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Heavy Metal Dynamics Across Soil And River Sediment Environments

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ABSTRACT

Heavy metal contamination remains a significant environmental concern because of its persistence, mobility, and potential ecological impacts across interconnected terrestrial and aquatic ecosystems. This study investigated heavy metal dynamics across soil and suspended river sediment environments within the Nurzec River catchment using a secondary environmental monitoring dataset collected between August 2021 and August 2022. The dataset comprised 1,240 analytical records, including 1,116 soil samples and 124 suspended river sediment samples, covering agricultural, pasture, and urban land-use categories. Concentrations of arsenic, cadmium, chromium, copper, mercury, nickel, lead, and zinc were evaluated through descriptive statistical analysis, Pearson correlation analysis, spatial assessment, and geochemical contamination indices, including the Geo-accumulation Index (Igeo) and Enrichment Factor (EF). The results demonstrated distinct differences in heavy metal distribution between soil and suspended river sediment, with sediments exhibiting greater accumulation of several metals, indicating their important role in contaminant transport and deposition. Land-use variation further influenced heavy metal occurrence, while strong positive correlations among selected metals suggested common environmental sources and transport pathways. Contamination indices supported the identification of anthropogenic enrichment and pollution intensity across the study area. Overall, the findings highlight the importance of integrating soil and river sediment assessments to better understand heavy metal behaviour within watersheds. Such an integrated approach provides valuable information for environmental monitoring, pollution management, ecological risk assessment, and the development of sustainable watershed protection strategies.

Key words: heavy metals, soil contamination, river sediment, watershed monitoring, environmental pollution

1. Introduction

One of the most persistent environmental problems is heavy metal contamination because they are not biodegradable and stay in the environment for long periods of time, concentrating in the terrestrial and aquatic environment. The transfer of these from soils to surface waters is subject to a myriad of weathering, erosion, runoff, sediment transport and human activity related interactions. This means that heavy metals may move between environmental compartments, and get deposited in river sediments, affecting the quality of ecosystem and environmental sustainability (Rajendiran, 2025; Jadaa & Mohammed, 2023). River sediments act as a repository and secondary sources of contaminants and are thus valuable indicators to assess the long-term pollution situation and contaminant mobility (Basti et al., 2024).

Heavy metals are found naturally in geological processes, but the levels have been greatly enhanced by man-made activities in many types of environments. Soils and water bodies are subjected to significant emission of metals from agricultural activities, mines, industrial emissions, urbanization, discharge of wastewater and transportation. The contaminant transfer is further aggravated by soil erosion as it carries metal laden particles into rivers where they get attached to the suspended and deposited sediments (Rashmi et al., 2022; Sharma et al., 2023; Goswami & Neog, 2023). The soil and sediment environment thus is an important pathway for the redistribution of contaminants across watersheds.

Environmental matrices can become contaminated by heavy metals, resulting in ecological and public health implications. High levels can affect soil quality, diminish agricultural yield, affect the diversity of aquatic life, and increase toxicity of food chains. Heavy metals are easily accumulated by aquatic species and can biomagnify via the food chain, and eventually reach human beings by food intake (Afzaal et al., 2022; Sarker et al., 2022). Exposure to toxic metals in the environment is linked to neurological disorders, renal function, developmental abnormalities and other health outcomes suggesting the need for continuous monitoring of the environment and monitoring of contamination (Ali et al., 2021; Munir et al., 2021).

Environmental factors such as the content of organic carbon, the redox potential, the sediment properties, and water quality parameters, also play a role in the behaviour of heavy metals. Organic matter has an influence on the adsorption, mobility, and bioavailability of metals, and indicators of organic pollution can explain the transport of contaminant in aquatic systems (Basti et al., 2024; Lv et al., 2024). In the recent years, there has been an increase in the identification of emerging contaminants like micro plastics, which are also known to act as potential vectors for heavy metals, thus facilitating their mobility and accumulation among the environmental compartments (Bhowmik & Saha, 2026). So, it is necessary to understand the heavy metal dynamics by an integrated assessment approach, instead of assessing one compartment alone.

