Available online at https://www.worldnewsnaturalsciences.com/

World News of Natural Sciences

An International Scientific Journal

WNOFNS 68 (2026) 201-225 EISSN 2543-5426

Integrated Assessment of Surface-Water Pollution, Human Health Risks, Oil-Spill Preparedness, and Community Resilience in Petroleum-Producing Communities of Delta State, Nigeria

Esemuede Taye Gideon and **Christopher Onosemuode***

Department of Environmental Management and Toxicology, Federal University of Petroleum Resources, Effurun, Delta State, Nigeria

*E-mail address: Pgra.inf@gmail.com

ABSTRACT

Pollution of surface water in a petroleum-producing community has overlapping environmental, health, livelihood, and resilience challenges. Water-quality assessment, human-health risk modelling and socioeconomic analysis was incorporated into this study for 9 communities in Delta State, Nigeria. A cross-sectional mixed methods design was used. Upstream, impact, and downstream locations in Okpai, Aboh, Kwale, Udu, Sapele, Ovwian-Aladja, Warri, Forcados, and Escravos yielded 81 surface-water samples, while 423 adult residents within the sampling area provided questionnaire data. Standard APHA and USEPA methods were used to analyse physicochemical parameters, heavy metals, oil and grease, BTEX compounds, and 16 priority polycyclic aromatic hydrocarbons. Pollution indices, ingestion and dermal exposure risks, multiple regression, correlation, PCA, and hierarchical community classification were used. The findings indicated a significant spatial difference between the inland and the coastal oil-rich communities. Escravos recorded the highest WQI (182.7), HPI (157.8), PLI (2.47), TPH (4.38 mg/L), Σ16 PAHs (0.126 mg/L), hazard index (1.96) and lifetime cancer risk (2.48×10^{-5}), followed by Forcados and Warri. All communities reported lead concentrations above the guideline value of 0.010 mg/L, and the hazard indices for 6 communities exceeded 1. Environmental deterioration ($\beta = -0.406$) and hydrocarbon pollution ($\beta = -0.182$) significantly contributed to the reduction in community resilience, while Oil Spill Preparedness ($\beta = 0.332$), Institutional Preparedness ($\beta = 0.248$), and Socioeconomic Stability ($\beta = 0.221$) contributed to the increase in community resilience. The model accounted for 71.6% of the variance in resilience; the first principal component accounted for 99.674% of the variance in environmental risk. The study concludes that pollution control policies should be implemented alongside policies on safe water provision, health surveillance, remediation, institutional

(Received 29 June 2026; Accepted 30 July 2026; Date of Publication 01 August 2026)

accountability, livelihood restoration, and community-based spill preparedness. These findings represent an evidence-based approach to prioritise intervention in environmentally burdened communities in the Niger Delta.

Keywords: Surface-water pollution, petroleum hydrocarbons, heavy metals, human-health risk assessment, community resilience, oil-spill preparedness

1. INTRODUCTION

The surface-water systems are important sources for drinking water supply, fisheries, agriculture, transportation as well as socioeconomic activities of riverine communities, but they have also become the major repository of the petroleum hydrocarbons and potential toxic metals, nutrients, organic wastes and other persistent pollutants from the rapid industrialization, urbanisation, oil exploration, gas flaring, pipeline leakage, artisanal petroleum refining, improper waste management and untreated effluents released by different activities. This is particularly so in the Niger Delta region, in which contaminants released from any spot in the region can spread through and transform in the adjacent environment, deposit and bioaccumulate in creeks, rivers, wetlands and estuaries through the geographical clustering of petroleum producing facilities and the hydrological linkage of the creeks, rivers, wetlands, and estuaries. In fact, according to [1], the mixed impact of oil exploitation, environmental degradation and issues of well-being of Niger Delta people have led to several multidimensional impacts besides pollution which ranges from environmental degradation, chronic pollution, disruption of livelihoods and social vulnerability among others, while [2] noted that recurring oil spills, inadequate rehabilitation/restoration activities, weak institutional measures are still among the key challenges faced by the Niger Delta people. Recent studies have shown that both the disturbed physicochemical characteristics of surface waters, even in fields with only a short history of petroleum extraction, can be significant in the region's oil production areas, as well as high concentrations of petroleum-derived and metallic contaminants [3].

Reported the negative impacts of contaminated crude oil from the Artisanal small-scale gold mining on surface water quality in one of the coastal towns called Ibienebo in Rivers State, while [4] reported the organic contamination of the surface water and sediment resources of the community of Opokuma in Bayelsa State [5] Reported surface water around the gas flaring sites in Delta State is contaminated with heavy metals, while [6] reported that the aquifer of Warri and Port Harcourt, Delta State, is being polluted by the presence of metals, and [7] reported results of the study of the interconnected variability in the physicochemical parameters of surface water from oil-producing communities in Delta State using a multivariate procedure. Other Niger Delta environments show similar data, indicating that metal and pollution levels vary with proximity to pollution and contamination sources, hydrology, sediment–water exchanges, and seasonality. Heavy metals were reported in the surface water and sediments of the Iko River ecosystem. [8] reported the spatiotemporal enrichment of the metals in the Qua Iboe River, and [9] have reported that metal pollution in surface water and sediments from eastern Niger Delta is a combination of anthropogenic and natural sources through geochemical and multivariate analysis.

Also, due to petroleum contamination, PAHs (some of which are persistent, mutagenic, and carcinogenic) can be introduced into the environment.

The concentrations of PAHs contamination and environmental risk of Niger Delta were found to be seasonal in multiple environmental media and food crops [10], while the combined analyses of the crude oil impacted water sources (groundwater and surface water) using physicochemical data, chemometric techniques and human health risk assessment have revealed some possibilities of exposure to arsenic and heavy-metal PAHs mixtures in the water sources [11]. The impact on the environment is greatly magnified, given that these contaminants persist, can be transported to sediments, and become incorporated into the aquatic food web and organisms.

Two examples to illustrate this point are the findings of [12] who suggested that the spread of the petrochemical contamination over a set of sediment, water and biota in the Bonny Estuary could pose ecological risks; and [13], who found that these petrochemical contamination in marine sponges located in the Niger Delta Ecological Zone were linked with bioaccumulation and genotoxic effects. Some vulnerable groups are exposed more than adults because of differences in body weight, frequency of exposure, and physiological susceptibility; exposure can be either direct (oral ingestion and cutaneous contact) or indirect (through activities that affect their livelihoods). International studies have also demonstrated the potential noncancerous and/or cancer-causing effects of polluted water and pollutants deposited in sediments [14].

Overall assessed the human-health risk associated with the widespread exposure to nitrate and fluoride in municipal and rural drinking waters in Bangladesh; [15] highlighted the high exposure-risk to heavy metals in the study area, which varies spatially; and [16] showcased the importance of multi-indicator assessment to better capture the pollution, ecological risk and implications of their effects on human-health in the study area [17]. Assessed the health hazards associated with PAHs and heavy-metal sediments in surface water in southern Nigeria, thereby reiterating the fallacy of considering PAHs and sedimented metals in surface water alone. The traditional method of water quality characterisation involves comparing contaminant concentrations against regulatory standards, but it does not adequately capture synergistic environmental risks, interactions between contaminants, spatial inequalities, or potential impacts on human health.

The complex measurements of throughputs can be translated into interpretative measures of environmental conditions and the severity of exposure, such as the Water Quality Index, Heavy Metal Pollution Index, Pollution Load Index, hazard quotient/hazard index, and lifetime cancer risk. For 'environmental variability' [18], however, underscored the importance of applying statistically robust approaches in trace-metal risk assessment, while [19], paid special attention to addressing the 'uncertainty in the assessment of human health risks caused by exposure to trace metal' by employing epidemiological evidence. Hence, multivariate techniques have increasingly been applied in various studies to identify contaminant associations, delineate pollution gradients, classify pollution, and ascertain likely pollution sources (e.g., [20], for interconnected Nigerian Lagoons and [11], for crude-oil-polluted waters of the Niger Delta of Nigeria).

Nevertheless, emerging studies in water management have successfully leveraged the potential of Artificial Intelligence, Machine Learning, and Integrated prediction to anticipate nonlinear associations and improve water-quality classification in complex/compromising situations [21-24]. However, the study by [25] highlighted that those key issues remain regarding model transferability, input data quality, and the representation of hydrological processes.

Worse, most of the studies carried out in the Niger Delta today remain largely pollutant-centric and fail to account for actual pollution measurements, readiness in the event of an oil spill, institutional response, or community responsiveness to pollution or to socioeconomic stability. Environmental degradation could result in reduced fish catch, reduced production (and livelihoods) from water access, increased household costs to access water from another source, reduced public trust in the regulator, and reduced capacity of vulnerable communities to predict, prepare for, and respond to a pollution incident. Likewise, different levels of containment of contaminant loads can be combined with different levels of preparedness resources, institutional effectiveness, livelihood diversification, and adaptive capacity, leading to differing vulnerabilities among communities with similar contaminant loads. Sustainable transition of industrial corridors, [26] indicates, necessitates an ecosystem-based approach that involves activities related to environmental protection, occupational and community safety, institutional governance, and green industrial development; however, empirical modelling of the linkages between environmental pollution metrics, human health risks, and preparedness and resilience outcomes is limited. Hence, the geographical, methodological, and policy gaps are as important as the health risk or the social perception alone; water chemistry alone would not reveal the chain of events that can lead to a persistent socioecological crisis.

