



Assessment of the Health and Ecological Risk of Flame Retardants in Sediment and E-waste along the Warri River/Creeks in Delta State, Nigeria

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Abstract: Polybrominated diphenyl ethers (PBDEs) are persistent organic pollutants widely used as flame retardants in electronic materials, with increasing environmental relevance due to their release from informal electronic waste (e-waste) recycling activities. This study assessed the occurrence, spatial distribution, and ecological risk of selected PBDE congeners in electronic waste materials and surface sediments along the Warri River and its associated creeks in Delta State, Nigeria. Electronic waste samples and surface sediments (0-5 cm) were collected from ten locations representing gradients of anthropogenic activity, and analyzed using gas chromatography-mass spectrometry following Soxhlet extraction and silica gel clean-up. Total PBDE concentrations (Σ PBDE) in e-waste ranged from 0.017 to 11.250 mg/kg, with the highest levels recorded at Efieki Edumurhe, indicating a major emission hotspot associated with informal dismantling activities. Sediment concentrations ranged from 0.009 to 2.635 mg/kg, with Udu Bridge identified as the principal depositional sink, reflecting hydrodynamic redistribution of particulate-bound contaminants. Congener profiles showed dominance of mid-brominated PBDEs in e-waste and higher brominated congeners in sediments, suggesting combined effects of legacy inputs, selective partitioning, and environmental transformation processes. Comparative analysis revealed clear source-sink decoupling, with downstream accumulation occurring independently of local emission intensity. Ecological risk assessment using the risk quotient approach indicated high to very high risk levels at several locations, particularly Udu Bridge and Ekpan Bridge, highlighting potential adverse effects on benthic organisms and aquatic ecosystem function. The findings demonstrate that informal e-waste handling significantly contributes to PBDE contamination and that sediment systems act as long-term sinks and secondary sources, with implications for ecological stability and potential human exposure through aquatic food webs.

Keywords: Polybrominated diphenyl ethers (PBDEs), Electronic waste (e-waste), Sediment contamination, Ecological risk assessment, Niger Delta.

INTRODUCTION

Polybrominated diphenyl ethers (PBDEs) are additive brominated flame retardants extensively used in polymers, textiles, polyurethane foams, and electronic components to reduce flammability. Commercial mixtures, including Penta-, Octa-, and Deca-BDE, were widely applied for several decades before restrictions under the Stockholm Convention due to their persistence, bioaccumulation, and toxicity (UNEP, 2023). Despite regulatory controls, PBDEs remain ubiquitous, primarily due to continuous release from legacy materials and inadequately managed waste streams.

Their environmental behavior is governed by strong hydrophobicity, with octanol-water partition coefficients ($\log K_{ow} > 6$) that favor sorption to organic matter and partitioning into particulate phases. Consequently, aquatic sediments function as long-term sinks, integrating both historical and ongoing inputs (Zhao et al., 2022). Reported sediment concentrations range from <0.01 mg/kg in background environments to >10 mg/kg in areas impacted by electronic waste and urban discharge (Zhang et al., 2023; Tue et al., 2022).

Electronic waste (e-waste) represents a major contemporary source of PBDEs. Global generation reached approximately 62 million tonnes in 2022, with only 22.3% formally recycled, leaving substantial volumes subject to informal handling (Forti et al., 2024). Practices such as manual dismantling, open burning, and uncontrolled storage promote the release of PBDE-associated particulates into surrounding environmental media. Evidence from established recycling hubs, including Guiyu and Agbogbloshie, shows sediment concentrations in the range of 1-15 mg/kg, often with distinct congener signatures linked to localized activities (Akortia et al., 2020; Tue et al., 2022; Zhang et al., 2023).

Following release, PBDEs undergo redistribution through hydrodynamic transport, particle association, and transformation processes. Higher brominated congeners such as BDE-209 preferentially accumulate in sediments, while lower brominated congeners may form through debromination, increasing mobility and bioavailability (Stapleton et al., 2020; Zhao et al., 2022). These transformation pathways are significant given the higher biological activity and bioaccumulation potential of lower brominated species.

