ISA Journal of Multidisciplinary (ISAJM)

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Volume 2, Issue 4, July-August, 2025 ISSN: 3049-1851

Integrated Environmental Risk Assessment of BTEX and PAHs in Water and Sediment Samples from the Bonny River, Nigeria

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Received: 08.08.2025 | **Accepted:** 21.08.2025 | **Published:** 21.08.2025

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DOI: 10.5281/zenodo.16921896

Abstract **Original Research Articles**

This study conducted an integrated environmental risk assessment of benzene, toluene, ethylbenzene, and xylene (BTEX) alongside selected polycyclic aromatic hydrocarbons (PAHs) in water and sediment samples from the Bonny River, Nigeria, a region subject to intensive petroleum exploration and industrial discharge. Samples were collected from five strategically selected sites and analysed using Gas Chromatography–Mass Spectrometry following EPA protocols. Results showed peak BTEX concentrations at Site 4, with benzene reaching 92.0 µg/L in water and 328.7 µg/kg in sediment, while xylene reached 405.2 µg/kg in sediment. PAHs such as naphthalene and benzo[a]pyrene also peaked at Site 4, with concentrations indicative of ongoing hydrocarbon contamination. Physicochemical indicators including temperature, conductivity, and salinity showed spatial increases downstream, supporting anthropogenic impact. Ecological risk assessment revealed Risk Quotient (RQ) values above 1 for BTEX at all sites, with the highest ecological threat observed at Site 4. Human health risk evaluation based on Average Daily Intake (ADI), Hazard Quotient (HQ), and Lifetime Cancer Risk (LCR) identified significant non-carcinogenic and carcinogenic risks, particularly at Sites 3, 4, and 5, where HQ exceeded 1 and LCR for benzene and benzo[a]pyrene surpassed the USEPA acceptable threshold of 1×10^{-4}. The study concludes that hydrocarbon contamination in the Bonny River presents a substantial ecological and public health concern, warranting immediate regulatory and remediation action supported by continuous environmental monitoring.

Keywords: BTEX, PAHs, Ecological Risk, Human Health, Bonny River.

Citation: Okpoji, A. U., Eboh-Ajoku, I. O., Mmuta, E. C., Ndubuisi, J. O., Alaekwe, I. O., Odibo, U. E., Nwoka, N. G., & Okafor, C. A. Obunezi O. C. (2025). Integrated environmental risk assessment of BTEX and PAHs in water and sediment samples from the Bonny River, Nigeria. *ISA Journal of Multidisciplinary (ISAJM)*, *2*(4), July–August. 14-21

1.0 INTRODUCTION

The Niger Delta region of Nigeria is globally recognised for its vast hydrocarbon reserves, but its economic relevance is increasingly overshadowed by pervasive environmental degradation linked to oil and gas exploitation. Activities such as crude oil extraction, illegal refining, pipeline vandalism, gas flaring, and indiscriminate discharge of industrial effluents have significantly impaired the region's air, soil, and water quality, converting many aquatic ecosystems into repositories of persistent organic pollutants [1–3]. Among the most hazardous classes of these pollutants are benzene, toluene, ethylbenzene, and xylene (BTEX), along with polycyclic aromatic hydrocarbons (PAHs), both of which are associated with acute toxicity, endocrine disruption, mutagenicity, and carcinogenic effects [4–6].

The Bonny River, a major estuarine system in Rivers State, Nigeria, flows through an industrial corridor housing petrochemical plant, oil refineries, export terminals, and several artisanal refining operations. The river is ecologically vital and supports fisheries, transportation, and domestic water supply for adjacent communities. Its location within a heavily industrialised area makes it particularly vulnerable to contamination from petroleum-derived compounds, especially BTEX and PAHs that are regularly introduced via stormwater runoff, accidental spills, illegal bunkering, and direct industrial discharge [7,8]. Previous investigations in similar Niger Delta water bodies have reported concerning levels of hydrocarbon contamination, often exceeding international safety limits for aquatic ecosystems [9,10].