This is the motivation for the integrated approach to the deterioration of surface water, contamination by heavy metals and petroleum hydrocarbons, human health risk, oil spill preparedness, institutional preparedness, community resilience, and socioeconomic stability of selected oil-producing communities, carried out in this work in Delta State, Nigeria. The study goes beyond simple concentration reporting by adding a community-level classification of vulnerability, a community-level analysis and characterisation of the link between environmental and resilience aspects, multivariate contaminant fingerprinting, an exposure-risk characterisation, a classification of contamination gradients, and a prioritisation of intervention areas. The novelty of this approach lies in obtaining an integrated analytical framework that couples, in a single assessment objective, measurements of the environment and indicators of health risk and the socio-institutional level. Outputs, including results, will be utilised to develop an evidence-based base for remediation responses, including risk,public-health surveillance conducted in a way that allows for the adjustment of both surveillance and response threats to the local setting, spill-response planning (enhanced), and regulatory enforcement and development of locally appropriate resiliency strategies for petroleum-affected communities in the Niger Delta.

2. MATERIALS AND METHODS

2. 1. Study Area and Research Design

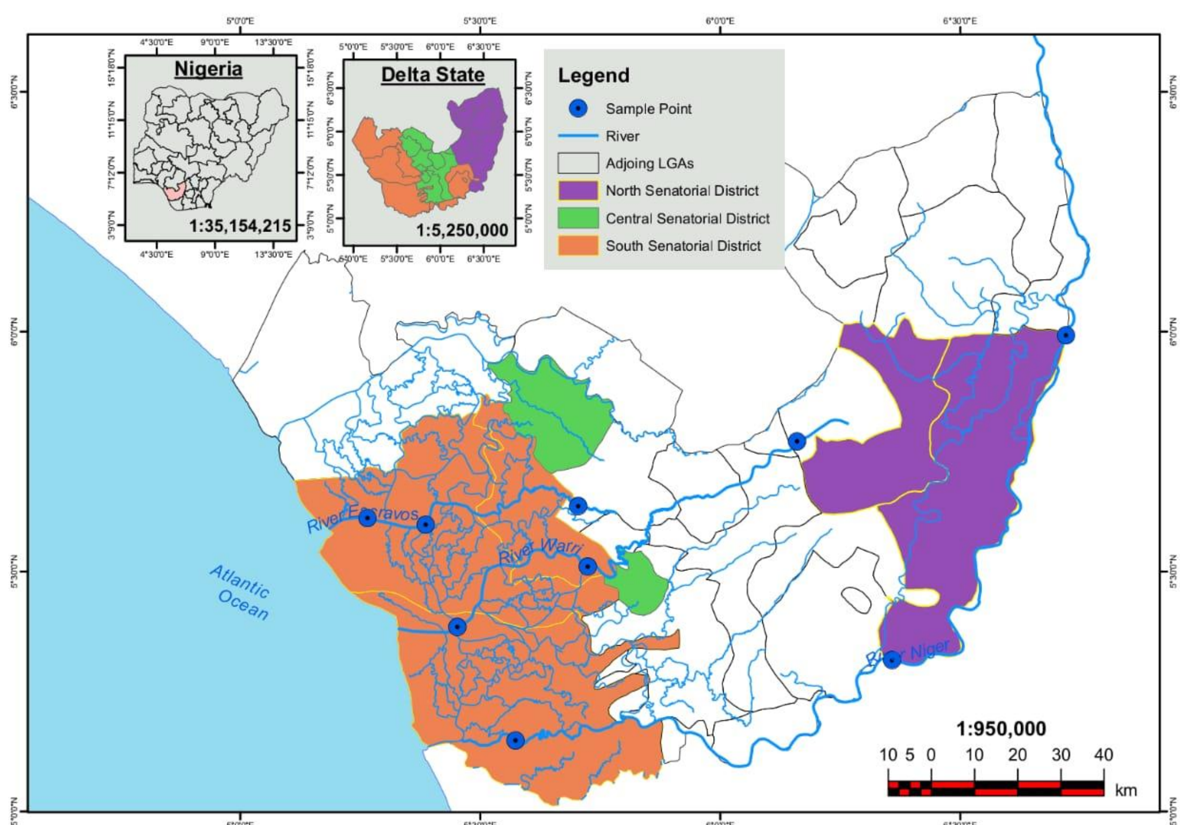
The study areas were nine petroleum-producing communities, viz. Okpai, Aboh and Kwale (Delta North); Udu, Sapele and Ovwian-Aladja (Delta Central); and Warri, Forcados and Escravos (Delta South), all of which are riverine and influenced by industrial activities. The geologic features of Delta State are the interconnectedness of rivers, creeks, estuaries, freshwater swamps, mangrove forests, and seasonally inundated wetlands, which allow the easy transport, deposition, and redistribution of environmental contaminants. The region is humid tropical, with high temperatures, high relative humidity, a long-wet season, and a short dry season (Map 1).

The amount of rainfall increases from the north inland towards the southern coastal communities. Potential sources of surface-water contamination include things like petroleum exploration and production operations, gas flaring, crude-oil transportation, marine terminals, industrial effluent discharge, artisanal refining, urban runoff, and agricultural activities.

The communities represented geographical and ecological differences in various levels of petroleum productivity, extent of industrialisation, population density, ecology and vulnerability to oil spills. The inland riverine and the petroleum producing areas were represented by Okpai, Aboh and Kwale; the urban–industrial and the river-dependent areas were represented by Udu, Sapele and Ovwian-Aladja, while the intensive petroleum–producing, coastal and marine areas were represented by Warri, Forcados and Escravos.

A cross-sectional mixed-methods design was used, combining laboratory-based assessment of surface water quality and questionnaire-based assessment of oil-spill preparedness, institutional preparedness, and community resilience/socio-economic stability. The analytical framework used was as follows. First, physicochemical conditions and contaminant concentrations were determined.

Then, composite pollution indices were calculated, followed by human-health-risk evaluations, preparedness and resilience constructs, and multivariate pollutant gradients and rankings, all ranked by the combined environmental and human-health-risk burdens. This design allowed the trigger to be situated within a single socioecological construct, in which objective environmental measurements at the trigger and residents' socioeconomic experiences can be examined.



Map 1. Map of the Study Area, Delta State, Nigeria.

2. 2. Study Population, Sample Size and Sampling Procedures

The study consisted of two types of surveys: environmental and social. A population of accessible surface-water bodies within the nine selected communities was identified as the environmental population; the social population comprised adult community residents (aged 18 or older) with sufficient residency to have knowledge of environmental conditions, oil-spill incidents, institutional responses, and community recovery processes. A multistage stratified sampling method was used. Delta State was first divided into its three senatorial zones, and then three communities were chosen from each zone, reflecting petroleum production activities, industrial influence and dependence on surface-water resources, and historical exposure to environmental pollution.

Three sampling stations were set up within each community: a control station, located upstream or reasonably remote from known petroleum facilities or industrial discharges, settlements, or other obvious pollution sources and an impact station added close to a known petroleum facility or industrial discharge, settlement, or other known pollution source; and a downstream station where the contaminant was likely to flow. Three replicate samples were taken from each of the 3 communities in each of the 3 senatorial districts, yielding 81 surface-water samples collected during each sample round. The initial minimum sample size for the social survey was determined to be: Cochran's formula used for a large population.

$$n = \frac{Z^2 pq}{e^2}$$

where: n is the minimum required sample size; Z = 1.96 is the critical value for 95% confidence; p = 0.50 is the estimated proportion in the population; q = 1,-p = 0.50; and e = 0.05 is the margin of error. A representative sample of 384 respondents was obtained through substitution. This number had to be raised to allow for some questionnaires to be incomplete and/or unusable, resulting in a final figure of 423 questionnaires that could be analysed. The respondents were evenly distributed across the selected communities; households were systematically selected within communities, and one adult was selected per household to participate. All attempts were made to ensure that both sexes, different age categories and occupational groups, especially fishermen, farmers, traders, transport operators, artisans, as well as local residents whose livelihoods were directly or indirectly dependent on the local environmental resources, were involved.

2. 3. Surface-Water Collection, Laboratory Analysis and Quality Control

Pre-cleaned high-density polyethene bottles were used to collect surface-water samples from approximately 20-30 cm below the water surface, while separate amber glass bottles with polytetrafluoroethylene-lined caps were used to collect samples for petroleum-hydrocarbon and organic-contaminant analyses to minimise the potential for photodegradation, volatilisation and adsorption. Laboratory detergent, deionised water, dilute nitric acid, and deionised water were used to clean the containers to be used for heavy metal analysis prior to field deployment. Samples for the determination of metal elements were acidified to about pH < 2 with ultrapure nitric acid, and other samples were preserved according to the respective analytical procedure. Each sample had an individual identification number comprising the senatorial district, community, station category, replicate number, date, and collection time. Samples were immediately put in an insulated ice chest at ~40 °C, transported to a laboratory, and analysed within their specified holding times.

