

COMPREHENSIVE RISK-BASED ASSESSMENT OF HEAVY METAL CONTAMINATION IN RIVER WATER AND SEDIMENT ACROSS THE HIMALAYAN RIVERS

Ashiqur Rahman^{*1}, Md Al Amin² and Khondoker Mahbub Hassan³

¹ Graduate Student, Department of Civil Engineering, KUET, e-mail: 6ashiq@gmail.com

² Research Assistant, Department of Civil Engineering, KUET, e-mail: mdalamin2308@gmail.com

³ Professor, Department of Civil Engineering, KUET, e-mail: khmhassan@ce.kuet.ac.bd.com

***Corresponding Author**

ABSTRACT

Heavy metal contamination in river water and sediment poses a significant environmental concern due to its adverse effects on the environment and public health. Himalayan rivers, originating from one of the most vital regions, are highly vulnerable due to rising anthropogenic activities, land use changes, and increasing industrial activities. This study represents a potential risk-based evaluation of heavy metal contamination across the Himalayan River catchments flowing through multiple countries, including Bangladesh, India, Nepal, Bhutan, and Pakistan. For this purpose, the heavy metal concentrations in the river water and sediments traversing these countries are obtained from the published literature. Additionally, contamination factors (Cf_{metal}), degree of contamination (C_{degree}), pollution load index (PLI), potential ecological risk index (PERI), and geo-accumulation index (I_{geo}) are employed for risk assessment. Sediment samples indicate low ($Cf_{metal} < 1$) to considerable ($3 \leq Cf_{metal} < 6$) degrees of contamination, except in the Pakistani river catchment ($Cf_{metal} = 63.11$). In contrast, the water samples exhibit a higher degree of contamination ($Cf_{metal} > 6$), while Nepal and Bhutan show lower contamination levels. For river water samples, the Padma River of Bangladesh indicates a higher contamination level, with Cd and PLI values of 571.15 and 30.49, respectively. India's Brahmaputra River dominates the river water contamination, having a PERI value of 1523.4, while Pakistan's Jhelum River basin shows the highest heavy metal pollution, with the highest I_{geo} value of 35.968. The sediment samples demonstrated minimal risk level except the Astrore River of Pakistan, having a PERI value of 15973.6. This study will help in understanding the heavy metal contamination pattern throughout the region and will help in developing mitigation strategies regarding the problem

Keywords: Heavy Metal, Water and Sediment Pollution, Ecological Risk, Risk Assessment.

1. INTRODUCTION

Heavy metal contamination in surface water and sediments is a particular concern due to its persistence, toxicity, and higher accumulation rate in the aquatic environment (Dong et al., 2010; Ali et al., 2019). Heavy metals are considered potentially toxic elements and eventually enter the rivers through natural weathering of rocks and anthropogenic sources, including agricultural runoff, industrial and vehicular emissions, and stormwater discharges (Siddiqui & Pandey, 2019; Fadlillah et al., 2023). These toxic elements eventually drain into the rivers and accumulate in the sediments, leading to long-term effects on the environment and public health (Ahamad et al., 2024). Sediments often act as both sinks and secondary receptors of toxic metals, releasing contaminants into the surface water through redox fluctuations and metal interactions (Xie et al., 2024). Therefore, it is crucial to conduct a risk-based assessment due to the exposure of these potentially harmful contaminants to understand and mitigate the hazardous impacts on ecological systems, public health, and aquatic environments (Azam & Tripathi, 2025). This study is particularly important in the Himalayan rivers, where geographic conditions and diverse climatic factors influence the mobilization and redistribution of heavy metals among the river networks (Li et al., 2019).