BTEX compounds are characterised by their high volatility and water solubility, enabling rapid distribution and bioavailability in aquatic environments. Benzene, in particular, is classified as a Group 1 carcinogen by the International Agency for Research on Cancer and has been linked to bone marrow suppression and haematological cancers such as leukaemia [4]. On the other hand, PAHs such as naphthalene, phenanthrene, anthracene, and benzo[a]pyrene are hydrophobic and persist in sediments, where they bioaccumulate and enter aquatic food chains, posing chronic ecological risks [11,12]. Several studies have shown elevated PAH concentrations in riverine sediments and biota across Nigerian coastal communities, often tracing their sources to petroleum combustion and refinery effluents [13,14].

Given the complex mixture of pollutants affecting aquatic systems in the Niger Delta, Integrated Environmental Risk Assessment (IERA) offers a robust framework for evaluating the cumulative effects of multiple contaminants. IERA combines chemical characterisation, ecological risk estimation, and human health exposure modelling to provide a comprehensive evaluation of environmental risk [5,18]. This approach is particularly essential in regions like the Niger Delta, where overlapping pollution sources and limited enforcement capacity require a prioritisation of remediation actions based on ecological sensitivity and population exposure.

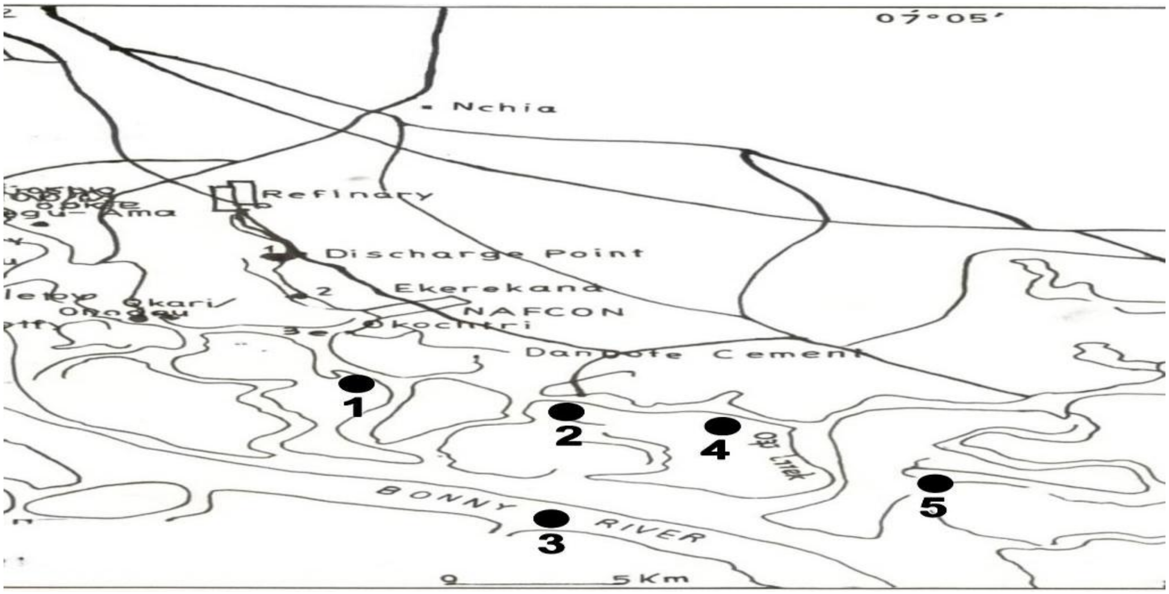
Despite the prevalence of hydrocarbon pollution in the Niger Delta, there is a limited number of studies employing a fully integrated risk assessment model to simultaneously evaluate BTEX and PAHs in both water and sediment matrices within the Bonny River. Moreover, spatial analyses of contaminant distribution patterns and source differentiation using advanced geochemical and statistical methods remain scarce. Bridging these gaps is critical for strengthening environmental governance, guiding risk mitigation strategies, and protecting the ecological integrity and public health of vulnerable riverine communities.

2.0 MATERIALS AND METHODS

2.1 Study Area

The study was carried out along the Bonny River, a prominent estuarine water body located in the Niger Delta region of Nigeria. This river system flows through one of the most industrialised zones of southern Nigeria, encompassing Port Harcourt and Bonny Island. It is heavily influenced by petroleum-related activities, including oil exploration, refining, shipping, and domestic effluent discharge. The area is ecologically characterised by extensive mangrove vegetation and significant tidal influence, which govern the hydrodynamics and contaminant transport within the estuary. Five sampling points were purposively selected along the river based on proximity to known pollution hotspots such as crude oil terminals, artisanal refining locations, and industrial effluent outfalls. These points, which lie between latitude 4.4016° N to 4.4792° N and longitude 7.1572° E to 7.2289° E, were georeferenced using a handheld Global Positioning System (GPS) device to facilitate spatial data integration.

