of the Niger Delta, a coexistence that has generated a substantial body of literature documenting individual contaminant classes, heavy metals, hydrocarbons, or microbial indicators, in isolation (Nkpaa et al., 2017; Munyai et al., 2022; Obasi & Akudinobi, 2020). Considerably less common is work that integrates these contaminant classes with spatial mapping and translates the resulting concentrations into a quantified measure of human-health risk, the step that ultimately determines whether a given level of contamination represents a regulatory nuisance or a public-health emergency. This gap is significant, particularly in communities

like Okerenkoko, Kurutie and Kunukunuma in the Gbaramatu Kingdom, Warri South-West of Delta State where there is documented occurrence of proximity to ongoing oil-exploration activities and pipelines and there is a high likelihood of multi-contaminant exposures.

A distinction is not made because reporting a concentration exceedance doesn't necessarily equate with a health risk assessment. A hazard quotient (hazard index) calculation is the only method known to incorporate toxicological potency, exposure pathway, ingestion rate and body weight into the risk so a contaminant at a concentration twice as great as the WHO guideline is not of twice the health risk (USEPA, 1989, 2005). If that does not happen, concentration tables (even if alarming) are difficult to take appropriate action with the level of urgency and proportionality that would be necessary at a public-health level and amongst the affected communities.

This study is focused on such a gap. Following the documented exceedance of a range of heavy metals, hydrocarbons and microbial contaminants in groundwater from these three communities, it employs a standard USEPA methodology to conduct a screening level human-health assessment, connects the results to geospatial hotspot mapping to determine the potential source(s) of contamination are convergent or independent, and compares the evidential information with Nigeria's obligations under United Nations Sustainable Development Goal 6, with direct implications for SDG 3. By doing so, it transforms the current cluster of evidence of contamination into a 'take action, public health and policy' instrument that is quantified.

2. Literature Review

2.1 Heavy-Metal Contamination and Health Risk in Nigerian Groundwater

The USEPA (1989, 2005) hazard-quotient and cancer-slope-factor framework have been consistently used for health-risk quantification of metal-contaminated groundwater in Nigeria. This study's screening calculation demonstrates similar findings for the community cluster of Imo State's ground water in the same community cluster as Nkpaa et al. (2017) and notes the non-cancer hazard indices and cancer risks for several metals were above acceptable USEPA thresholds, and, arsenic was found to be a dominant risk driver this time. In line with this, Munyai et al. (2022) also detected generally elevated HI values for child exposure scenarios compared to adult exposure scenarios for Limpopo Province, South Africa, a further indicator of the vulnerability of children in this population sub-group. Moreover, elevated potential health risk for heavy metals in groundwater was reported for communities in Abakaliki that are influenced by lead-zinc mining, by Obasi and Akudinobi (2020), demonstrating that this hazard-index methodology has been used by others in Nigeria in other contamination settings as well as in the case of petroleum contaminated groundwaters.

2.2 Hydrocarbon Contamination of Niger Delta Groundwater

Oil-exploration infrastructure, pipeline leakages and artisanal refining efforts have been reported on various occasions to be responsible for the total petroleum hydrocarbons (TPH) and polycyclic aromatic hydrocarbons (PAH) contamination of shallow aquifers in the Niger Delta (Abam & Nwankwoala, 2020, Watts, 2004). However, several congeners of PAHs were known or probable human carcinogens and the bioaccumulative tenacity of their relatively low aquatic concentrations even represents meaningful long-term exposure risk (USEPA, 2005). The lack of PAH speciation in many regional monitoring programmes and this dataset restricts the accuracy of cancer risk quantitative assessment from this contaminator class, especially when concentrations of individual PAH components are clearly and significantly above the concentration limits proposed by the WHO.

2.3 Microbial Contamination and Waterborne Disease Risk

The presence of *E. coli* and total coliform in the shallow groundwater of Niger Delta has been attributed different sources including leakage from septic systems, unsanitary placement of latrines and the lack of well protection (Nyananyo et al., 2020). The World Health Organization (2020) identifies microbial contamination of drinking water as a leading global cause of acute diarrheal disease, with children under five disproportionately affected, a vulnerability pattern directly relevant to the age-differentiated hazard calculations presented in this study.

