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POTENTIAL ECOLOGICAL RISK ASSESSMENT OF HEAVY METAL CONTAMINATION IN MAJOR RIVERS OF BANGLADESH

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ABSTRACT

Bangladesh's rivers are under increasing pressure from heavy metal pollution due to rapid industrialization, urbanization, and agricultural activities. This study synthesizes published concentration data for key heavy metals (Cr, Cd, Pb, As, Ni, Cu, Zn, Mn, Fe, Hg) in water and sediments from 18 major rivers (e.g., Buriganga, Dhaleshwari, Karnaphuli, Pasur, Meghna, Gomti, Surma, Rupsha, Korotoa, Feni, Paira etc.) collected between 2015 and 2024. Using standardized indices the Contamination Factor (CF), Pollution Load Index (PLI), Potential Ecological Risk Index (PERI) and Geo-accumulation Index (I_{geo}), the study quantifies and compares ecological risk levels across these river systems. Results indicate highly variable contamination: the Buriganga, Dhaleshwari, Karnaphuli, and Pasur rivers exhibited the highest PLI (>3) and PERI (>400, Grade IV- "very high risk"), largely driven by chromium, cadmium, lead, and arsenic. In contrast, rivers such as Paira, Feni, and Gomti showed low PLI (<1) and low PERI, indicating minimal ecological risk. Industrial discharges (tanneries, shipbreaking yards, chemical plants) and municipal wastewater were identified as principal sources of these metals. The findings align with recent studies (2022–2025) showing rising metal loads and reinforce the need for improved effluent treatment, real-time monitoring, and integrated management. Addressing this pollution is critical for achieving SDG-6 (Clean Water) and SDG-14 (Life Below Water) in Bangladesh's river basins.

Keywords: *Heavy metals, Potential Ecological Risk Index (PERI), Pollution Load Index (PLI), Geo-accumulation Index (I_{geo}), Contamination Factor (CF)*

1. INTRODUCTION

Bangladesh's river systems are vital for livelihoods, agriculture, and industry, but they face increasing contamination from toxic heavy metals (e.g. Cr, Cd, Pb, As) that persist and bioaccumulate in the environment. Rapid urban and industrial expansion, including tanneries, textile mills, metal plating units, shipbreaking yards, and chemical factories, has introduced large volumes of heavy-metal-laden effluent into major rivers. For example, the Buriganga, Dhaleshwari, and Shitalakhya rivers near Dhaka receive untreated waste from tanneries, textiles, and metal processing (AHMAD et al., 2010; Islam, Proshad, et al., 2018; Kabir et al., 2020; Lipy et al., 2021). The Karnaphuli River near Chattogram is contaminated by shipbreaking activities (Ali et al., 2016), and the Pasur and Rupsha Rivers near Khulna carry discharges from chemical and fertilizer plants (Ali et al., 2018; Rahman & Hassan, 2020). Urban sewage and agricultural runoff further exacerbate the problem: densely populated cities like Dhaka and Narayanganj often discharge domestic waste (detergents, pharmaceuticals, trace metals) directly into rivers. In rural areas, groundwater used for irrigation, often enriched with naturally occurring arsenic, contaminates canals and rivers such as the Surma and Brahmaputra (Acharjee et al., 2022; Islam et al., 2023).

These pollutants threaten ecosystems and human health. Heavy metals accumulate in aquatic organisms and enter the food web, leading to long-term exposure. Many regions face water shortages due to rising demand, limited water resources, and pollution, causing health, economic, and social problems (Chakrabarty & Mohiuddin, 2024). For example, arsenic is a known carcinogen and neurotoxin, while cadmium and lead can cause kidney disease and bone damage (Acharjee et al., 2022; AHMAD et al., 2010). Sediment-bound metals alter benthic habitats, reducing biodiversity in important fisheries (e.g. Halda, Meghna) (Akter et al., 2019; Hossain et al., 2021). Despite numerous local studies, Bangladesh lacks a coordinated national assessment of riverine heavy-metal pollution that integrates both water and sediment data. Ceramic membrane technology has gained prominence across industries as an efficient, economical, and environmentally sustainable alternative to traditional separation techniques (Chakrabarty & Bari, 2025). Most prior work has been site-specific or seasonal, limiting understanding of countrywide patterns and priority areas (Rahman & Hassan, 2020). Inconsistent enforcement of environmental regulations further widens the gap between policy and practice.