The following parameters were measured in situ or immediately after collection: temperature, pH, electrical conductivity, total dissolved solids, and dissolved oxygen using calibrated digital meters. Turbidity was nephelometrically measured, TSS was gravimetrically measured, and biochemical oxygen demand was measured after 5 days of incubation at 200 °C; chemical oxygen demand was assessed by controlled chemical oxidation. Alkalinity, hardness, and chloride were determined by appropriate titrimetry, and sulfate, nitrate, and phosphate were determined by spectrophotometry in properly validated procedures. A measured portion of each sample was transferred to an appropriate tube, acidified with analytical-grade nitric acid and, if required, an additional oxidising acid, and boiled under controlled conditions until the digest became clear, filtered, and made up to an appropriate volume with deionised water for the determination of heavy metals. These (iron, manganese, zinc, copper, lead, cadmium, chromium, and nickel) were determined by an atomic absorption spectrophotometer calibrated, or by other instrumental methods of the same nature approved by the person, using methods known to be valid for the purpose. The 16-priority polycyclic aromatic hydrocarbons (PAHs) were extracted with appropriate organic solvents and analysed by gas chromatography equipped with an appropriate detector, along with total petroleum hydrocarbons, oil and grease, and benzene, toluene, ethylbenzene, and xylene (BTEX) compounds. All analytical procedures were followed, as referenced in the etc. APHA (Standard Methods). Quality control measures comprised of field blanks, trip blanks, reagent blanks, procedural blanks, duplicate samples, matrix spikes and Certified Reference Material (CRM). Prior to use, testing instruments were calibrated using certified standards, and only those with a coefficient of determination≥0.995 were used. Analytical recovery was acceptable, with a range of 80–120%, and a second analysis of about 10% of samples was performed as appropriate for the methods. Samples that were out of range of the analytical calibration were diluted, reanalysed, and checked for improbable values, deviations from quality control values, blank contamination, and transcription errors.

2. 4. Water-Pollution and Human-Health Risk Assessment

Measured water-quality variables were compared with existing guideline values in relevant Nigerian and international standards, and composite indices were calculated to represent general water-quality deterioration, heavy-metal contamination, and pollution burden. The weight to be given to each parameter was calculated relative to the others and used for the Water Quality Index as follows:

$$W_i = \frac{w_i}{\sum_{i=1}^{n} w_i}$$

where: W_i represents the relative weight, w_i is the assigned importance weight, and n is the number of water-quality parameters. The quality rating was determined as:

$$q_i = \frac{C_i}{S_i} \times 100$$

where: represents the measured concentration and C_i is the corresponding guideline value.

The parameter-specific sub-index and overall Water Quality Index were calculated as:

$$SI_i = W_i q_{i;};\ \ WQI = \sum_{i=1}^{n} SI_i$$

The Heavy Metal Pollution Index was computed as:

$$HPI = \frac{\sum_{i=1}^{n} W_i Q_i}{\sum_{i=1}^{n} W_i}$$

where: Q_i is the sub-index for metal iii, and W_i represents its unit weight. The contamination factor for each metal and the overall Pollution Load Index were obtained using:

2. 5. Questionnaire Design, Measurement, Validity and Reliability

The study objectives, conceptual framework, and relevant empirical literature were translated into a structured questionnaire to elicit information on respondents' demographic characteristics, environmental experiences, oil spill preparedness, institutional preparedness, community resilience, and socioeconomic stability. Items assessed the level of preparedness for an oil spill using topics related to knowledge of response procedures, early-warning information availability, emergency planning, response materials available, knowledge of evacuation, and community training and participation in preparedness activities. Institutional preparedness included aspects of environmental monitoring and risk communication, response time, response staff and equipment, remediation, government agency and petroleum company/community response and regulatory enforcement/compensation.

Community resilience was measured by collective action, social support, information access, adaptive learning, community leadership, livelihood adjustment, and recovery from environmental shocks. Socioeconomic stability was indicated by variables related to recovery from the effects of pollution-related changes, livelihood continuity, income security, employment, fishing productivity, agricultural productivity, and access to essential services. The answers were rated on a 5-point Likert scale, with point 1 representing disagreement and point 5 representing agreement. Negatively worded items were reverse-scored such that positive composite scores consistently reflected high levels of preparedness, resilience and/or socioeconomic stability.

Face and content validity of the instrument were established through an evaluation by experts in the fields of environmental science, disaster risk management, public health, and social research. A pilot study was conducted with the respondents who had attributes of the target population but were not from the actual study communities. Items that were confusing were changed based on pilot feedback. Cronbach's alpha was used to determine the internal consistency of the instrument ($\alpha \geq 0.70$ was deemed as acceptable). Prior to calculating composite construct scores, completed questionnaires were checked for excessive missing responses, inconsistent response patterns, and coding errors.

2. 6. Statistical and Multivariate Data Analysis

Data collected from the environment and questionnaires were coded, cleaned, and analysed using suitable analysis software. The data for continuous variables were presented as mean, standard deviation, minimum, maximum, and coefficient of variation, and the data for categorical variables were displayed as frequencies and percentages. Histograms, normal probability plots, skewness, kurtosis and normality test were used to evaluate the data distribution. Where the contaminant concentrations were positively skewed, they were log-transformed. Analysis of variance (ANOVA) with appropriate adjusted post-hoc comparisons was conducted when statistical assumptions were met to test differences between senatorial districts, communities and station categories in parameter values and water quality; otherwise, non-parametric alternatives were used for assessing differences in parameter values and water quality in pollutant concentrations and health-risk estimates among senatorial districts, communities and station categories. Pearson or Spearman correlation was first used to test the relationships between pollution, health risk, preparedness, and resilience indicators and socioeconomic indicators. Given that the respondents were hierarchically clustered across nine communities, multilevel regression with a random intercept at the community level or community-robust standard errors was employed, rather than treating the community scores for each respondent as independent.

Due to the small number of communities, results from the inferential analyses were examined with some caution, and where feasible, the wild-cluster bootstrap procedures were used. The measures of multicollinearity were assessed using tolerance and variance inflation factors, and the measures of linearity, homoscedasticity, and influential observations were assessed by examining the residuals and influence diagnostics. To standardise the various variables for the exploratory Community-level analysis, WQI, HPI, PLI, TPH, Σ16 PAHs, HI and LCR were converted to z-scores. Pearson correlation was performed to assess the relationship between these indicators, and principal component analysis was used to find the predominant common pollution–health-risk gradient. Parameters were examined in terms of eigenvalues, PC explained variance, and scree plot behaviour, and absolute loadings ≥ 0.70 were considered strong.

Ward's hierarchical clustering using squared Euclidean distance was then used to cluster communities that have similar environmental and health risk factors. These low, moderate, high and critical classifications were used here as exploratories as only nine observations were used in the multivariate community level analysis. Effect size measures, standard errors and confidence intervals were reported along with p-values where applicable and evaluation of statistical significance was set as $p < 0.05$.

2. 7. Integrated Environmental–Health Risk Burden Index

An Integrated Environmental–Health Risk Burden Index was compiled to rank the communities based on water-quality deterioration, heavy-metal contamination, petroleum hydrocarbon burden, non-carcinogenic risk, and carcinogenic risk. They represented complementary environmental and human-health dimensions that were incorporated in the index, which included WQI, HPI, PLI, TPH, Σ16 PAHs, HI and LCR.

2. 8. Ethical Considerations

During the study, ethical standards for human participants were respected. Before fieldwork was conducted, ethical approval was granted by the appropriate institutional research ethics body; administrative and community entry permissions were granted by various government bodies, traditional institutions, and community leaders. All potential respondents were given a clear explanation of the study's purpose, what was involved, how long it would take, any inconvenience they might experience, assurances of confidentiality, and the planned use of the findings. Enrollment was voluntary, and informed consent was obtained prior to questionnaires. Respondents were reminded that they could skip any question and/or leave the study at any time without penalties. Unique identification codes were assigned to completed questionnaires in the analytical database, and names and other direct personal identifiers were removed from it. All research records were maintained both electronically and in hard copy and secured in such a way that it could only be accessed by members of the research team who were authorised to do so. Results were presented as group data to avoid identifying the participants. Surface-water sampling was conducted to avoid disturbing aquatic habitat, community activities, or private property. Systematic documentation of the field and laboratory protocols, application of quality-control protocols, reporting of the particular limitations of the analytical method(s), and avoidance of data fabrication, suppression, or selective.

3. RESULTS AND DISCUSSION

Table 1. Surface Water Sampling Design.

Senatorial District	Community	Sampling Stations	Replicates per Station	Total Samples
Delta North	Okpai	3	3	9
	Aboh	3	3	9
	Kwale	3	3	9
Delta Central	Udu	3	3	9
	Sapele	3	3	9
	Ovwian-Aladja	3	3	9
Delta South	Warri	3	3	9
	Forcados	3	3	9
	Escravos	3	3	9
Total	9 Communities	27	81	81

Table 2. Physicochemical Characteristics of Surface Water (Mean ± SD).

