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Heavy Metal Pollution and Spatial Distribution in Surface Water and Sediments of Dhamrai Upazila, Bangladesh

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Abstract

Rapid industrialization is transforming Dhamrai Upazila into a suburban hub near capital, Dhaka, with predominantly unplanned development. Industrial effluents are discharged into the Banshi, Gazikhali, and Dhaleswari Rivers, raising concerns about contamination, particularly heavy metals. This study investigated the spatial distribution and pollution assessment of heavy metals (Cr, Mn, Fe, Co, Ni, Cu, Cd, Pb, As, and Al) in surface water and sediments using the Heavy Metal Pollution Index (HPI), Geo-accumulation Index (Igeo), Contamination Factor (CF), and Pollution Load Index (PLI). Seven surface water samples and corresponding sediment samples (15 cm and 60 cm depths) were collected from upstream to downstream locations and analyzed using an inductively coupled plasma mass spectrometer (ICP-MS). Mean heavy metal concentrations decreased in the order of Fe > Mn > Cu > As > Ni > Pb > Cr > Cd in water and Mn > As > Cr > Cu > Pb > Ni > Co > Al > Fe > Cd in sediments. The HPI indicated largely unpolluted surface water, whereas the Igeo revealed moderate to extreme contamination. The CF indicated moderate to very high contamination, whereas the PLI suggested polluted conditions. The Igeo classified sediments as uncontaminated to extremely contaminated, particularly for As, Pb, Cd, and Cu. Similarly, CF indicated moderate to very high contamination at 15 cm, while PLI confirmed sediment pollution at both depths, with lower contamination at 60 cm. Correlation analysis and PCA indicated that Fe, Mn, and Al were primarily of geogenic origin, whereas Cr, Co, Ni, Cu, Cd, and Pb were mainly derived from anthropogenic sources. Although As is primarily geogenic in Bangladesh, its elevated concentrations and statistical association with anthropogenic metals suggest both geogenic and anthropogenic influences. These findings emphasize the need for effective pollution control through industrial effluent treatment, wastewater management, agricultural runoff control, and integrated river basin management (IRBM) in the study area.

Keywords

Anthropogenic Contamination, Contamination Factor, Geo-Accumulation Index, Heavy Metal, Pollution Load Index, Heavy Metal Pollution Index

1. Introduction

In recent decades, heavy metal contamination of sediments has emerged as a significant environmental issue in many developing countries (e.g., Bangladesh, India, China, Malaysia) due to accelerated urbanization and industrial growth (Selvaraj et al., 2004; Hossain et al., 2015; Khan et al., 2017; Duncan et al., 2018). Rivers, floodplains, and associated sedimentary systems are particularly vulnerable because they receive continuous inputs of industrial effluents, urban runoff, agricultural discharge, and municipal waste. In addition, Natural (geogenic) processes also contribute to background metal enrichment. Heavy metals are of particular concern due to their persistence, non-biodegradable nature, and toxicity, which promote accumulation in sediments and aquatic biota and facilitate their transfer through the food chain (Bhuyan et al., 2019). In Bangladesh, industrial effluents, especially from textile, dyeing, and spinning industries, represent major sources of metal contamination, resulting in elevated concentrations of toxic elements in surface water and sediments (Islam et al., 2015; Bhuyan et al., 2019). The continuous discharge of untreated wastewater into natural water bodies further degrades water quality and enhances metal bioaccumulation, thereby posing significant ecological and public health risks (Bhuyan et al., 2019).

Dhamrai Upazila is undergoing rapid urbanization and industrialization, transforming it into a peri-urban hub largely driven by its strategic proximity to the capital city. Unplanned expansion coupled with the continuous discharge of untreated industrial effluents into the Banshi, Gazikhali, and Dhaleswari rivers is accelerating pollution levels and degrading environmental quality. These processes pose increasing threats to surface water, soils, sediments, and groundwater systems in the surrounding region. Hydrogeochemically, contaminants introduced into surface water and sediments can migrate through infiltration and leaching processes, creating vertical and lateral pollutant transport pathways. Over time, these processes increase the risk of contaminant transfer into underlying aquifers, thereby threatening groundwater quality and long-term water security. Therefore, the cumulative contamination of surface water and sediments represents not only an ecological problem but also a serious risk to drinking water safety, agricultural sustainability, and regional environmental resilience. Heavy metals disrupt aquatic ecosystems, reduce soil fertility, degrade water quality, and adversely affect fisheries and biodiversity. Their persistence in sediments ensures long-term bioavailability and increases the risk of bioaccumulation within the food chain, ultimately threatening human health through contaminated fish and crops (Bhuyan et al., 2019). Furthermore, the degradation of river systems also reduces

their ecological and socio-economic value, thereby undermining sustainable resource management and community livelihoods.

Several studies have investigated heavy metal contamination in river systems across Bangladesh. Akbor et al. (2020) examined heavy metal pollution in both surface water and sediments of the Buriganga River -one of the most polluted rivers in Dhaka- using pollution indices and ecological risk assessment to evaluate contamination levels and identify pollution sources through principal component analysis. Similarly, Kabir et al. (2020) assessed sediment contamination resulting from rapid urbanization and industrialization in Bangladesh, highlighting sediments as both sinks and secondary sources of pollutants using pollution indices and multivariate statistical techniques. Despite a growing number of studies on heavy metal contamination in river water and sediments of Bangladesh, several important knowledge gaps remain. Most previous investigations have focused exclusively on either surface water or surface sediments and have generally relied on single-layer sediment samples, without considering the vertical distribution of contaminants. Furthermore, many studies have used Upper Continental Crust (UCC) values as geochemical background references for calculating pollution indices. In the absence of established regional geochemical background values, some studies have also used the least contaminated or comparatively fresh samples as local background references. Since no regional background values are currently available for Bangladesh, the present study adopted UCC and Canadian Sediment Quality Guidelines (SQG) values to represent the natural geogenic background to evaluate potential ecological risks and distinguish between geogenic and anthropogenic contributions. In addition, by investigating heavy metal concentrations in sediment samples collected at two depths (15 cm and 60 cm), this study represents an initial effort to establish baseline geochemical information that may contribute to the development of regional background values for future environmental monitoring and pollution assessment in Bangladesh. Similarly, most previous investigations have assessed surface water contamination primarily by comparing measured metal concentrations with drinking water quality standards, without considering the specific ecological functions and natural geochemical variability of river systems. In Bangladesh, groundwater is the main source of drinking water, whereas surface water is predominantly used for irrigation, fisheries, and sustaining aquatic ecosystems. In the absence of regional reference values, some studies have used drinking water standards or least-contaminated sites as background conditions. Therefore, these two standards may not provide an appropriate framework for evaluating surface water contamination and ecological risks. Furthermore, established regional baseline values for surface water quality are currently unavailable in Bangladesh, creating challenges in distinguishing natural background conditions from anthropogenic metal enrichment. In the present study, World Average River values and Water Quality Guidelines (WQG) are used as global geochemical references applied to assess potential ecological risks. This approach provides a more comprehensive evaluation of surface water contamination

by integrating global reference values and ecological threshold limits. The generated dataset represents an important contribution toward establishing baseline surface water quality information and may support future monitoring programs and the development of regional reference values for river systems in Bangladesh.