Exposure to PBDEs has been associated with endocrine disruption, thyroid hormone dysregulation, neurodevelopmental impairment, oxidative stress, and reproductive toxicity (Costa et al., 2021; EFSA, 2024). Sediments serve as a key exposure interface for benthic organisms, facilitating bioaccumulation and trophic transfer, with implications for human populations dependent on aquatic food resources.

In the Niger Delta, rapid urbanization, increasing electronic consumption, and limited waste management infrastructure have heightened the risk of PBDE contamination. Studies in southern Nigeria confirm their presence in sediments, soils, and aquatic systems, although detailed information on congener distribution, spatial variability, and ecological risk remains limited (Olukunle et al., 2020; Iwegbue et al., 2024). The Warri River system, which traverses densely populated and industrialized areas of Delta State, is particularly vulnerable due to combined inputs from informal e-waste handling, urban runoff, and riverine transport processes.

This study addresses these gaps by assessing the occurrence, spatial distribution, and ecological risk of selected PBDE congeners in electronic waste and surface sediments along the Warri River and its associated creeks. Representative samples were collected across the river corridor and analyzed using validated techniques to quantify congener-specific concentrations in both matrices. Spatial variability was evaluated to identify contamination hotspots linked to e-waste activities, while congener profiles were used to infer emission sources and transformation processes. Measured sediment concentrations were compared with established environmental benchmarks, and ecological risk was characterized using risk quotient approaches to provide a comprehensive assessment of PBDE contamination within this Niger Delta system.

MATERIALS AND METHODS

Study Area

The study was conducted along the Warri River and its interconnected creek systems in Delta State, southern Nigeria, within the western Niger Delta. The river system is influenced by urban discharge, transportation activities, informal electronic waste handling, and tidal hydrodynamics.

The region experiences a humid tropical climate with mean annual rainfall exceeding 2,000 mm and average temperatures ranging from 26 to 32°C. Seasonal flooding and tidal exchange enhance suspended particulate transport and promote deposition of hydrophobic contaminants such as PBDEs in low-energy sedimentary environments.

Sampling Locations

Sampling locations were selected to capture gradients in anthropogenic activity, including e-waste handling zones, urban runoff interfaces, and downstream depositional environments. Geographical coordinates were recorded for all sampling locations.