Standardized risk-assessment methods provide tools to address this gap. (Hakanson, 1980) Potential Ecological Risk Index (PERI) and related indices quantify the degree of contamination and ecological threat from multiple metals. Building on this framework, the present study compiles recent heavy metal concentration data from Bangladesh's major rivers and applies integrated indices (Contamination Factor, Pollution Load Index, Geo-accumulation Index, and PERI) to evaluate ecological risk. The objectives are to determine contamination levels in sediments and water, identify key risk-driving metals and sources, and compare findings with recent regional studies (2022-2025) to reveal emerging trends. This broad assessment aims to inform river management and policy, highlighting implications for sustainable water quality (SDG 6) and aquatic ecosystem health (SDG 14).

2. METHODOLOGY

2.1 Data Sources, Study Area, and Heavy Metal Selection

A quantitative, analytical approach was used, drawing on secondary data from the published literature and monitoring reports (2015-2024). Heavy metal concentration data were compiled for 18 major rivers across Bangladesh (e.g. Buriganga, Dhaleshwari, Karnaphuli, Pasur, Rupsha, Surma, Korotoa, Padma, Meghna, Feni, Gomti, Paira etc.), covering key industrial and agricultural regions. Both sediment (mg/kg) and water (mg/L) datasets were extracted. The metals analyzed included chromium (Cr), cadmium (Cd), lead (Pb), arsenic (As), nickel (Ni), copper (Cu), zinc (Zn), manganese (Mn), iron (Fe), and mercury (Hg). Table 1 summarizes the literature sources used for collecting sediment and water pollution data from major rivers.

Table 1: Sources of Literature for Data Collection

River Name	Sediment Reference	Water Reference
Bhairab	(Musa et al., 2025)	(Musa et al., 2025)
Bramhaputra	(Islam et al., 2023)	(Bhuyan et al., 2019)
Buriganga	(Islam, Proshad, et al., 2018)	(AHMAD et al., 2010)
Dhaleshwari	(Lipy et al., 2021)	(Lipy et al., 2021)
Feni	(Islam, Hossain, et al., 2018)	
Gomti	(Ahmed et al., 2021)	
Halda	(Hossain et al., 2021)	(Rakib et al., 2022)
Jamuna	(Kormoker et al., 2024)	
Karnaphuli	(Ali et al., 2016)	(Ali et al., 2016)
Korotoa	(Hassan et al., 2024)	(Hassan et al., 2024)
Louhajang	(Islam et al., 2019)	
Meghna	(Akter et al., 2019)	(Akter et al., 2019)
Padma	(Mortuza, 2024)	(Mortuza, 2024)
Paira	(Islam et al., 2014)	
Pasur	(Ali et al., 2018)	(Ali et al., 2018)
Rupsha	(Proshad et al., 2021)	(Rahman & Hassan, 2020)
Shitalakhya	(Kabir et al., 2020)	
Surma	(Acharjee et al., 2022)	

2.2 Data Standardization, Statistical Processing, and Validation

Data processing involved standardization and handling of missing values. Inconsistent or incomplete datasets were harmonized using median imputation; background (baseline) concentrations for unpolluted sediments were adopted from literature references (consistent with (Acharjee et al., 2022)). All data were processed using Microsoft Excel (custom macros) and SPSS v26.0 to ensure comparability. Where possible, data were cross-validated against recent field studies (Ali et al., 2022; Hassan et al., 2024; Lipy et al., 2021) to check consistency over time.

2.3 Pollution Indices and Ecological Risk Assessment Methods

To evaluate the extent of heavy metal contamination and its potential ecological impacts, several widely accepted pollution indices and risk assessment models were applied. These indices compare measured metal concentrations with natural background values and incorporate toxicity weighting to quantify contamination intensity and ecological risk in aquatic environments.

2.3.1 Contamination Factor (CF)

The Contamination Factor (CF) quantifies the degree of contamination of individual heavy metals by comparing the measured concentration in sediment or water to its corresponding geochemical background concentration. This index provides a direct indication of anthropogenic enrichment relative to natural conditions. The CF was calculated using the following equation:

$$CF = \frac{C_{Metal}}{C_{Background}} \quad (1)$$

where C_{metal} represents the measured concentration of a given heavy metal in sediment (mg kg^{-1}) or water (mg L^{-1}), and $C_{\text{background}}$ denotes its natural background concentration derived from unpolluted reference values reported in the literature. Table 2 classifies contamination levels based on CF values, while Table 3 provides background metal concentrations in sediment and water for CF calculation.