Figure 1: Map of Bonny River showing the sampling sites



2.2 Sample Collection and Determination

Fieldwork was conducted during the dry season from January to February 2025, a period chosen due to minimal surface runoff and relatively stable pollutant concentrations, which aid in capturing persistent contamination trends. At each site, surface water samples were collected approximately 20 to 30 centimetres below the surface using one-litre pre-cleaned amber glass bottles sealed with Teflon-lined caps to minimise volatilisation and photolytic degradation. Sediment samples were collected using a Van Veen grab sampler, targeting the upper 5 centimetres of sediment for analysis. The sediment was immediately wrapped in clean aluminium foil, sealed in acid-washed containers, and placed in ice-filled coolers prior to laboratory transport within 24 hours to preserve the integrity of labile organic contaminants.

In situ measurements of water quality parameters, including temperature, pH, dissolved oxygen (DO), electrical conductivity, and salinity, were performed at each site using a portable multi-parameter probe (HACH HQ40d). These parameters were recorded to evaluate the prevailing physicochemical conditions influencing contaminant behaviour and bioavailability in the aquatic system.

Sample preparation for chemical analysis followed standardised protocols. Water samples underwent liquid–liquid extraction based on USEPA Method 3510C, using dichloromethane (DCM) as the organic solvent. Each 500 mL water sample was extracted in triplicate, with pooled extracts dried over anhydrous sodium sulfate and subsequently concentrated using a rotary evaporator under controlled temperature and pressure. Sediment samples were air-dried at ambient temperature, ground and sieved through a 2 mm mesh, and subjected to Soxhlet extraction for 16 hours using a DCM:acetone (1:1 v/v) solvent system. Post-extraction clean-up was performed via column chromatography packed with activated silica gel and anhydrous sodium sulfate to eliminate interfering compounds.

Quantitative determination of target analytes, including BTEX compounds (benzene, toluene, ethylbenzene, and xylene isomers) and selected PAHs (naphthalene, anthracene, phenanthrene, pyrene, and benzo[a]pyrene), was conducted using Gas Chromatography–Mass Spectrometry (GC-MS) operated in selected ion monitoring mode. An Agilent 7890A gas chromatograph coupled to a 5975C mass selective detector was employed for all analyses. Calibration was conducted using five-point standard curves generated from certified reference materials (Sigma-Aldrich, ≥99% purity), and method performance was verified through analysis of procedural blanks, matrix spikes, and replicate samples. Internal standards were added to all samples prior to extraction to ensure accuracy and compensate for matrix effects. Recoveries ranged from 83% to 114%, while relative standard deviations were consistently below 15%, confirming acceptable analytical precision.

2.3 Ecological and Human Health Risk Assessment

The evaluation of ecological and human health risks associated with BTEX and PAHs in water and sediment from the Bonny River was conducted using established quantitative models. For ecological risk assessment, the Risk Quotient (RQ) method was employed to estimate the potential adverse effects of each contaminant on aquatic life. The RQ was computed as the ratio of the Measured Environmental Concentration (MEC) to the Predicted No-Effect Concentration (PNEC), such that:

$$\mathrm{RQ}=\frac{MEC}{PNEC}\ \underline{\hspace{5cm}}1$$

The PNEC values were derived from sediment quality guidelines, specifically the Threshold Effect Concentration (TEC) and Probable Effect Concentration (PEC), which are widely used in ecotoxicological assessments. An RQ value less than 0.1 was interpreted as indicating insignificant risk, values between 0.1 and 1 denoted low risk, those between 1 and 10 indicated moderate ecological risk, while values equal to or greater than 10 signified high ecological risk. This classification enabled a clear prioritisation of sites and contaminants requiring regulatory attention.