The Himalayan rivers serve as critical sources of fresh water that sustain major transboundary rivers across South Asia. Water pollution in the rivers of this region is a global concern due to the transportation and deposition of toxic elements into the aquatic ecosystem (Ahamad et al., 2024). Several studies have reported elevated concentrations of heavy metals in the tributaries of the Himalayan River catchments, indicating significant risks due to the abundance of heavy metals. Studies by Dhiman et al. (2022) and Siddiqui and Pandey (2019) revealed a higher abundance of Iron (Fe), Manganese (Mn), lead (Pb), Chromium (Cr), and Copper (Cu) in the water and sediments of the Ganga River due to the influence of urban and industrial emissions. Another study by Hazarika and Kalita (2020) observed enrichment of Cr, Pb, Cu, Cd, and Mn due to weathering and anthropogenic inputs. The tributaries from the Nepal and Bhutan catchments have also indicated high pollution of heavy metals, driven by combined activities of natural and anthropogenic emissions. For example, the Koshi and Indrawati rivers demonstrated high accumulation of toxic metals, including Li, Cd, Si, Fe, and Mn in both water and sediments, indicating a stronger influence of geochemical weathering and anthropogenic effects on water quality (Paudyal et al., 2015).

Moreover, Padma, Jamuna, and Karnafully river catchments are also contaminated with higher concentrations of toxic metals, including Pb, Cr, Cu, Zn, exhibiting a severe impact on the aquatic ecosystem, public health, and the overall environment. The elevated concentration of these toxic pollutants is eventually consumed by the aquatic species, and people living near the regions are affected, causing several long-term health effects. However, the literature provided a quantitative approach and sources of heavy metal concentration at the regional level and did not integrate the multi-country catchments along with ecological risk matrices. In particular, there is a crucial demand to provide a comprehensive assessment of contamination levels by incorporating several matrices to understand the risk levels and possible pathways to control the emission of these terrestrially driven metals into the surface water and sediments of the river networks.

Addressing this gap, this study provides a risk-based study that incorporates the heavy metal concentration from several published studies and applies risk indices, including Contamination Factor (Cf_{metal}), Degree of Contamination (C_{degree}), Pollution Load Index (PLI), Potential Ecological Risk Index (PERI), and Geo-accumulation Index (I_{geo}) to understand the level of contamination due to heavy metal pollution across the region. By integrating heavy metal concentrations from multiple basins and risk indices, this study aims to (i) quantify the risk levels due to contamination, (ii) understand the spatial patterns and hotspots of potential risk (iii) provide regional insights to support monitoring systems and mitigation strategies. Heavy metal concentrations across different basins originating from the Himalaya, along with comprehensive risk assessments, will provide key insights into the pollution dynamics in the Himalayan rivers and transboundary toxicological perspectives.

2. METHODOLOGY

2.1 Study Area

The Himalayan River system comprises one of the largest and most important transboundary networks in the South Asian region. The river originating from the high-altitude glacier constitutes several major river basins, including the Indus, Ganges, and Brahmaputra (IGB) system (Lutz et al., 2014; Ganjoo, 2021). The basin spans dramatic terrain, ranging from peaks rising above 7,000 m on the Tibetan Plateau to floodplains situated just 20 m above sea level in Bangladesh (S. N. Islam, 2016). This extreme elevation shapes the region's hydrology and sediment dynamics, influencing everything from water flow and sediment loads to the movement and accumulation of pollutants (Wulf et al., 2012). In this study, heavy metal concentration data for both water and sediment across the Himalayan River catchments have been adopted from a wide range of published studies, incorporating datasets from Bangladesh, India, Pakistan, Nepal, and Bhutan, irrespective of their specific geographic origin within the basin. Table 1 represents the study areas and the corresponding literature sources from which the datasets have been compiled.