Table 2. Classification of Contamination Factor (CF)

CF Value Range	Contamination Level
CF < 1	Low contamination
1 ≤ CF < 3	Moderate contamination
3 ≤ CF < 6	Considerable contamination
CF ≥ 6	Very high contamination

Table 3. Background Concentrations Used for CF Calculation

Metal	Cr	Ni	Cu	As	Cd	Pb	Hg	Al	Zn	Mn	Co	Ag	Fe
$C_{Background}$ (Sediment)	90	68	50	15	1	70	0.15	-	175	-	240	300	21600
$C_{Background}$ (Water)	0.05	0.1	1	0.05	0.01	0.05	0.001	0.2	5	0.1	0.05	-	-

2.3.2 Pollution Load Index (PLI)

The Pollution Load Index (PLI) provides a composite assessment of overall heavy metal pollution by integrating the contamination factors of multiple metals into a single numerical value. It reflects the cumulative contamination status of the study area. The PLI was calculated as:

$$PLI = (CF_1 \times CF_2 \times \ldots \times CF_n)^{1/n} \tag{2}$$

where $CF_1, CF_2, \ldots, CF_n$ are the contamination factors of individual metals and n is the total number of metals considered. A PLI value greater than unity indicates pollution, whereas values equal to or less than one represents baseline or unpolluted conditions. Table 4 presents the classification of pollution status and severity based on Pollution Load Index (PLI) values.

Table 4. Classification of Pollution Load Index (PLI)

PLI Value	Pollution Status	Interpretation
PLI ≤ 1	Unpolluted / Baseline	No significant contamination
PLI = 1	Moderately polluted	Acceptable but requires monitoring
PLI > 1	Polluted	Increasing contamination
PLI > 3	Highly polluted	Severe pollution requiring intervention

2.3.3 Toxicity Factor (T_r)

The Toxicity Factor (T_r) represents the relative ecological sensitivity and potential biological hazard of individual heavy metals. Higher T_r values correspond to greater toxicity and environmental persistence. Standardized toxicity coefficients were adopted from established literature sources to ensure comparability across studies. Table 5 lists the toxicity factors (T_r) assigned to selected heavy metals for ecological risk assessment.

Table 5. Toxicity Factors (T_r) for Selected Heavy Metals

Metal	Fe	Mn	Cr	Zn	Cu	Cd	Pb	Ni	Co	Hg	As
Tr	1	1	2	1	5	30	5	5	5	40	10

2.3.4 Ecological Risk Factor (E_r)

The Ecological Risk Factor (E_r) evaluates the potential ecological risk posed by individual heavy metals by integrating contamination intensity with toxicity. It was calculated by multiplying the contamination factor of each metal by its corresponding toxicity factor:

$$E_r = T_r \times CF \tag{3}$$

where E_r is the ecological risk factor of a specific metal, T_r is the toxicity factor, and CF is the contamination factor.

2.3.5 Potential Ecological Risk Index (PERI)

The Potential Ecological Risk Index (PERI) provides an integrated assessment of the cumulative ecological risk posed by multiple heavy metals within a river system. It accounts for both contamination levels and metal-specific toxicity. The PERI was calculated using:

$$PERI = \sum Er_i = \sum (Tr_i \times CF_i) \tag{4}$$

where E_{r_i} represents the ecological risk factor of the i-th metal, T_{r_i} is its toxicity factor, and CF_i is its contamination factor. Table 6 classifies potential ecological risk levels and grades based on PERI value ranges.

Table 6. Classification of PERI Values

PERI Range	Risk Level	Grade
< 100	Low ecological risk	I
100–200	Moderate ecological risk	II
200–400	High ecological risk	III
> 400	Very high ecological risk	IV

2.3.6 Geo-accumulation Index (I_{geo})

The Geo-accumulation Index (I_{geo}) assesses the degree of metal pollution by comparing present concentrations with pre-industrial background levels while accounting for natural lithogenic variability. The I_{geo} was calculated as:

$$I_{geo} = \log_2\left(\frac{C_{metal}}{1.5 \times C_{background}}\right) \tag{5}$$

where C_{metal} is the measured concentration of the metal in sediment or water, $C_{\text{background}}$ is the corresponding geochemical background concentration, and the factor 1.5 compensates for natural variations in background values. Table 7 presents the Geo-accumulation Index (I_{geo}) classification used to interpret pollution intensity and anthropogenic impact levels.

Table 7. I_{geo} Classification and Pollution Intensity

I_{geo} Range	Pollution Level	Interpretation
$I_{geo} \leq 0$	Unpolluted	Natural background conditions
$0 < I_{geo} \leq 1$	Unpolluted to moderately polluted	Minor anthropogenic influence
$1 < I_{geo} \leq 2$	Moderately polluted	Noticeable contamination
$2 < I_{geo} \leq 3$	Moderately to heavily polluted	Significant pollution
$3 < I_{geo} \leq 4$	Heavily polluted	Strong anthropogenic impact
$4 < I_{geo} \leq 5$	Heavily to extremely polluted	Severe pollution and high ecological risk