Human health risk assessment was conducted for both non-carcinogenic and carcinogenic effects based on chronic exposure to BTEX and PAHs through oral ingestion and dermal contact. The Average Daily Intake (ADI) for each exposure route was calculated using standard USEPA risk equations. For ingestion exposure, the ADI was estimated using the following expression:

$$\mathrm{ADIing}=\frac{C\times \mathrm{IR}\times \mathrm{EF}\times \mathrm{ED}}{BW\times \mathrm{AT}}\ \underline{\hspace{5cm}}2$$

where C represents the contaminant concentration (mg/L or mg/kg), IRIRIR is the ingestion rate (L/day for water or mg/day for sediment), EF is the exposure frequency (days/year), ED is the exposure duration (years), BW is the average body weight (kg), and AT is the averaging time (days), calculated as ED×365ED for non-carcinogenic effects and 70 years × 365 days for carcinogenic risk.

For dermal exposure, the ADI was estimated using:

$$\mathrm{ADIderm}=\frac{C\times \mathrm{SA}\times \mathrm{AF}\times \mathrm{ABS}\times\ \mathrm{EF}\times\ \mathrm{ED}}{BW\times \mathrm{AT}}\ \underline{\hspace{5cm}}3$$

where SA is the exposed skin surface area (cm²), AF is the adherence factor (mg/cm²/day), ABS is the dermal absorption fraction (unitless), and the remaining parameters are as previously defined. The non-carcinogenic risk was characterised using the Hazard Quotient (HQ), obtained by dividing the ADI by the contaminant's reference dose (RfD):

$$\mathrm{HQ}=\frac{ADI}{RfD}\ \underline{\hspace{5cm}}4$$

To assess the cumulative non-carcinogenic risk from multiple pollutants or exposure pathways, the individual HQs were summed to compute the Hazard Index (HI):

$$\mathrm{HI}=\quad \sum \mathrm{HQi}\underline{\hspace{4cm}}5$$

An HQ or HI value less than 1 suggests no significant risk, whereas values equal to or exceeding 1 indicate the potential for adverse health effects, particularly in sensitive populations such as children. For carcinogenic compounds such as benzo[a]pyrene and benzene, the Lifetime Cancer Risk (LCR) was calculated using the equation:

LCR=ADI×CSF _______________ 6

where CSF is the cancer slope factor (mg/kg/day) $^{-1}$, specific to each carcinogenic compound. According to USEPA guidelines, an LCR value below 1×10^{-6} is considered negligible, a range between 1×10^{-6} to 1×10^{-4} represents a tolerable risk zone, while values above 1×10^{-4} are deemed unacceptable and warrant regulatory or remediation action. All exposure parameters were selected based on USEPA default assumptions for both adults and children, and site-specific data were used where applicable.

2.4 Data Analysis

Statistical analysis of the dataset was carried out using IBM SPSS Statistics version 25 to examine spatial trends and interrelationships between physicochemical parameters and contaminant levels. Pearson correlation matrices were generated to identify significant associations among variables. Principal Component Analysis (PCA) was applied to extract latent factors driving contamination patterns and to infer potential pollutant sources. Additionally, spatial interpolation and mapping of BTEX and PAH concentrations across the study area were performed using ArcGIS 10.7 software, employing the Inverse Distance Weighting (IDW) algorithm to visualise spatial contaminant gradients.

3.0 RESULTS

The temperature of water samples across the five sites ranged from 26.4°C at Site 1 to 29.2°C at Site 5, showing a slight spatial increase along the river. The pH values were mildly acidic to neutral (6.4 to 7.2), with Site 5 exhibiting the most neutral condition. Dissolved oxygen (DO) levels declined downstream from 6.1 mg/L at Site 1 to a minimum of 4.2 mg/L at Site 3, indicating potential organic pollution or oxygen-demanding substances. Electrical conductivity (EC) progressively increased from 1,250 µS/cm at Site 1 to 2,310 µS/cm at Site 5, suggesting elevated ion concentration and possible saline intrusion. Similarly, salinity increased from 4.1 ppt at Site 1 to 7.3 ppt at Site 5, indicating brackish water influence, especially at downstream sites as shown in Table 1.