Table 1: Study Area and Sources of Heavy Metals in Himalayan Rivers

Country	River Name	Reference
Bangladesh	Padma, Meghna, Jamuna	(Usha et al., 2025)
	Karnafuli	(Ali et al., 2016)
	Karotoa	(Islam et al., 2014)
	Ramaganga, Ghaghara, Gandak (Tributaries of Ganga)	(Azam & Tripathi, 2025)
India	Yamuna	(Asim & Rao, 2021; Jaiswal et al., 2022; Gani et al., 2024)
	Ganga River Basin	(Dhiman et al., 2022)
	Brahmaputra River	(Hazarika & Kalita, 2020)
	Teesta River	(Rai et al., 2024)
	Koshi River, Indrawati River	(Paudyal et al., 2015; Tripathi et al., 2016)
Nepal	Bagmati River	(Paudyal et al., 2016)
	Seti River Basin, Badigad River, Gandhaki River	(Pant et al., 2019; Pant et al., 2023; Pant et al., 2021)
	Indus River	(Usman et al., 2020; Muhammad & Usman, 2021)
Pakistan	Astoro River	(W. Ali & Muhammad, 2023)
	Jhelum River	(Inayat et al., 2023)
	Kurram River	(Ali et al., 2018)
Bhutan	Beki River, Manas River	(Singh et al., 2019)

2.2 Heavy Metal Contamination Indices

2.2.1 Contamination Factor (Cf_{metal})

Contamination factor is the ratio of the measured concentration of the individual metal to its background concentration, and was calculated by the formula provided by Hakanson (1980) as mentioned in Eq.(1)

$$Cf_{metal} = \frac{C_{metal}}{C_{background}} \quad (1)$$

Here, C_{metal} denotes the individual concentrations of the heavy metals and $C_{background}$ is the background concentration of the metals. Here, $1 < Cf_{metal} < 3$ indicates lower to moderate contamination; $3 < Cf_{metal} < 6$ indicates moderate to high contamination and $Cf_{metal} > 6$ indicates very high contamination (Hakanson, 1980).

2.2.2 Degree of Contamination (C_{degree})

The degree of contamination is the cumulative risk index that indicates the overall level of pollution in the sample. It is a summation of contamination factors of the heavy metals in the sample (Hakanson, 1980), which has been demonstrated in Eq. (2)

$$C_{degree} = \sum_{i=1}^n (Cf_{metal})_i \quad (2)$$

The synergistic contamination level has been classified into four classes: $C_{degree} < 8$ indicates lower degree of contamination; $8 \leq C_{degree} < 16$ indicates moderate contamination; $16 \leq C_{degree} < 32$ indicates high contamination and $C_{degree} > 32$ indicates a very high contamination level (Hakanson, 1980).

2.2.3 Pollution Load Index (PLI)

It is a numerical index that evaluates the toxicity and pollution status of overall heavy metal contamination in a sample (Tomlinson et al., 1980) and is obtained according to the formula in Eq. (3):

$$PLI = (Cf_1 \times Cf_2 \times \dots \times Cf_n)^{\frac{1}{n}} \quad (3)$$

Here, n indicates the number of heavy metals in a sample and Cf_1, Cf_2, \dots, Cf_n are the contamination factors of each metal. PLI value 1 indicates baseline contamination level, and $PLI > 1$ indicates high toxicity level.

2.2.4 Geo-accumulation Index (I_{geo})

In environmental geochemistry, it is one of the most usable methods for evaluating contamination levels of heavy metals in various components of the environment (Hasan et al., 2012). Müller (1969) originally proposed the formula for calculating the geo-accumulation index of heavy metals, as shown in Eq.(4):

$$I_{geo} = \log_2 \frac{C_{metal}}{1.5C_{background}} \quad (4)$$

Here, 1.5 is the background correction matrix to reduce the lithogenic effects (Hasan et al., 2020). The I_{geo} can be classified according to Muller's theorem as per Table 2.

