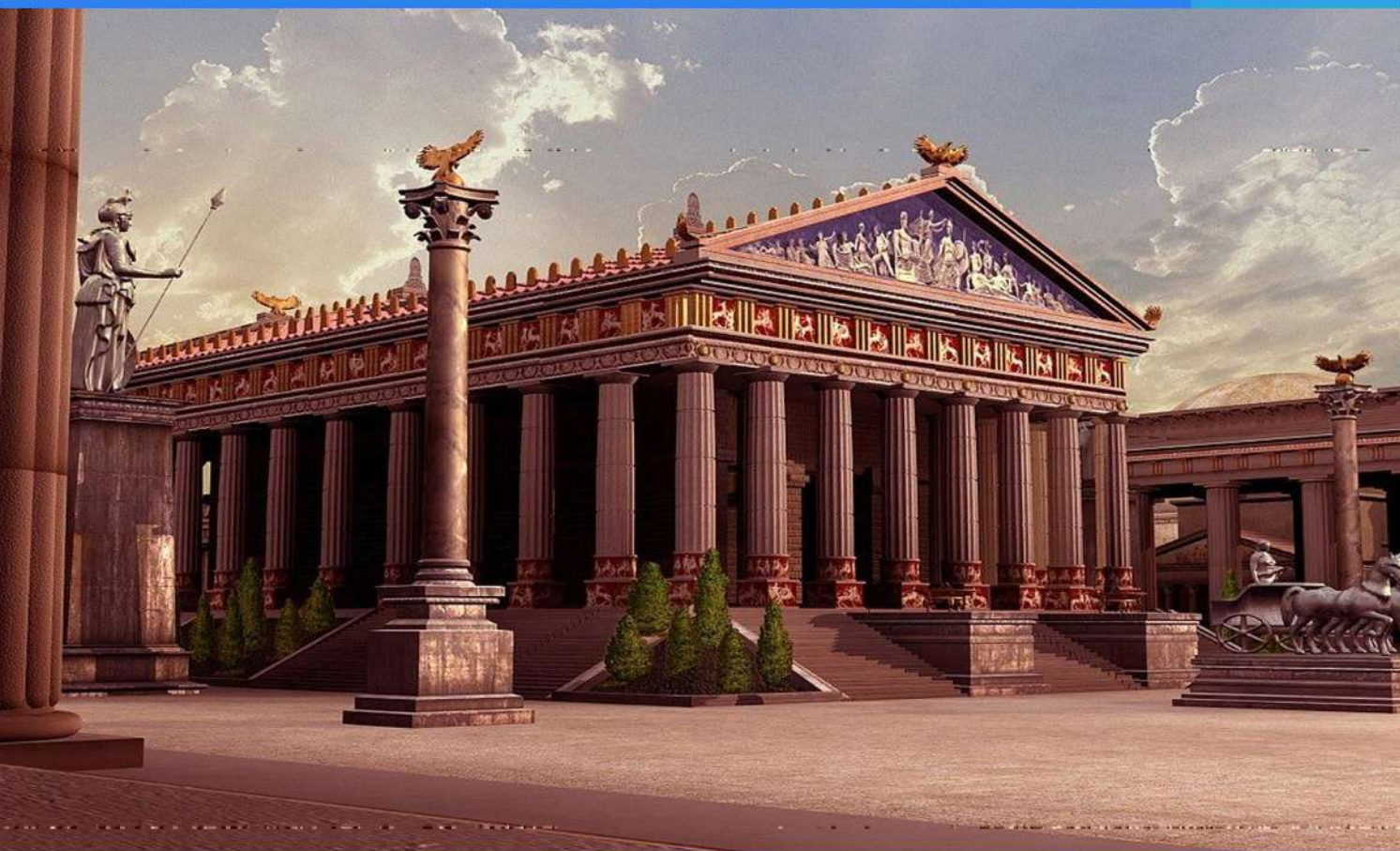


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**LONG-TERM SPATIOTEMPORAL DYNAMICS OF HEAVY METALS
IN SURFACE SEDIMENTS OF THE DA BAC RIVER, VIETNAM:
POLLUTION ASSESSMENT AND ECOLOGICAL RISK**

***Abstract:** heavy metal accumulation in river sediments is an important environmental concern because sediments act as long-term reservoirs of contaminants and potential secondary pollution sources. This study evaluated the spatiotemporal dynamics of arsenic (As), lead (Pb), chromium (Cr), zinc (Zn), and copper (Cu) in surface sediments of the Da Bac River, northern Vietnam, using monitoring data collected at three sampling sites from 2020 to 2025. Sediment quality was assessed using the geo-accumulation index (Igeo), enrichment factor (EF), contamination factor (CF), pollution load index (PLI), and potential ecological risk index (PERI). The results showed that Pb, Zn, and Cu concentrations generally remained below the Canadian Interim Sediment Quality Guidelines (ISQG), whereas As and Cr occasionally exceeded their guideline values. Most pollution indices indicated low contamination with minimal to moderate enrichment, suggesting that natural geological processes were the dominant source of heavy metals, although localized anthropogenic inputs were evident for arsenic.*

Overall ecological risk was classified as low, with As contributing the largest proportion of PERI because of its higher toxic-response factor. These findings provide baseline information for long-term sediment quality monitoring and support sustainable environmental management of the Da Bac River basin.