Community	pH	Temp (°C)	EC (µS/cm)	Turbidity (NTU)	TDS (mg/L)	DO (mg/L)	BOD_5 (mg/L)	COD (mg/L)	Nitrate (mg/L)	Phosphate (mg/L)	Sulphate (mg/L)
Okpai	6.82 ±0.18	28.5 ±0.7	471 ±22	6.4 ±0.5	276 ±15	5.81 ±0.24	4.11 ±0.36	18.9 ±1.5	4.32 ±0.36	0.54 ±0.05	13.8 ±1.3
Aboh	6.76 ±0.17	28.7 ±0.8	486 ±24	7.2 ±0.6	289 ±17	5.63 ±0.26	4.47 ±0.39	20.5 ±1.7	4.68 ±0.39	0.59 ±0.05	14.9 ±1.4

Kwale	6.59 ±0.16	29.1 ±0.8	514 ±28	8.5 ±0.7	316 ±18	5.34 ±0.28	5.08 ±0.42	23.7 ±2.0	5.16 ±0.42	0.68 ±0.06	16.8 ±1.6
Udu	6.68 ±0.15	28.8 ±0.7	498 ±25	7.8 ±0.6	303 ±16	5.49 ±0.26	4.79 ±0.40	22.3 ±1.8	4.88 ±0.40	0.64 ±0.05	15.8 ±1.5
Sapele	6.87 ±0.14	28.4 ±0.6	462 ±21	5.9 ±0.5	268 ±14	5.96 ±0.23	3.92 ±0.34	17.8 ±1.4	4.09 ±0.34	0.51 ±0.04	12.8 ±1.2
Ovwian-Aladja	6.64 ±0.15	29.0 ±0.8	507 ±27	8.0 ±0.7	311 ±18	5.38 ±0.27	4.97 ±0.41	23.0 ±1.9	5.02 ±0.41	0.67 ±0.06	16.5 ±1.6
Warri	6.56 ±0.18	29.3 ±0.9	526 ±31	9.1 ±0.8	327 ±20	5.17 ±0.30	5.41 ±0.45	25.6 ±2.1	5.38 ±0.45	0.74 ±0.07	17.9 ±1.7
Forcados	6.43 ±0.19	29.7 ±0.9	549 ±34	10.3 ±0.9	347 ±22	4.95 ±0.32	5.87 ±0.48	28.7 ±2.4	5.84 ±0.48	0.80 ±0.07	19.4 ±1.8
Escravos	6.37 ±0.20	29.9 ±1.0	565 ±36	11.1 ±0.9	361 ±23	4.79 ±0.34	6.13 ±0.51	30.4 ±2.6	6.07 ±0.51	0.85 ±0.08	20.1 ±1.9

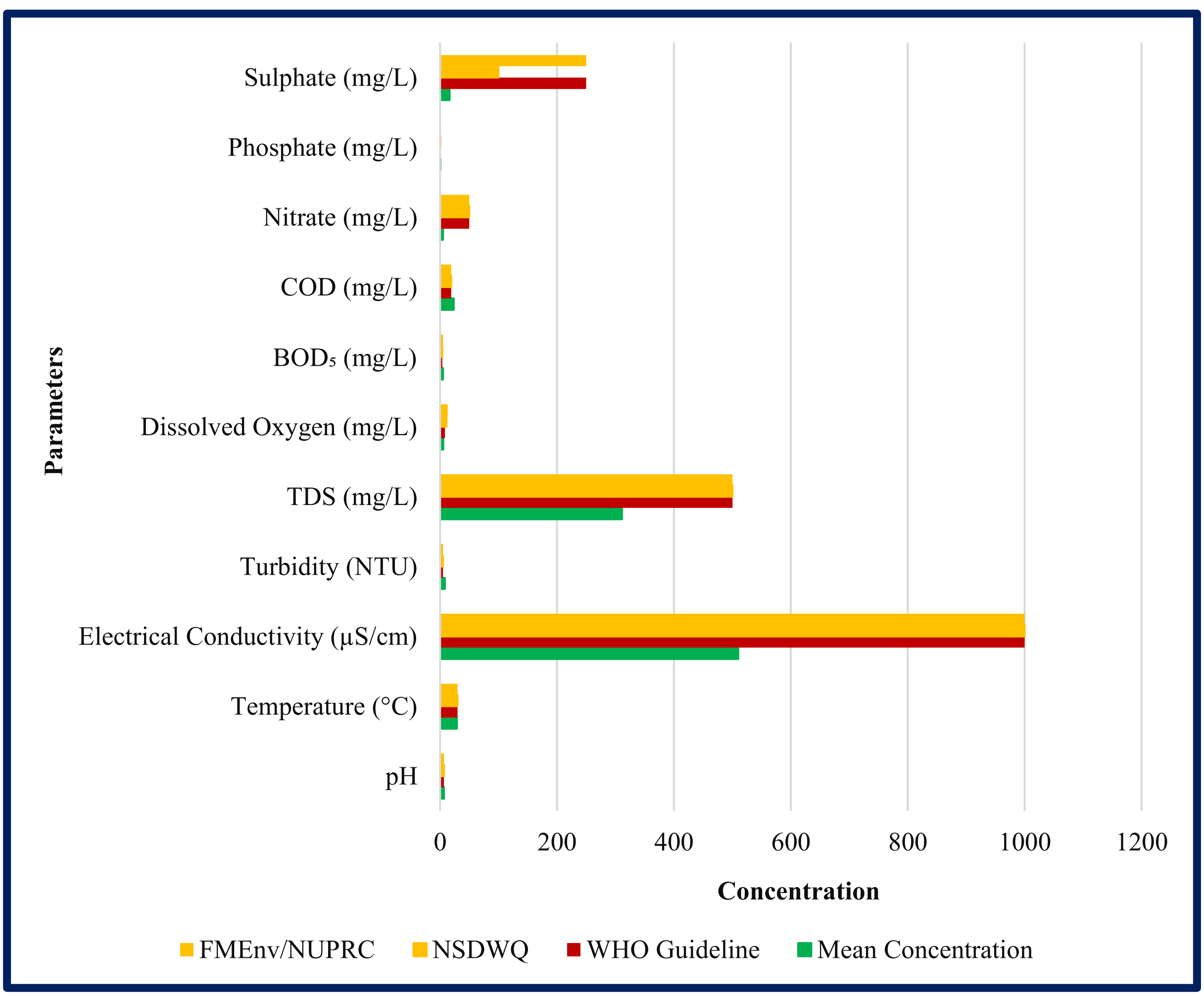


Figure 1. Summary Statistics and Compliance Assessment for Surface Water.

Table 3. Heavy Metal Concentrations in Surface Water (mg/L; Mean ± SD).

Community	Pb	Cd	Cr	Ni	Cu	Zn	Fe	Mn
Okpai	0.013 ±0.002	0.002 ±0.001	0.021 ±0.003	0.028 ±0.004	0.051 ±0.006	0.182 ±0.014	0.29 ±0.03	0.061 ±0.005
Aboh	0.015 ±0.002	0.003 ±0.001	0.024 ±0.003	0.031 ±0.004	0.054 ±0.006	0.191 ±0.015	0.31 ±0.03	0.064 ±0.005
Kwale	0.021 ±0.003	0.004 ±0.001	0.032 ±0.004	0.040 ±0.005	0.066 ±0.007	0.214 ±0.017	0.39 ±0.04	0.073 ±0.006
Udu	0.018 ±0.003	0.003 ±0.001	0.028 ±0.004	0.036 ±0.005	0.061 ±0.007	0.207 ±0.016	0.36 ±0.04	0.070 ±0.006
Sapele	0.012 ±0.002	0.002 ±0.001	0.020 ±0.003	0.026 ±0.004	0.049 ±0.006	0.176 ±0.014	0.27 ±0.03	0.058 ±0.005
Ovwian-Aladja	0.020 ±0.003	0.004 ±0.001	0.031 ±0.004	0.039 ±0.005	0.065 ±0.007	0.212 ±0.017	0.38 ±0.04	0.072 ±0.006
Warri	0.024 ±0.003	0.005 ±0.001	0.036 ±0.005	0.045 ±0.006	0.071 ±0.008	0.226 ±0.018	0.44 ±0.05	0.079 ±0.007
Forcados	0.031 ±0.004	0.007 ±0.002	0.044 ±0.005	0.053 ±0.006	0.082 ±0.009	0.247 ±0.020	0.53 ±0.05	0.091 ±0.008
Escravos	0.034 ±0.004	0.008 ±0.002	0.048 ±0.006	0.057 ±0.007	0.087 ±0.009	0.259 ±0.021	0.57 ±0.06	0.096 ±0.008
WHO Limit	0.010	0.003	0.050	0.070	2.000	3.000	0.30	0.10
Overall Mean	0.021	0.004	0.032	0.039	0.065	0.213	0.39	0.074

Table 4. Petroleum Hydrocarbon Concentrations in Surface Water.

Community	TPH (mg/L)	Oil & Grease (mg/L)	Benzene (mg/L)	Toluene (mg/L)	Ethylbenzene (mg/L)	Xylene (mg/L)	Σ16 PAHs (mg/L)
Okpai	1.62 ±0.15	2.31 ±0.20	0.006 ±0.001	0.012 ±0.002	0.004 ±0.001	0.018 ±0.002	0.036 ±0.004
Aboh	1.81 ±0.17	2.58 ±0.22	0.007 ±0.001	0.014 ±0.002	0.005 ±0.001	0.020 ±0.002	0.041 ±0.004
Kwale	2.54 ±0.22	3.74 ±0.31	0.011 ±0.002	0.019 ±0.003	0.008 ±0.001	0.029 ±0.003	0.062 ±0.006
Udu	2.33 ±0.21	3.48 ±0.29	0.010 ±0.002	0.018 ±0.003	0.007 ±0.001	0.027 ±0.003	0.058 ±0.005
Sapele	1.49 ±0.14	2.19 ±0.19	0.005 ±0.001	0.011 ±0.002	0.004 ±0.001	0.017 ±0.002	0.032 ±0.003
Ovwian-Aladja	2.47 ±0.22	3.61 ±0.30	0.011 ±0.002	0.019 ±0.003	0.008 ±0.001	0.028 ±0.003	0.061 ±0.006
Warri	3.18 ±0.28	4.72 ±0.38	0.015 ±0.002	0.025 ±0.003	0.010 ±0.002	0.036 ±0.004	0.084 ±0.007
Forcados	4.06 ±0.35	5.81 ±0.46	0.020 ±0.003	0.031 ±0.004	0.013 ±0.002	0.045 ±0.005	0.112 ±0.010
Escravos	4.38 ±0.37	6.24 ±0.50	0.022 ±0.003	0.034 ±0.004	0.015 ±0.002	0.048 ±0.005	0.126 ±0.011

Total Petroleum Hydrocarbons (TPH), Oil and Grease (O&G), Benzene, Toluene, Ethylbenzene, Xylene (BTEX) and the sum of sixteen priority Polycyclic Aromatic Hydrocarbons (Σ16 PAHs).