Table 2: Geo-accumulation Index and Corresponding Risk Level

I_{geo}	Contamination Level
$I_{geo} \leq 0$	Partially Contaminated
$0 < I_{geo} < 1$	Uncontaminated to moderately contaminated
$1 < I_{geo} < 2$	Moderately Contaminated
$2 < I_{geo} < 3$	Moderately to heavily contaminated
$3 < I_{geo} < 4$	Heavily Contaminated
$4 < I_{geo} < 5$	Heavily to extremely contaminated
$I_{geo} > 5$	Extremely Contaminated

2.2.5 Potential Ecological Risk Index (PERI)

It is used to assess the ecological risk posed by heavy metal contamination in the sediment samples. The PERI, proposed by Hakanson (1980), depends on the toxicity factor (T_r) and Contamination factors (Cf_{metal}) of the heavy metal.

$$E_r^n = T_r^n \times \left(\frac{C_{metal}}{C_{background}} \right) \quad (5)$$

$$PERI = \sum_{i=1}^n E_r^n \quad (6)$$

In this study, E_r^n and T_r represents ecological risk and the toxicity index of the n -th metal. T_r values for each metal have been adopted as per the guidelines provided by Hakanson (1980). Based on E_r and $PERI$. The risk levels have been categorized into the following categories as per Table 3

Table 3: Ecological Risk and Potential Ecological Risk indices as per Hakanson (1980)

E_r	$PERI$	Risk Level
$E_r < 40$	$PERI < 150$	Low Risk
$40 \leq E_r < 80$	$150 \leq PERI < 300$	Moderate Risk
$80 \leq E_r < 160$	$300 \leq PERI < 600$	Considerable
$160 \leq E_r < 320$	$PERI \geq 600$	High Risk
$E_r \geq 320$		Very High Risk

3. RESULTS AND DISCUSSION

3.1 Heavy Metal Abundance

The study reveals a heterogeneous distribution of contamination levels around the region, influenced mostly by both natural and anthropogenic sources. In Bangladesh, an elevated concentration of Cu, Ni, Pb, and Fe was detected in the Padma, Meghna, and Jamuna rivers, while lower concentrations were observed in the Karnafuli and Korotoa rivers. Studies by Hossain et al. (2022) and Uddin and Jeong (2021) suggested that the impact of industrial effluents, urban waste disposal, and agricultural runoff results in an elevated concentration of heavy metals around these regions. Another study by M. M. Ali et al. (2016) reveals that lesser industrialization and natural background activities serve as a key factor comparatively lower metallic pollution scenario in the Karnafuli and Korotoa rivers. The Ganga River basin exhibits a higher concentration of Fe, Pb, and Cd in water and sediment samples, especially in the downstream segment with densely populated and industrial regions. The Gandaki and Ghaghara rivers demonstrated moderate concentration affected primarily by geogenic factors and agricultural runoff (Azam & Tripathi, 2025). Beki and Manas rivers demonstrated comparatively lower abundances across the region, reflecting minimal anthropogenic activities and a higher influence of rock-weathering and geochemical processes.

In Pakistan Catchment, the Indus River and its tributaries, notably the Jhelum and Kurram rivers, have the highest levels of pollution. Mining and smelting activities, and higher population density, are mainly responsible for the heavy metal pollution in these rivers as they release industrial waste and untreated sewage.

Rivers like the Koshi, Bagmati, and Gandhaki have shown lower contamination levels across the region. Studies by Kandel et al. (2024); Sharma et al. (2020) observed lower industrial developments and the influence of natural weathering activities than anthropogenic emissions, resulting in lower metallic load in these rivers.

3.2 Risk Assessment of Heavy Metal Pollution

3.2.1 Contamination Factor (Cf_{metal}) Evaluation

In Water Samples, Several Rivers exhibited extreme contamination with Cf_{metal} values exceeding 6 for specific metals, highlighting a critical pollution level. The Jhelum River in Pakistan showed exceptionally high Cf_{metal} for Cr (132.7), Pb (220.95), Co (287.42) and Cd (15.4), reflecting anthropogenic influence, likely associated with industrial discharge, urban wastewater, and mining activities reported in the basin (Tripathee et al., 2016; Uddin & Jeong, 2021). Similarly, severe contamination was observed in the Padma river (Bangladesh) for Ni (70.5), Cd (216) and Cr (56) and