Keywords: *Da Bac River, heavy metals, ecological risk, geoaccumulation index, enrichment factor, potential ecological risk index.*

1. Introduction.

Heavy metal contamination has become a major environmental concern in freshwater ecosystems because of its persistence, toxicity, and resistance to degradation. Once released into aquatic environments, heavy metals can remain for long periods, accumulate in sediments, and enter aquatic food webs, posing risks to ecosystem integrity and human health. Although natural weathering contributes to background metal levels, rapid industrialization, mining, urban expansion, agriculture, and domestic wastewater discharge have substantially increased metal inputs to river systems worldwide (Iordache et al., 2022, Wang et al., 2025). As a result, understanding the distribution and ecological effects of heavy metals has become an important component of river basin management.

Surface sediments are widely used to evaluate heavy metal contamination because they integrate contaminant inputs over time and reflect both natural and anthropogenic influences. Fine particles, clay minerals, organic matter, and Fe-Mn oxides efficiently adsorb dissolved metals, leading to concentrations that are generally higher and more stable than those in the overlying water. However, sediments are not permanent sinks. Variations in *pH*, redox conditions, or hydrodynamic processes can remobilize sediment-bound metals, making sediments a secondary source of contamination. Consequently, sediment quality provides valuable information for assessing long-term pollution and potential ecological risks (Sin et al., 2001, Thuong et al., 2015).

Over the past two decades, heavy metal contamination in river sediments has been investigated in many regions of the world. Studies in Europe have demonstrated that industrial and urban activities are major drivers of metal accumulation in river sediments (Iordache et al., 2022). Similar findings have been reported for the Yellow River in China, where elevated Cr and Cd concentrations were associated with rapid urban development (Wang et al., 2025). Investigations in Bangladesh and several African river systems further showed that heavy metal distributions vary considerably with land use, mining activities, agriculture, and domestic wastewater discharge (Onoja et al., 2022, Ogah et al., 2023, Goodness et al., 2025, Olowo et al., 2025). Despite differences among river basins, these studies consistently emphasize the importance of long-term sediment monitoring for pollution assessment and environmental management.

In Vietnam, heavy metal contamination has been documented in several major rivers and estuarine environments, including the Red River, To Lich River, Cam River estuary, Saigon River, Ba Che estuary, and Cau River basin (Hien et al., 2016, Thanh et al., 2020, Thanh et al., 2023, Lich et al., 2025, Ve et al., 2025). These studies indicate that metal accumulation is closely associated with urbanization, industrial activities, mining, navigation, and agricultural development. Recent investigations have increasingly combined concentration measurements with pollution indices and ecological risk assessment, providing a more comprehensive evaluation of sediment quality. Nevertheless, most available studies have focused on large river systems or heavily urbanized watersheds, whereas medium-sized rivers influenced by mixed natural and anthropogenic processes remain less well documented.

Among the available assessment methods, the geo-accumulation index (I_{geo}), enrichment factor (EF), contamination factor (CF), pollution load index (PLI), and Hakanson's potential ecological risk index ($PERI$) are the most frequently applied for evaluating sediment quality. I_{geo} assesses contamination relative to natural background concentrations, EF distinguishes anthropogenic enrichment from lithogenic sources, CF quantifies contamination for individual metals, and PLI summarizes the overall pollution status of sediments. $PERI$ further incorporates the toxic response of each metal to estimate potential ecological risk. Together, these indices provide complementary information on contamination status and ecological implications and facilitate comparisons among different river systems (Müller, 1969, Hakanson, 1980, Tomlinson et al., 1980, Sutherland, 2000).

Despite substantial progress, important knowledge gaps remain. Most previous studies have been based on short-term surveys or single sampling campaigns, providing limited information on long-term changes in sediment quality (Hieu et al., 2013, Binh et al., 2020). Seasonal variation has been considered in several river systems (Islam et al., 2015, Asuquo et al., 2023), yet few studies have simultaneously evaluated temporal, seasonal, and longitudinal variations using a consistent multi-year dataset. In addition, long-term investigations of boundary rivers in northern Vietnam remain scarce, despite increasing environmental pressures associated with mining, industrial development, urban expansion, and agriculture.