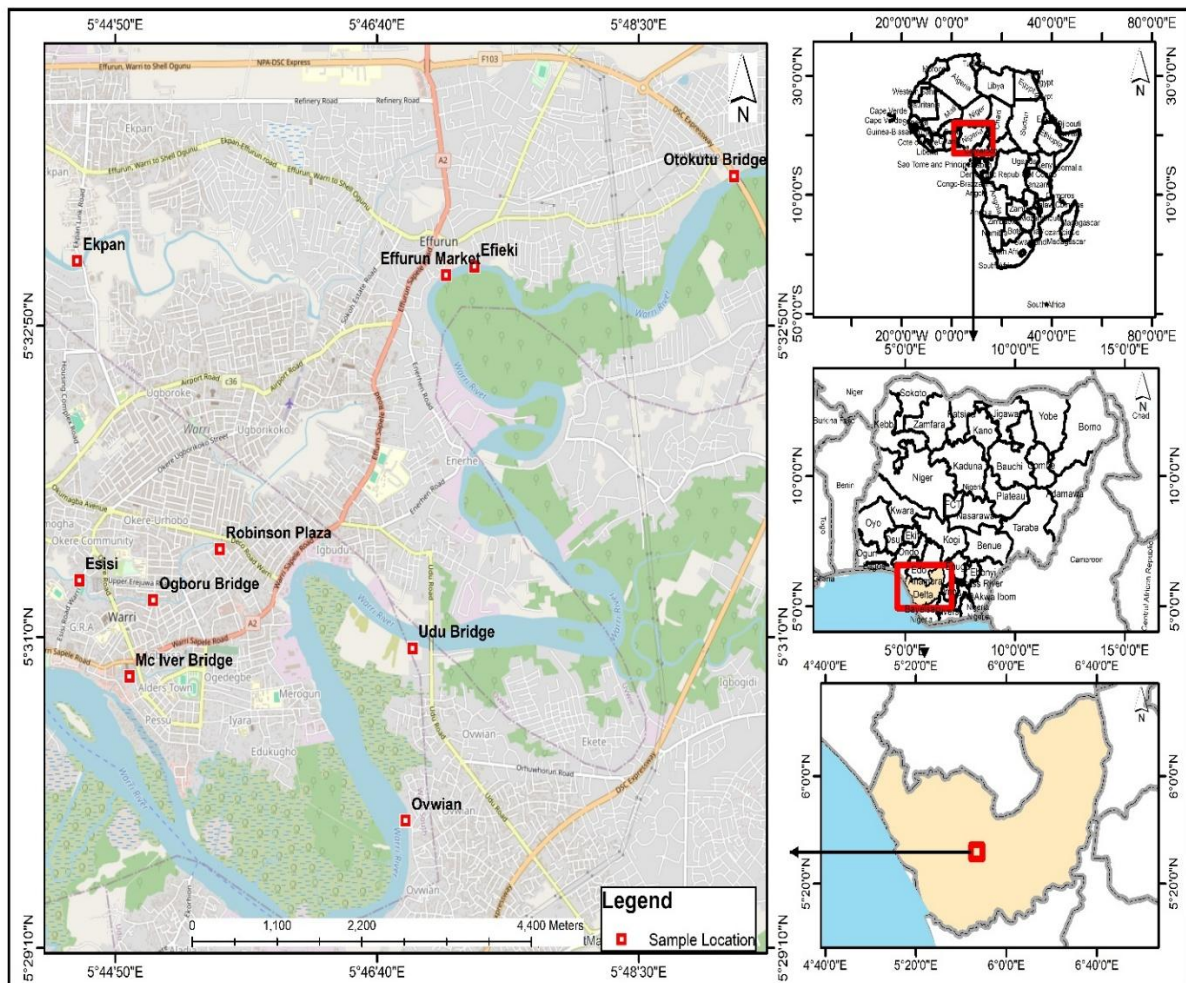


Figure 1: Map of the study area in Delta state, Nigeria.

Table 3.1: Sampling Locations and Environmental Characteristics

Site	Location Name	Area	Environmental Setting
A	Effurun Market	Effurun	Active scrap/e-waste handling zone
B	Efieki Edumurhe	Effurun	High-intensity informal dismantling
C	Ekpan Bridge	Ekpan	Mixed residential-industrial corridor
D	Esis Bridge	Warri	Peri-urban transition zone
E	Mclver Bridge	Warri	Urban runoff convergence zone
F	Ogburu Bridge	Warri	Moderately impacted riverbank
G	Otokutu Bridge	Otokutu	Semi-urban environment
H	Ovwian	Udu	Riverine residential community
I	Robinson Plaza	Warri	Urban commercial area
J	Udu Bridge	Udu	Downstream depositional zone

Study Design

A cross-sectional environmental monitoring design was adopted to assess PBDE occurrence and spatial distribution. At each location, composite sediment samples were obtained by combining three sub-samples collected within a 5-10 m radius. This approach reduces micro-scale heterogeneity and improves representativeness in heterogeneous sediment matrices (USEPA, 2021). Due to analytical and logistical constraints, one composite sample per site was analyzed for each matrix. The study is therefore interpreted as a screening-level spatial assessment, and findings are discussed in terms of spatial trends rather than statistical inference.

Sample Collection and Handling

Surface sediment samples (0-5 cm) were collected using a stainless steel grab sampler to represent recently deposited material. Electronic waste samples, including plastic casings, cable insulation, and printed circuit board laminates, were collected from dismantling zones at each site. Metallic fractions were removed prior to analysis. Samples were placed in pre-cleaned amber glass containers, transported on ice, and stored at approximately 4 °C prior to processing.

Target Analytes

Eight PBDE congeners representing major commercial formulations were analyzed.