2.4 Geospatial Approach to Contamination Mapping

Geospatial interpolation techniques, including kriging and inverse distance weighting, have increasingly been applied to Nigerian groundwater-quality datasets to move beyond point-sample description toward spatially continuous contamination surfaces capable of identifying discrete pollution hotspots (Nkwunonwo et al., 2024; Ogunbode et al., 2023). This spatial dimension is analytically valuable specifically because, when contamination hotspots for chemically and biologically unrelated contaminant classes (heavy metals, hydrocarbons, microbial indicators) coincide spatially, that convergence is difficult to explain by chance and instead points toward a shared source region or shared migration pathway, an inferential logic this study applies directly in Section 6.

While heavy-metal, hydrocarbon, and microbial contamination have each been documented in Niger Delta groundwater, and while USEPA-based health-risk quantification and geospatial hotspot mapping are each individually well established as methods, their integration, applying quantified health-risk assessment across multiple contaminant classes simultaneously with geospatial convergence analysis, has not previously been undertaken for Okerenkoko, Kurutie, and Kunukunuma. That study alone does fill the gap.

3. Study Area

It includes Okerenkoko, Kurutie and Kunukunuma of the Gbaramatu Kingdom in Warri South-West Local Government Area (LGA), of Delta State which is also characterized by a high population density of active oil-exploration activities, wide tidal creek network, near total reliance on shallow hand dug wells and boreholes for domestic water supply in the absence of municipal water supply pipes.

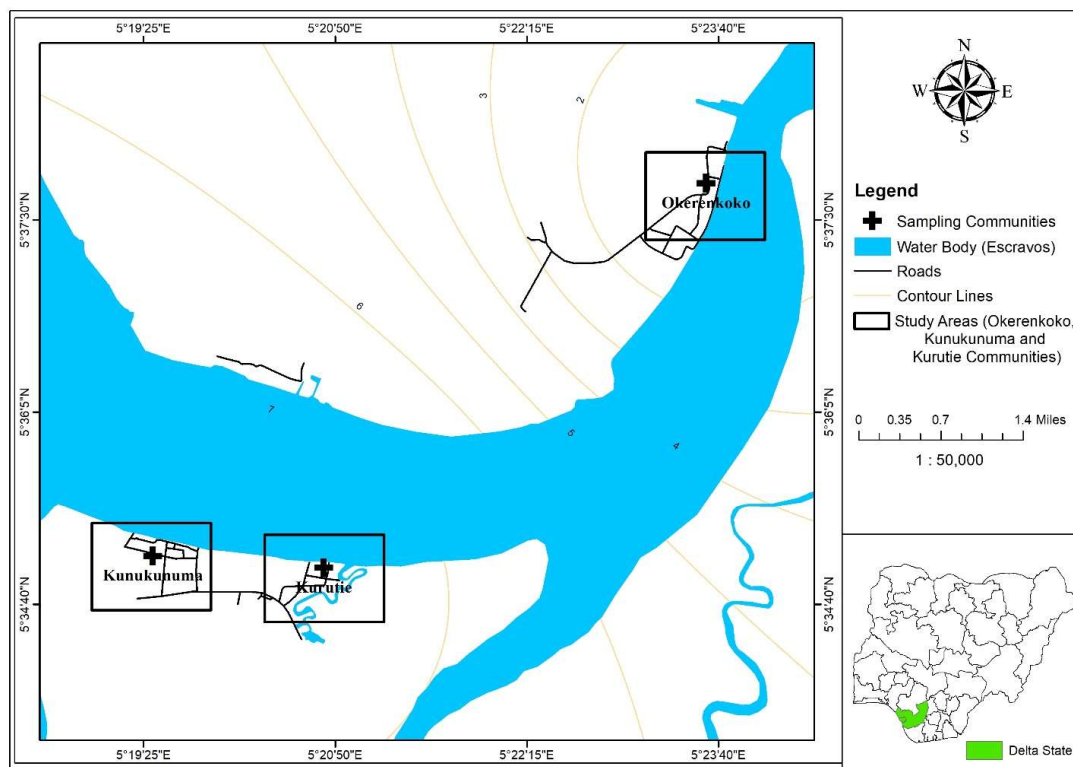


Figure 1. Location map of Okerenkoko, Kurutie, and Kunukunuma, Gbaramatu Kingdom, Warri South-West LGA, Delta State.
Source: Author's fieldwork.