The Da Bac River forms part of the natural boundary between Quang Ninh Province and Hai Phong City before joining the Bach Dang River system. Besides its importance for regional transportation, fisheries, and water resources, the river receives runoff from catchments affected by mining, industrial production, urban development, and agricultural activities. These characteristics make the river a potential pathway for the transport and accumulation of sediment-associated heavy metals. However, information on the long-term contamination status of its surface sediments remains limited.

This study therefore investigated the spatiotemporal dynamics of As, Pb, Cr, Zn, and Cu in the surface sediments of the Da Bac River during 2020–2025. The specific objectives were to (i) determine temporal changes in heavy metal concentrations, (ii) evaluate seasonal and longitudinal variations along the river, (iii) assess sediment contamination using the I_{geo} , EF , CF , and PLI , and (iv) evaluate potential ecological risks using Hakanson's $PERI$. The results provide baseline information for sediment quality assessment and support future environmental management of the Da Bac River and similar river systems in northern Vietnam.

2. Materials and methods.

2.1. Study area.

The Da Bac River is located in northeastern Vietnam and forms part of the natural boundary between Quang Ninh Province and Hai Phong City before joining the Bach Dang River system. The river plays an important role in regional drainage, inland water transport, fisheries, and socio-economic development. However, increasing urbanization, industrial activities, mining, agriculture, and navigation within the watershed have raised concerns regarding the accumulation of heavy metals in river sediments. To evaluate the longitudinal variation of sediment contamination, three representative sampling locations were selected along the river, including the upstream site (MK (X:2424447, Y:438994)), the midstream site (YT1 (X:2424447, Y:438994)), and the downstream site (YT2 (X:2430366, Y:440499)). The coordinates of the sampling locations were determined using the VN-2000 coordinate system and are presented in Fig. 1.



Fig. 1. Location of sampling sites along the Da Bac River, Vietnam.

2.2. Heavy metal dataset.

Heavy metal data used in this study were obtained from the official environmental monitoring program conducted annually in the Da Bac River during the period from 2020 to 2025. Surface sediment samples were collected twice each year, representing the early rainy season (May) and the dry season (November). The monitoring program was implemented by competent environmental agencies following the Vietnamese national technical regulations for environmental monitoring. Sample collection, preservation, laboratory analysis, and quality assurance/quality control (QA/QC) procedures were performed according to standardized national protocols by accredited laboratories.

Concentrations of arsenic (As), lead (Pb), chromium (Cr), zinc (Zn), copper (Cu), and iron (Fe) were compiled from validated monitoring reports. Iron was selected as the conservative reference element for enrichment factor calculations because of its natural abundance, relatively stable geochemical behavior, and limited anthropogenic influence in aquatic sediments.

2.3. Pollution assessment indices.

Five commonly used geochemical indices were employed to evaluate sediment contamination and potential ecological risk, including the I_{geo} , EF , CF , PLI , and $PERI$.

2.3.1. Contamination factor (CF).

The contamination factor was used to evaluate the contamination level of each heavy metal relative to its geochemical background value (Hakanson, 1980):

$$CF_i = \frac{C_i}{B_i} (1).$$

where C_i is the measured concentration of metal i in sediment (ppm), and B_i is the corresponding background concentration.

The contamination level was classified as follows: $CF < 1$: low contamination, $1 \leq CF < 3$: moderate contamination, $3 \leq CF < 6$: considerable contamination, $CF \geq 6$: very high contamination.

2.3.2. Geo-accumulation index (I_{geo}).

The geo-accumulation index proposed by Müller (1969) was applied to evaluate the degree of heavy metal accumulation relative to natural background concentrations:

$$I_{geo} = \log_2 \left(\frac{C_i}{1.5 \cdot B_i} \right) (2).$$

where the constant 1.5 accounts for natural variations in background metal concentrations associated with lithological differences.

According to Müller (1969), I_{geo} values are classified into seven contamination classes ranging from unpolluted ($I_{geo} \leq 0$) to extremely polluted ($I_{geo} > 5$).

2.3.3. Enrichment factor (EF).

The enrichment factor was calculated to distinguish anthropogenic enrichment from natural geological contributions using iron (Fe) as the reference element:

$$EF = \frac{(C_i/C_{Fe})_{sample}}{(B_i/B_{Fe})_{background}} \quad (3).$$

where C_i and C_{Fe} denote the measured concentrations of the investigated metal and Fe in sediment samples, respectively, while B_i and B_{Fe} represent their corresponding background concentrations.

According to Sutherland (2000), EF values are interpreted as follows: $EF < 2$: deficiency to minimal enrichment, $2 \leq EF < 5$: moderate enrichment, $5 \leq EF < 20$: significant enrichment, $20 \leq EF < 40$: very high enrichment, $EF \geq 40$: extremely high enrichment.