Table 3.2: Target PBDE Congeners

Congener	Chemical Name
BDE-28	2,4,4'-Tribromodiphenyl ether
BDE-47	2,2',4,4'-Tetrabromodiphenyl ether
BDE-99	2,2',4,4',5-Pentabromodiphenyl ether
BDE-100	2,2',4,4',6-Pentabromodiphenyl ether
BDE-153	2,2',4,4',5,5'-Hexabromodiphenyl ether
BDE-154	2,2',4,4',5,6-Hexabromodiphenyl ether
BDE-183	2,2',3,4,4',5,6-Heptabromodiphenyl ether
BDE-209	2,2',3,4,4',5,5',6,6'-Decabromodiphenyl ether

Sample Preparation and Extraction

Sediment samples were air-dried, homogenized, and sieved (<2 mm). E-waste samples were mechanically reduced to <1 mm particle size.

Extraction followed laboratory protocol:

- Sediment: 10 g (0.010 kg)
- E-waste: 5 g (0.005 kg)

Samples were mixed with anhydrous sodium sulfate and extracted using Soxhlet extraction with n-hexane:acetone (1:1 v/v) for 16 hours.

Extracts were concentrated using rotary evaporation and adjusted to a final volume of 2 mL, consistent with laboratory quantification conditions.

Extract Clean-Up

Extract purification was performed using a silica gel column.

Column configuration:

- Top: anhydrous sodium sulfate
- Middle: activated silica gel (pre-conditioned at 120°C for 12 h)

Elution was carried out using::

- n-hexane (non-polar fraction)
- n-hexane:dichloromethane (1:1) for PBDE recovery
- Eluates were concentrated to 2 mL prior to GC-MS analysis.

Instrumental Analysis (GC-MS)

PBDEs were quantified using GC-MS under the following conditions:

1. Column: DB-5MS (30 m × 0.25 mm × 0.25 µm)
2. Carrier gas: Helium (1.0 mL/min)
3. Injection: 1 µL, splitless mode
4. Ionization: Electron ionization (70 eV)

Temperature program:

1. 80°C (2 min)
2. 80-200°C at 20°C/min
3. 200-300°C at 5°C/min (10 min hold)
4. Final: 320°C (10 min hold)

Detection was conducted in selected ion monitoring (SIM) mode.

Calibration and Quantification

External calibration was performed using certified PBDE standards across a multi-point calibration range. Calibration linearity was accepted at $R^2 \geq 0.99$.

Total PBDE concentration (Σ PBDE) was calculated as the sum of detected congeners. Internal standards were used to correct for extraction and instrumental variability.

Quality Assurance and Quality Control

Quality control included:

1. procedural blanks
2. duplicate samples
3. calibration verification

Recovery efficiencies ranged between 70-120% and duplicate precision was maintained within $\pm 15\%$.

Method detection limit (MDL): 0.001 mg/kg

Results were accepted when:

- blanks < MDL
- calibration criteria satisfied
- chromatographic separation was adequate

Data Treatment and Ecological Risk Assessment

Concentrations were expressed in mg/kg dry weight. Ecological risk was evaluated using:

$$RQ = \frac{C_{\text{measured}}}{PNEC}$$

Where:

- C_{measured} = highest congener per site
- PNEC = 0.005 mg/kg (sediment screening value based on recent PBDE risk assessment frameworks, e.g., ECHA, 2022; EFSA, 2024)

Risk categories:

- <1: Low
- 1-10: Moderate
- 10-100: High
- ≥ 100 : Very high

RESULTS AND DISCUSSION

Primary Source Matrix: Electronic Waste (E-waste)

Measured concentrations of PBDE congeners in electronic waste samples collected along the Warri River corridor in Delta State are presented in Table 4.1. Total PBDE concentrations (Σ PBDE) varied substantially across sampling locations, reflecting pronounced spatial differences in emission intensity within this industrially active section of the Niger Delta.