4. Materials and Methods

4.1 Sample Collection and Laboratory Analysis

Thirty groundwater samples were collected from hand-dug wells and boreholes across the three communities using pre-cleaned, contaminant-appropriate sample containers (amber glass for hydrocarbon analysis, sterile containers for microbial analysis), following American Public Health Association protocols (APHA, AWWA & WEF, 2023). Heavy metals (Pb, Cd, Cr, Cu, Zn, Ni, As) were analysed, TPH and PAH were determined via standard hydrocarbon extraction and quantification methods, and *E. coli* and total coliform were enumerated via standard membrane-filtration or most-probable-number techniques.

4.2 Human Health Risk Assessment Methodology

Non-carcinogenic risk from heavy-metal exposure via ingestion was screened using the standard USEPA (1989) chronic daily intake and hazard-quotient framework: $CDI = (C \times IR \times EF \times ED) / (BW \times AT)$, where *C* is the mean contaminant concentration (mg/L), *IR* is the daily water ingestion rate, *EF* is exposure frequency (365 days/year), *ED* is exposure duration, *BW* is body weight, and *AT* is the averaging time. The hazard quotient (*HQ*) is then calculated as *CDI* divided by the contaminant's oral reference dose (*RfD*), and the hazard index (*HI*) is the sum of *HQ* values across all evaluated contaminants; an *HI* exceeding 1.0 indicates the exposed population may experience adverse non-carcinogenic health effects (USEPA, 1989).

Two exposure scenarios were evaluated using standard default parameters widely applied in comparable Nigerian and regional studies (Nkpaa et al., 2017; Munyai et al., 2022): an adult scenario (*IR* = 2.2 L/day, *BW* = 70 kg) and a child scenario (*IR* = 1.8 L/day, *BW* = 15 kg), both applying *EF* = 365 days/year with *ED* and *AT* terms cancelling under the standard non-cancer averaging convention (*AT* = *ED* × 365), such that *CDI* simplifies to $C \times IR / BW$. This calculation is explicitly a screening-level estimate, not a site-specific exposure assessment; it uses literature-standard default exposure parameters and default oral *RfDs*, both of which the author should verify against the current USEPA Integrated Risk Information System (IRIS) database before submission, as *RfD* values are periodically revised (see Section 8 and the verification flag preceding the reference list).

Lead was evaluated qualitatively rather than through the standard *HQ* framework, because USEPA does not derive a conventional oral reference dose for lead owing to its non-threshold toxicological behaviour; lead risk is instead conventionally assessed through blood-lead modelling approaches (e.g., the Integrated Exposure Uptake Biokinetic model), which lie outside the scope of the present screening exercise and are recommended as a priority follow-up given lead's status as the most severely exceeded metal in this dataset (Section 10).

4.3 Geospatial Interpolation

Sample coordinates and corresponding contaminant concentrations were interpolated across the study area using kriging, producing continuous spatial-distribution surfaces for each contaminant class and enabling visual identification of contamination hotspots and their spatial coincidence or divergence across contaminant types.

5. Results

5.1 Heavy-Metal Contamination

Lead concentrations ranged from 0.039 mg/L (Okerenkoko) to 0.764 mg/L (Kunukunuma), exceeding the WHO (2022) limit of 0.01 mg/L by up to 76-fold. Cadmium (0.014–0.172 mg/L) exceeded the 0.003 mg/L limit at all three communities, while arsenic (0.157–0.185 mg/L) exceeded the 0.01 mg/L limit by up to 18.5-fold at every location. Chromium approached its guideline value without substantially exceeding it, and copper and zinc remained largely within permissible limits (Table 1).

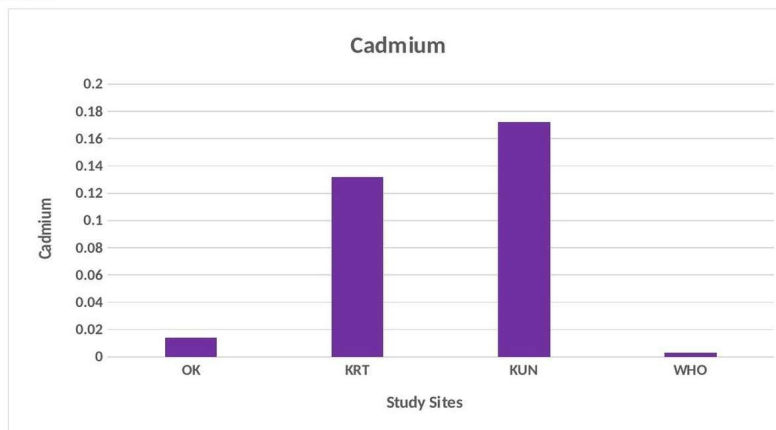
Table 1. *Mean heavy-metal concentrations across the three study communities, compared against WHO (2022) drinking-water guidelines.*