2.3.4. Pollution load index (PLI).

The pollution load index was used to evaluate the overall sediment quality by integrating the contamination factors of all investigated metals (Tomlinson et al., 1980):

$$PLI = (CF_1 \times CF_2 \times \dots \times CF_n)^{1/n} \quad (4).$$

where n is the number of investigated metals.

A PLI value less than 1 indicates no overall pollution, PLI equal to 1 represents baseline contamination, whereas PLI greater than 1 indicates progressive deterioration of sediment quality.

2.3.5. Potential ecological risk index ($PERI$).

The ecological risk posed by heavy metals was evaluated using the potential ecological risk index proposed by Hakanson (1980). The ecological risk factor for each metal was calculated as:

$$E_r^i = T_r^i \times CF_i \quad (5).$$

where T_r^i is the toxic-response factor of metal i , and CF_i is the contamination factor.

The overall ecological risk index was determined by:

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

The toxic-response factors adopted in this study were 10 for As, 5 for Pb, 5 for Cu, 2 for Cr, and 1 for Zn (Hakanson, 1980).

Background concentrations of As (13 ppm), Pb (20 ppm), Cr (90 ppm), Zn (95 ppm), and Cu (45 ppm) were adopted from Turekian and Wedepohl (1961).

Measured concentrations were additionally compared with the Canadian Interim Sediment Quality Guidelines (ISQG) to provide an ecological reference for sediment quality.

2.4. Statistical analysis.

Descriptive statistical analysis was conducted to summarize the distribution characteristics of heavy metal concentrations during the monitoring period. Spatial variation was evaluated by comparing the upstream, midstream, and downstream sampling locations, while temporal variation was assessed across six consecutive years (2020–2025) and between the two annual sampling periods (May and November). The pollution indices (I_{geo} , EF , CF , PLI , and $PERI$) were calculated for each sampling event to characterize contamination status and ecological risk. All statistical analyses and graphical presentations were performed using Microsoft Excel 365 and OriginPro 2024.

3. Results and discussion.

3.1. Heavy metal concentrations.

The concentrations of As, Pb, Cr, Zn, and Cu in the surface sediments of the Da Bac River varied across sampling sites and monitoring periods (Fig. 2). Among the investigated metals, Zn showed the highest mean concentration, followed by Cu, Pb, Cr, and As. Iron (Fe), used as the reference element, remained the dominant major element in all samples. The observed variability reflects differences in sediment characteristics, seasonal hydrological conditions, and local human activities within the river basin.

Arsenic concentrations ranged from 1.59 to 16.97 ppm, with the lowest value recorded at MK in November 2023 and the highest at YT1 in November 2025. Most samples exceeded the Canadian ISQG value of 5.9 ppm, indicating that As was the metal of greatest environmental concern. Although As concentrations were generally higher at YT2, spatial differences were not consistent among sampling campaigns. Higher concentrations were more frequently observed during the November surveys.

Lead concentrations ranged from 6.73 to 88.39 ppm. The highest values occurred simultaneously at the three sampling sites in November 2024, reaching 88.39, 83.50, and 78.20 ppm at YT1, MK, and YT2, respectively. Except for several sampling events in late 2020, late 2023, and November 2024, Pb concentrations remained below the ISQG value of 35 ppm. These short-term peaks are more likely associated with episodic external inputs than with sustained accumulation.

Chromium concentrations varied between 0.51 and 40.21 ppm. The maximum concentration was recorded at MK in May 2025, while the minimum occurred at YT1 in November 2023. Nearly all samples remained below the ISQG threshold of 37.3 ppm, with only one sample slightly exceeding this value. Compared with the other investigated metals, Cr exhibited relatively limited temporal variability.

Zinc was the most abundant trace metal, with concentrations ranging from 15.97 to 298.94 ppm. Elevated Zn concentrations were mainly observed at the downstream site (YT2), particularly in November 2024 and May 2025. Although most samples remained below the ISQG value (123 ppm), several downstream samples exceeded this threshold, indicating localized Zn accumulation in the lower reach of the river.

Copper concentrations ranged from 7.89 to 105.91 ppm. The highest concentrations were measured at YT2 (105.91 ppm) and YT1 (99.26 ppm) during.