Although there has been extensive literature on the heavy metal contamination in soils or aquatic systems, less attention has been paid to the distribution of heavy metals in linked soil and river sediment systems based on spatial consistent environmental data. Much of the research focuses on the concentration of contamination in a single environmental compartment, and does not consider the combined effect of land use, sediment transport, and environmental processes on metal redistributions. Moreover, contamination indices are often used in isolation and do not provide a complete picture of the dynamics of heavy metals (El-Sharkawy et al., 2025; Angon et al., 2024).

Thus, in the present study the dynamics of heavy metals over soil and river sediment environments are studied by utilizing a comprehensive environmental monitoring data. The study includes a comparison of the heavy metal distribution in terrestrial and aquatic compartments, an assessment of contamination characteristics based on established geochemical indicators and an analysis of spatial variation in various land-use settings. The results will be useful in understanding the movement of contaminants within a watershed, as well as enhancing monitoring, management and protection of the environment in a sustainable way.

2. Materials and Methods

2.1 Study Area

The environmental information of the Nurzec River catchment in the north-eastern part of Poland was used in this study. The catchment is made up of agricultural, pasture and urban land-use systems and it includes a range of environmental conditions and potential heavy metal contaminant sources. The study area was chosen in order to combine both terrestrial and aquatic environments in the same watershed area, thus making it possible to carry out a comparative evaluation of the distribution of heavy metals in the soils and in the suspended river sediments.

Sampling locations were chosen across the catchment to ensure variations with land use and geographical location were sampled.

2.2 Dataset Description

The analysis was done with the environmental monitoring data taken between August 2021 and August 2022 (Ziya, 2023). Totally, 1,240 analytical records (1,116 soil and 124 suspended river sediment) were collected from 10 monitoring stations. Eight elements of environmental importance were analyzed for heavy metal concentrations: arsenic (As), cadmium (Cd), chromium (Cr), copper (Cu), mercury (Hg), nickel (Ni), lead (Pb) and zinc (Zn). This data set includes elemental concentrations, sample location, land-use category, geographic coordinates, background concentrations, Geo-accumulation Index (Igeo), Enrichment Factor (EF) and laboratory detection limits. These variables allowed to make a thorough assessment of heavy metal occurrence in various environmental compartments.

2.3 Data Preparation

Data was checked for completeness, consistency and analysis prior to statistical analysis. If the same observation was duplicated, it was eliminated; and the name of the observed variable was standardized to facilitate data processing. Heavy metal concentrations were checked for the same measurement units, and the data with concentration values less than the analytical limit of quantification was replaced by half the detection limit to reduce analytical bias. It was found that there were missing values and data inconsistencies, which were evaluated and only complete observations were used for further analyses. The prepared data set was subsequently grouped by sample type, land-use category, sampling period and monitoring location.

2.4 Statistical Analysis

The distribution of the heavy metal concentrations of the soil and river suspended sediment samples was summarized using descriptive statistical analysis. Statistics were calculated for each heavy metal to give an indication of the variability of each concentration within each environmental compartment, such as mean, median, standard deviation, minimum and maximum values. The soils and river sediments were then compared to assess differences between soil and river sediment samples and differences between land-use categories. Pearson correlation analysis was used to examine the correlation between heavy metals and determine the elements with similar environmental behavior and/or possible common source. The relationships of the metals studied were evaluated based on the magnitude and direction of the correlation coefficients. All statistical analyses were carried out using Python. Data Management: The Pandas library was used for data management.Data Descriptive Statistical Calculations: NumPy was used to perform descriptive statistical calculations. Where applicable, a 95% confidence level ($p < 0.05$) was accepted as the level for statistical significance.

2.5 Contamination Assessment

Two geochemical indicators from the dataset were used to assess the heavy metal contamination. Contamination intensity assessment was done using the Geo-accumulation Index (Igeo) which identifies contamination intensity by comparing the concentration of the heavy metal measured with the background concentration of the region taking into consideration lithological variation. Elemental concentrations were normalized at background conditions using the Enrichment Factor (EF). A total score of contamination from the four indices was formed to give a general picture of contamination conditions at the sampling sites.