Table 4.1: PBDE Concentrations in Electronic Waste (mg/kg)

Site	Location	Σ PBDE (mg/kg)	Dominant Congener	Source Rank
A	Effurun Market	0.102	HexaBDE	5
B	Efiki Edumurhe	11.250	HexaBDE	1
C	Ekpan Bridge	4.915	HeptaBDE	2
D	Esisi Bridge	0.031	TetraBDE	9
E	Mclver Bridge	0.105	HexaBDE	4
F	Ogburu Bridge	0.017	TetraBDE	10
G	Otokutu Bridge	0.191	TetraBDE	3
H	Ovwian	0.083	HexaBDE	6
I	Robinson Plaza	0.074	HexaBDE	7
J	Udu Bridge	0.056	HexaBDE	8

The distribution pattern identifies Efiki Edumurhe (Site B) as the dominant emission hotspot (11.250 mg/kg), followed by Ekpan Bridge (Site C) (4.915 mg/kg). Other sites show relatively low concentrations (<0.2 mg/kg), indicating that contamination is localized around specific activity hubs rather than evenly distributed across the river corridor.

In the context of the Niger Delta, where informal recycling, urban expansion, and industrial activities coexist, such spatial clustering is expected. The magnitude observed at Site B aligns with values reported for informal e-waste recycling zones in West Africa and parts of Asia, where Σ PBDE concentrations between 1 and 15 mg/kg are linked to active dismantling and material recovery operations (Akortia et al., 2020; Tue et al., 2022; Zhang et al., 2023). This strongly suggests that Site B functions as an intense anthropogenic emission point.

Congener patterns show a dominance of mid-brominated PBDEs, particularly HexaBDE (notably BDE-154), across most locations, while HeptaBDE (BDE-183) is dominant at Ekpan Bridge. DecaBDE (BDE-209) was not detected in any e-waste sample, indicating that the contamination profile is not driven by current deca-BDE materials but more likely reflects legacy inputs or selective environmental partitioning.

This pattern is consistent with the historical use of penta- and octa-BDE mixtures in electronic components prior to regulatory controls (UNEP, 2023). In the Niger Delta, where formal recycling infrastructure is limited, these legacy materials remain in circulation and continue to contribute to environmental contamination.

The spatial distribution supports a point-source emission model, with contamination concentrated around dismantling and recovery sites. Activities such as manual disassembly, open burning, and material sorting release PBDE-associated particulates into surrounding

soils and air. Given the low-lying, water-connected landscape of the Niger Delta, these particulates are readily transported into adjacent aquatic systems, including the Warri River.

Exposure implications are particularly important in this setting. Workers and nearby residents are likely exposed through inhalation of contaminated dust and direct dermal contact. PBDEs are semi-volatile and strongly bind to particulates, increasing the likelihood of occupational exposure. Toxicological evidence links such exposures to endocrine disruption, thyroid dysfunction, and neurodevelopmental effects (Costa et al., 2021; EFSA, 2024). In densely populated communities along the Warri River, these exposure pathways are likely amplified by proximity to informal recycling activities.

Environmental Sink Matrix: Sediment

Sediment PBDE concentrations are presented in Table 4.2. These values reflect the combined effects of contaminant transport, deposition, and long-term accumulation within the Warri River system.

Table 4.2: PBDE Concentrations in Surface Sediments (mg/kg dry weight)

Site	Location	Σ PBDE (mg/kg)	Dominant Congener	Sink Rank
A	Effurun Market	1.810	HeptaBDE	3
B	Efiei Edumurhe	0.413	HexaBDE	4
C	Ekpan Bridge	2.474	HeptaBDE	2
D	Esi Bridge	0.043	HexaBDE	5
E	Mclver Bridge	0.039	HexaBDE	6
F	Ogburu Bridge	0.009	Minor	9
G	Otokutu Bridge	0.012	Minor	8
H	Ovwian	0.030	HexaBDE	7
I	Robinson Plaza	0.025	TetraBDE	10
J	Udu Bridge	2.635	DecaBDE	1