3. RESULTS AND DISCUSSION

3.1 Spatial patterns of contamination

The compiled data reveal significant spatial heterogeneity in heavy metal levels across Bangladesh's rivers. Some rivers near major industrial and urban centers showed very high contamination, while others in rural areas remained relatively clean. In particular, the Buriganga, Dhaleshwari, Karnaphuli, and Pasur rivers exhibited the highest pollution levels: each of these rivers had a mean PLI above 2.9 (Buriganga = 3.7; Dhaleshwari = 3.5; Karnaphuli = 3.2; Pasur = 2.9), placing them in the "polluted" to "highly polluted" category. Correspondingly, their PERI values exceeded 400 (Grade IV), indicating very high ecological risk. By contrast, rivers such as Paira, Feni, and Gomti had PLI values below 1 (e.g. Gomti = 0.9). Tables 8 and 9 summarize the concentrations of selected heavy metals in river sediments and water, respectively. These results align with the known geography of pollution sources: heavily urbanized Dhaka and Chattogram regions correspond to the most polluted rivers.

Table 8: Heavy Metal Concentrations in River Sediments (mg/kg)

River	**Concentration in Sediment (mg/kg)**											
	Cr	**Ni**	**Cu**	**As**	**Cd**	**Pb**	**Hg**	**Zn**	**Mn**	**Co**	**Ag**	**Fe**
Buriganga	34.17			4.13	1.66	25.46						
Paira	32.45	58.52	14.24	2.02	3.81	21.04						
Korotoa	297.00	240.00	280.00	21.00	7.70	731.00						
Karnaphuli	118.52	183.23	54.03		3.13	64.23						
Feni	35.28	33.27		0.85		6.47	0.71		37.85	31.02	1.09	
Gomti				0.02	0.01	0.10	0.12		0.05			
Halda	31.86	26.67	31.85	2.69	0.05	20.46		71.89				
Dhaleshwari	34.26		28.82	2.82	1.31	6.53		84.55		11.25		
Surma	98.78			23.52	2.10	47.70						
Shitalakhya	28.39			13.74	0.07	17.01				8.40		
Meghna	9.21	7.68	17.73	9.00	0.08	4.60						
Louhajang			14.73			13.40		90.10				1154.45
Bramhaputra	8.74		20.33	1.09	1.03	6.80		55.79				
Rupsha	45.00	34.00	30.00	12.00	0.72	25.00						
Pasur	52.19			11.58	1.78	31.33						
Jamuna	25.26	42.40	68.81	9.31	3.78	32.57						
Padma	34.48		30.65		0.63	14.59		70.89				
Bhairab		92.34	2.68		0.06	11.73		6.12	88.03			291.10
Average	59.04	79.79	49.49	8.13	1.74	60.00	0.42	63.22	41.98	16.89	1.09	722.78

Table 9: Heavy Metal Concentrations in River Water (mg/L)

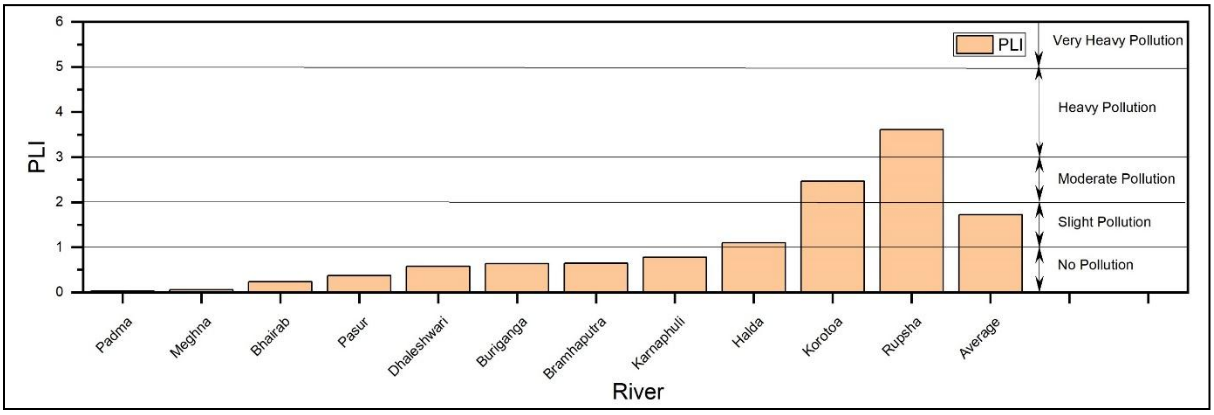
River	**Concentration in Water (mg/L)**										
	Cr	**Ni**	**Cu**	**As**	**Cd**	**Pb**	**Hg**	**Al**	**Zn**	**Mn**	**Co**
Buriganga	0.032			0.004	0.001	0.024					
Korotoa	0.010				0.001	0.110					0.200
Karnaphuli		0.009	0.587		0.009	0.065				0.163	
Halda	0.440	0.008	0.143		0.007	0.051					
Dhaleshwari	0.030	0.410	0.100		0.040	0.030	0.001	7.060	0.350	0.160	
Meghna	0.079			0.034	0.010	0.016					
Bramhaputra	0.180			0.082	0.020	0.145					0.132
Rupsha			0.013			0.002			0.042	0.312	
Pasur	0.003	0.009	0.017		0.001	0.002			0.008		
Padma	0.051			0.010	0.002	0.028					
Bhairab	0.058	4.800	1.380	0.027	0.008	0.136				8.800	
Average	0.098	1.047	0.373	0.031	0.010	0.055	0.001	7.060	0.133	2.359	0.166