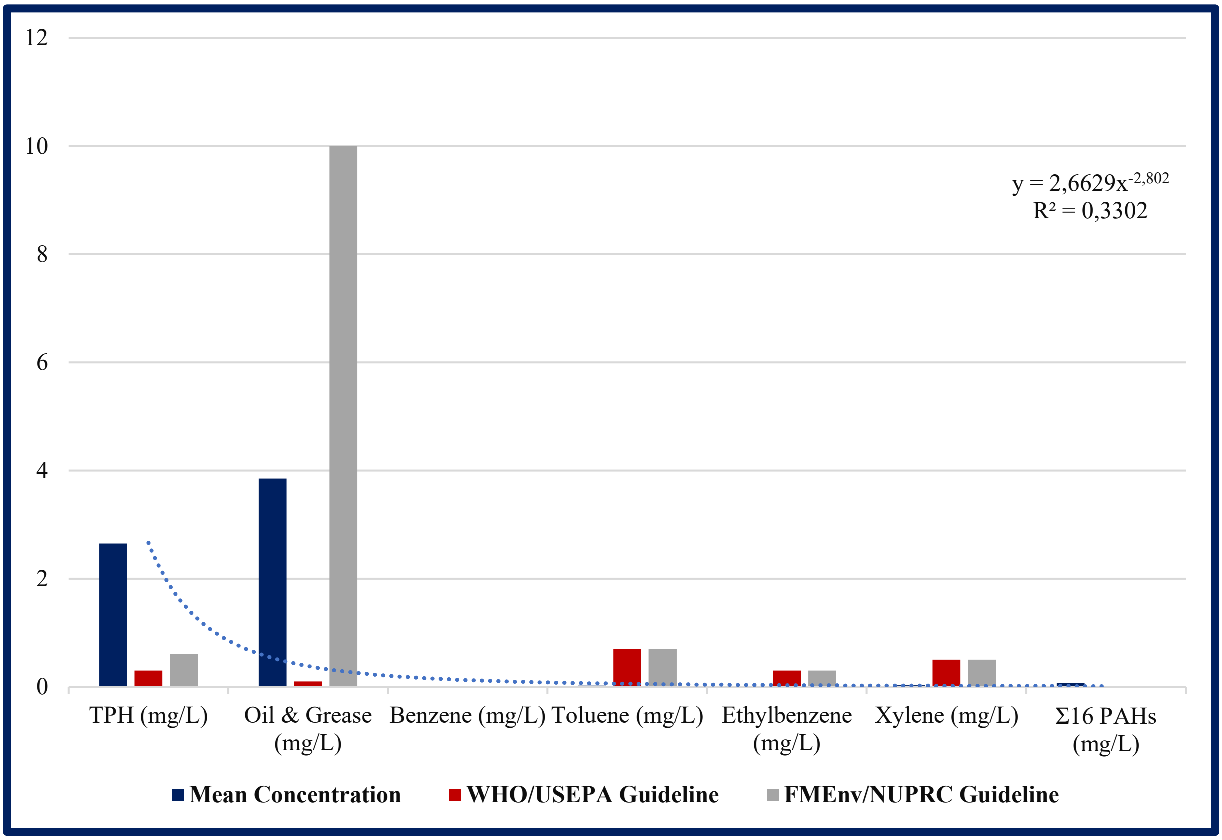


Figure 2. Comparison of Hydrocarbon Concentrations with Regulatory Guidelines.

Table 5. Pollution Indices for Surface Water.

Community	Water Quality Index (WQI)	Heavy Metal Pollution Index (HPI)	Metal Index (MI)	Contamination Factor (CF)	Pollution Load Index (PLI)
Okpai	71.8	48.6	0.84	1.12	0.96
Aboh	79.5	55.8	0.92	1.25	1.03
Kwale	108.6	86.7	1.34	1.82	1.41
Udu	99.4	80.5	1.27	1.69	1.34
Sapele	67.9	45.2	0.79	1.03	0.91
Owvian-Aladja	104.3	83.6	1.31	1.75	1.37

Warri	138.5	116.2	1.88	2.44	1.89
Forcados	171.4	149.5	2.41	3.09	2.33
Escravos	182.7	157.8	2.57	3.24	2.47

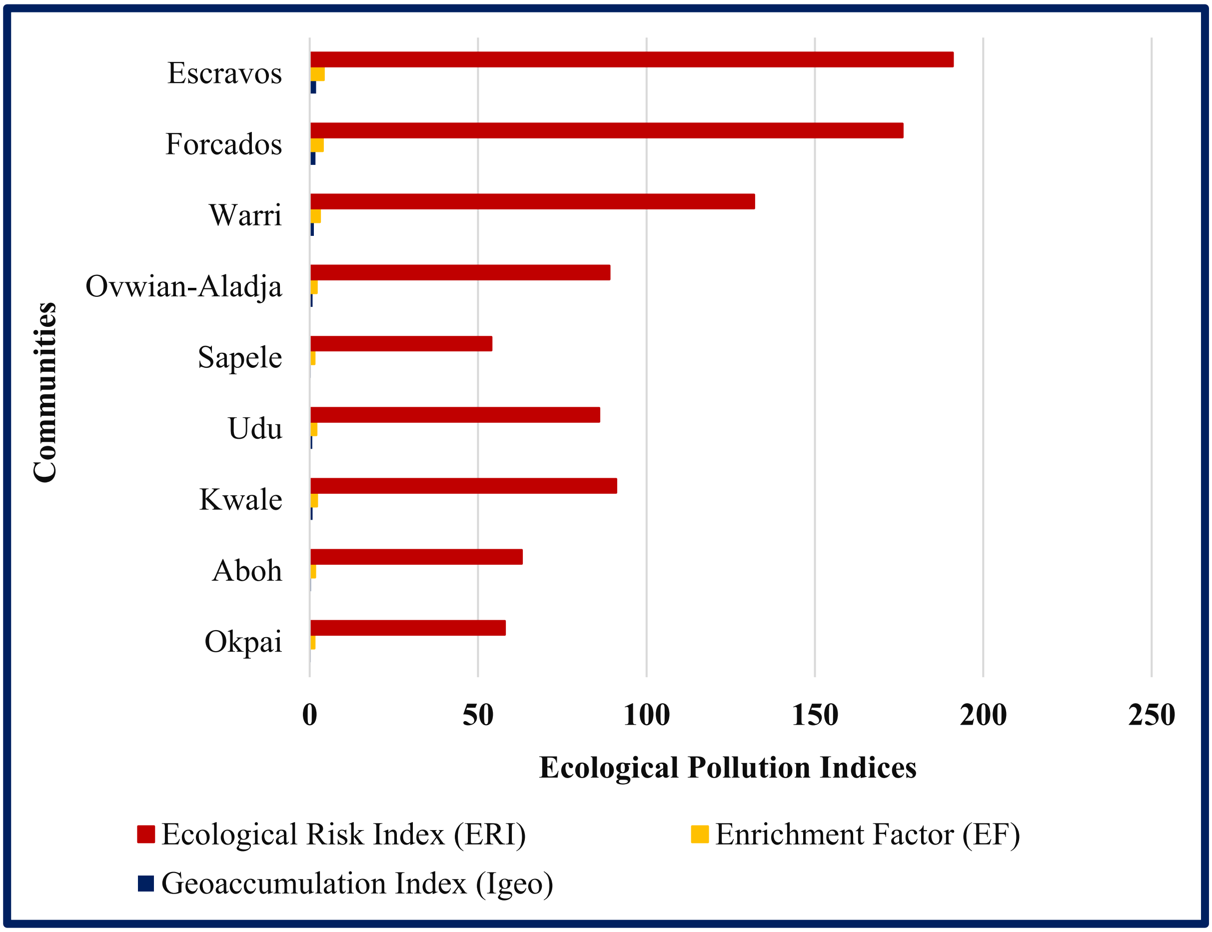


Figure 3. Ecological Pollution Indices Based on Heavy Metals.

Table 6. Human Health Risk Assessment of Surface Water.

Community	Average Daily Dose (ADD) (mg/kg/day)	Hazard Quotient (HQ)	Hazard Index (HI)	Cancer Risk (CR)	Lifetime Cancer Risk (LCR)
Okpai	3.12×10^{-4}	0.42	0.71	2.8×10^{-6}	3.5×10^{-6}
Aboh	3.45×10^{-4}	0.48	0.79	3.2×10^{-6}	4.1×10^{-6}

Kwale	4.91×10^{-4}	0.71	1.12	6.8×10^{-6}	8.2×10^{-6}
Udu	4.63×10^{-4}	0.67	1.05	6.1×10^{-6}	7.5×10^{-6}
Sapele	2.96×10^{-4}	0.39	0.66	2.6×10^{-6}	3.2×10^{-6}
Ovwian-Aladja	4.78×10^{-4}	0.69	1.09	6.4×10^{-6}	7.9×10^{-6}
Warri	6.12×10^{-4}	0.94	1.48	1.12×10^{-5}	1.36×10^{-5}
Forcados	7.81×10^{-4}	1.18	1.84	1.94×10^{-5}	2.21×10^{-5}
Escravos	8.36×10^{-4}	1.26	1.96	2.16×10^{-5}	2.48×10^{-5}

Table 7. Multiple Regression Model Predicting Community Resilience.