The present study aims to assess the concentration of heavy metals in surface water and sediments, investigate their spatial distribution, and evaluate contamination levels using various pollution indices. Additionally, the study seeks to identify potential sources of heavy metal pollution and highlight areas of environmental concern. Furthermore, the study aims to differentiate between geogenic and anthropogenic sources of heavy metal pollution and to provide informed recommendations to support mitigation strategies, environmental management, and relevant policy interventions. In addition, this study contributes to the development of site-specific reference baseline values for heavy metals in surface water and sediments for long-term environmental monitoring and sustainable water resource management in Bangladesh.

2. Materials and Methods

2.1. Study Area

The study was conducted in Dhamrai Upazila, an administrative unit under Dhaka District, which is located in the central region of Bangladesh (**Figure 1**). It is located approximately 40 km northwest of Dhaka, the capital of Bangladesh. Geographically, Geographically, Dhamrai Upazila extends between 23˚48' - 24˚03' N and 90˚00' - 90°16' E, covering an area of approximately 307.14 km^2. It is bordered by Mirzapur, Kaliakair, and Nagarpur to the north; Singair to the south; Savar to the east; and Saturia to the west. Physiographically, the study area is located on the Brahmaputra-Jamuna Floodplain, one of the major Holocene fluvial depositional environments in Bangladesh. The study area is characterized by gently undulating, low-relief topography, with elevation varying by up to 5 m. The major rivers in the study area are Bangshi, Dhalashwari, and Gazikhali. The Bangshi River forms the northern and eastern boundaries of the study area, whereas the Dhaleswari River defines its southern boundary. The Gazikhali River flows through the central part of the upazila. The surface sediments of the Dhamrai Upazila are mainly composed of recent alluvial deposits, comprising dark gray to light gray and grayish-brown clay, silty clay, and silt. Hydrogeologically, the area is characterized by shallow alluvial aquifers that are hydraulically connected to adjacent rivers and floodplain sediments.

2.2. Sampling and Sample Preparation

Samples were collected from seven stations of the study area from upstream to downstream. At each station, one surface water sample and two sediment samples (collected at depths of 15 cm and 60 cm) were obtained. The sample locations are shown in **Figure 1**. All samples were collected between February and March, corresponding to the pre-monsoon season in Bangladesh. This period was selected

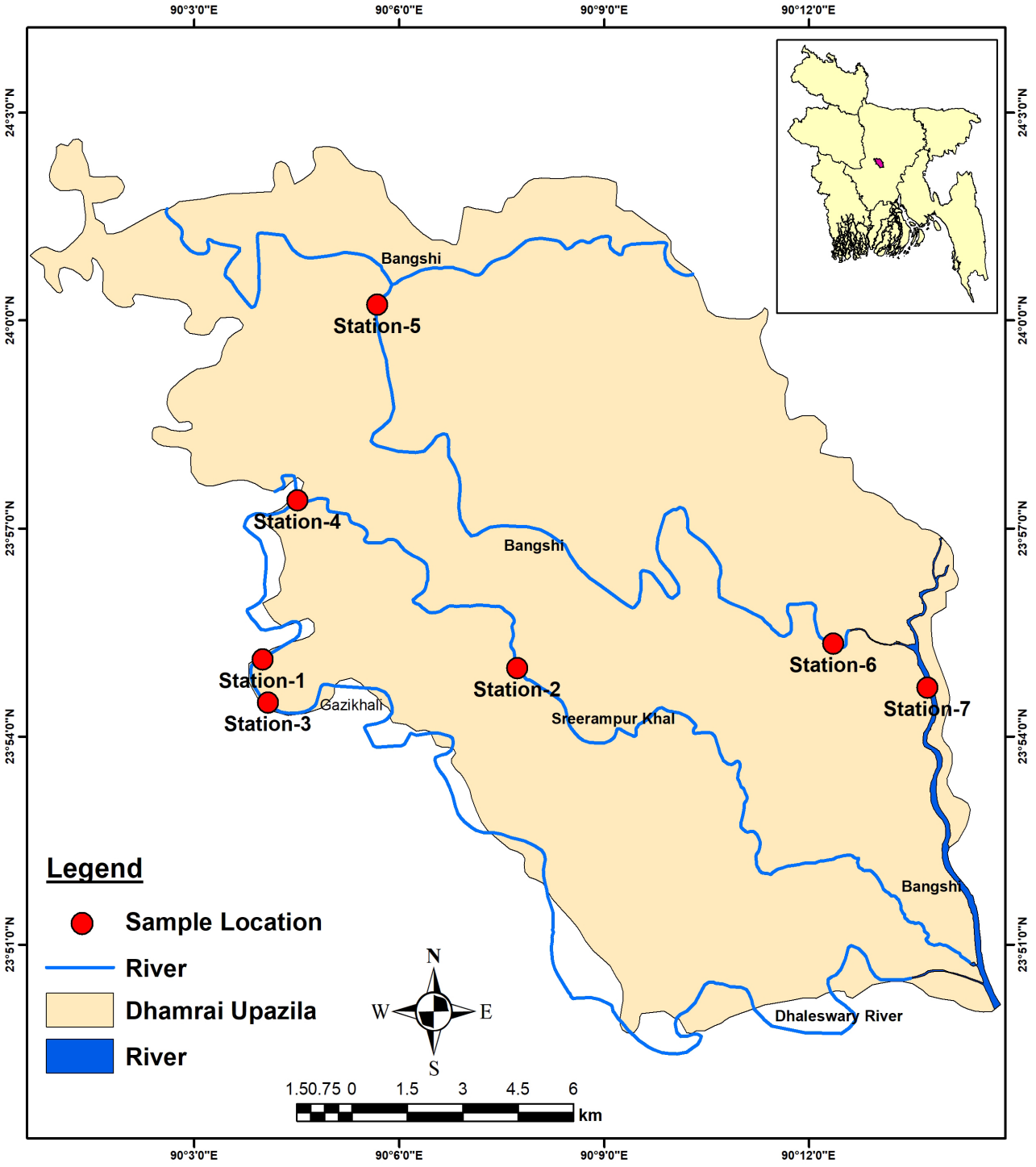

Figure 1. Location map of the study area with sample locations.

because river flow is relatively stable and less affected by monsoon induced dilution. Sediment samples were collected at 15 cm and 60 cm depths to investigate the vertical distribution of heavy metals. The 15 cm depth was selected to avoid the biologically active surface layer, where recent organic matter accumulation, biological disturbance, and anthropogenic debris (e.g., garbage and other surface

materials) may influence metal concentrations. The 60 cm depth represented a deeper sediment layer and was selected to evaluate the downward migration (leaching) and accumulation of heavy metals over time, thereby providing insight into vertical enrichment patterns and the long-term behavior of contaminants within the sediment profile. The collected water samples were generally muddy to blackish in color and exhibited a rotten egg odor. The sediment samples consisted predominantly of light to dark gray clay and silty clay. The clay sometimes showed a soft and sticky nature. The water samples were collected in high-density polyethylene bottles pre-cleaned and conditioned with 20% HNO_3 in the lab. Each bottle was rinsed three times before sample collection, with sampling water immediately before filling up, and then filtered to remove large particles using filters. All the collected water samples were treated with conc. HNO_3 acid to keep the pH value below 2. The bottles were labelled accordingly (SW-1 to SW-7) and stored in a refrigerator at 4˚C, and transported to the laboratory in an ice box. Sediment samples were collected using a hand auger with minimal disturbance and sealed in airtight polyethylene bags. The collected samples were dried at room temperature and pulverized using a mortar and pestle before digestion and geochemical analysis in the laboratory.