2.6 Spatial Analysis

The geographic coordinates given in the dataset were used to conduct spatial analysis to look at the distribution of heavy metals in the Nurzec River catchment. The sites with agricultural activities were compared with the pasture and urban sites to assess the effect of land use on heavy metal accumulation. Spatial visualization aided in the identification of contamination patterns and differences between the terrestrial soil environment and the river sediment that is suspended in the river and sampled at the monitoring station.

3. Results

3.1 Characteristics of Heavy Metal Distribution in Soil and River Sediment

In total 1,240 analytical records were used, with 1,116 of those taken from soil samples and 124 from suspended river sediment samples. The data set included various land-use types (agriculture, pasture and urban) and four sampling campaigns (August 2021–August 2022). Concentrations of a large variety of trace elements including the environmentally important heavy metals (As, Cd, Cr, Cu, Hg, Ni, Pb and Zn) were reported. All these measurements gave a detailed basis to assess the distribution of heavy metals in contrasting environmental compartments. The profile of analytical data set such as sampling environments, monitoring period, land-use classes and major heavy metals assessed in this study are summarized in Table 1. The dataset is extensive in both space (soil samples) and time (repetition of observations) and allows to compare the occurrence of heavy metals in terrestrial and aquatic ecosystems.

Table 1. Characteristics of the Dataset Used for Heavy Metal Assessment

Parameter	**Description**
Dataset source	Nurzec River Dataset
Total analytical records	1,240
Soil samples	1,116
Suspended river sediment samples	124
Sampling period	August 2021–August 2022
Land-use categories	Agricultural, Pasture, Urban
Heavy metals evaluated	As, Cd, Cr, Cu, Hg, Ni, Pb, Zn
Environmental compartments	Soil and suspended river sediment

3.2 Comparative Distribution of Heavy Metals Between Soil and River Sediment

The concentration of heavy metal showed a different distribution between soil and suspended river sediments, which is due to the difference in geochemical properties of the two environmental matrices. Soil samples were a reflection of long-term accumulation in terrestrial environments, while suspended river sediments were a reflection of transport and redistribution of metal-bearing sediment in the river system. These variations reflect how river sediments are dynamic vectors of contaminant mobilised from the surrounding catchments. A comparison of the distribution of heavy-metal concentrations in soil and suspended river sediment is displayed in Figure 1. The mean concentration of As, Cd, Cu, Hg, Pb and Zn were higher in the river sediment while Cr and Ni were higher in the soil.

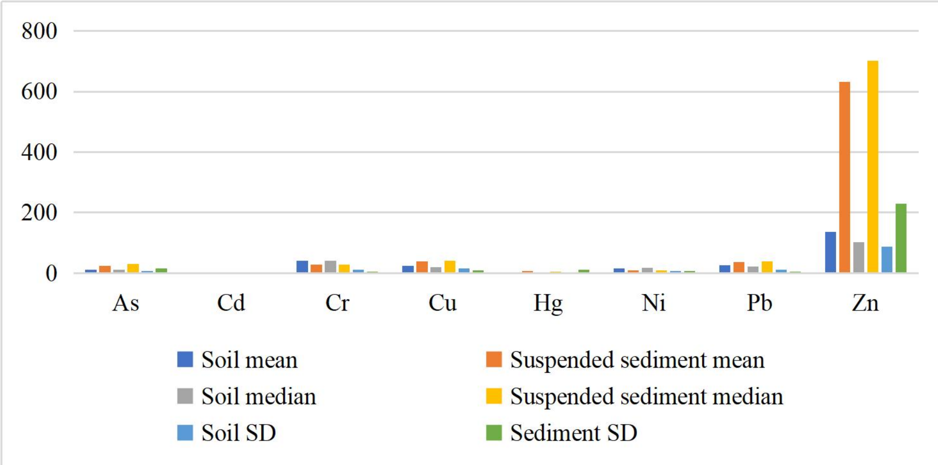

Figure 1. Comparative Distribution of Heavy Metal Concentrations in Soil and Suspended River Sediment