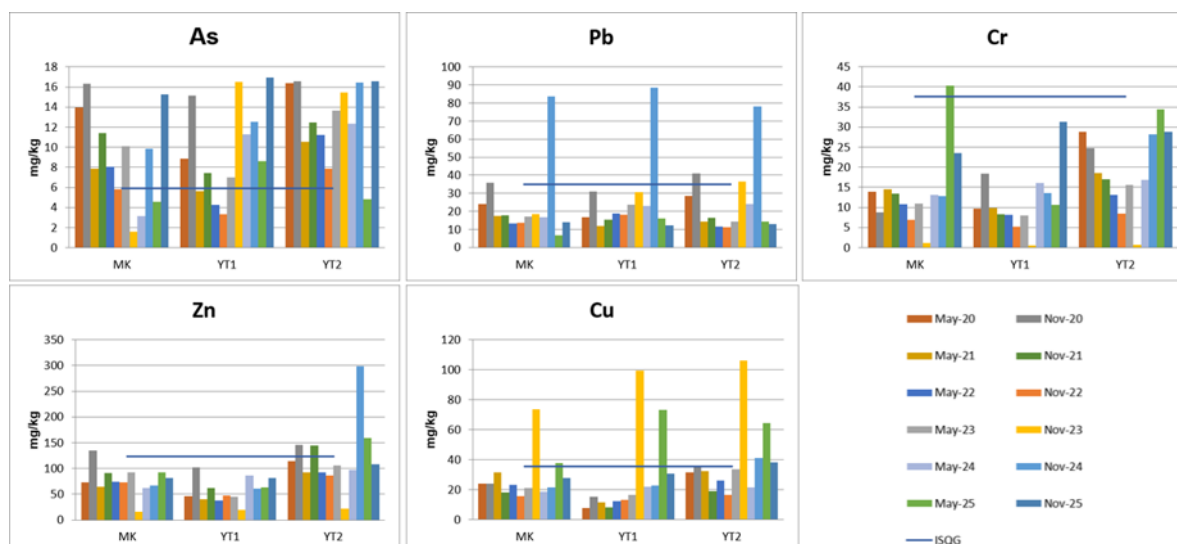


Fig. 2. Comparison of heavy metal concentrations (As, Pb, Cr, Zn, and Cu) in Da Bac River sediments with ISQG values.

November 2023. Exceedances of the ISQG value (35.7 ppm) became more frequent after 2023, especially at the middle and downstream sites. Unlike As, Cu did not show a persistent temporal trend but was characterized by several localized concentration peaks, indicating intermittent external inputs.

No consistent increasing or decreasing trend was observed for any of the investigated metals over the six-year monitoring period. Instead, concentrations fluctuated among sampling campaigns, with Pb, Zn, and Cu showing more pronounced increases during 2023–2025, particularly in November. Higher concentrations during the November surveys suggest the influence of seasonal runoff, sediment transport, and depositional processes following the rainy season. Spatially, Zn and Cu were generally enriched at the downstream site, whereas As and Pb displayed greater spatial heterogeneity.

Comparison with the ISQG indicates that As was the only metal that frequently exceeded the guideline value, while exceedances of Pb, Cr, Zn, and Cu were restricted to a limited number of samples. Overall, the sediment quality of the Da Bac River remained relatively good during the study period, although localized enrichment of several heavy metals highlights the need for further evaluation using pollution indices and ecological risk assessment.

3.2. Pollution assessment.

The contamination status of surface sediments in the Da Bac River was evaluated using the I_{geo} , EF , CF , and PLI . Overall, all four indices indicate that sediment quality remained within the low to moderate contamination category during 2020–2025, although clear differences were observed among metals and sampling sites.