2.3. Laboratory Procedures

The concentrations of Mn, As, Cr, Cu, Pb, Ni, Co, Al, Fe, and Cd were determined using a NexION 1100 Inductively Coupled Plasma Mass Spectrometer (ICP-MS) at the Geological Survey of Bangladesh (GSB) laboratory. The instrument parameters were optimized to ensure high sensitivity and accurate quantification, particularly for elements prone to polyatomic interferences, such as REEs and PGEs (Gupta & Kapoor, 2018). For sediment sample digestion, finely grind (<63 μm) samples (0.2 g) were used with a three-acid mixture of hydrofluoric acid (HF), nitric acid (HNO_3), and perchloric acid ($HClO_4$) following protocols adapted from the USGS (Taggart, 2002) and EPA Method 3052 (United States Environmental Protection Agency, 1998). This digestion procedure provided near-total dissolution of silicate-rich matrices, enabling comprehensive elemental analysis. Approximately 0.2 g of each powdered sample was placed in a Teflon beaker, and the acids were added sequentially (HF, then HNO_3, then $HClO_4$) under controlled conditions until near dryness. The residue was re-dissolved in 2 mL of concentrated HNO_3, followed by the addition of 20 mL of 2% HNO_3 for dilution. The final solution was filtered through a 0.45 μm membrane filter and brought to a final volume of 100 mL with 2% HNO_3. The resulting solutions were stored in acid-washed containers and analyzed by ICP-MS for trace, rare earth, and platinum group elements. Surface water samples did not require acid digestion because they had been filtered and preserved immediately after collection. The samples were acidified with concentrated HNO_3 to maintain the pH below 2 and stored at 4˚C until analysis. The preserved samples were analyzed directly by ICP-MS for the determination of dissolved trace elements. To ensure data accuracy, precision, and in-

strument stability, a rigorous quality control (QC) protocol was employed throughout the ICP-MS analysis. This protocol incorporated both initial and ongoing QC checks using repeated measurements of calibration blanks and a mid-range calibration standard. Such a protocol follows best practices recommended in environmental and analytical standards (United States Environmental Protection Agency, 1998; Thomas, 2004). The instrument calibration was initially conducted using a multi-point calibration curve for each analyte, covering a range from the detection limit to an upper concentration expected in samples. The calibration curve was constructed by measuring standard solutions at known concentrations, establishing linearity with a correlation coefficient (R^2) of ≥0.999, as recommended for trace metal analysis (Gupta & Kapoor, 2018). Calibration standards were prepared by serial dilution of multi-element standard solutions (Sigma-Aldrich 54704) for trace elements. 1% HNO_3 solution was used as the calibration blank. This solution was prepared with high-purity nitric acid and deionized water to minimize potential contaminants. The calibration blank (0 µg/L for all analytes) was measured 10 times at the beginning of the analysis to establish a baseline and confirm the absence of contamination or carryover effects. Each calibration blank measurement was used to evaluate the instrument's zero-point stability and background noise. The average calibration blank value and its standard deviation were calculated, and a threshold of the average ± 3σ was set to identify acceptable blank variation. Calibration blanks help detect potential contamination or systematic errors (Crock et al., 1983). A mid-range calibration standard was measured periodically (after every 10 samples) to assess instrument stability throughout the run, serving as a Continuing Calibration Verification (CCV) check. This procedure was used to monitor instrumental sensitivity and analytical drift throughout the analytical sequence. If the measured concentration of the CCV standard deviated by more than ±5% from its certified value, the instrument was recalibrated before further sample analysis.

2.4. Calculation of Environmental Pollution Indices

Several widely used pollution indices were applied to evaluate heavy metal contamination in the collected surface water and sediment samples. These are the Index of geo-accumulation (Igeo) (Tabelin et al., 2020; Bantan et al., 2020), Contamination factor (CF) (Hakanson, 1980; Abrahim & Parker, 2008; Tomlinson et al., 1980), Pollution load index (PLI) (Odat, 2015), and Heavy metal pollution index (HPI) (Mohan et al., 1996). The Upper Continental Crust (UCC) values were used as the geochemical background for sediment quality assessment, whereas the Water Quality Guidelines (WQGs) for the protection of aquatic life were used as reference values for evaluating heavy metal contamination in surface water.

2.4.1. Index of Geo-Accumulation (Igeo)

The Igeo index is widely used to evaluate sediment quality and/or the degree of contamination in geologic materials. This index is calculated from the following equation (Müller, 1969):

$$\text{Igeo} = \log 2\left(\text{Cn}/1.5\text{Bn}\right). \quad (1)$$

where Cn is a measured heavy metal concentration of a given sediment sample, and Bn is the geochemical background. Factor (1.5) is the background matrix correction factor due to lithological differences. The Igeo index consists of seven grades or classes (Müller, 1969). Class 0 (practically uncontaminated): Igeo ≤ 0; Class 1 (uncontaminated to moderately contaminated): 0 < Igeo < 1; Class 2 (moderately contaminated): 1 < Igeo < 2; Class 3 (moderately to heavily contaminated): 2 < Igeo < 3; Class 4 (heavily contaminated): 3 < Igeo < 4; Class 5 (heavily to extremely contaminated): 4 < Igeo < 5; Class 6 (extremely contaminated): Igeo > 5. However, Class 6 is an open class and comprises all values of the Igeo index greater than Grade 5 (Müller, 1969).

2.4.2. Contamination Factor (CF)

The CF (Müller, 1969) is widely used to calculate the PLI value. The CF ratio value is calculated by dividing the concentration of each metal in the sediments by the baseline/background value taken from fresh materials (Müller, 1969):

$$\text{CF} = \text{C}_{\text{metal}}/\text{C}_{\text{background value}} \quad (2)$$

where C_{metal} = metal concentration is taken from the sediment sample, $\text{C}_{\text{background value}}$ = geochemical background/baseline value of the metal. The CF index consists of four major categories to express the metal contamination factor (Müller, 1969; Khan et al., 2017): CF < 1 refers to the low contamination factor; 1 ≤ CF < 3 refers to the moderate contamination factor; 3 ≤ CF < 6 refers to the considerable contamination, and CF > 6 denotes a very high contamination factor.

2.4.3. Pollution Load Index (PLI)

The PLI is commonly used to assess the pollution level of heavy metals in the natural environment (Tomlinson et al., 1980; Bhuiyan et al., 2010; Bentum et al., 2011; Hossain et al., 2015). The PLI value is estimated using the equation:

$$\text{PLI} = \sqrt[n]{\left(\text{CF1}\times\text{CF2}\times\text{CF3}\times\cdots\times\text{CFn}\right)}. \quad (3)$$

where C_{metal} = metal concentration is taken from the sediment sample, $\text{C}_{\text{background value}}$ = geochemical background/baseline value of the metal, and n = total number of metals. The PLI > 1 implies heavy metal pollution, and PLI < 1 shows no pollution (Hakanson, 1980; Tomlinson et al., 1980).

2.4.4. Heavy Metal Pollution Index (HPI)

The Heavy Metal Pollution Index (HPI) is a highly effective framework used to evaluate the overall quality of water by assessing its heavy metal content. This method assigns a specific rating or weightage (W_i) to each metal under consideration.