3.3 Spatial Variation Across Land-Use Categories

A spatial variation analysis for each land-use category was performed. The concentrations of heavy metals showed differences among agricultural, pasture, and urban areas suggesting that the land uses were the causes of the differences in contaminant accumulation. Fertilizer application and other agricultural activities are typical influences in agricultural areas, while urban locations can have other influences from domestic activities, surface runoff and traffic. The spatial variation observed in the study implies that the natural geological conditions and anthropogenic activities played their role in the occurrence of heavy metals throughout the study area. Table 2 shows the matrix which was used to compare the occurrence of heavy metals in the three land use categories which are incorporated in the data set. This comparison can be used to identify those environmental settings with a relatively high contamination potential. The locations of soil and suspended-sediment sampling points are shown in the Nurzec River study area in figure 2. There were nine stations for soils and one station at Otapy for suspended river sediment.

Table 2. Heavy Metal Assessment Across Different Land-Use Categories

Land-use category	**Environmental characteristics**	**Potential anthropogenic influence**
Agricultural	Cultivated soils	Fertilizers, pesticides, agricultural runoff
Pasture	Grassland environments	Livestock activities, natural weathering
Urban	Built-up areas	Traffic emissions, domestic runoff,

infrastructure

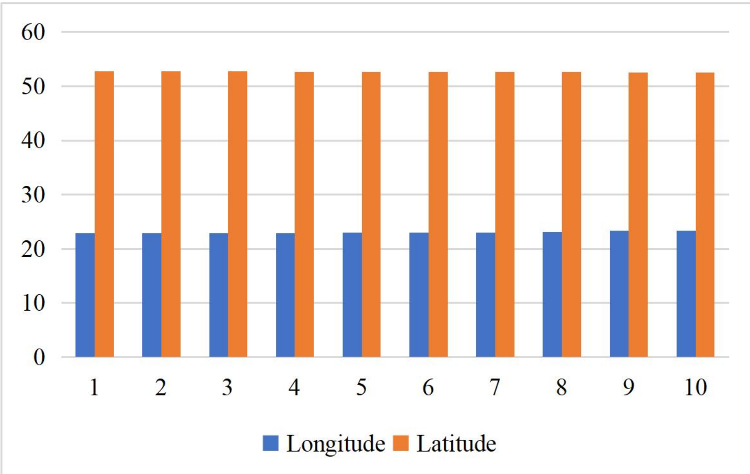

Figure 2. Spatial Distribution of Soil and River Sediment Sampling Locations

3.4 Relationships Among Heavy Metals

To assess the relationship between each of the heavy metals and to examine possible similarities in their environmental behaviour the correlation analysis was carried out. The metals with positive associations can have a common geochemical source or mobility in the same environmental processes; the weaker relationships can indicate more than one source as well as different mobility patterns. These relationships can be used to give insight into contaminant transport in both terrestrial and aquatic environments. The Pearson correlation between the heavy metals examined are presented in figure 3. The strongest positive relationship occurred between Cu and Pb ($r = 0.839$), followed by Cr and Ni ($r = 0.748$), As and Cd ($r = 0.700$), and Cu and Zn ($r = 0.655$). The associations show that some metals may share a similar source or a similar transport and/or accumulation process.