Table 1: Physicochemical Parameters of Water Samples

Sampling Site	Temp (°C)	pH	DO (mg/L)	EC (µS/cm)	Salinity (ppt)
Site 1	26.4	6.4	6.1	1,250	4.1
Site 2	27.0	6.6	5.7	1,580	5.3
Site 3	28.3	6.8	4.2	2,050	6.1
Site 4	29.0	7.1	4.5	2,220	6.8
Site 5	29.2	7.2	4.7	2,310	7.3

BTEX (Benzene, Toluene, Ethylbenzene, and Xylene) concentrations showed a consistent spatial increase from Site 1 to Site 4, peaking at Site 4 before slightly declining at Site 5. Benzene increased from 15.0 µg/L to a maximum of 92.0 µg/L at Site 4. Toluene followed a similar trend, rising from 30.1 µg/L at Site 1 to 105.1 µg/L at Site 4. Ethylbenzene and Xylene concentrations also peaked at Site 4, reaching 67.2 µg/L and 110.4 µg/L respectively. These levels suggest an anthropogenic source of hydrocarbon contamination, potentially from industrial or oil-related discharges into the river system as shown in Table 2.

Table 2: BTEX Concentrations in Water Samples (µg/L)

Compound	Site 1	Site 2	Site 3	Site 4	Site 5
Benzene	15.0	23.4	48.5	92.0	61.2
Toluene	30.1	36.7	70.3	105.1	85.4
Ethylbenzene	18.2	24.1	44.0	67.2	52.3
Xylene	25.4	29.5	57.1	110.4	86.0

BTEX compounds in sediment samples exhibited a progressive accumulation along the river, with the highest concentrations observed at Site 4. Benzene increased from 115.2 µg/kg at Site 1 to 328.7 µg/kg at Site 4, while Toluene and Xylene reached 387.4 µg/kg and 405.2 µg/kg respectively at the same site. Ethylbenzene followed a similar trend, peaking at 297.0 µg/kg. Although a slight reduction was recorded at Site 5, the concentrations remained significantly high, reflecting persistent hydrocarbon contamination and sediment retention of pollutants as shown in Table 3.

Table 3: BTEX Concentrations in Sediment Samples (µg/kg)

Compound	Site 1	Site 2	Site 3	Site 4	Site 5
Benzene	115.2	172.4	240.3	328.7	281.0
Toluene	140.5	193.2	256.1	387.4	342.6
Ethylbenzene	102.3	148.9	215.4	297.0	263.8
Xylene	117.4	164.7	235.0	405.2	351.9

Polycyclic aromatic hydrocarbons (PAHs) in water samples revealed substantial variation across sites. Naphthalene was the most abundant compound, rising from 34.1 µg/L at Site 1 to 81.3 µg/L at Site 4, followed closely by 78.0 µg/L at Site 5. Anthracene, Phenanthrene, and Benzo[a]pyrene concentrations also increased along the gradient, with Benzo[a]pyrene peaking at 12.0 µg/L at Site 4. These findings point to significant PAH pollution potentially linked to petroleum-related activities and runoff into the aquatic environment as shown in Table 4.

Table 4: PAHs Concentrations in Water Samples (µg/L)

Compound	Site 1	Site 2	Site 3	Site 4	Site 5
Naphthalene	34.1	40.3	65.2	81.3	78.0
Anthracene	8.0	12.4	18.7	23.0	21.5
Phenanthrene	10.3	15.6	25.4	30.1	27.6
Benzo[a]pyrene	3.2	4.6	8.3	12.0	11.4

PAH levels in sediment samples demonstrated high retention, with all compounds reaching maximum concentrations at Site 4. Naphthalene was predominant, increasing from 204.4 µg/kg at Site 1 to 417.3 µg/kg at Site 4. Anthracene rose from 82.0 µg/kg to 195.1 µg/kg, while Phenanthrene and Benzo[a]pyrene peaked at 211.0 µg/kg and 128.0 µg/kg respectively at Site 4. Despite minor reductions at Site 5, the levels remained elevated, indicating that sediments serve as reservoirs for persistent organic pollutants in the Bonny River ecosystem as shown in Table 5.