in the Jamuna River for Cr (70), Cd(32) and Pb (49), highlighting the role of agricultural runoff and untreated effluents in downstream transboundary rivers (Uddin & Jeong, 2021). An extremely high Cf_{metal} of 398.27 for Hg in the Brahmaputra River indicates a serious ecological and human health concern, potentially linked to atmospheric deposition and upstream mining-related activities (Das et al., 2021; Jha et al., 2022). In contrast, rivers in Nepal and Indian tributaries of the Ganga basin generally exhibited low to moderate contamination ($Cf_{metal} < 3$), suggesting reduced anthropogenic pressure and effective natural dilution (Kandel et al., 2024). Sediment contamination levels were comparatively lower, though notable hotspots were identified, including very high Mg contamination in the Astore River ($Cf_{metal} = 189.2$) and significant Cd enrichment in Jhelum sediments ($Cf_{metal} = 14.86$). Elevated Mg and Fe in sediments from the Ganga and Brahmaputra basins further indicate combined lithogenic contributions and localized human inputs (Gupta et al., 2022; Kumar et al., 2023).

3.2.2 Geo-accumulation Index Analysis (I_{geo})

The geo-accumulation index indicated pronounced metal enrichment in several Himalayan rivers, particularly water samples from highly impacted basins. The Jhelum River showed extreme contamination with I_{geo} values for Cr (6.47), Pb (7.20), Co (11.90), and Fe (7.04), and heavy contamination for Cd (3.36). Thus, indicates a substantial deviation from natural geochemical backgrounds. The Kurram River in Pakistan and the Padma and Jamuna Rivers from Bangladesh exhibited heavy to extreme I_{geo} values for Ni, Cr, Cd, and Pb, reflecting sustained anthropogenic emission from industrial activities, urban expansion, and intensive agricultural discharges within these catchments (Zahra et al., 2013; Uddin & Jeong, 2021). The Brahmaputra River exhibited exceptionally high Hg contamination ($I_{geo}=8.05$), indicating element-specific enrichment that may be attributed to long-range atmospheric transport and upstream mining-related mercury fluxes in Himalayan river systems (Zhang et al., 2021; Li et al., 2022). Conversely, rivers in Nepal, Bhutan, and Indian tributaries of the Ganga basin predominantly showed negative I_{geo} values, signifying unpolluted to slightly polluted conditions associated with lower industrial intensity and effective hydrological dilution (Kandel et al., 2024). Sediment samples showed comparatively localized contamination, with heavy Cd enrichment in Jhelum River sediments ($I_{geo}= 3.31$) and extreme Mg contamination in Astore River sediments ($I_{geo}= 6.98$), while moderate Mg contamination in the Ganga and Brahmaputra sediments ($I_{geo}= 1.84-2.54$) suggests a combined effect of lithogenic sources and site-specific human inputs (Gupta et al., 2022; Kumar et al., 2023).

3.2.3 Pollution Load Index (PLI)

Figure 1 illustrates a descriptive representation of PLI due to heavy metal contamination of different rivers in the Himalayan region. The figure represents a contrasting pattern in cumulative metal pollution across the Himalayan River system. The lowest PLI values were recorded in Nepal, notably in the Badigad River (0.0076) and Seti River Basin (0.0085), indicating nearly pristine conditions with minimal pollution influence. A study by Paudyal et al.(2015) revealed that limited industrial activity and strong dilution capacity in the upland basins are mainly responsible for minimal heavy metal contamination across the catchment. In Contrast, the Jhelum river in Pakistan (20.62) and the Padma(30.49) and Jamuna (27.45) rivers of Bangladesh exhibited severe pollution levels, driven by different inputs associated with dense population, industrial discharge, and agricultural runoff in the downstream floodplain (Kumar et al.,2023). The rivers from the Indian catchment exhibited mixed conditions, with the Ghaghara River showing low pollution, and moderate pollution was observed with the Brahmaputra River(1.53). This highlights the influence of localized anthropogenic emissions on high-flow systems (Singh et al.,2020).