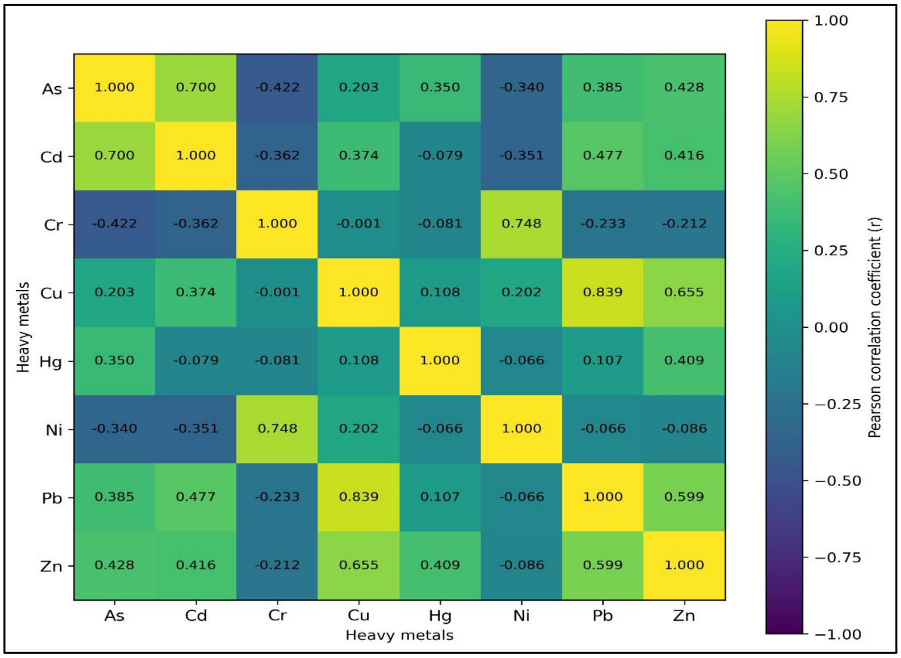

Figure 3. Pearson Correlation Heatmap of Heavy Metals

3.5 Contamination Assessment

Geochemical indices included in the dataset such as Geo-accumulation Index (Igeo) and Enrichment Factor (EF) were used to assess the contamination status of sampling sites. These indices are supplementary to the previous ones as they give information about contamination intensity and the relative contribution of anthropogenic inputs. They work together to allow for discrimination between background levels and levels in the environment. The framework for the contamination assessment used in the study is presented in Table 3. Table 3 summarizes the contamination assessment framework adopted in the study.

Table 3. Geochemical Indices Used for Heavy Metal Contamination Assessment

Index	**Purpose**	**Interpretation**
Geo-accumulation Index (Igeo)	Evaluates contamination relative to background concentrations	Indicates contamination intensity
Enrichment Factor (EF)	Assesses anthropogenic enrichment	Distinguishes natural and human-derived inputs

4. Discussion

The present study shows that there was variation in heavy metal content between suspended river sediments and soil which could be attributed to the role of environmental transport processes and land use of the watershed. Generally, the levels of several metals were higher in river sediments than in soils, suggesting that sediments serve as a significant store for contaminants that can be mobilized by runoff and erosion. This trend reinforces the idea of the continuous transfer of heavy metals from terrestrial ecosystems to aquatic ecosystems where they become attached to the suspended and deposited particles depending on the hydrological conditions (Junakova et al., 2022; Deng et al., 2026).

The high spatial variability found within the various land-use categories (agricultural, pasture and urban) also indicated the presence of more than one source of contamination in the distribution of heavy metals. Metal inputs to agricultural areas can be from fertilizers and soil amendments, while metal inputs to urban areas can be from road runoff, domestic discharge and industrial activity. High levels found in the suspended sediments suggest that the contaminants present in the sediments are being picked up from the surrounding landscapes and are being carried into river systems as surface runoff and sediment redistribution. The same can be seen for mining and rural catchments where heavy metal loading and environmental quality is strongly affected by runoff and atmospheric deposition (Chen et al., 2024; Gunasekara et al., 2025).

Several heavy metals were found to have strong positive correlation in the correlation study indicating that some may be related to each other, possibly from the same source of geochemical or anthropogenic origin. These associations tend to be related to similar transport pathways, including weathering products, soil erosion and watershed hydrological connectivity. In river catchments, the distribution and deposition of heavy metals in sedimentary environments are affected by the movement of suspended particles and dissolved contaminants, which are regulated by the ecohydrological processes. Thus, the assessment of both soil and river sediments, offers a more holistic picture of contaminant pathways than the assessment of an environmental compartment alone.

The contamination indices embedded in the data further enhanced the interpretation of the pollution condition, and the separation of background geochemical conditions from anthropogenic enrichment. These indicators help in better identification of contaminated sites, and help in environmental decision making by giving a standardized measurement of the pollution intensity. Also, geochemical indices were highlighted to be combined with source identification techniques like isotopic tracing for better understanding of contaminant sources and pathways in aquatic ecosystems (Amana & Fetahi, 2025). These integrated assessments can improve watershed management approaches, and provide a basis for targeted pollution controls.