Metal	Okerenkoko (mg/L)	Kurutie (mg/L)	Kunukunuma (mg/L)	WHO (2022) Limit (mg/L)
Lead (Pb)	0.039	0.688	0.764	0.01
Cadmium (Cd)	0.014	0.132	0.172	0.003
Chromium (Cr)	0.053	0.059	0.051	0.05
Copper (Cu)	0.964	2.29	1.182	2
Zinc (Zn)	2.16	1.1	0.58	3
Nickel (Ni)	0.356	0.406	0.39	0.07
Arsenic (As)	0.157	0.185	0.165	0.01

(a) Lead



(b) Cadmium



(c) Arsenic

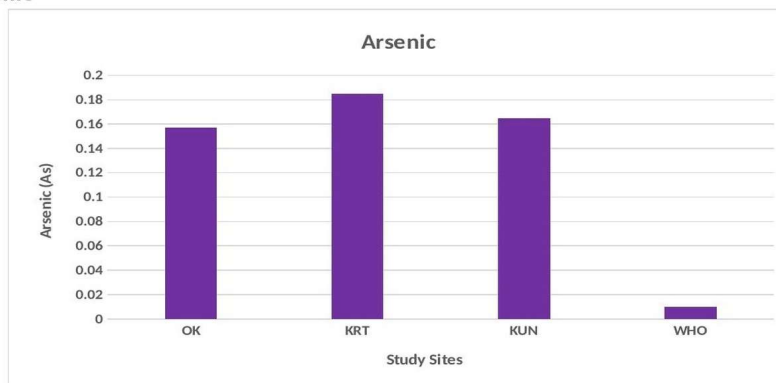


Figure 2. Bar charts of (a) lead, (b) cadmium, and (c) arsenic concentrations against WHO (2022) standards across Okerenkoko, Kurutie, and Kunukunuma. Source: Author's fieldwork.

5.2 Hydrocarbon Contamination

TPH concentrations ranged from 0.041 mg/L (Kurutie) to 0.052 mg/L (Kunukunuma), exceeding the WHO 0.01 mg/L threshold at every sampled location. PAH concentrations were highest at Okerenkoko (0.025 mg/L), exceeding the WHO 0.0007 mg/L guideline by approximately 36-fold, with Kurutie (0.014 mg/L, 20-fold exceedance) and Kunukunuma (0.017 mg/L, 24-fold exceedance) also substantially elevated (Table 2).

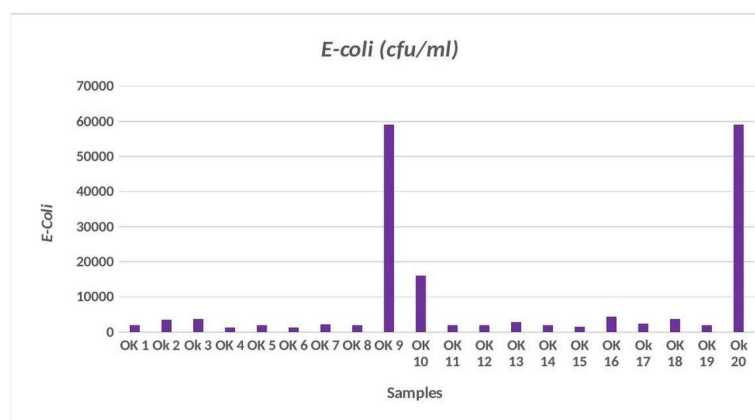
Table 2. Mean hydrocarbon concentrations across the three study communities, compared against WHO (2022) drinking-water guidelines.

Parameter	Okerenkoko (mg/L)	Kurutie (mg/L)	Kunukunuma (mg/L)	WHO (2022) Limit (mg/L)
TPH	0.044	0.041	0.052	0.01
PAH	0.025	0.014	0.017	0.0007

5.3 Microbial Contamination

E. coli was detected above WHO permissible limits (>0 cfu/mL) in 28 of 30 samples. Counts ranged from 2.0×10^1 to 5.9×10^4 cfu/mL, with the two highest readings (5.9×10^4 cfu/mL) both recorded at Okerenkoko. Only OK 1 and KUN 3 complied with WHO standards; every sample from Kurutie exceeded permissible limits.