3.2.1. Contamination factor (CF).

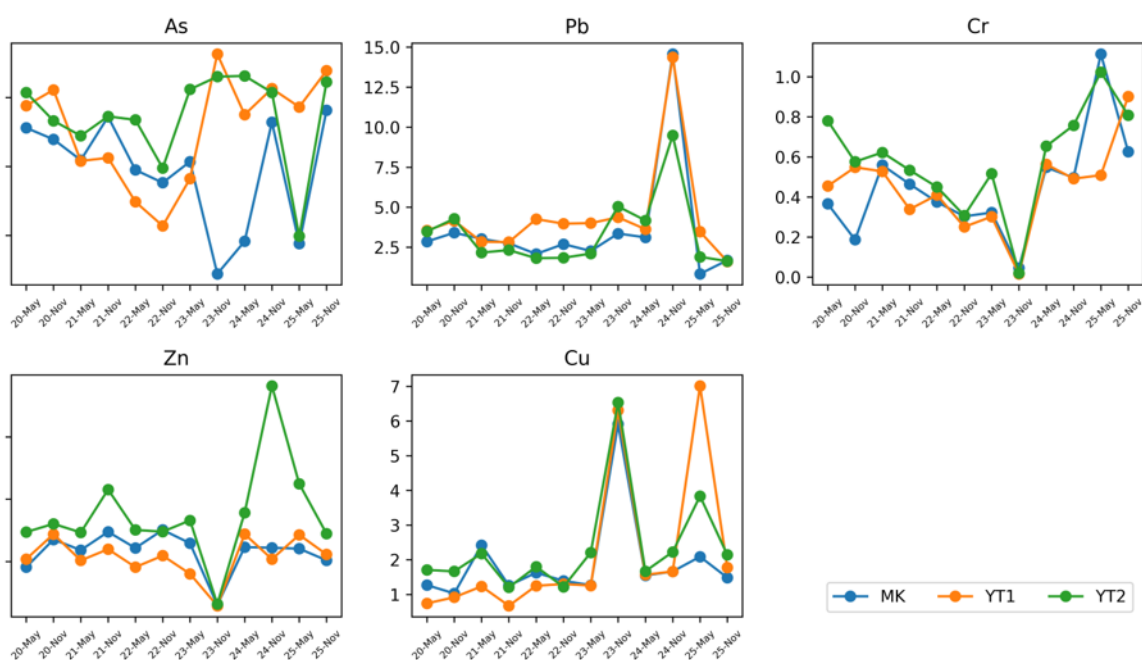


Fig. 3. Enrichment factor (EF) of heavy metals in surface sediments of the Da Bac River.

CF values varied considerably among the investigated metals. Chromium consistently exhibited CF values below 1, indicating low contamination throughout the study period. Zinc and Cu also remained predominantly within the low contamination category, although several samples collected at YT2 during 2023–2025 reached moderate contamination ($CF = 1$ to 3).

Lead showed greater temporal variability. Most samples were classified as low contamination, whereas moderate contamination occurred during November 2020, November 2023 and, most notably, November 2024. The highest CF was recorded at YT1 in November 2024.

Among the five metals, As consistently produced the highest CF values. Moderate contamination was frequently observed, particularly during November sampling campaigns at YT1 and YT2, identifying As as the principal contributor to sediment contamination in the Da Bac River.

3.2.2. Enrichment factor (EF).

The EF values, calculated using Fe as the reference element, indicate that most metals experienced little anthropogenic enrichment. Chromium and Zn generally showed EF values close to one, suggesting that their concentrations were largely controlled by natural geological materials.

Cu and Pb displayed slightly higher EF values during several sampling campaigns, especially at YT2, indicating localized anthropogenic inputs. Arsenic showed the highest enrichment among all investigated metals. Most samples were classified as deficient to minimal or moderate enrichment ($EF < 5$), implying that As originated from both natural sources and additional human activities. No sample reached the category of significant enrichment ($EF \geq 5$), suggesting that anthropogenic influence remained limited overall (Fig. 3).

3.2.3. Geo-accumulation index (I_{geo}).

The I_{geo} results further confirmed the relatively low contamination status of the river sediments. Chromium remained in the unpolluted category ($I_{geo} \leq 0$) throughout the monitoring period. Similar conditions were observed for Zn and Cu, although a few samples approached the boundary between unpolluted and moderately polluted.

Lead exhibited slight increases during November 2024 but generally remained below the pollution threshold. Arsenic showed the highest Igeo values, with several samples classified as unpolluted to moderately polluted, particularly at YT1 and YT2 during late-year surveys. Nevertheless, Igeo values rarely exceeded Class 1, indicating that contamination was generally limited.

3.2.4. Pollution load index (*PLI*).

PLI values were mostly close to or below 1, indicating that sediment quality was generally unaffected by overall heavy metal pollution. Slightly elevated *PLI* values occurred at YT2 during 2023–2025, reflecting localized deterioration in sediment quality.

Spatially, *PLI* followed the order: YT2 > YT1 > MK.

This pattern coincided with elevated concentrations of Pb, Zn and Cu in the downstream reach, suggesting cumulative metal accumulation associated with sediment transport and downstream deposition.

3.2.5. Overall contamination pattern.

The four pollution indices consistently identified As as the dominant contaminant in the Da Bac River sediments, followed by Pb and Cu, whereas Zn and especially Cr showed relatively low contamination.

Spatial variation was also consistent among the indices. The downstream station (YT2) exhibited the highest contamination levels, while MK generally remained the least contaminated site. These findings indicate progressive downstream accumulation of sediment-associated metals but do not suggest severe sediment pollution during the monitoring period.

3.3. Potential ecological risk.

Potential ecological risk was assessed using Hakanson's ecological risk index, including the individual ecological risk factor (E_r^i) and the integrated potential ecological risk index (*PERI*).

Among the investigated metals, As contributed most to ecological risk because of its relatively high contamination factor and toxic-response coefficient ($T_r^i = 10$). Most As samples were classified as low ecological risk, while several surveys at YT2 approached the moderate-risk threshold, indicating that As is the primary ecological concern in the study area.

Lead and Cu showed lower ecological risk despite occasional concentration peaks. Their E_r^i values remained within the low-risk category for almost all samples, with temporary increases corresponding to elevated concentrations during 2023–2025.

Chromium and Zn consistently exhibited very low ecological risk. Low contamination levels combined with relatively small toxic-response factors resulted in negligible contributions to total ecological risk.