To determine the HPI for the river water samples, the following mathematical model was applied (Mohan et al., 1996):

$$\text{HPI} = \frac{\sum_{i=1}^{n}\left(Q_i W_i\right)}{\sum_{i=1}^{n} W_i} \quad (4)$$

where, Q_i represents the sub-index of the ith parameter, W_i represents the unit weightage of the ith parameter, n is the total number of heavy metal parameters considered.

The sub-index (Q_i) for each individual metal parameter is calculated using the following equation:

$$Q_i = \sum_{i=1}^{n} \frac{|M_i - I_i|}{S_i - I_i} 100 \tag{5}$$

where M_i is the actual monitored (detected) concentration of the ith heavy metal, I_i is the ideal (permissible) value for the ith heavy metal, S_i is the standard allowable limit for the ith heavy metal, $M_i - I_i$ denotes the absolute numerical difference between the monitored and ideal values, ignoring the algebraic sign. HPI < 100 suggests unpolluted and HPI > 100 implies a polluted condition (Prasad & Bose, 2001).

2.5. Statistical Analyses

Spatial dissemination and pollution of surface water and sediments were examined by statistical correlation and principal component analysis (PCA). The PCA with varimax normalization is commonly used as a tool to identify anthropogenic or natural source identification in sediments or soils (Rubio et al., 2000; Gotelli & Ellison, 2004; Zhou et al., 2008; Chabukdhara & Nema, 2013; Yuan et al., 2014; Hossain et al., 2015). The analytical data were statistically processed using the Minitab statistical software package version 21.0 for Windows. Pearson's correlation coefficients were calculated to evaluate the relationships among heavy metals and to support the interpretation of the multivariate statistical analyses.

3. Result and Discussion

3.1. Distribution of Heavy Metal Concentrations in Surface Water and Sediments

The concentrations of heavy metals (Cr, Mn, Fe, Co, Ni, Cu, Cd, Pb, As, Al) in surface water and corresponding sediment samples collected at depths of 15 cm and 60 cm are presented in **Tables 1-3**. Heavy metal concentrations in surface water decreased in the order of Fe > Mn > Cu > As > Ni > Pb > Cr > Cd. In sediments, the concentration order was Mn > As > Cr > Cu > Pb > Ni > Co > Al > Fe > Cd, at both 15 cm and 60 cm depths. Because site-specific and national background values for heavy metals are unavailable for the study area, the measured concentrations were compared with internationally recognized reference values. For surface water, World Average (River) data and Water Quality Guidelines (WQG, Canada) for protection of aquatic life were used as reference data. Similarly, for sediments, the Upper Continental Crust (UCC) values and the Canadian Sediment Quality Guidelines (SQGs) were used as geochemical background and sediment quality reference values, respectively. As the Sediment Quality Guidelines (SQG) do not provide reference values for all measured elements, only the available guideline values were used to assess sediment contamination in this study.

Table 1. Concentration values of heavy metals in surface water.

Surface water samples									
Sample	Cr (µg/L)	Mn (µg/L)	Fe (µg/L)	Co (µg/L)	Ni (µg/L)	Cu (µg/L)	As (µg/L)	Cd (µg/L)	Pb (µg/L)
SW-1	1.01	150.21	1556.17	0.48	3.99	13.69	35.87	0.01	1.35
SW-2	3.82	610.44	1899.56	0.62	4.91	54.17	4.28	0.01	0.81
SW-3	5.48	1730.07	5020.73	1.03	12.49	81.68	25.33	1.73	18.80
SW-4	0.23	53.16	1903.83	0.47	4.61	3.77	36.46	0	0.42
SW-5	0.20	42.11	1801.79	0.45	5.78	3.40	95.95	0	0.93
SW-6	5.91	650.58	1443.01	1.74	7.73	30.37	5.10	0.07	4.42
SW-7	7.36	380.38	1446.77	2.13	4.64	21.61	4.08	0.06	2.56
Minimum	0.20	42.11	1443.01	0.45	3.99	3.40	4.08	0	0.42
Maximum	7.36	1730.07	5020.73	2.13	12.49	81.68	95.95	1.73	18.80
Mean (n = 7)	3.43	516.71	2153.12	0.99	6.31	29.81	29.58	0.27	4.18
SD	2.74	546.67	1185.18	0.64	2.77	26.69	30.24	0.60	6.10
World Average (River)	0.7	34	66	0.148	0.801	1.48	0.62	0.08	0.079
WQG (Canada) for the protection of aquatic life	2	430	300	0.148	25	2	5	0.09	1

Table 2. Concentration values of heavy metals in Sediments (15 cm).

Sediments at 15 cm										
	Al (%)	Cr (mg/kg)	Mn (mg/kg)	Fe (mg/kg)	Co (mg/kg)	Ni (mg/kg)	Cu (mg/kg)	Cd (mg/kg)	Pb (mg/kg)	As (mg/kg)
SSU-1	9.03	76.92	1182.02	4.59	17.23	50.80	104.69	0.34	79.22	346.31
SSU-2	9.66	86.07	1022.08	4.99	19.63	54.97	51.53	0.15	37.48	53.40
SSU-3	11.35	91.86	1239.06	5.45	21.81	61.39	60.91	0.21	77.00	285.31
SSU-4	10.50	84.45	1253.84	5.21	19.50	55.14	52.95	0.15	60.04	207.94
SSU-5	8.54	59.72	1014.28	4.24	15.14	40.31	33.54	0.11	32.47	53.17
SSU-6	9.95	76.18	228.45	4.78	6.61	41.28	27.49	0.08	30.50	58.74
SSU-7	10.36	76.65	1328.59	4.83	17.77	49.99	44.18	0.15	47.93	54.46

Continued

Minimum	8.54	59.72	228.45	4.24	6.61	40.31	27.49	0.08	30.50	53.17
Maximum	11.35	91.86	1328.59	5.45	21.81	61.39	104.69	0.34	79.22	346.31
Mean (n = 7)	9.91	78.84	1038.33	4.87	16.81	50.55	53.61	0.17	52.09	151.33
SD	0.87	9.52	348.13	0.37	4.60	7.06	23.42	0.08	18.91	117.32
UCC	8.15	92	775	3.92	17.3	47	28	0.09	17	4.8
SQG Canada (Freshwater)	-	37.3	-	-	-	18	35.7	0.6	35	5.9

Table 3. Concentration values of heavy metals in Sediments (60 cm).