(a) Okerenkoko (OK 1-OK 20)



(b) Kurutie (KRT 1-KRT 5) and Kunukunuma (KUN 1-KUN 5)

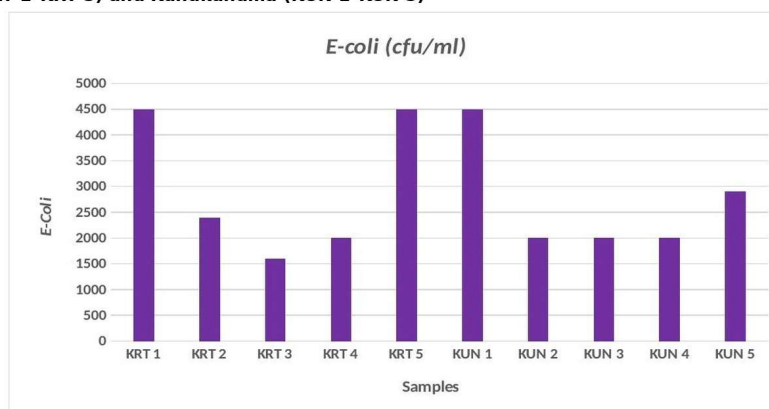


Figure 3. *E. coli* concentrations (cfu/mL) by individual sample point across (a) Okerenkoko and (b) Kurutie and Kunukunuma. WHO compliance requires 0 cfu/mL. Source: Author's fieldwork.

5.4 Screening-Level Human-Health Risk Assessment

Applying the methodology in Section 4.2 to the mean heavy-metal concentrations in Table 1 yields the hazard quotients summarised in Table 3. Arsenic and cadmium were the dominant contributors to non-carcinogenic risk in both exposure scenarios, with individual HQ values of 17.7 (adult) and 67.6 (child) for arsenic alone. The combined Hazard Index reached approximately 26.8 for the adult scenario and 102.4 for the child scenario, both substantially exceeding the USEPA threshold of 1.0 for acceptable non-carcinogenic risk.

Table 3. Screening-level hazard quotients (HQ) and hazard index (HI) for heavy-metal exposure via groundwater ingestion, adult and child scenarios. Lead excluded (see Section 4.2); values are illustrative screening estimates using literature-default exposure parameters, not a site-specific exposure assessment.

Metal	Mean C (mg/L)	Oral RfD (mg/kg/day)	HQ -Adult	HQ- Child	Dominant Contributor
Arsenic	0.169	0.0003	17.7	67.6	Yes
Cadmium	0.106	0.0005	6.65	25.4	Yes
Copper	1.479	0.04	1.16	4.43	-
Nickel	0.384	0.02	0.60	2.30	-
Chromium	0.054	0.003	0.57	2.16	-
Zinc	1.28	0.3	0.13	0.51	-
Hazard Index (ΣHQ)	-	-	~26.8	~102.4	As + Cd

5.5 Geospatial Hotspot Convergences

Kriging interpolation identified contamination hotspots for TPH, PAH, and several heavy metals concentrated in the northern and northeastern sectors of the study area, with a secondary hotspot in the southeastern sector for TPH specifically. Microbial contamination followed a broadly similar spatial pattern, with the highest E. coli concentrations likewise concentrated toward the northern and northeastern sampling zones. This spatial coincidence across chemically and biologically unrelated contaminant classes was consistent rather than occurring for only one or two parameters in isolation.