Table 5: PAHs Concentrations in Sediment Samples (µg/kg)

Compound	Site 1	Site 2	Site 3	Site 4	Site 5
Naphthalene	204.4	276.0	360.2	417.3	392.0
Anthracene	82.0	106.4	164.8	195.1	181.7
Phenanthrene	96.2	132.5	184.3	211.0	198.5
Benzo[a]pyrene	51.0	68.2	96.5	128.0	120.3

The ecological risk assessment of BTEX compounds (benzene, toluene, ethylbenzene, and xylene) in both water and sediment matrices revealed notable spatial variability and elevated contamination levels across all five sampling sites along the Bonny River. In the water column, benzene and xylene exhibited RQ values consistently above 1 across all sites, indicating moderate to high ecological risk. The highest RQ values were recorded at Site 4**,** where benzene reached an RQ of 9.20 and xylene reached 4.42**,** suggesting a strong influence of localised hydrocarbon input, likely from industrial or refining activity. Toluene and ethylbenzene also showed increasing RQ values downstream, with Site 4 again presenting the greatest ecological concern. These results highlight a progressive increase in hydrocarbon pollution from upstream to downstream, particularly at sites adjacent to known pollution hotspots as shown in Table 6

Table 6: Ecological Risk Quotients (RQ) – Water Samples

Sampling Site	RQ Benzene	RQ Toluene	RQ Ethylbenzene	RQ Xylene
Site 1	1.50	0.75	0.61	1.02
Site 2	2.34	0.92	0.80	1.18
Site 3	4.85	1.76	1.47	2.28
Site 4	9.20	2.63	2.24	4.42
Site 5	6.12	2.13	1.74	3.44

In sediment samples, all RQ values for the BTEX compounds exceeded the threshold of 1, suggesting persistent and significant ecological risks to benthic organisms. Site 4 again showed the highest RQ values across all four compounds, with xylene and benzene reaching 4.50 and 6.57 respectively. The elevated RQs in sediment reflect the accumulative and persistent nature of BTEX compounds in the benthic environment, which can serve as long-term sources of exposure to aquatic biota as shown in Table 7

Table 7: Ecological Risk Quotients (RQ) – Sediment Samples

Sampling Site	RQ Benzene	RQ Toluene	RQ Ethylbenzene	RQ Xylene
Site 1	2.30	1.41	1.28	1.30
Site 2	3.45	1.93	1.86	1.83
Site 3	4.81	2.56	2.69	2.61
Site 4	6.57	3.87	3.71	4.50
Site 5	5.62	3.43	3.30	3.91

The human health risk assessment revealed significant variation in benzene and benzo[a]pyrene exposure across the five sampling sites. For benzene, the Average Daily Intake (ADI) ranged from 0.00219 mg/kg/day at Site 1 to 0.01341 mg/kg/day at Site 4. The corresponding Hazard Quotient (HQ**)** values also increased along the gradient, with **Sites** 3, 4, and 5 exceeding the safety threshold of 1**,** indicating a potential non-carcinogenic health risk for adults consuming water from these sites. The highest HQ of 3.35 at Site 4 suggests a strong likelihood of adverse health effects from chronic benzene exposure. In terms of carcinogenic risk, the Lifetime Cancer Risk (LCR) for benzene ranged from 6.4×10^{-5} at Site 1 to 3.9×10^{-4} at Site 4. These values fall within or exceed the USEPA's tolerable risk range (1×10^{-6} to 1×10^{-4}), with Sites 3, 4, and 5 surpassing acceptable levels, thereby indicating a potentially unacceptable cancer risk from prolonged benzene ingestion. For benzo[a]pyrene**,** the ADI values ranged from 0.00047 to 0.00178 mg/kg/day, with corresponding LCRs ranging from 0.00343 to 0.01299**.** These LCR values are substantially higher than the USEPA threshold of 1×10^{-4}**,** indicating a high lifetime cancer risk at all sites, particularly at Site 4 where the LCR reached 0.01299**—**well above regulatory limits as shown Table 8.

Table 8: Human Health Risk Assessment (Oral Ingestion – Adults)

Sampling Site	ADI Benzene (mg/kg/day)	HQ Benzene	LCR Benzene	ADI BaP (mg/kg/day)	LCR BaP
Site 1	0.00219	0.55	0.00006	0.00047	0.00343
Site 2	0.00341	0.85	0.00010	0.00068	0.00498
Site 3	0.00707	1.77	0.00021	0.00123	0.00898
Site 4	0.01341	3.35	0.00039	0.00178	0.01299
Site 5	0.00891	2.23	0.00026	0.00169	0.01234

4.0 DISCUSSION

The environmental status of the Bonny River reflects a clear footprint of anthropogenic hydrocarbon pollution. This was evidenced by high concentrations of BTEX and PAHs across all sampling matrices, with particularly severe contamination at Site 4. These pollutants are widely recognised as major contributors to aquatic ecosystem degradation and human health impairment in petroleum-producing regions [4,1].