	Sediments at 60 cm									
	Al (%)	Cr (mg/kg)	Mn (mg/kg)	Fe (mg/kg)	Co (mg/kg)	Ni (mg/kg)	Cu (mg/kg)	Cd (mg/kg)	Pb (mg/kg)	As (mg/kg)
SSL-1	9.21	63.03	1014.71	4.06	14.66	43.62	44.15	0.14	56.44	208.07
SSL-2	9.28	56.79	954.97	4.34	14.43	40.15	36.35	0.15	48.62	58.49
SSL-3	12.13	75.32	871.51	4.67	16.57	53.20	50.57	0.16	71.35	183.69
SSL-4	9.16	66.82	1035.90	4.29	14.93	43.36	38.51	0.13	29.69	50.78
SSL-5	8.77	48.90	900.41	3.81	13.15	34.12	28.58	0.09	28.77	47.09
SSL-6	6.97	36.59	1670.91	2.61	11.79	22.43	23.10	0.12	28.90	57.53
SSL-7	9.75	58.35	986.16	4.00	13.69	39.35	36.32	0.14	38.54	82.83
Minimum	6.97	36.59	871.51	2.61	11.79	22.43	23.10	0.09	28.77	47.09
Maximum	12.13	75.32	1670.91	4.67	16.57	53.20	50.57	0.16	71.35	208.07
Mean (n = 7)	9.32	57.97	1062.08	3.97	14.17	39.46	36.80	0.13	43.19	98.35
SD	1.41	11.62	254.47	0.61	1.39	8.79	8.47	0.02	15.19	62.91
UCC	8.15	92	775	3.92	17.3	47	28	0.09	17	4.8
SQG Canada (Freshwater)	-	37.3	-	-	-	18	35.7	0.6	35	5.9

3.2. Risk Assessment of Heavy Metal Concentrations of Water and Sediment Samples

For heavy metal risk assessment of surface water samples, Igeo, CF, PLI, and HPI have been calculated. Although the Igeo was originally developed for contaminated sediments and sediments in aquatic environments (Müller, 1969), the present study, has tried to get an idea to compare Igeo for both surface water and

sediment samples, which is applied as a comparative indicator to use surface water quality guideline values as reference concentrations. Based on Igeo values most samples ranged from moderately contaminated ($1 < \text{Igeo} \leq 2$) to heavily contaminated ($3 < \text{Igeo} \leq 4$), with some sites indicating extreme contamination (Igeo > 5) (Figure 2). In contrast, Cd and Ni exhibited uncontaminated conditions (Igeo ≤ 0) at some sampling sites. CF values indicated contamination levels ranging from moderate ($1 \leq \text{CF} < 3$) to very high (CF ≥ 6). Likewise, all collected samples clearly indicated a polluted condition (PLI > 1) in the PLI analysis. In contrast, the majority of samples are classified as unpolluted (HPI < 100) in the HPI analysis, except for one sample that stands out as polluted (HPI ≥ 100).

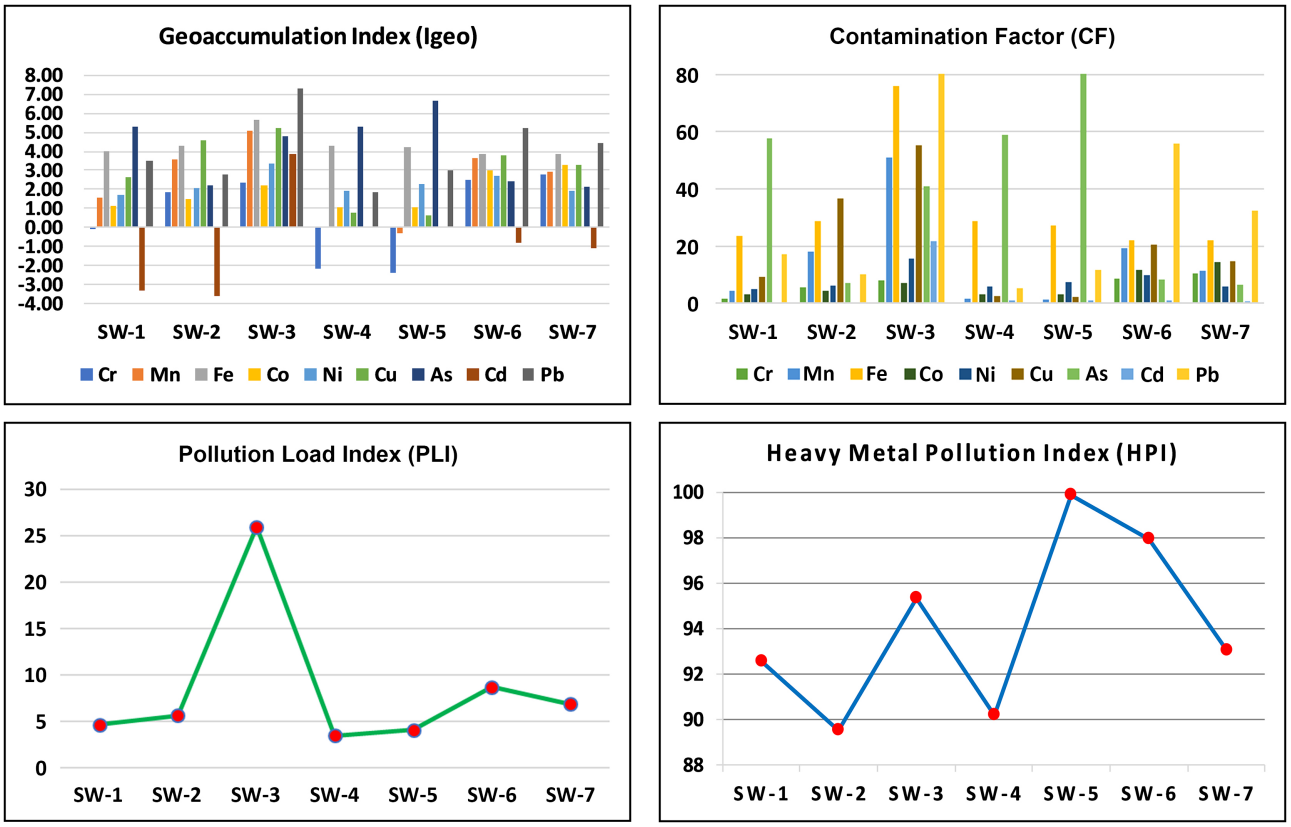

Figure 2. Graphical representation of Igeo, CF, PLI, and HPI of surface water samples.

Sediment samples collected from both 15 cm and 60 cm were used to analyze heavy metal risk assessment by Igeo, CF, and PLI calculation. At a depth of 15 cm, the Igeo values indicated contamination levels ranging from uncontaminated ($\text{Igeo} \leq 0$) to moderately contaminated ($1 < \text{Igeo} \leq 2$). However, arsenic (As) exhibited considerably higher contamination, ranging from heavily contaminated ($3 < \text{Igeo} \leq 4$) to extremely contaminated (Igeo > 5). Similarly, CF values indicated moderate contamination ($1 \leq \text{CF} < 3$) for most elements, whereas arsenic consistently exhibited very high contamination (CF ≥ 6) across all sampling locations. The elevated Igeo and CF values for arsenic (As) reflected its comparatively high measured concentration value in this sedimentary basin. Based on PLI, Six col-

lected samples were classified as polluted (PLI > 1), whereas only one site (SSU-6) was classified as unpolluted (PLI < 1). At a depth of 60 cm, the Igeo values generally ranged from uncontaminated (Igeo ≤ 0) to uncontaminated to moderately contaminated (0 < Igeo ≤ 1), while the CF values indicated moderate contamination (1 ≤ CF < 3) for most elements. Arsenic remained the dominant contaminant, reflecting elevated measured arsenic concentrations relative to the background value. In PLI analysis, five collected samples represent pollution (PLI > 1), and two samples, sample no. SSL-5 and SSL-6 are being unpolluted (PLI < 1). Overall, the pollution indices indicated the amount of pollution is less at a depth of 60 cm in comparison to 15 cm (Figure 3).