The integrated *PERI* values were consistently below 150, indicating low ecological risk according to Hakanson (1980). Although temporal fluctuations occurred, particularly during several November surveys, none of the sampling sites reached the moderate-risk category.

Spatially, *PERI* increased from upstream to downstream: YT2 > YT1 > MK.

This trend reflects the cumulative accumulation of sediment-bound metals along the river course. Elevated *PERI* values were primarily associated with increased As concentrations, while Pb and Cu contributed secondarily during several sampling campaigns (Fig. 4).

Overall, the ecological risk of the Da Bac River sediments remained low during 2020–2025. Nevertheless, the repeated contribution of As to the total ecological risk suggests that continued monitoring is warranted, particularly in downstream areas.

3.4. Spatiotemporal variation.

Heavy metal concentrations showed noticeable temporal and spatial variability during the six-year monitoring period. However, no consistent long-term increasing or decreasing trend was identified for any metal.

Temporal fluctuations became more pronounced after 2023, particularly for Pb, Zn and Cu. In contrast, Cr remained relatively stable throughout the study period, while.

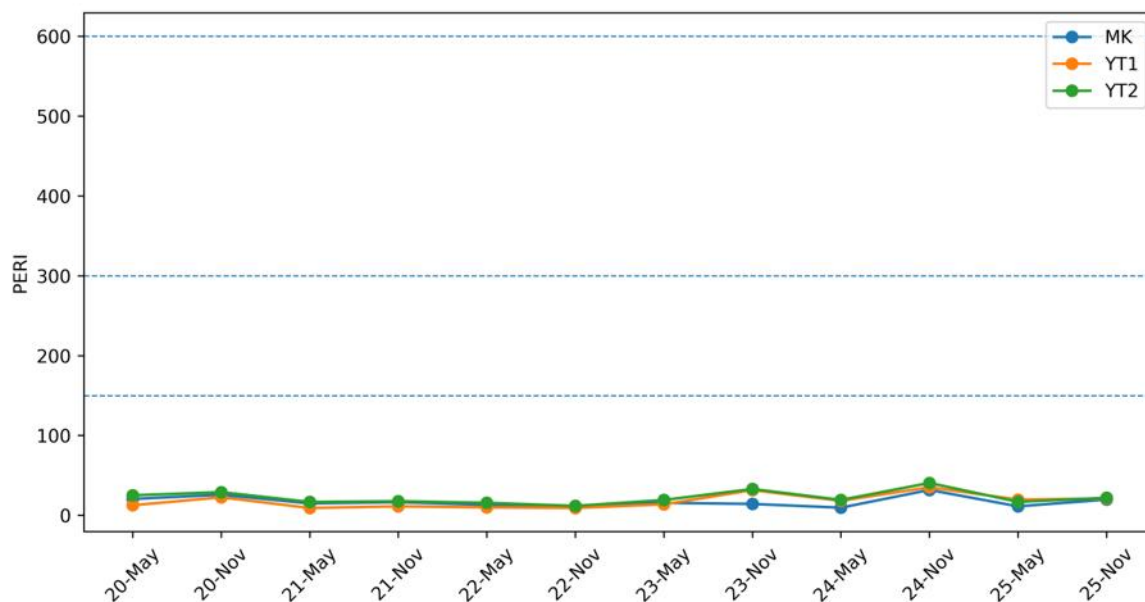


Fig. 4. Potential ecological risk index (PERI) for surface sediments of the Da Bac River.

As showed moderate interannual variation without a persistent upward trend. These patterns indicate that heavy metal inputs were episodic rather than continuous.

Seasonal differences were evident for As, Pb, Zn and Cu, with concentrations generally higher in November than in May. The contrast was particularly pronounced during 2023 and 2024. Increased runoff during the rainy season likely enhanced the transport of contaminated fine sediments from upstream areas, promoting deposition during late-year sampling. Chromium showed comparatively weak seasonal variation, suggesting stronger control by natural geological sources.

Clear longitudinal differences were also observed. MK generally recorded the lowest concentrations and the smallest temporal variability. YT1 showed intermediate conditions, whereas YT2 consistently exhibited the highest concentrations of As, Zn and Cu together with the greatest temporal fluctuations.

The downstream enrichment at YT2 is consistent with sediment transport and depositional processes. Fine particles carrying adsorbed metals tend to accumulate under lower-energy hydraulic conditions near the river outlet, while additional inputs from navigation, urban development, industrial activities and agricultural runoff further increase metal accumulation.

Overall, the Da Bac River showed moderate temporal fluctuations, distinct seasonal differences and progressive downstream accumulation of heavy metals. Although no evidence of continuous deterioration was observed during 2020–2025, recurrent increases in As, Pb, Zn and Cu at YT2 indicate localized anthropogenic influence and highlight the importance of long-term sediment monitoring.