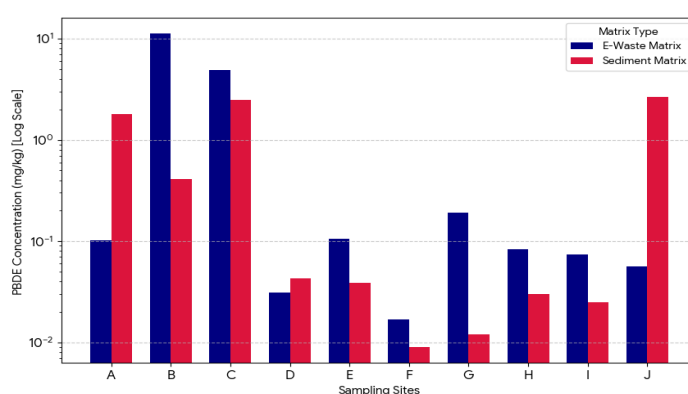


Figure 2: (E-waste vs. Sediment Comparison)

The sediment profile shows a clear redistribution pattern, with Udu Bridge (Site J) emerging as the primary accumulation zone (2.635 mg/kg), followed by Ekpan Bridge (Site C) and Effurun Market (Site A). This pattern becomes more instructive when examined alongside the e-waste matrix (Figure 2), where Site J exhibits relatively low PBDE burden

compared to sites such as B and C. The contrast highlights a pronounced spatial disconnect between emission intensity and eventual environmental accumulation.

Site J does not correspond to a major emission source in the e-waste matrix, indicating strong source-sink decoupling. Within the hydrologically dynamic Niger Delta, tidal influence, seasonal flooding, and sediment transport processes play a central role in redistributing contaminants away from their original sources. The comparative profile further shows that while sites like B and C are dominant in the e-waste matrix, their sediment concentrations do not scale proportionally, reinforcing the role of lateral transport and depositional sorting in controlling contaminant fate.

The dominance of DecaBDE at Site J reflects its high hydrophobicity and strong affinity for particulate organic matter, which promotes accumulation in fine sediments typically found in low-energy depositional zones (Zhao et al., 2022). Its presence, despite absence in the primary source matrix, suggests additional inputs such as upstream transport, atmospheric deposition, or differential partitioning. This is consistent with the observed figure-based trend, where congeners associated with heavier bromination show stronger enrichment in sediment relative to their representation in the e-waste matrix.

Across most other sites, HeptaBDE and HexaBDE dominate, indicating contributions from both direct deposition and transformation processes. Notably, their relatively consistent presence across both matrices suggests partial coupling between source and sink compartments, unlike the pronounced decoupling observed for DecaBDE at Site J. Under anaerobic conditions common in Niger Delta sediments, reductive debromination can convert higher brominated PBDEs into lower congeners, modifying the contaminant profile over time (Stapleton et al., 2020). This transformation pathway provides a mechanistic explanation for the broader congener distribution observed in sediments compared to the more source-specific e-waste signature.

Sediment concentrations exceeding 1 mg/kg at Sites A, C, and J are comparable to those reported in heavily impacted e-waste environments globally (Zhang et al., 2023; Tue et al., 2022). However, the figure-based comparison underscores that elevated sediment burdens are not solely a function of local contamination intensity but also of hydrodynamic focusing and sedimentological controls. In the Niger Delta context, such levels are significant given the dependence of local communities on aquatic ecosystems for food and livelihood.

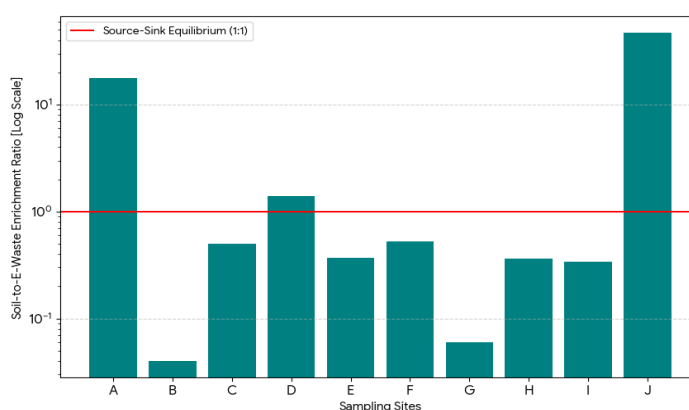
Source-Sink Dynamics and Spatial Redistribution

To clarify contaminant movement within the system, emission rankings were compared with sediment accumulation rankings (Table 4.3).