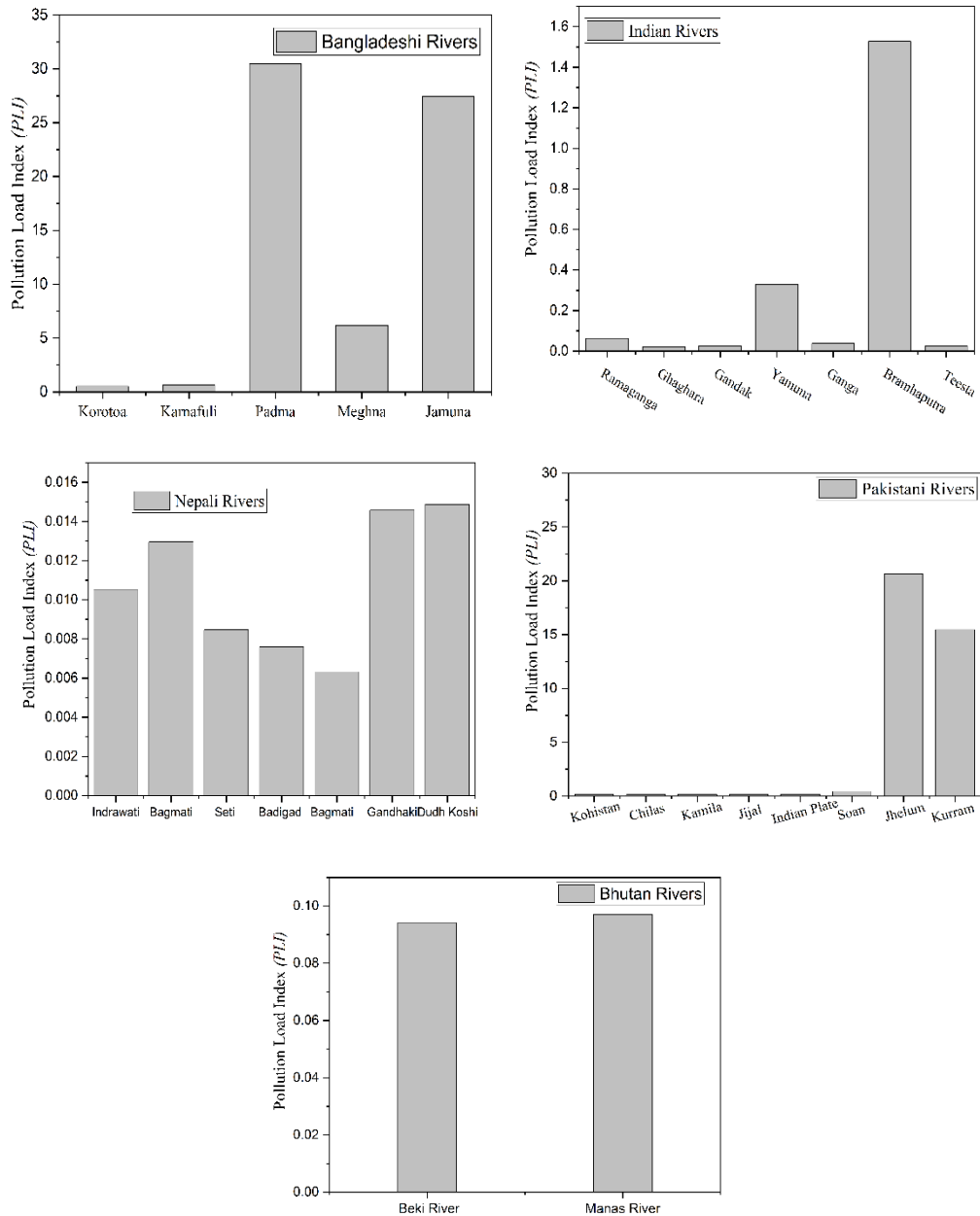
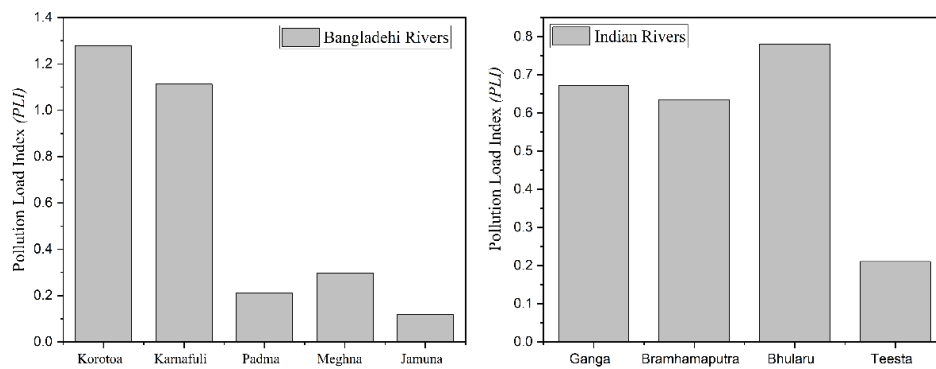