A. Model Summary

R	R^2	Adjusted R^2	Std. Error	Durbin-Watson
0.846	0.716	0.712	0.418	1.94

B. Model Summary

Source	SS	df	MS	F	p-value
Regression	188.62	5	37.72	215.47	<0.001
Residual	74.02	417	0.177		
Total	262.64	422			

C. Regression Coefficients

Predictor	B	SE	Beta	t	p-value
Constant	1.124	0.162		6.94	<0.001
Environmental Quality Index	-0.382	0.044	-0.406	-8.68	<0.001
Oil Spill Preparedness	0.317	0.039	0.332	8.13	<0.001
Institutional Preparedness	0.226	0.037	0.248	6.11	<0.001
Socioeconomic Stability	0.194	0.035	0.221	5.54	<0.001
Hydrocarbon Pollution Index	-0.164	0.031	-0.182	-5.29	<0.001

Table 8. Correlation Matrix of Environmental Pollution and Health-Risk Indicators.

Indicator	WQI	HPI	PLI	TPH	Σ16 PAHs	HI	LCR
WQI	1.000						
HPI	0.999	1.000					
PLI	0.999	0.998	1.000				
TPH	0.999	0.999	0.998	1.000			
Σ16 PAHs	0.998	0.997	0.997	0.999	1.000		
HI	1.000	1.000	0.999	0.999	0.998	1.000	
LCR	0.990	0.987	0.992	0.990	0.994	0.988	1.000

Table 9. Principal Component Eigenvalues and Explained Variance.

Component	Eigenvalue	Variance explained (%)	Cumulative variance (%)
PC1	6.977	99.674	99.674
PC2	0.018	0.257	99.931
PC3	0.004	0.050	99.981
PC4	0.001	0.011	99.992
PC5	0.001	0.007	99.999
PC6	<0.001	<0.001	>99.999
PC7	<0.001	<0.001	100.000

Table 10. Component Loadings of Environmental and Health-Risk Indicators.

Indicator	PC1 loading	PC2 loading	Communality
WQI	1.000	−0.022	1.000
HPI	0.999	−0.047	1.000
PLI	0.999	−0.011	0.999
TPH	0.999	−0.018	0.999
Σ16 PAHs	0.999	0.019	0.999
HI	0.999	−0.036	1.000
LCR	0.993	0.115	1.000

Table 11. PCA Scores and Hierarchical Pollution Classification of Communities.

Community	PC1 score	PC2 score
Sapele	−3.012	0.171
Okpai	−2.751	0.122
Aboh	−2.327	0.032
Udu	−0.887	−0.079
Ovwian-Aladja	−0.645	−0.115
Kwale	−0.467	−0.155
Warri	1.525	−0.203
Forcados	3.874	0.057
Escravos	4.689	0.170

This clear spatial gradient in surface-water quality from relatively impact-free areas to heavily impacted coastal communities, as revealed by the combined effects of all five data sets (physicochemical, heavy metal, and hydrocarbon data), indicates that surface-water quality degrades with distance. The increase in the values of EC, TDS and Turbidity coupled with decrease in pH value and dissolved oxygen were observed from Sapele 462 µS/cm and 268 mg/l and 5.9 NTU respectively to Escravos, 565 µS/cm and 361 mg/l and 11.1 NTU respectively; while the increase in BOD and COD values were observed from Sapele 3.92 mg/l and 17.8 mg/l respectively to Escravos 6.13 mg/l and 30.4 mg/l respectively as shown in Table 2 and Figure 1. The relationship between DO and organic and petroleum-associated loads was negative, and the relationships between DO and microbial decomposition and biological stress (Oxygen-demanding parameters) were also negative.

The above interpretation is corroborated by the results presented in Table 3, where lead was also detected at concentrations above 0.010 mg/L in all the communities, and cadmium was also above 0.003 mg/L in some of the communities, while Iron was detected at a concentration of 0.57 mg/L in the Escravos community, against the benchmark of 0.05mg/L. Table 4 and Figure 2 present the more direct petroleum fingerprints, with TPH, oil and grease, benzene, and Σ16 PAHs detected in Sapele at 1.49, 2.19, 0.005, and 0.032 mg/L, respectively, and in Escravos at 4.38, 6.24, 0.022, and 0.126 mg/L, respectively.

This observation agrees with the previous observations of other studies on the degradation of the water quality of the Niger Delta and blame on the Petroleum Industry, transportation and remobilisation of sediments during rainy and dry seasons and industrial effluents were blamed by [4-7, 9, 11, 17, 20, 27-29]. Moreover, [30, 31] indicate that vertical transport or bioaccumulation of contaminants may occur from water to sediments and aquatic organisms, respectively, which may be an underestimated risk in water measurements. The results also align with broader evidence on industrial water [32-37]. However, [38-44] studied sediment/soil/landfill/street dust pollution; they agree on mixed anthropogenic metal inputs, but the results are not directly comparable numerically due to differences in contaminant retention and mobility between solid matrices and surface water. The concentrations of indicators were always a combination of impacts on the environment and human health – there was a set of integrated indicators and toxicological estimates that represented this. In Table 5 and Figure 3, WQI rose from 67.9 in Sapele to 182.7 in Escravos, HPI increased from 45.2 to 157.8, and PLI increased from 0.91 to 2.47. Other parameters generated, such as WQI, HPI and PLI, were similarly elevated for Forcados (171.4, 149.5 and 2.33, respectively) and for Warri (138.5, 116.2 and 1.89, respectively). The ports of Escravos, Forcados and Warri have consistently been pollution hotspots, based on the various indices compiled. All other localities, including Sapele, do not exceed 10ge/100,000 inhabitants of potential health impacts, while the Hazardous Index (HI) values at all localities range between 0.66 and 1.96, with HI value > 1 at 4 locations, namely Kwale, Udu, Ovvian-Aladja, Warri, Forcados and Escravos, while for lifetime cancer risk, all localities have a value ranging between 3.2×10^{-6} and 9.3×10^{-6}, with estimated lifetime cancer risk > 9.3×10^{-6} at Kwale, Udu, Ovvian-Aladja, Warri, Forcados and Escravos localities. The elevators that are closely used by the inhabitants and childhouses, depending on surface water, are still very important. This is in line with the findings of [14-16, 45, 46], which indicated that contaminants are policy-relevant when converted into pathway-specific hazard and/or cancer risk estimates. [1, 2, 39, 47] also show the impacts of water pollution, including interconnected environmental, infectious disease, livelihood, and chronic health impacts. The results of both metals (lead and cadmium) are very similar to those obtained in [47-50]. The dermal exposures (from soil ingestion) calculated cannot be compared with exposures from water. [19, 51, 52] share the compound-exposure element and explore various forms of exposure, including microplastics, heat–ozone interactions, and exposure translation level, respectively. Critically, the classification of the indices relies on reference concentrations, statistical weightings, and uncertainties, as warned by [18, 55], underscoring the difficulties in modelling risks with a small dataset. Therefore, these results (Table 6) should only be interpreted as a “screening level risk”, and not as an indication of a specific disease. The relatively low risk identified on both Sapele and Okpai would therefore not clash with the risk documentation from the region, as the risk is simply determined using how the pollution is distributed, which is the distance from the pollution sources, tidal exchange, hydrology, and history of releases from the pollution sources and season with responsible waste inputs from the local activities. Lastly, the social and multivariate results show that social environmental degradation is correlated with a loss of resilience, and that resilience can also be measured by preparedness capacity and institutional capacity. Environmental burden and hydrocarbon pollution were negatively associated with community resilience, whereas other variables (oil-spill preparedness, institutional preparedness, and socioeconomic stability) were positively associated with community resilience (Table 7). Chemical exposure was found to interact with the capacity to respond socially, and the model explained 71.6% of the variance in resilience. This is consistent with the findings of [26], who have shown an interconnection among environmental protection, health, safety, and institutional governance, and with those of [56], who have shown a connection between pollution management and socioeconomic sustainability. [57] also call for an 'Integrated Environmental, Health and Governance Risk Modelling' that, however, is at the sectoral level rather than the community level. The results indicate correlations between the WQI and the HI, LCR, TPH, Σ16 PAHs, HPI, and PLI, as shown in Table 8, implying that the most contaminated community has the highest health impact. This, in turn, led to the dominance of a single principal component, which accounted for 99.674% of the variance among the various areas studied. The intermediate burden areas were Udu and Ovwian-Aladja; the high burden areas were Warri; Forcados was the critical burden area; and Okpai and Sapele were the relatively low burden areas. It is a multivariate behaviour that can be explained by the chemometric approach presented by [8, 11]. Several of these indices, however, were mathematically concocted in a way that would make for such a contrast of idealised relationships: Some of these indices would have been based on an overlapping concentration and so would not have been causal confirmations. [21, 23-25, 58] mentioned their significance for prediction, monitoring, contaminant transport, bioaccumulation and the prediction of public health, respectively, while [61] mentioned their significance for contaminant transport. Lastly, [59-65] all advocate for bioremediation, biochar and contaminant-fate intervention, but the soil-oriented remediation approaches would need to be adapted to aquatic systems. When considered alongside Tables 2-11 and Figures 1-3, a 'trajectory' can be discerned from petroleum and metal contamination to ecological degradation and health hazards, to reduced resilience, and finally to differentiated remediation, safe water, health monitoring and surveillance, restoration of livelihoods, and institutional preparedness.