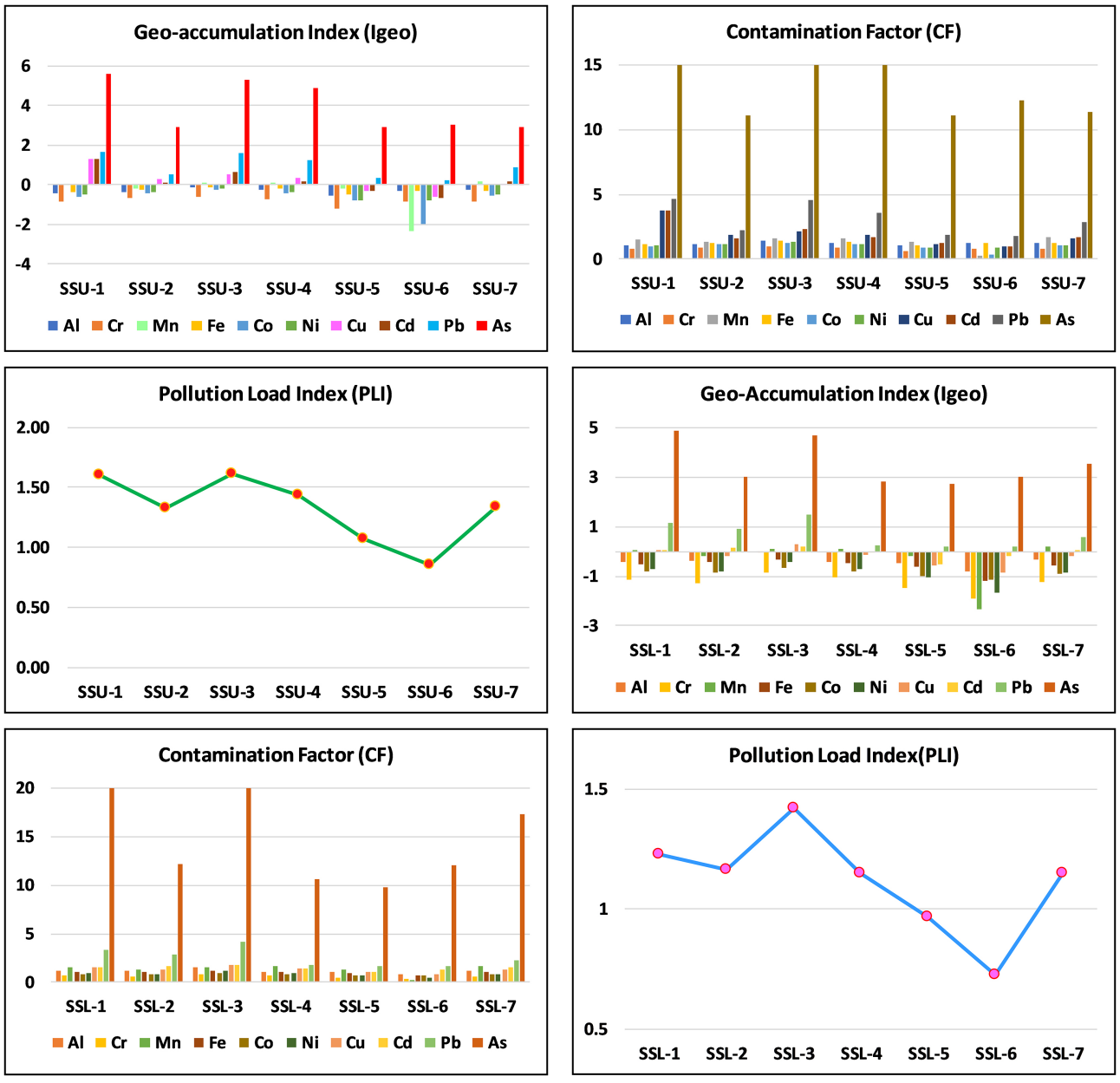

Figure 3. Graphical representation of Igeo, CF, and PLI of sediment samples at 15 cm and 60 cm depth.

3.3. Correlation and Principal Component Analysis (PCA) of Surface Water and Sediment Samples

Pearson correlation analysis (PCA) of surface water samples revealed strong positive relationships among Mn, Ni, Cu, Pb, Fe, and Cd (Figure 4). The strong positive correlation between the examined heavy metals indicates that they are primarily derived from similar source materials (Hossain et al., 2015). The occurrence of these metals is commonly associated with industrial effluents, urban runoff, and other anthropogenic activities. Therefore, these correlations indicate a common anthropogenic origin for these elements in the study area. In contrast, arsenic (As) exhibited moderate to strong negative correlations with most analyzed metals, implying a different source or geochemical behavior. The distinct behavior of arsenic (As) may be attributed to geogenic origin, the natural geological processes, and different mobilization behavior. Overall, these findings highlight the influence of both anthropogenic and geogenic factors on heavy metal distribution in the surface waters of the study area.

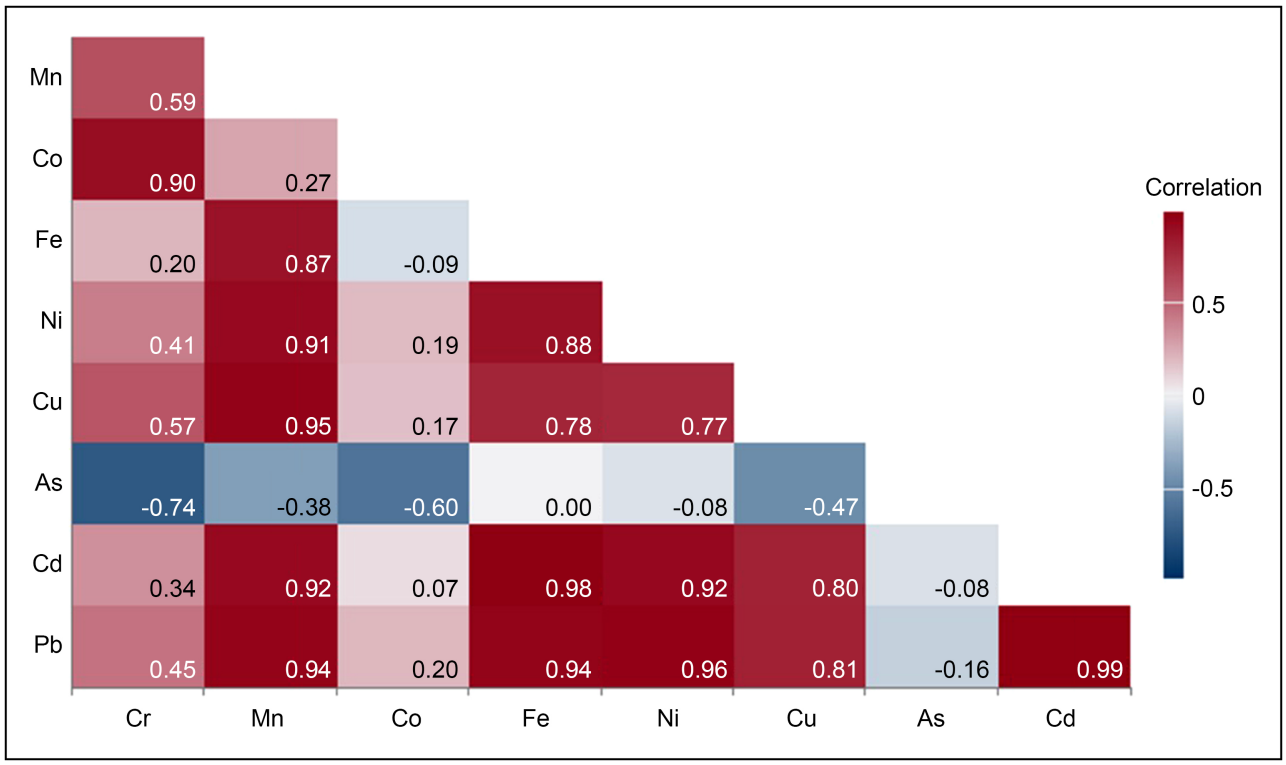

Figure 4. Pearson correlation of heavy metals in surface water samples.