This study's results have implications for environmental monitoring and sustainable management of watersheds. Frequent sampling of soils and river sediments helps to early identify contaminant hotspots and help understand contaminant transport between soil and river systems. The need for effective monitoring is especially high in areas under growing land-use pressure, urbanization, and alteration of climatic conditions that can lead to a faster transport of contaminants. Adaptation can also be strengthened by collaborative environmental assessment frameworks and expert consensus, which will support evidence-based management decision making to protect ecosystems over the long-term (O'Faircheallaigh, 2021; Biesbroek et al., 2026).

There are some caveats to be pointed out. Only one river sediment monitoring station was available in the data set, thus only general spatial comparisons were made to soil monitoring locations. Secondly, secondary environmental data was used and biological indicators were not included or metal bioavailability measured. However, the data set was comprehensive with all the heavy metal concentrations and contamination indices which enabled robust comparative analysis across all the environmental compartments. Additional sediment monitoring sites should be added to future studies, as well as biological assessment, source apportionment using isotopes, and long-term environmental monitoring to better understand heavy metal transport and the ecological risks. Standardized analytical methods and data interpretation are crucial, as they guarantee accurate and consistent environmental assessments and scientific results (Halpin, 2024).

5. Conclusion

The aim of this study is to make a comparative assessment of heavy metal dynamics in the two environments (soil and suspended river sediments) in the Nurzec River catchment. Results show that, the distribution of heavy metal pollutants is different among environmental compartments, suspended river sediment accumulating more quantities of several metals, which is a good indicator of pollutant transport and deposition within rivers. Spatial variations between agricultural, pasture and urban land-use categories also suggest that both natural processes and anthropogenic activities affect the occurrence of heavy metals throughout the watershed. The results of the correlation analysis showed good correlation between the selected metals, indicating possible common transport pathways and possible common contamination sources, the Geo-accumulation Index (E.G.) and Enrichment Factor (E.F.) were used to identify the pollution intensity and anthropogenic enrichment, respectively. In conclusion, the combination of the two analyses (soil and river sediment) allows a better description of the general behaviour of the heavy metals than either of the two components separately. The results highlight the need to combine both terrestrial and aquatic monitoring for a comprehensive and effective pollution assessment and watershed management. Future study should be conducted to increase monitoring networks for sediments, include biological and physicochemical indicators, and utilize new source-tracing techniques to enhance environmental risk assessment and facilitate sustainable management of contaminated ecosystems.

References

1. Afzaal, M., Hameed, S., Liaqat, I., Ali Khan, A. A., Abdul Manan, H., Shahid, R., & Altaf, M. (2022). Heavy metals contamination in water, sediments and fish of freshwater ecosystems in Pakistan. Water Practice & Technology, 17(5), 1253-1272.

2. Ali, M. M., Hossain, D., Khan, M. S., Begum, M., & Osman, M. H. (2021). Environmental pollution with heavy metals: A public health concern. In Heavy metals-their environmental impacts and mitigation. IntechOpen.

3. Amana, D., & Fetahi, T. (2025). Stable isotope-based tracing of lead (Pb) pollution in aquatic environments: Source apportionment and implications. Journal of African Earth Sciences, 105827.

4. Angon, P. B., Islam, M. S., Das, A., Anjum, N., Poudel, A., & Suchi, S. A. (2024). Sources, effects and present perspectives of heavy metals contamination: Soil, plants and human food chain. Heliyon, 10(7).

5. Basti, S., Sahu, C., Pati, S. S., & Sahu, S. K. (2024). Impact of organic carbon on heavy metals of river sediments and aquatic ecosystems: A review. Environmental quality management, 34(2), e22253.

6. Bhowmik, A., & Saha, G. (2026). Microplastics in the rural environment: Sources, transport, and impacts. Pollutants, 6(1), 3.

7. Biesbroek, R., Engbersen, D., Bonenkamp, J., Broek, E., Boon, E., Meijering, J., ... & Ebi, K. L. (2026). Expert agreement on key elements of transformational adaptation to climate risks. Nature Climate Change, 16(3), 273-280.

8. Cao, Z., Wang, S., Luo, P., Xie, D., & Zhu, W. (2022). Watershed ecohydrological processes in a changing environment: Opportunities and challenges. Water, 14(9), 1502.