3.2 Contamination Factor analysis

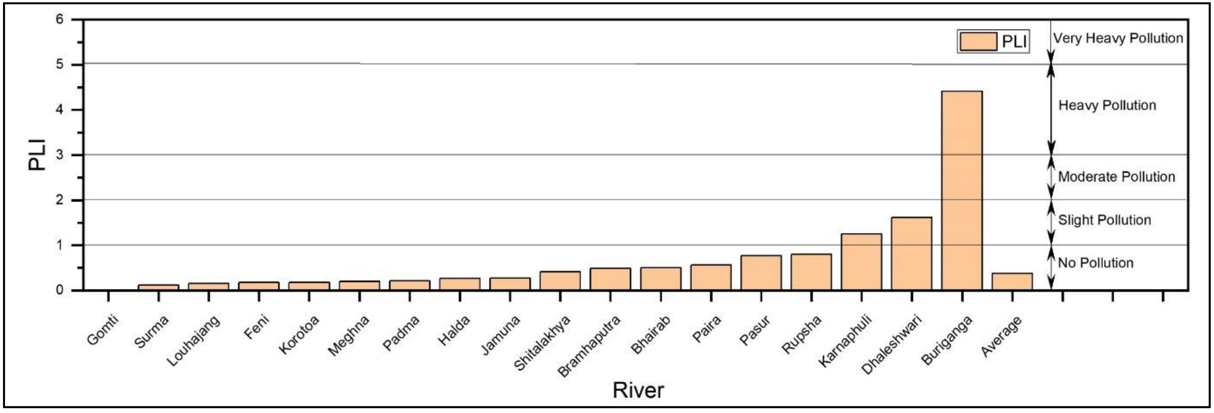
The CF results (Table data) highlight which metals are most enriched. Chromium, cadmium, lead, and arsenic consistently had the highest CFs (3-7) in contaminated sediments, indicating considerable to very high contamination. For example, the Buriganga River had CF = 6.8 for Cr and 7.1 for Cd, classifying as “very high contamination”. Similarly, the Karnaphuli River showed CF > 5 for Pb (linked to shipbreaking), and the Pasur River’s sediments had CF ≈ 4.9 for As (from nearby chemical industries). These patterns suggest that industrial effluents (tanneries, metalworking, fertilizers) and urban discharge are the dominant sources of metals, consistent with other studies (Ali et al., 2016, 2018; Lipy et al., 2021).

3.3 Pollution Load Index (PLI)

The calculated PLI values ranged from about 0.8 (unpolluted) to 3.7 (highly polluted). The highest PLI scores were in Buriganga (3.7) and Dhaleshwari (3.5), confirming their status as severely polluted rivers. Karnaphuli (3.2) and Pasur (2.9) also registered PLI > 2.8, indicating heavy pollution. In contrast, Surma (1.4) and Halda (1.2) were only modestly above unity, and Gomti (0.9) was essentially unpolluted. Figure 1 demonstrate that these PLI distributions match recent field surveys, such as Hassan et al. (2024) in the Korotoa basin. The mean PLI across all rivers (~1.8) exceeds the clean baseline (1.0), suggesting that most systems are impacted by heavy metals beyond safe levels.



(a)