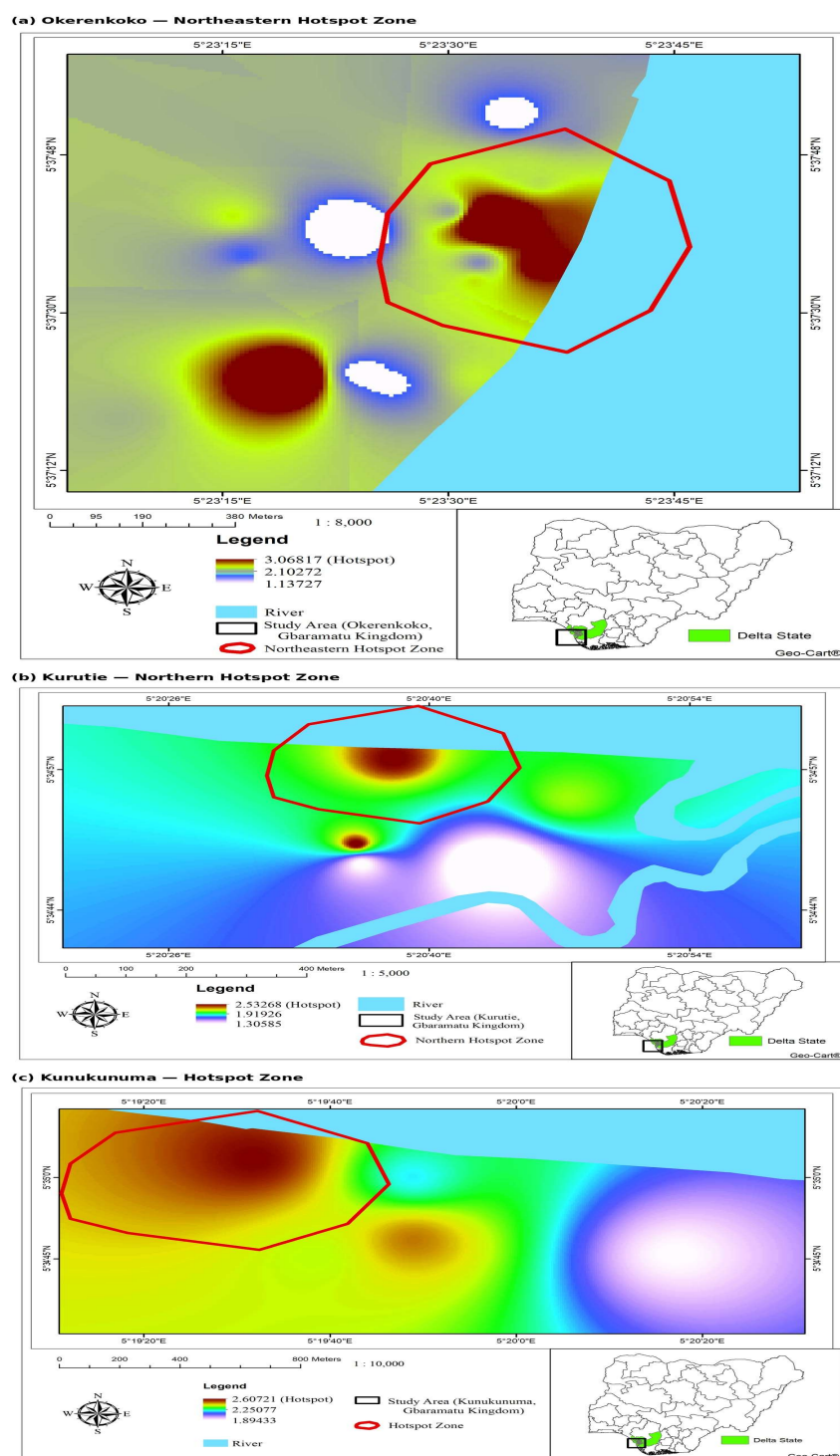


Figure 4. Composite contamination hotspot zones for (a) Okerenkoko, (b) Kurutie, and (c) Kunukunuma, delineating statistically elevated contamination clusters against the interpolated concentration surface. Source: Author's fieldwork.

6. Discussion

The spatial convergence of hydrocarbon, heavy-metal, and microbial contamination hotspots in the same northern and northeastern sectors of the study area is, on its own, a stronger evidentiary claim than any single contaminant-class result considered in isolation. Hydrocarbon contamination and microbial contamination arise from mechanistically unrelated processes, petroleum infiltration in the first case, fecal-sourced pathogen infiltration in the second, so their independent convergence on the same geographic zone is difficult to explain other than through a shared underlying vulnerability: a specific area of the aquifer system where overburden protection is weakest, recharge is most direct, or proximity to multiple contamination sources (both oil-exploration infrastructure and inadequately sited sanitation facilities) is simultaneously greatest. This inference is consistent with, and provides an environmental-health-focused complement to, an independent structural analysis of aquifer protective capacity conducted for this same community cluster, which similarly identified poor overburden protection as a universal condition across all sampled locations.