Figure 1: Countrywise PLI Analysis Due to Heavy Metal Contamination in River Water



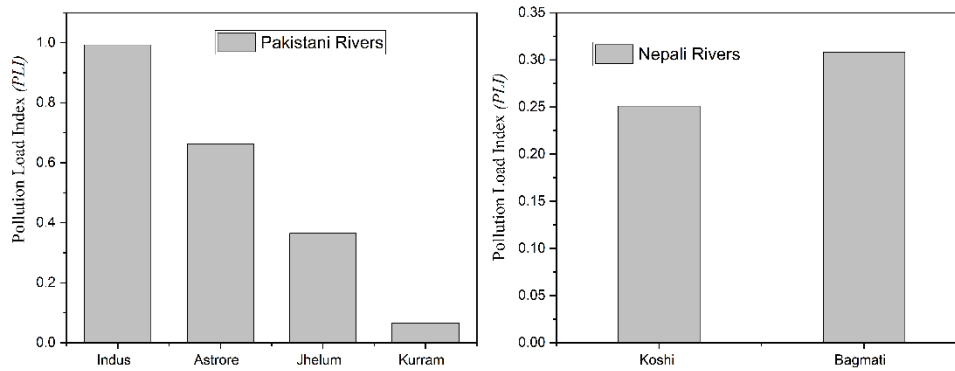


Figure 2: Countrywise PLI Analysis Due to Heavy Metal Contamination in River Sediment

Figure 2 represents a country-wise sediment-based PLI analysis due to heavy metal contamination in the corresponding rivers. The analysis exhibited lower and less variable PLI, with most rivers exhibiting below the threshold ($PLI < 1$). The Jamuna River in Bangladesh (0.14), the Kurram River in Pakistan, and the Teesta River in India showed comparatively lower contamination despite the presence of toxic metals and microplastic particles. This highlights the necessity of continuous surveillance and regular assessment of river water quality and toxic metal pollution. However, the Korotoa River and Karnafuli River of Bangladesh demonstrated moderate pollution levels, as notable metallic contamination was observed in these rivers.

3.2.4 Potential Ecological Risk Assessment

The Potential Ecological Risk Index (PERI) demonstrated higher pollution levels, particularly for water samples. Multiple rivers displayed "Very High" to "Extremely High" risk ($PERI \geq 600$), including the Padma River, Bangladesh (7,191.37), the Jhelum River, Pakistan (2,468.57), and the Kurram River, Pakistan (1,356.37). In sediment samples, the PERI was substantially lower. Most sites presented "Low" to "Moderate" risk, with the Jhelum River, Pakistan (449.08 - Considerable Risk) and the Astore River, Pakistan (216.10 - Considerable Risk) being the most concerning. The Meghna River in Bangladesh (104.06) also showed a "Moderate" ecological risk from its sediments.