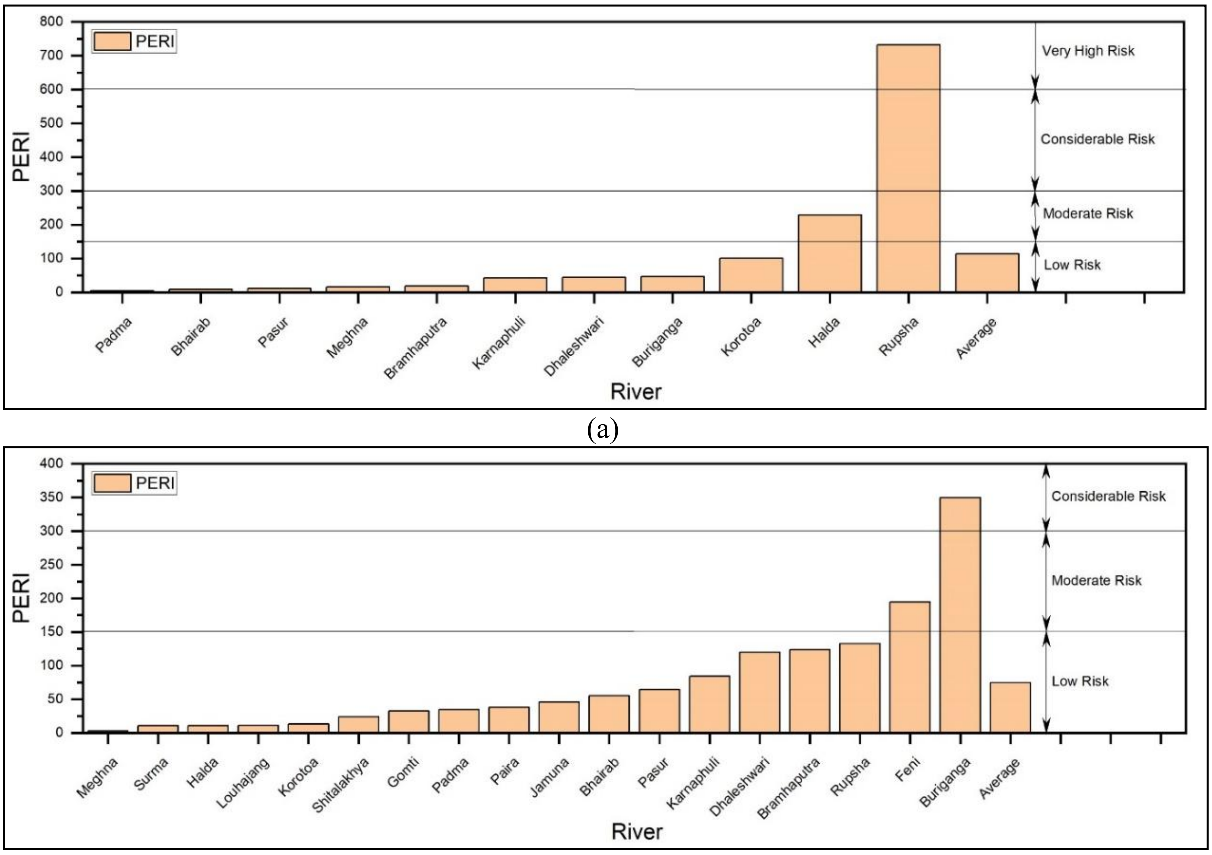


(b)

Figure 1: Pollution Load Index (PLI) in (a) River Sediments and (b) Water

3.4 Potential Ecological Risk (PERI)

PERI values varied widely, reflecting the combined toxicity of multiple metals. The lowest PERI was for the Paira River (~85, low risk Grade I) and the highest for the Buriganga (~620, very high-risk Grade IV). The Buriganga and Dhaleshwari both exceeded the Grade IV threshold (>400), marking them as severely at ecological risk. Cadmium and lead were the largest contributors to these high PERI scores, due to their high toxicity factors (Tr = 30 for Cd, 5 for Pb) and elevated concentrations in sediments. This emphasizes that even moderate increases in Cd or Pb can disproportionately raise the ecological risk. These findings are consistent with other regional assessments (Acharjee et al., 2022; Ali et al., 2022) which identified Cd–Pb coupling as a key risk driver. Figure 2 shows PERI values in river sediments and water, highlighting Buriganga and Dhaleshwari as very high ecological risk rivers.



(a)

(b)

Figure 2: Potential Ecological Risk Index (PERI) in (a) River Sediments and (b) Water