4. CONCLUSIONS

The major conclusion of this study is that contamination of the surface water in the nine selected communities in Delta State exhibits a clear spatial gradient, with petroleum production, industrialisation, waste inputs, and local hydrological conditions all playing distinct roles. The physicochemical results and the results for heavy and hydrocarbon metals consistently pointed to the two oil hotspots (Escravos and Forcados), followed by Warri, then Sapele, Okpai, and Aboh, with comparatively lower pollution burdens. However, evidence of petroleum hydrocarbons and numerous environmental exceedances of lead suggest that no community was without some measure of environmental concern. Results from the Water Quality Index, Heavy Metal Pollution Index, Pollution Load Index, hazard index, Lifetime Cancer Risk, and principal component-based classification corroborate that as water quality declines, the risk to the environment and human health increases. Six communities have hazard indexes greater than one, suggesting possible non-carcinogenic concern, but cancer-risk estimates, even though in the conventional range of risk management, are relevant in possible chronic exposure conditions. The regression results also confirm that environmental degradation and hydrocarbon pollution reduce community resilience, while oil-spill preparedness, institutional preparedness, and socioeconomic stability increase adaptive and recovery capacity. Finally, the study shows that the contamination of surface water by petroleum products is a problem that can affect the environment, public health, livelihoods and governance. Leading pollution prevention and remediation efforts, safe water provision, health protection, and institutional accountability and resilience strategies for communities should therefore be part of effective management, not the only or even the first response in affected communities.

References

[1] Gbadamosi, F., & Aldstadt, J. (2025). The interplay of oil exploitation, environmental degradation and health in the Niger Delta: A scoping review. *Tropical Medicine & International Health*, 30(5), 351-367

[2] Chukwudi, O. U., & Chinonso, N. V. (2025). Oil Spillage and Environmental Degradation: Assessing the Challenges of Host Communities in the Niger Delta Region of Nigeria. *IOSR Journal of Pharmacy and Biological Sciences*, 5(2), 31-34

[3] Ibienebo Chris, D., Kallem, P., Wen Goh, K., Lananan, F., Abdul Kari, Z., Azra, M. N., & Kenneth Wokeh, O. (2025). Present Status of Surface Water Quality Impacted by Artisanal Crude Oil Contamination in a Coastal Community in Rivers State, Nigeria. *Pollution*, 11(3), 738-757

[4] Adebowale, I. J., Moses, P., & Abalist, R. O. (2026). Organic contamination in water and sediment of Opokuma Community, Kolokuma/Opokuma Local Government Area, Bayelsa State, Niger Delta, Nigeria. *International Journal of Technology, Health and Sustainability*, 2(01), 333-339

[5] Bardi, J. I., Docas, B. S., Ayodele, O., Bardi Stephen, I., & Koplamma, N. B. (2025). Analysis of Heavy Metal Concentration of Surface Water Around Gas-flaring Stations in Selected Areas of Delta State, Nigeria. *Open J Environ Biol*, 10(1), 029-036

[6] Edward, M. O., Falese, T. T., Falade, N. O., Ola, E. T., & Akindole, O. (2025). Metals contamination of Aquifer in Warri and Port-Harcourt (Niger–Delta Region). *Proceedings of the Nigerian Academy of Science*, 17(2), 101-113

[7] Biose, E., & Ogwo, P. A. (2026). Multivariate Assessment of Physicochemical Parameters and Heavy Metal Contamination in Surface Waters of Oil-Producing Communities, Delta State, Nigeria. *J. Mater. Environ. Sci*. 17 (3), 453

[8] Kudamnya, E., Edet, A., & Bassey, B. (2026). Appraisal of sources, pollution and risks of some metals in soil and water using geochemical and multivariate statistical approach, eastern Niger Delta, Nigeria. *Discover Geoscience*, 4(1), 94

[9] Etesin, U. M., & Essien, A. L. (2025). Distribution of Heavy metals in sediments and surface waters from Iko River Marine Ecosystems, Akwa Ibom State, Niger Delta, Nigeria. *Communication in Physical Sciences*, 12(2)

[10] Akinkpelumi, V. K., Onyena, A. P., Abdulai, P. M., Ossai, C. M., Frazzoli, C., & Orisakwe, O. E. (2025). Seasonality and ecological risks of polycyclic aromatic hydrocarbons PAHS in environmental media and food crops of Ibaa, Niger Delta, Nigeria. *Environmental Sciences Europe*, 37(1), 215

[11] Ali, H. A., & Farhan, M. B. (2025). Bioremediation Techniques for Water and Soil Pollution. *Natural and Engineering Sciences*, 10(1), 89-109

[12] Chinedu, N. B., Isangadighi, G. E., Essien, U. B., Adedamola, S. B., Orabuego, A. U., & Momoh, P. O. (2026). Computational fluid dynamics (CFD) simulation of airborne toxic pollutants and associated human health risks in industrial zones of Delta state, Nigeria. *Journal of Air Pollution & Health*, 11(1), 77

[13] Chidugu-Ogborigbo, R. U., Nkopuyo, U. S., Nikolas, J. H., & Barker, J. (2025). Bioaccumulation and genotoxic effect of heavy metal pollution in marine sponges from the Niger Delta. *Marine Pollution Bulletin*, 211, 117386

[14] Abdipour, H., Azari, A., Kamani, H., Pirasteh, K., Mostafapour, F. K., & Rayegnnakhost, S. (2025). Human health risk assessment for fluoride and nitrate

contamination in drinking water of municipal and rural areas of Zahedan, Iran. *Applied Water Science*, 15(3), 47

[15] Hossain, M. S., Rahman, A., Asefa, E. M., Parveen, M., & Uddin, M. R. (2025). Assessing spatial distribution of heavy metal contamination in groundwater and associated human health risk in the Chittagong industrial area, Bangladesh. *Journal of Hazardous Materials Advances*, 18, 100728

[16] Liu, T., Zhang, Y., Liu, Y., & Chen, B. (2025). Multi-indicator assessment of heavy metal pollution in Qinzhou Harbour sediments: Unraveling ecological and human health risks. *Marine Pollution Bulletin*, 211, 117442

[17] Samson, E. O., & Thelma, E. K. (2025). Health risk assessment of polycyclic aromatic hydrocarbons and heavy metals in surface water from Bakana River in southern Nigeria. *GSC Advanced Research and Reviews* 22(1), 290-301

[18] Ogwu, M. C., Izah, S. C., Sawyer, W. E., & Amabie, T. (2025). Environmental risk assessment of trace metal pollution: a statistical perspective. *Environmental Geochemistry and Health*, 47(4), 94

[19] Shaffer, R. M., Lee, A. L., Nachman, R., Christensen, K., & Bateson, T. F. (2025). A perspective from US Environmental Protection Agency (EPA) scientists: how your epidemiologic analyses can inform the human health risk assessment process. *Environmental Health Perspectives*, 133(3-4), 045001

[20] Jolaosho, T. L., et al., (2025). Seasonal and spatial variations of physicochemical parameters and heavy metals in surface water of interconnected Nigeria lagoons experiencing distinct anthropogenic disturbances. *Scientific Reports*, 15(1), 38816

[21] Zheng, Y., Zhang, X., Zhou, Y., Zhang, Y., Zhang, T., & Farmani, R. (2025). Deep representation learning enables cross-basin water quality prediction under data-scarce conditions. *NPJ Clean Water*, 8(1), 33

[22] Mohan, S., Kumar, B., & Nejadhashemi, A. P. (2025). Integration of machine learning and remote sensing for water quality monitoring and prediction: A review. *Sustainability*, 17(3), 998

[23] Gacu, J. G., Monjardin, C. E. F., Mangulabnan, R. G. T., Pugat, G. C. E., & Solmerin, J. G. (2025). Artificial intelligence (AI) in surface water management: a comprehensive review of methods, applications, and challenges. *Water*, 17(11), 1707

[24] Ding, F., et al., (2025). Using multiple machine learning algorithms to optimize the water quality index model and their applicability. *Ecological Indicators*, 172, 113299

[25] Lucas, L. V., art., (2025). Gaps in water quality modeling of hydrologic systems. *Water*, 17(8), 1200

[26] Acha, S., et al., (2025). Ecosystem-Based Sustainability Transitions: Applying Environmental Biology and HSSE Frameworks for Green Industrial Growth in the Delta Industrial Corridor, Nigeria. *Journal of Built Environment and Geological Research* 10(4), 237-253

[27] Ibienebo Chris, D., Kallem, P., Wen Goh, K., Lananan, F., Abdul Kari, Z., Azra, M. N., & Kenneth Wokeh, O. (2025). Present Status of Surface Water Quality Impacted by

Artisanal Crude Oil Contamination in a Coastal Community in Rivers State, Nigeria. *Pollution*, 11(3), 738-757

[28] Jonah, U. E. (2025). Evaluating Spatiotemporal Enrichment and Contamination of Heavy Metals in the Surface Water of Qua Iboe River, Niger Delta, Nigeria. *Zanco Journal of Pure and Applied Sciences* 37(3), 103-114

[29] Onyena, A. P. (2025). Ecological risk assessment of the hydrochemistry for benthic macroinvertebrates adjoining Chanomi Creek, Niger Delta, Nigeria. *Ocean & Coastal Management*, 267, 107735