Physicochemical properties such as temperature (26.4–29.2°C), pH (6.4–7.2), and DO (4.2–6.1 mg/L) showed typical tropical estuarine characteristics, but the decreasing DO values downstream—especially at Site 3 (4.2 mg/L)—suggest increasing organic pollution. EC rose from 1,250 to 2,310 µS/cm and salinity from 4.1 to 7.3 ppt, indicating the growing influence of saline intrusion and industrial discharges [15,8]. These changes support the mobilisation and persistence of hydrophobic pollutants like BTEX and PAHs in the aquatic environment.

BTEX levels in water samples peaked at Site 4 with benzene (92.0 µg/L), toluene (105.1 µg/L), ethylbenzene (67.2 µg/L), and xylene (110.4 µg/L). At Site 1, concentrations were considerably lower, with benzene at 15.0 µg/L and xylene at 25.4 µg/L. Sediment values also followed this spatial trend, with Site 4 recording the highest levels: benzene (328.7 µg/kg), toluene (387.4 µg/kg), ethylbenzene (297.0 µg/kg), and xylene (405.2 µg/kg). The sediment data highlight the persistence and bioaccumulative potential of these compounds, which are known to bind to organic matter and fine particles [3,17]. Similar spatial accumulation has been reported in auto workshop soils and urban rivers [13,12].

PAH concentrations in water were highest at Site 4: naphthalene (81.3 µg/L), anthracene (23.0 µg/L), phenanthrene (30.1 µg/L), and benzo[a]pyrene (12.0 µg/L). In sediments, values were even more elevated—naphthalene reached 417.3 µg/kg, benzo[a]pyrene 128.0 µg/kg, phenanthrene 211.0 µg/kg, and anthracene 195.1 µg/kg. These exceed international safety limits for aquatic ecosystems and suggest chronic pollution exposure [6,4]. High concentrations of naphthalene and benzo[a]pyrene reflect the presence of petrogenic sources and possible pyrogenic input from fuel combustion, similar to findings from Eket and Nsukka [7, 13].

Ecological risk quotients (RQ) for BTEX in water samples exceeded 1 for benzene and xylene across all sites, peaking at

Site 4: RQ benzene = 9.20, RQ xylene = 4.42. Sediment RQs were universally above 1 for all BTEX compounds, with Site 4 again showing the highest values: RQ benzene = 6.57, RQ toluene = 3.87, RQ ethylbenzene = 3.71, RQ xylene = 4.50. These values signify moderate to high ecological risk to aquatic organisms and benthic invertebrates, consistent with findings in polluted creeks of the Niger Delta [1,10].

The oral ingestion health risk assessment for adults indicated significant concern. At Site 4, benzene's average daily intake (ADI) was 0.01341 mg/kg/day, with a hazard quotient (HQ) of 3.35—over three times the safety limit (HQ > 1). Lifetime cancer risk (LCR) for benzene was 0.00039, while benzo[a]pyrene LCR was 0.01299—both well above the USEPA's acceptable threshold of 1×10^{-4}. These levels suggest serious carcinogenic potential, particularly for populations reliant on untreated river water [7,2]. Even Site 5 had benzene LCR = 0.00026 and BaP LCR = 0.01234, confirming the widespread risk. Chronic exposure to such concentrations can result in hematologic cancers and long-term physiological dysfunction [19,4,16].

The consistent spatial patterns across physicochemical, BTEX, PAH, ecological, and health risk data clearly identify Site 4 as the most contaminated location, likely due to its proximity to active discharge points or industrial hubs. The hydrocarbon pollution at this site aligns with reports of PAH hotspots in oil-impacted estuaries and creek systems throughout the Niger Delta [18,19]. Long-term sediment retention of PAHs and BTEX suggests that remediation efforts must address both water and benthic compartments.

CONCLUSION

The study revealed significant spatial variations in physicochemical properties and contaminant levels across sampling sites in Bonny River. Elevated concentrations of BTEX and PAHs in both water and sediment samples, particularly at downstream sites, indicate ongoing pollution likely linked to industrial and oil-related activities. These findings underscore the need for continuous environmental monitoring and stricter regulatory enforcement to mitigate ecological and public health risks in the region.

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