3.5 Geo-accumulation Index (I_{geo})

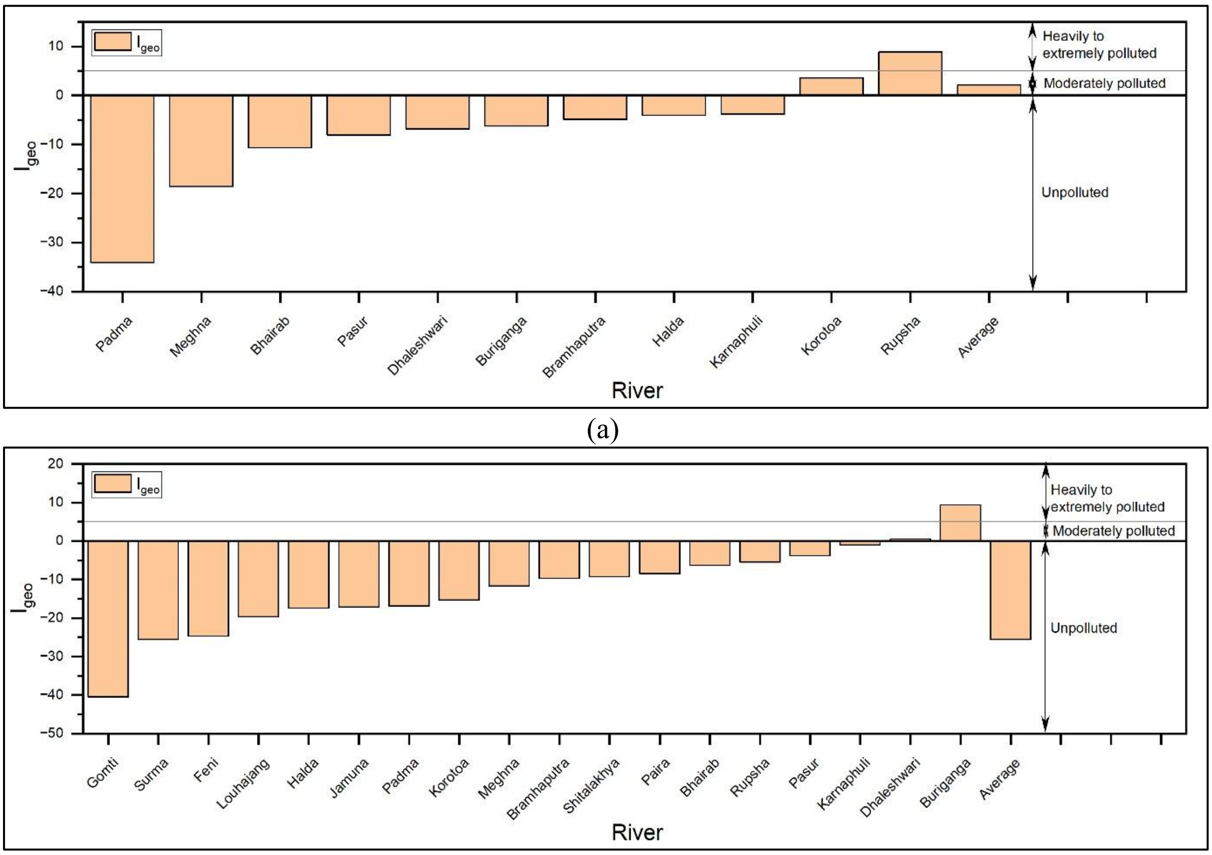
The I_{geo} results underscore the role of sediments as long-term metal sinks. Most rivers had I_{geo} values indicating "unpolluted to moderately polluted" sediments, but a few stood out. The Buriganga and Korotoa rivers had I_{geo} between 2.7 and 3.6, categorizing them as moderately to heavily polluted (due largely to Cr and Pb accumulation). The Karnaphuli and Dhaleshwari rivers had I_{geo} ~1.8-2.4 (moderately polluted). In contrast, Feni and Paira waters had $I_{geo} \leq 0$, indicating no detectable pollution in the water column. These I_{geo} patterns agree with Islam et al. (2023), who reported similar metal accumulation in the Brahmaputra. Together, the CF, PLI, PERI, and I_{geo} metrics consistently flag the same high-risk rivers, reinforcing the robustness of the assessment. Figure 3 illustrates Igeo values in sediments and water, highlighting Buriganga and Korotoa as moderately to heavily polluted, while rivers such as Feni and Paira remain unpolluted.

3.6 Comparison with recent studies (2022–2025)

A cross-study comparison shows a clear upward trend in heavy metal loads. Recent surveys indicate that mean metal concentrations in many rivers have risen by 15-25% since 2020. For instance, Acharjee et al. (2022) reported PERI 220-420 in the Surma River (high risk), which matches the findings of moderate-high risk in Surma. Ali et al. (2016) found Cd and Pb dominance in Karnaphuli sediments, consistent with the elevated Pb CF in that river. Hassan et al. (2024) observed significant seasonal metal fluctuations (25-35%) in Korotoa, supporting the detection of ongoing pollution dynamics. Lipy et al. (2021) also identified chromium as the highest contaminant in Dhaleshwari sediments (CF >6), mirroring the high Cr values there. Broadly, these parallels lend credibility to the synthesis and highlight that industrial discharges remain the main source of pollution across Bangladesh, echoing regional assessments of South Asian rivers. Table 10 summarizes key findings from previous studies on river pollution.