[30] Chinedu, N. B., Orhuebor, E. N., Bankole, A., Isangadighi, G. E., Essien, U. B., Isangadighi, G. E., & Isangadighi, J. G. (2026). Integrated Sediment–Water–Biota Assessment of Petrochemical Contaminants, Partitioning and Ecological Risk in the Bonny Estuary, Niger Delta, Nigeria. *Sriwijaya Journal of Environment*, 11(1), 42-53

[31] Okpoji, A. U., Anarado, C. O., Mmuta, E. C., Ekwere, I. O., Alaekwe, I. O., Odibo, U. E., .. & Obunezi, O. C. (2025). Toxicological evaluation of Pb, Cd, As, and Hg in blue crab from oil-polluted creeks in the Niger Delta. *Journal of Life Science and Public Health*, 1(1), 24-31

[32] Cao, R., et al., (2025). Organic micropollutants in surface water across China: Occurrence and ecological risk. *Water Research*, 281, 123616

[33] Das, A. (2025). Surface water potential zones delineation and spatiotemporal variation characteristics of water pollution and the cause of pollution formation in Brahmani River Basin, Odisha. *HydroResearch*, 8, 99-112

[34] Salma, U., Nishimura, Y., Tokumura, M., Hossain, A., Watanabe, K., Noro, K., .. & Makino, M. (2025). Occurrence, seasonal variation, and environmental risk of multiclass antibiotics in the urban surface water of the Buriganga River, Bangladesh. *Chemosphere*, 370, 143956

[35] Saxena, V. (2025). Water quality, air pollution, and climate change: investigating the environmental impacts of industrialization and urbanization. *Water, Air, & Soil Pollution*, 236(2), 73

[36] Shamsudduha, M., Lee, J., Joseph, G., Bahuguna, A., Wijesundera, S., Nair, S. S., .. & Ayling, S. C. (2025). Assessing the water quality hazard and challenges to achieving the freshwater goal in Sri Lanka. *Scientific Reports*, 15(1), 10187

[37] Shi, X., Gao, Y., Qian, H., Chen, J., Li, W., Li, S., & Liu, Y. (2025). Elucidating the hydrochemistry and REE evolution of surface water and groundwater affected by acid mine drainage. *Environmental Pollution*, 366, 125495

[38] Adu, J. T., & Aneke, F. I. (2025). Evaluation of heavy metal contamination in landfills from e-waste disposal and its potential as a pollution source for surface water bodies. *Results in Engineering*, 25, 104431

[39] Ali, N. M., Khan, M. K., Mazhar, B., & Mustafa, M. (2025). Impact of water pollution on waterborne infections: emphasizing microbial contamination and associated health hazards in humans. *Discover Water*, 5(1), 19

[40] Amini, Z., Hatami-Manesh, M., Aazami, J., & Savabieasfahani, M. (2025). Ecological risk assessment of heavy metals (Pb, Cd, Cr, Ni, Zn, Fe) and metalloid (As) in surface sediment of Anzali international Wetland, Iran. *Geology, Ecology, and Landscapes*, 9(3), 1046-1064

[41] Feraj, M., & Hasan, H. (2025). Assessment of soil contamination by heavy metals in the Al-Fatayeh Region, Derna, Libya. *AlQalam Journal of Medical and Applied Sciences*, 1081-1091

[42] Hou, D., et al., (2025). Global soil pollution by toxic metals threatens agriculture and human health. *Science*, 388(6744), 316-321

[43] Öncü, T., Yazman, M. M., Ustaoğlu, F., Hristova, E., & Yüksel, B. (2025). Source dynamics and environmental risk of street dust as a vector of human exposure to potentially toxic elements in Istanbul, Türkiye. *Scientific Reports*, 15(1), 30550

[44] Zahidi, K., Mouhir, L., Madinzi, A., Khattabi Rifi, S., & Souabi, S. (2025). Impact of industrial emissions on soil contamination: the case of Mohammedia soil, Morocco. *Euro-Mediterranean Journal for Environmental Integration*, 10(4), 2679-2702

[45] Kravchenko, E., Minkina, T., Mandzhieva, S., Bauer, T., Lacynnik, E., Wong, M. H., & Nazarenko, O. (2025). Ecological and health risk assessments of heavy metal contamination in soils surrounding a coal power plant. *Journal of Hazardous Materials*, 484, 136751

[46] Nour, H. E., & Aljahdali, M. H. (2025). Ecological and health risk assessment of Sharm El-sheikh beach sediments, Red Sea coast. *Marine Pollution Bulletin*, 212, 117577

[47] Luo, N., Zhang, X. J., Gong, L. F., Yang, L. Q., Yao, Q., & Song, J. F. (2025). Review of remediation methods for soil contaminated with cadmium. *Eurasian Soil Science*, 58(1), 3

[48] Chețan, F., Moraru, P. I., Rusu, T., Șimon, A., Dinca, L., & Murariu, G. (2025). From contamination to mitigation: Addressing cadmium pollution in agricultural soils. *Agriculture*, 15(20), 2179

[49] Petruzzelli, G., Pezzarossa, B., & Pedron, F. (2025). The fate of chemical contaminants in soil with a view to potential risk to human health: A review. *Environments*, 12(6), 183

[50] Rouhani, A., Hejcman, M., & Trögl, J. (2025). A review of soil pollution by potentially toxic elements and remediation strategies in copper mining areas in Iran. *International Journal of Environmental Science and Technology*, 22(10), 9793-9806

[51] Lane, T., Wardani, I., & Koelmans, A. A. (2025). Exposure scenarios for human health risk assessment of nano-and microplastic particles. *Microplastics and Nanoplastics*, 5(1), 28

[52] He, Z., Wu, Z., Herzog, O., Hei, J., Li, L., & Li, X. (2025). Compound health effects and risk assessment of extreme heat and ozone air pollution under climate change: a case study of 731 urban areas in China. *Sustainable Cities and Society*, 119, 106084

[53] Wu, T., Zhao, L., Ren, M., He, S., Zhang, L., Fang, M., & Wang, B. (2025). Small-sample learning for next-generation human health risk assessment: harnessing AI, exposome data, and systems biology. *Environmental Science & Technology*, *59*(1), 5-10

[54] Isangadighi, G. E., Orhuebor, E. N., Essien, U. B., Matthew, P., Islam, M., Ahanor, E., & Obahor, G. (2024). Machine learning-enhanced multidisciplinary assessment of petroleum hydrocarbon pollution: Biochemical, microbial, toxicological, and environmental perspectives. *Journal of Science Innovation and Technology Research*.

[55] Orhuebor, E. N., Chinedu, N. B., Isangadighi, G. E., Ofoegbu, C. J., Essien, U. B., & Damilola, T. E. (2026). Machine learning-driven predictive modelling of toxic hydrocarbon emissions and public health risks in the Port Harcourt refining corridor: Integrating data governance, ethical AI, and intellectual property protection frameworks. *European Journal of Applied Science, Engineering and Technology*, 4(1), 60-72

[56] Rasul, H. I., Salih, A. M., Raheem, S. M., Sirwan, K., Hameed, K., Yaqub, K. Q., .. & Abdul, N. A. (2025). Economic, environmental and management perspectives on soil pollution and sustainable remediation strategies. *Asian Journal of Soil Science and Plant Nutrition*, 11(2), 123-139

[57] Chaudhry, S. M., Chen, X. H., Ahmed, R., & Nasir, M. A. (2025). Risk modelling of ESG (environmental, social, and governance), healthcare, and financial sectors. *Risk Analysis*, *45*(3), 477-495

[58] Das, A. (2026). Prediction of Urban Surface Water Quality Scenarios Using Water Quality Index (WQI), Multivariate Techniques, and Machine Learning (ML) models in water resources, in Baitarani river basin, odisha: potential benefits and associated challenges. *Earth Systems and Environment*, 10(1), 605-641

[59] Omo-Okoro, P., Ofori, P., Amalapridman, V., Dadrasnia, A., Abbey, L., & Emenike, C. (2025). Soil pollution and its interrelation with interfacial chemistry. *Molecules*, 30(12), 2636

[60] Meng, F., Wang, Y., & Wei, Y. (2025). Advancements in biochar for soil remediation of heavy metals and/or organic pollutants. *Materials*, 18(7), 1524

[61] Isangadighi, G. E., Obahor, G., Ekanem, M. E., Judith, U. O., Paul, C. J., Adedamola, S. B., & Ozohili, L. I. (2024). Machine learning-based prediction of bioaccumulation and ecotoxicity of emerging contaminants in aquatic ecosystems. *Journal of Systematic, Evaluation and Diversity Engineering* 6(5), 191-207

[62] Correia, A. A. S., & Rasteiro, M. G. (2025). A review of persistent soil contaminants: assessment and remediation strategies. *Environments* 12(7), 229

[63] Ozobu, C. O., Adikwu, F. E., Odujobi, O., Onyekwe, F. O., & Nwulu, E. O. (2025). A review of health risk assessment and exposure control models for hazardous waste management operations in Africa. *International Journal of Advanced Multidisciplinary Research and Studies*, 5(2), 570-582

[64] Waichman, A. V., de Souza Nunes, G. S., de Oliveira, R., López-Heras, I., & Rico, A. (2025). Human health risks associated to trace elements and metals in commercial fish from the Brazilian Amazon. *Journal of Environmental Sciences*, 148, 230-242

[65] Wang, M., et al., (2025). Advanced three-dimensional prediction model based on stable machine learning for soil pollution: A case study from a contaminated site in Southern China. *Journal of Hazardous Materials*, 494, 138561