3.5. Discussion.

3.5.1. Comparison with previous studies and possible sources.

The results indicate that heavy metal contamination in the surface sediments of the Da Bac River remained generally low during 2020–2025. Most concentrations were below the Vietnamese sediment quality guideline (QCVN 43:2025/BTNMT), although As exceeded the Canadian ISQG more frequently than the other metals. Exceedances of Pb, Cr, Zn, and Cu were less frequent and mainly occurred at specific sites or sampling periods, indicating localized enrichment rather than widespread contamination.

The overall contamination level was lower than that reported for highly urbanized or industrialized river systems. For example, substantially higher metal concentrations have been documented in the To Lich River, where untreated domestic and industrial wastewater represent major pollution sources (Thuong et al., 2015). Studies of the Red River and Saigon River also demonstrated that heavy metal distributions are strongly controlled by land use, hydrological conditions, and anthropogenic activities (Hien et al., 2016, Binh et al., 2020). Similar contamination concerns have been reported in the Cau River basin and the Red River estuary, particularly for As, Pb, and Cd (Lich et al., 2025, Ve et al., 2025).

Compared with heavily impacted rivers in Romania, China, Bangladesh, and Nigeria, the Da Bac River currently exhibits a relatively lower contamination burden (Islam et al., 2015, Iordache et al., 2022, Goodness, 2025, Olowo et al., 2025).

The combined interpretation of I_{geo} , EF , CF , PLI , and $PERI$ suggests that sediment composition is controlled mainly by natural geological materials, with additional localized anthropogenic inputs. The relatively low enrichment of Cr and Zn and EF values close to unity are consistent with a predominantly lithogenic contribution. In contrast, As showed the greatest enrichment and contributed most to the ecological risk. Its distribution may reflect the combined influence of natural geological sources and human activities within the catchment, including mining, agriculture, urban drainage, and industrial development. However, the present dataset does not allow individual sources to be identified conclusively. The higher concentrations and index values observed at YT2 are more reasonably interpreted as the result of downstream transport and deposition of fine sediment, together with cumulative inputs from the upstream catchment. The episodic Pb increase in late 2024 further suggests that short-term hydrological or anthropogenic events may influence metal accumulation.

3.5.2. Ecological and management implications.

The $PERI$ results indicate that the overall ecological risk of the investigated sediments remained low during the study period. As was the principal contributor to the total risk because of its relatively high toxic-response coefficient and repeated enrichment, whereas Pb, Cr, Zn, and Cu contributed less to the overall risk. Nevertheless, the low present-day risk should not be interpreted as the absence of future concern. Changes in redox conditions, flooding, dredging, or sediment resuspension may alter metal mobility and bioavailability.

Given the generally low contamination levels, pollution prevention and regular monitoring should be prioritized over intensive remediation. Particular attention should be given to As and downstream depositional areas. Continued application of I_{geo} , EF , CF , PLI , and $PERI$, together with expanded monitoring of elements such as Cd, Hg, and Ni, would improve long-term assessment of the Da Bac–Bach Dang river system. Future source-apportionment and biological studies would further strengthen the evaluation of ecological risks.

4. Conclusion.

This study investigated the long-term spatiotemporal distribution of As, Pb, Cr, Zn, and Cu in surface sediments of the Da Bac River, northern Vietnam, using monitoring data collected from 2020 to 2025. Sediment quality was evaluated through an integrated assessment based on the I_{geo} , EF , CF , PLI , and $PERI$.

Metal concentrations showed clear spatial and seasonal variability but no consistent long-term increasing or decreasing trend. The downstream site (YT2) generally contained higher concentrations of Zn and Cu than the upstream locations, indicating the influence of sediment transport and deposition along the river. Most measured concentrations complied with the Canadian Interim Sediment Quality Guidelines (ISQG), although As frequently and Cr occasionally exceeded their guideline values at several sampling periods.

The pollution indices consistently indicated low contamination across the study area. I_{geo} , CF , and PLI classified most sediments as unpolluted to slightly polluted, while EF values suggested that natural geological sources predominated, with only limited anthropogenic enrichment. According to Hakanson's ecological risk assessment, the overall ecological risk remained low throughout the monitoring period. Among the investigated metals, As contributed the largest proportion of the total ecological risk because of its higher toxic-response factor, whereas Pb, Cr, Zn, and Cu presented relatively minor ecological risks.

These findings indicate that sediment quality in the Da Bac River is generally good, although localized arsenic enrichment deserves continued attention. The six-year dataset provides an important baseline for future sediment monitoring and supports environmental management of the Da Bac–Bach Dang river system. Future research should expand spatial coverage, include additional priority metals such as Cd and Hg, and combine geochemical assessment with source apportionment techniques to better identify contamination sources and evaluate long-term environmental change.

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