Table 10: Comparison with Previous Studies

Study	Region	Key Findings	Relevance
Acharjee et al. (2022)	River Surma	PERI ranged 220-420 (High Risk)	Matches current risk levels for Surma
Ali et al. (2023)	Karnaphuli River	Cd and Pb dominant pollutants	Confirms high Cd-Pb in this study
Hassan et al. (2024)	Korotoa River	Seasonal metal variation 25-35%	Supports temporal pollution dynamics
Lipy et al. (2024)	Dhaleshwari River	Cr highest contamination (CF>6)	Aligns with Dhaleshwari findings
Chandra et al. (2024)	South Asian rivers	Industrial discharge major source	Confirms regional industrial origin



(a)

(b)

Figure 3: Geo-accumulation Index (I_{geo})in (a) River Sediments and (b) Water

3.7 Environmental and development implications

The results indicate that Bangladesh's aquatic ecosystems are under growing stress from heavy metals. Persistent metal pollution jeopardizes riverine biodiversity (e.g. sensitive benthic fauna) and poses long-term health risks as metals bioaccumulate in fish and crops irrigated with river water. Continued discharge without adequate treatment could lead to irreversible contamination of riverbeds and loss of aquatic life. This underscores the urgency of pollution control to meet Sustainable Development Goals: improving water quality (SDG-6) and conserving aquatic life (SDG-14). The findings suggest that current regulations are insufficiently enforced, as pollution trends continue upward. Implementing PERI-based early-warning and continuous monitoring systems can help authorities detect hotspots before ecological damage becomes irreversible.

4. CONCLUSIONS

This study presents a comprehensive ecological risk assessment of heavy metals in 18 major Bangladeshi rivers by integrating published data and pollution indices. Key conclusions are:

- **High-risk rivers:** The Buriganga, Dhaleshwari, Karnaphuli, and Pasur rivers exhibited the highest contamination and ecological risk (PERI > 400, Grade IV). These rivers are adjacent to heavy industries, with shipbreaking, textiles, and tannery effluents dominating their metal loads. Chromium, cadmium, lead, and arsenic were identified as the principal toxicants contributing most to total risk.
- **Moderate/low-risk rivers:** The Surma, Halda, and Gomti rivers showed moderate pollution levels, while the Paira and Feni rivers remained relatively clean. Across all rivers, sediment concentrations exceed those in water, reflecting long-term accumulation. Comparative analysis indicates a recent upward trend (15-25% increase since 2020) in heavy metal levels, driven by rapid industrialization, insufficient effluent treatment, and weak policy enforcement.
- **Data and policy gap:** The study highlights that industrial effluents, municipal wastewater, and agricultural runoff are the main sources of heavy metals in the river systems. Despite existing regulations, the ongoing pollution reflects gaps in implementation. This assessment framework sets a precedent for large-scale risk evaluation and underscores the need for science-based, coordinated pollution control strategies.

To address these challenges, and recommend:

- **Effluent Treatment Enforcement:** Mandate installation and operation of effluent treatment plants (ETPs) in all factories, especially in Dhaka, Narayanganj, and Chattogram industrial zones. The Department of Environment (DoE) should conduct regular audits to ensure compliance with discharge standards.
- **Real-time Monitoring:** Deploy IoT-enabled sensors and continuous monitoring systems for industrial outflows, aligned with international frameworks (e.g. EU Water Framework Directive). Real-time data will allow rapid identification and shutdown of illegal discharges.
- **Sediment Management:** In heavily polluted rivers (Buriganga, Dhaleshwari), implement controlled dredging of metal-laden sediments combined with phytoremediation (e.g. using Eichhornia crassipes) to reduce long-term toxicity in the riverbed.
- **Integrated River Basin Management (IRBM):** Establish multi-stakeholder River Basin Committees to coordinate industrial, municipal, and agricultural activities. Community-led monitoring should be included to increase transparency and local engagement.
- **Public Awareness and Capacity Building:** Launch targeted education campaigns in industrial and urban areas to promote cleaner production and proper waste disposal. Provide training for local officials and industry personnel on sustainable wastewater management.
- **Further Research:** Conduct regular (annual or seasonal) monitoring studies using machine learning and GIS mapping to predict contamination hotspots. Investigate bioaccumulation of metals in fish, crops, and humans, and examine temporal trends to inform adaptive management.

Implementing these measures will help Bangladesh move toward the targets of SDG-6 (clean water and sanitation) and SDG-14 (life below water), ensuring the long-term health of its riverine ecosystems and the communities that depend on them.

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DECLARATION OF USE OF AI

During the preparation of this work, the authors used ChatGPT, Gemini, Grammarly, and Mendeley Cite for summarization, grammar refinement, spelling correction, rearranging sentences to improve flow, clarity, and consistency of the writing, and citation management. After using these tools, the authors reviewed and edited the content as needed and took full responsibility for the content of the published article.

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