9. Chen, L., Ren, B., Deng, X., Yin, W., Xie, Q., & Cai, Z. (2024). Potential toxic heavy metals in village rainwater runoff of antimony mining area, China: Distribution, pollution sources, and risk assessment. Science of the Total Environment, 920, 170702.

10. Deng, X., Chen, L., Ren, B., Xie, Q., Yin, W., & Cai, Z. (2026). Atmospheric Deposition of Trace Toxic Metal Elements (TMEs) from Weathering of a Black Shale High Geological Background Areas in the Loushao Basin, Hunan Province, China: Pollution Characteristics and a Health Risk Assessment. Sustainability, 18(11), 5522.

11. El-Sharkawy, M., Alotaibi, M. O., Li, J., Du, D., & Mahmoud, E. (2025). Heavy metal pollution in coastal environments: ecological implications and management strategies: a review. Sustainability, 17(2), 701.

12. Goswami, R., & Neog, N. (2023). Heavy metal pollution in the environment: impact on air quality and human health implications. In Heavy metal toxicity: Environmental concerns, remediation and opportunities (pp. 75-103). Singapore: Springer Nature Singapore.

13. Gunasekara, M. I., Mahawaththa, I., Madhubhashini, D., & Amarasena, K. (2025). Pollution from land-based sources: industrial and urban runoff. Coastal and marine pollution: source to sink, mitigation and management, 27-44.

14. Halpin, S. N. (2024). Inter-coder agreement in qualitative coding: Considerations for its use. American Journal of Qualitative Research, 8(3), 23-43.

15. Jadaa, W., & Mohammed, H. (2023). Heavy metals–definition, natural and anthropogenic sources of releasing into ecosystems, toxicity, and removal methods–an overview study. Journal of Ecological Engineering, 24(6), 249-271.

16. Junakova, N., Junak, J., & Balintova, M. (2022, September). The effect of physicochemical properties of bottom sediments on nitrogen and phosphorus sorption. In IOP Conference Series: Materials Science and Engineering (Vol. 1252, No. 1, p. 012059). IOP Publishing.

17. Lv, Z., Ran, X., Liu, J., Feng, Y., Zhong, X., & Jiao, N. (2024). Effectiveness of chemical oxygen demand as an indicator of organic pollution in aquatic environments. Ocean-Land-Atmosphere Research, 3, 0050.

18. Munir, N., Jahangeer, M., Bouyahya, A., El Omari, N., Ghchime, R., Balahbib, A., ... & Shariati, M. A. (2021). Heavy metal contamination of natural foods is a serious health issue: A review. Sustainability, 14(1), 161.

19. O'Faircheallaigh, C. (2021). Explaining outcomes from negotiated agreements in Australia and Canada. Resources Policy, 70, 101922.

20. Rajendiran, D. (2025). Heavy metals on the move: from land to water: sources and transfer dynamics. In Global Perspectives of Toxic Metals in Bio Environs: Volume 1: Environmental Impact, Ecotoxicology, Health Concerns, and Modelling (pp. 85-108). Cham: Springer Nature Switzerland.

21. Rashmi, I., Karthika, K. S., Roy, T., Shinoji, K. C., Kumawat, A., Kala, S., & Pal, R. (2022). Soil erosion and sediments: a source of contamination and impact on agriculture productivity. In Agrochemicals in soil and environment: Impacts and remediation (pp. 313-345). Singapore: Springer Nature Singapore.

22. Sarker, A., Kim, J. E., Islam, A. R. M. T., Bilal, M., Rakib, M. R. J., Nandi, R., ... & Islam, T. (2022). Heavy metals contamination and associated health risks in food webs—a review focuses on food safety and environmental sustainability in Bangladesh. Environmental Science and Pollution Research, 29(3), 3230-3245.

23. Sharma, A., Grewal, A. S., Sharma, D., & Srivastav, A. L. (2023). Heavy metal contamination in water: consequences on human health and environment. In Metals in water (pp. 39-52). Elsevier.

24. Ziya. (2023). Heavy Metal Soil Data for Predictive Analysis [Data set]. Kaggle. https://www.kaggle.com/datasets/ziya07/soil-heavy-metal