A total of two principal components (PCs) with eigenvalues (>1) were extracted for surface water samples (Figure 5). These two components explained 93.3% of the total variance (Table 4(a)), indicating the first two principal components have summarized the heavy metal patterns almost completely. The scree plot of all components and loadings of the first two PCs for the analyzed heavy metals are presented in Figure 5.

Table 4. Principal component analysis for heavy metals in (a) surface water and (b) sediments.

(a)		
Parameter	Principal Component	
	PC1	PC2
Cr	0.232	−0.571
Mn	0.413	−0.057
Fe	0.378	0.283
Ni	0.388	0.163
Cu	0.380	−0.144
As	−0.133	0.696
Cd	0.396	0.202
Pb	0.404	0.131
Variance (%)	72.4	20.9
CV	72.4	93.3

(b)			
Parameter	Principal Component		
	PC1	PC2	PC3
Al	0.296	−0.378	−0.335
Cr	0.336	−0.276	−0.213
Mn	0.281	−0.074	0.714
Fe	0.313	−0.409	−0.152
Ni	0.367	−0.185	0.044
Cu	0.324	0.354	0.079
As	0.282	0.400	−0.312
Cd	0.277	0.439	0.021
Pb	0.333	0.299	−0.225
Co	0.340	−0.080	0.390
Variance (%)	68.6	16.0	7.5
CV	68.6	84.6	92.1

PC2 clearly separates arsenic (As) from the other metals, indicating a distinct source or geochemical behavior. PCA analysis of surface water heavy metals revealed two distinct groupings. Mn, Fe, Ni, Cu, Cd, and Pb exhibited strong positive correlations and high PC1 loadings (Figure 5), indicating a dominant anthropogenic source, mainly from industrial and urban activities. In contrast, arsenic showed a distinct behavior, characterized by high loading on PC2 and weak or negative correlations with other metals. Given the geological setting, the behavior of arsenic is consistent with a predominantly geogenic origin, with possible localized anthropogenic influences. Overall, the PCA results suggest that the distribution of heavy metals in surface water was influenced by both industrial pollution and natural processes in the study area.

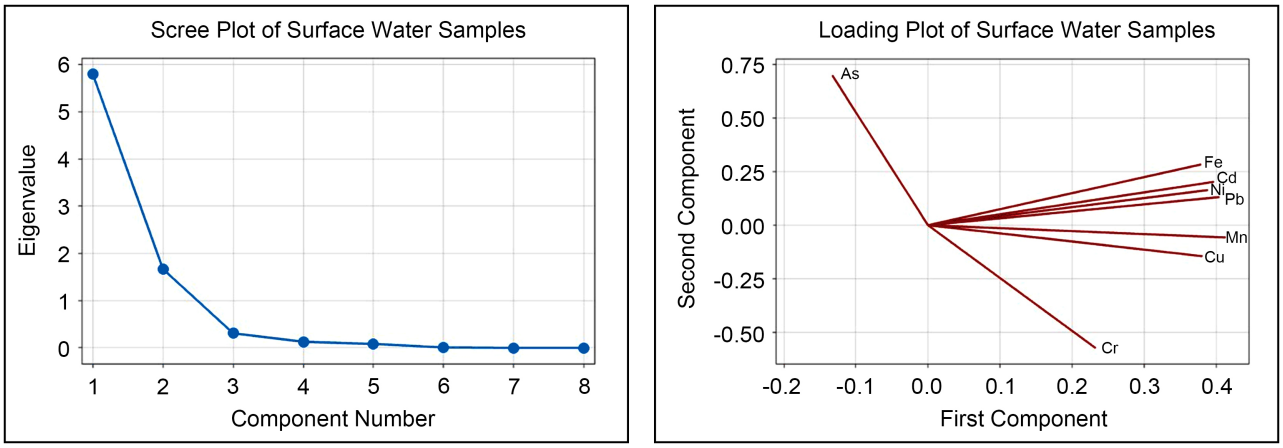

Figure 5. Scree plot and loading plot of heavy metals in surface water samples.

Pearson correlation analysis of sediment samples revealed strong positive relationships among Al, Cr, Fe, and Ni, indicating geogenic sources like mineral weathering. In contrast, Cu, Cd, Pb, and As also showed a strong positive correlation with one another, signifying anthropogenic sources related to industrial and urban pollution (Figure 6). Although As is geogenic in origin, the strong positive correlation indicates the combined influence of natural processes and human interventions on sediment heavy metal contamination. Overall, the correlation analysis indicates that heavy metal contamination in the sediments was controlled by the combined influence of geogenic and anthropogenic sources.

A total of three principal components (PCs) with eigenvalues (>1) were extracted for the sediment samples (n = 14), comprising samples collected from both the 15 cm and 60 cm depths (Figure 7), and elucidate 92.1% of the total variance (Table 4(b)), indicating that the first three principal components have summarized almost entirely the outlines of heavy metals. The scree plot of all components and possible scores and loadings of the first three PCs for the analyzed heavy metals is displayed in (Figure 7). PC1 explained 68.6% of the total variance and was characterized by strong positive loadings of Al, Cr, Mn, Fe, Ni, Cu, As, Cd, Pb, and Co. The Strong positive loading of all metals indicates that the metals increase

together and reflecting heavy metal enrichment in the sediments. This pattern suggests a common influence of both geogenic and anthropogenic processes on sediment composition.