3.3 Overall Scenario

This study provides a multi-index, risk-based assessment of Heavy metal pollution in the Himalaya River catchments that flow through five countries: Bangladesh, India, Pakistan, Nepal, and Bhutan. The results illustrate a contrasting pattern in pollution dynamics, indicating a significant influence of natural and anthropogenic factors across the region. The rivers, Jhelum in Pakistan, Padma, and Jamuna in Bangladesh, are exposed to the highest levels of contamination. Studies by Tripathy et al. (2016) and Uddin and Jeong (2021) revealed that the influence of industrial discharge, mining, and agricultural runoff may act as a key factor for higher contamination levels across the region. Conversely, rivers in Nepal and Indian tributaries of the Ganga basin generally display low to moderate contamination, reflecting reduced industrialization and more effective dilution or natural attenuation processes (Kandel et al., 2024; Sharma et al., 2020). The Geo-accumulation Index further confirms these patterns, with heavily contaminated sediments in hotspots such as the Jhelum and Astore Rivers contrasting with largely uncontaminated sediments in many Nepalese and Bhutanese rivers (Gupta et al., 2022; Kumar et al., 2023). Pollution Load Index (PLI) analyses underscore the severity of contamination in critical basins like the Jhelum, Padma, and Brahmaputra, while underscoring relatively pristine conditions elsewhere. The exceptionally high Potential Ecological Risk Index (PERI) scores in several rivers reveal urgent ecological threats primarily driven by bioavailable dissolved metals, emphasizing the need for transboundary water quality management, pollution source control, and regular monitoring to mitigate ecological and human health impacts. Together, these findings provide a comprehensive baseline for strategic interventions tailored to the diverse contamination dynamics within the Himalayan River ecosystems (Das et al., 2021; Jha et al., 2022).

4. CONCLUSION

This study presents a comprehensive, multi-index assessment of heavy metal contamination in river water and sediments across major Himalayan river systems spanning Bangladesh, India, Nepal, Bhutan, and Pakistan. By integrating contamination factor, geo-accumulation index, pollution load index, degree of contamination, and potential ecological risk index, the research provides a robust evaluation of pollution intensity, spatial variability, and associated ecological risks across transboundary catchments. The findings reveal pronounced spatial heterogeneity in contamination patterns, with rivers in Bangladesh and Pakistan, particularly the Padma, Jamuna, Jhelum, and Astore Rivers, exhibiting severe to extreme contamination and ecological risk. Elevated concentrations of toxic metals such as Cd, Pb, Cr, Hg, and Co were identified as the primary contributors, largely driven by industrial effluents, mining activities, agricultural runoff, and untreated urban wastewater. In contrast, rivers in Nepal and Bhutan, as well as several Indian tributaries of the Ganga basin, generally displayed low to moderate contamination levels, reflecting reduced anthropogenic pressure, effective dilution, and dominant geogenic controls. Various contamination indices collectively demonstrate both acute and chronic risks, with extremely high Cf_{metal} , I_{geo} , and PERI values indicating severe anthropogenic enrichment and serious ecological and human health concerns, particularly in river water. Sediments generally show lower contamination levels, although localized hotspots highlight the importance of site-specific monitoring. Overall, the study underscores the urgent need for coordinated transboundary river management, strengthened pollution control strategies, improved wastewater treatment, and long-term monitoring to mitigate heavy metal pollution in Himalayan rivers.

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DECLARATION OF AI

The Authors use AI tools to improve clarity, grammar, and language quality. All the main ideas, analysis, and drafting remain solely with the Author.

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