To clarify contaminant movement within the system, emission rankings were compared with sediment accumulation rankings (Table 4.3) and evaluated using soil-to-e-waste enrichment ratios (Figure 3), where values >1 indicate sink dominance, ≈ 1 indicate coupling, and <1 indicate source dominance.

Table 4.3: Source-Sink Comparative Profile

Site	Location	Source Rank	Sink Rank	Interpretation
A	Effurun Market	5	3	Dual influence
B	Efieki Edumurhe	1	4	Source dominant
C	Ekpan Bridge	2	2	Dual hotspot
D	Esis Bridge	9	5	Transitional
E	Mclver Bridge	4	6	Transitional
F	Ogburu Bridge	10	9	Background
G	Otokutu Bridge	3	8	Source skewed
H	Ovwian	6	7	Transitional
I	Robinson Plaza	7	10	Background
J	Udu Bridge	8	1	Sink dominant

**Figure 3: Source-Sink Relationship and Enrichment Ratios**

The combined analysis reveals pronounced source-sink decoupling. Efieki Edumurhe (Site B), despite being the strongest source (Rank 1), shows a low enrichment ratio and only moderate sediment accumulation (Rank 4), confirming limited retention capacity. In contrast, Udu Bridge (Site J) exhibits extreme enrichment ($\gg 1$) and ranks highest in sediment accumulation (Rank 1) despite low emission input (Rank 8), establishing it as the principal depositional sink. This reflects hydrodynamic focusing, where contaminants from multiple upstream sources converge and accumulate in low-energy environments.

Ekpan Bridge (Site C) shows matched source and sink rankings (Rank 2) with an enrichment ratio close to unity, supporting its classification as a dual hotspot, albeit slightly source-leaning. Transitional sites (D, E, and H) display ratios near unity, indicating balanced influence, whereas Otokutu Bridge (Site G) shows strong source dominance with low enrichment, suggesting efficient contaminant export. Background sites (F and I) similarly exhibit low enrichment and minimal contamination.

Effurun Market (Site A), though classified as dual influence, shows elevated enrichment, indicating that moderate emissions are amplified by favourable depositional conditions. This highlights the limitation of rank-based classification alone and the importance of ratio-based metrics in capturing non-linear accumulation behaviour.

Overall, the enrichment profile (Figure 3) quantitatively supports the ranking framework (Table 4.3) while revealing the non-linearity of contaminant redistribution.

These patterns reflect hydrodynamic controls in the Warri River system, where tidal forcing and sediment transport govern contaminant fate, consistent with observations in other e-waste-impacted aquatic systems (Tue et al., 2022; Tan et al., 2020). In the Niger Delta context, the delineation of source-, sink-, and coupled zones is critical for risk assessment, as sink environments such as Site J act as long-term reservoirs with sustained ecological and bioaccumulation risks.

Ecological Risk Characterization

Ecological risk was assessed using the Risk Quotient (RQ) approach based on sediment concentrations (Table 4.4).

Table 4.4: Ecological Risk Assessment of Sediment PBDEs

Site	Location	Highest Congener (mg/kg)	RQ	Risk Category
A	Effurun Market	1.798	360	Very high
B	Efieki Edumurhe	0.320	64	High
C	Ekpan Bridge	2.457	491	Very high
D	Esis Bridge	0.039	7.8	Moderate
E	Mclver Bridge	0.015	3.0	Moderate
F	Ogburu Bridge	<0.02	<4	Low-Moderate
G	Otokutu Bridge	<0.02	<4	Low-Moderate
H	Ovwian	<0.02	<4	Low-Moderate
I	Robinson Plaza	<0.02	<4	Low
J	Udu Bridge	2.635	527	Very high