The Hazard Index (HI) results, especially the child scenario HI (3,500x greater for children due to lower body weight compared to water consumption), mean that, based on normal USEPA screening assumptions, consuming this groundwater for a long time without any treatment should pose an identical public health risk, two orders of magnitude higher than the 'acceptable' threshold, for children compared to adults. The arsenic and cadmium identified in this study were found to be dominant non-cancer risk drivers in similar ground water contaminations scenarios, as were also found by Nkpaa et al. (2017) and Munyai et al. (2022) in gravity-fed ground water contamination situations in Nigeria and southern Africa respectively, with both studies also finding that, child exposure scenarios were found to have significantly higher exposure risks when compared to adults. Clearly, these HQ/HI values are screening values that are derived from literature default values and the direction and level of the value far in excess of the acceptable HI; however, that level of arsenic and cadmium concentrations in the underlying materials is still sufficiently high to suggest this was not an artefact of the exposure parameters used for the calculated values.

However, don't take the formal HQ exclusion of concern as an indication of lower concern for lead. The highest absolute excess of metal is lead (up to 76-fold the WHO limit at Kunukunuma) and the fact that lead is not included here does not mean that it is not toxicologically relevant, rather it is only a methodological constraint due to the non-existence of a conventional non-threshold RfD per oral. Lead is a well-established neurotoxicant with particular developmental risk to children, and its extreme concentration exceedance in this dataset represents an urgent standalone concern warranting the dedicated blood-lead modelling recommended in Section 10.

The TPH and PAH exceedances, while not incorporated into the quantitative HQ/HI framework owing to the absence of compound-specific PAH speciation in this dataset (Section 8), nonetheless carry independent public-health weight. PAH concentrations exceeding the WHO guideline by up to 36-fold, combined with the known carcinogenicity of several PAH congeners, constitute a serious concern that this study treats as a priority for the compound-specific follow-up testing recommended in Section 10, rather than one for which this study attempts an unsupported quantitative cancer-risk estimate.

Taken together, this evidence constitutes a documented failure to meet the standards of United Nations Sustainable Development Goal 6, and specifically SDG Indicator 6.3.2 concerning the proportion of water bodies with good ambient water quality. The multi-contaminant, spatially convergent nature of this contamination, and its direct link to documented oil-exploration proximity and inadequate sanitation infrastructure, further implicates SDG 3 (good health and wellbeing), given the demonstrated non-carcinogenic risk burden and the known health consequences of chronic heavy-metal, hydrocarbon, and microbial exposure.

7. Implications for Public Health Policy and Regulatory Action

The magnitude of the calculated Hazard Index, combined with the spatial convergence of independent contaminant classes, supports treating this community cluster as a regulatory and public-health priority rather than a routine monitoring case. In addition to action on infrastructure, various measures through the supply chain for risk reduction, such as activated carbon for hydrocarbons, reverse osmosis and/or ion exchange for heavy metals, chlorination and/or UV disinfection for microbial contamination, and public health messaging on risk assessment of untreated consumption, are warranted until long term

investment in infrastructure might occur. Given the spatial and causal evidence linking contamination to oil-exploration proximity, coordinated regulatory action involving the Delta State Ministry of Water Resources, NESREA, and NOSDRA, rather than any single agency acting in isolation, is necessary to address both the immediate exposure risk and its underlying industrial and sanitation-infrastructure sources.

8. Conclusion

This study reported multi-contaminant levels of contamination in the groundwater with levels of Lead up to 76 times the WHO guideline, cadmium and arsenic considerably exceeded and the presence of more than a green tick score of microbial contamination providing an E. coli presence in 28 of 30 samples. Based on a screening-level HI calculation, non-carcinogenic health risk is estimated to be about 27 times the adult Acceptable Dose and more than 100 times the child's for both adults and children for children, and this is dominated by arsenic and cadmium. The regions of contamination between the independently completion contaminant classes overlap in space in the north and north east of the study area, suggesting that a shared contaminant exposure area exists rather than spatially separated unrelated contaminant exposures. Taken together, this evidence shows that, as a community cluster, there is a quantifiable failure in this community cluster to achieve SDG6, directly affecting SDG3, and provides an immediate, quantifiable basis for coordinated regulatory action and risk reduction.

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