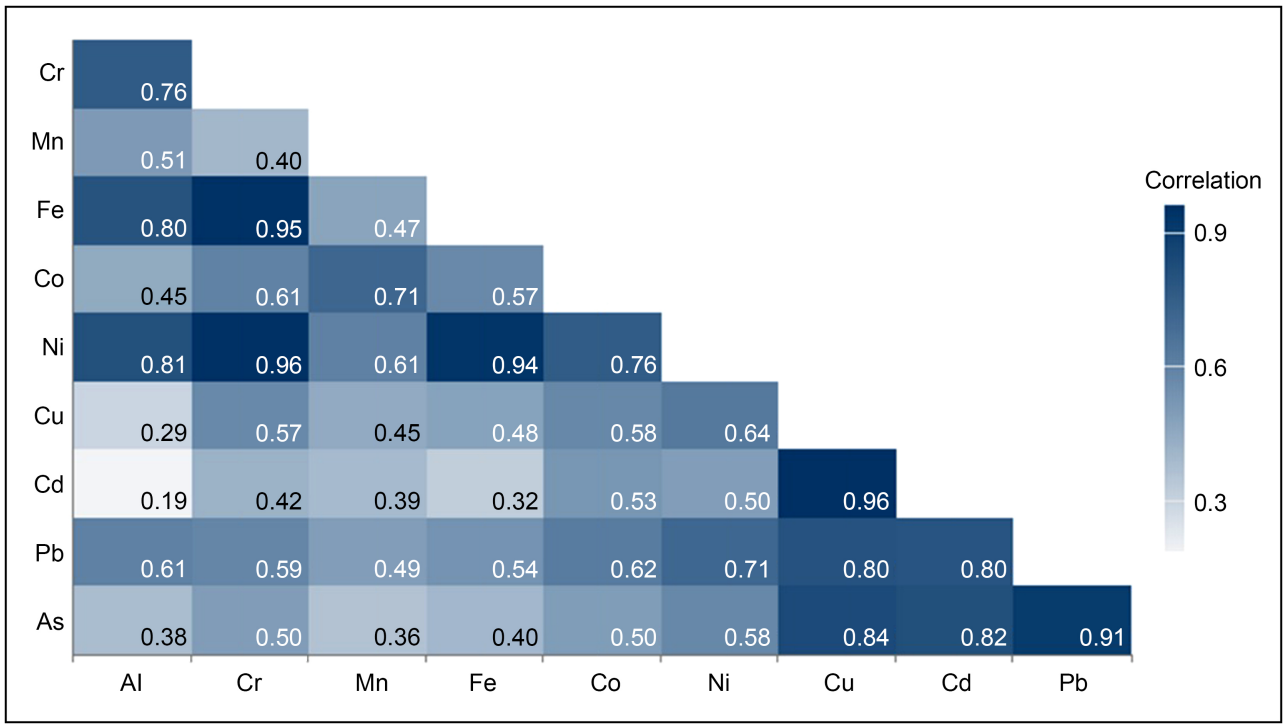

Figure 6. Pearson correlation of heavy metals in sediment samples.

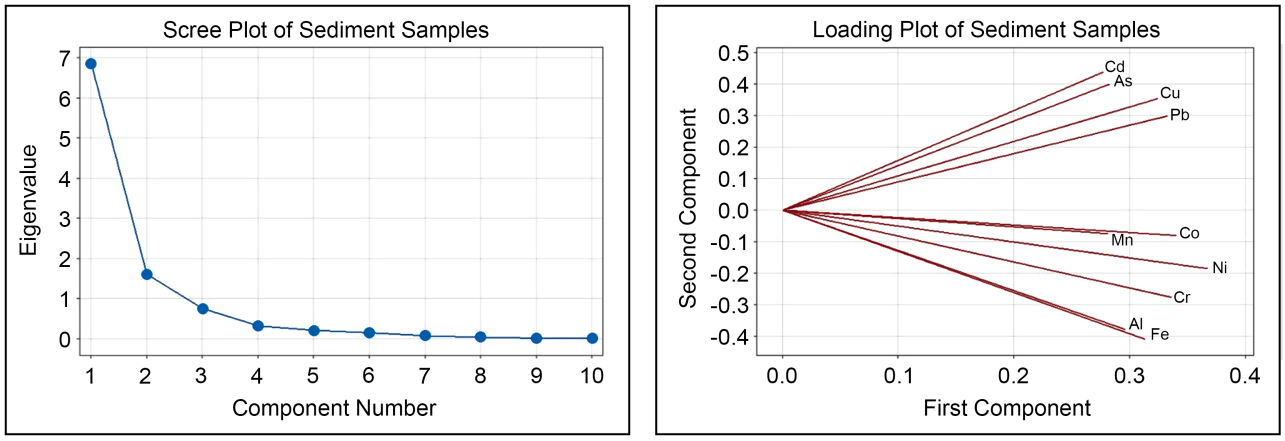

Figure 7. Scree plot and loading plot of heavy metals in sediment samples.

In contrast, PC2 represented positive loading for Cu, As, Cd, Pb, and negative or weak loading for Al, Cr, and Fe (Figure 7). PC2 accounted for 16.0% of the total variance and suggested that Cu, Cd, Pb, and As are likely associated with anthropogenic inputs, including industrial and agricultural activities, whereas Al, Cr, and Fe were more closely related to natural (geogenic) contributions derived from soil and bedrock weathering. Although arsenic is naturally present in the

geological materials of Bangladesh, its strong positive loading with Cu, Cd, and Pb suggests that its distribution in the study area may be influenced by both geogenic processes and anthropogenic activities. PC3 (7.5% variance) emphasized Mn and Co, suggesting a separate geogenic source or localized industrial influence. Overall, these findings highlight mixed pollution pathways affecting the quality of sediment samples up to 60 cm depth.

4. Conclusion

Heavy metal pollution, both in surface water and sediments, is a significant issue in Dhamrai. Both surface water and sediment samples clearly indicated significant levels of contamination. All the collected samples of surface water represent moderate to high levels of contamination, although the Heavy Metal Pollution Index (HPI) suggested that most surface water samples remained below the critical pollution threshold. Most of the sediment samples exhibited moderate contamination; however, overall contamination levels were lower than those observed in surface water and generally decreased with increasing sediment depth. This vertical trend suggests that heavy metal accumulation was more pronounced in the shallow sediment layer, reflecting the greater influence of recent contaminant inputs. Arsenic (As) posed the greatest environmental concern among the analyzed heavy metals in both surface water and sediments, as evidenced by its consistently elevated Geo-accumulation Index (Igeo) and Contamination Factor (CF) values. Correlation analysis and Principal Component Analysis (PCA) suggested that the distribution of heavy metals in the study area is influenced by both natural (geogenic) processes and anthropogenic activities. However, the relative contribution of these sources requires further investigation. The findings highlight the need for continuous monitoring of surface water and sediments to support effective pollution management and environmental protection. The observed contamination of surface water and shallow sediments also highlights the potential risk of long-term contaminant migration to groundwater, underscoring the importance of integrated surface water, groundwater, and land management strategies. In addition, the absence of site-specific and national geochemical benchmark values for Bangladesh highlights the need to establish regional reference concentrations for surface water and sediments. This study will provide a foundation for future research in this field. Moreover, effective regulation and treatment of industrial wastewater before discharge into rivers, canals, and other water bodies are essential. Meanwhile, community awareness and enforcement of environmental laws are necessary for sustainable practices.

5. Limitations

The study provides valuable baseline insights into local contamination, but a few limitations must be considered. Sampling was restricted to a single period; the dataset does not account for critical seasonal fluctuations. Due to the small sample size (n = 7), multivariate statistical results should be interpreted as localized

screening indicators rather than definitive regional patterns. Moreover, the lack of a Certified Reference Material (CRM) restricted the direct calculation of ICP-MS recovery rates. However, analytical precision and reliability were strictly maintained through alternative quality control measures, including procedural blanks, duplicate samples, and internal standards to correct for instrumental drift.

Author Contributions

Shahtaj Karim conducted the field investigation, laboratory analysis, data interpretation, and prepared the original draft of the manuscript. Riyadul Islam participated in field sampling, data analysis, interpretation of the results, and manuscript review. Khaleda Afrin assisted with laboratory work, data interpretation, draft preparation, served as the corresponding author, and contributed to manuscript revision. Md. Rashedul Hasan contributed to field sampling, laboratory work, and manuscript revision. All authors reviewed, revised, and approved the final version of the manuscript.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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