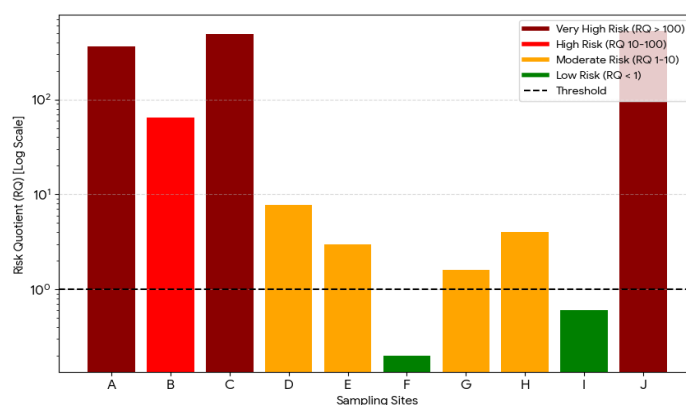


Figure 4: Ecological Risk Quotients and Safety Threshold Mapping

The results show that Sites J, C, and A fall within the very high ecological risk category ($RQ > 100$), with values far exceeding screening thresholds, as illustrated in Figure 4. Efieki Edumurhe (Site B) exhibits high risk ($RQ = 64$), while Sites D and E fall within the moderate range ($RQ = 1-10$), indicating a clear gradient of decreasing ecological pressure across locations.

Sites F, G, and H are grouped as low-moderate in Table 4.4 ($RQ < 4$); however, Figure 4 provides finer resolution, placing Site F within the low-risk category ($RQ < 1$) and Sites G

and H within the lower end of the moderate range. Robinson Plaza (Site I) remains consistently within the low-risk category. This distinction underscores the value of continuous risk representation in resolving spatial variability that may be masked by categorical classification.

Sediment-associated PBDEs remain bioavailable to benthic organisms through ingestion and porewater exposure. Their lipophilicity facilitates bioaccumulation, while transformation to lower brominated congeners enhances trophic mobility. Such exposures have been associated with endocrine disruption, impaired growth, and reproductive toxicity in aquatic organisms (Costa et al., 2021).

The spatial distribution of RQ values, with pronounced hotspots at Sites J, C, and A, reflects the combined influence of contaminant input and depositional processes, consistent with the source-sink dynamics identified earlier. Elevated sediment burdens at these locations indicate sustained ecological exposure, with potential transfer to higher trophic levels through contaminated fish and benthic fauna.

CONCLUSION

This study provides a detailed assessment of polybrominated diphenyl ether (PBDE) contamination in electronic waste materials and surface sediments along the Warri River corridor, revealing clear spatial heterogeneity driven by localized anthropogenic activities and hydrodynamic transport processes. Elevated PBDE concentrations in electronic waste samples, particularly at Efieki Edumurhe and Ekpan Bridge, confirm that informal e-waste dismantling and handling sites function as primary emission sources within the study area. The predominance of mid-brominated congeners in these materials reflects legacy usage patterns and highlights the continued environmental relevance of aged polymeric components in regions lacking structured recycling systems.

In contrast, sediment contamination patterns demonstrate pronounced source-sink decoupling, with downstream locations such as Udu Bridge acting as major depositional environments despite relatively low local emission intensity. This redistribution underscores the role of particulate transport and sedimentation dynamics in controlling contaminant fate within tropical river systems. The dominance of higher brominated congeners in sediments, alongside detectable levels of lower brominated species, indicates that both direct deposition and in situ transformation processes contribute to the evolving contaminant profile.

Ecological risk assessment revealed that several locations, particularly Udu Bridge, Ekpan Bridge, and Effurun Market, fall within high to very high risk categories, suggesting significant potential for adverse effects on benthic organisms and aquatic ecosystem integrity. Given the known bioaccumulative properties of PBDEs and their capacity for trophic transfer, these findings also imply potential indirect human exposure through consumption of contaminated aquatic resources.

Effective mitigation of PBDE contamination in the Warri River system requires the establishment of regulated electronic waste management frameworks, enforcement of environmentally sound dismantling practices, and continuous environmental monitoring to limit pollutant release and safeguard ecosystem and public health.

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