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Article

Seasonal dynamics of trace metal concentrations and hydrological parameters in the Balu River, Bangladesh

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Abstract: This study investigates the seasonal dynamics of trace metal concentrations and hydrological parameters in the Balu River, Bangladesh, to inform sustainable water management practices and support efforts to meet environmental standards. Water level, discharge, rainfall, and groundwater data were collected from February to August 2019, alongside sediment samples analyzed for Zn, Pb, Cu, Cr, and Cd concentrations. Statistical analyses, including correlation studies, time series modeling, and Kolmogorov-Smirnov tests, revealed significant seasonal variations. Water levels and discharge rates increased dramatically during the wet season, with upstream levels rising by 862.68% and downstream by 752.92%. Trace metal concentrations showed diverse responses: Cd increased by 554.52%, Zn by 11.86%, while Pb, Cu, and Cr decreased by 44.15%, 5.16%, and 32.72% respectively. Strong correlations were observed between certain metals, particularly in wet periods, with notable relationships between Cr-Cu ($r = 0.870$) and Zn-Cr ($r = 0.742$). The integrated analysis of hydrological parameters and metal concentrations, using Gower coefficient and partial correlation analyses, suggests complex interactions between seasonal changes and pollutant dynamics. These findings highlight the need for season-specific water management strategies and more frequent monitoring to better understand and mitigate the environmental impacts of trace metal pollution in the Balu River system. The study contributes valuable insights into the interplay between hydrological conditions and trace metal behavior, essential for developing effective pollution control measures and achieving sustainable river management in Bangladesh.

Keywords: trace metal pollution; seasonal variation; hydrological parameters; urban river system; Bangladesh water quality

1. Introduction

Heavy metal contamination has emerged as a critical threat to water quality globally, posing significant risks to ecosystems and human health [1–3]. The proliferation of industrial activities, unsustainable agricultural practices, urban wastewater discharge, and excessive traffic contribute to the escalating levels of heavy metals in our environment [2,4–6]. This pollution not only endangers the availability of safe drinking water but also threatens aquatic life and the entire food chain through bioaccumulation [7,8]. Recognizing the severity of this issue, the United Nations'

Sustainable Development Goals have explicitly targeted the improvement of water quality by reducing pollution and minimizing the release of hazardous chemicals by 2030 [9].

In developing countries like Bangladesh, river pollution has reached alarming levels, with hundreds of factories discharging toxic effluents directly into nearby waterways. The Balu River, flowing around the Dhaka metropolitan area, has become a primary receiver of industrial wastewater [10]. Despite government efforts to relocate tanneries and implement pollution control measures, progress has been slow, and the discharge of contaminated effluents continues to pose a significant threat to the river's ecosystem [11,12].

The assessment of heavy metal concentrations in water and sediment is crucial for evaluating the overall quality of aquatic environments [13]. Sediments, in particular, play a vital role as both habitats for benthic organisms and potential reservoirs of pollutants [14,15]. The behavior of heavy metals in aquatic systems is complex, with factors such as pH and dissolved oxygen levels influencing their adsorption and release from sediments [14]. Furthermore, the bioaccumulation of these metals in fish and other aquatic organisms presents a direct pathway for human exposure through the food chain [16,17].

The heavy metals examined in this study-zinc (Zn), lead (Pb), copper (Cu), chromium (Cr), and cadmium (Cd)-were selected due to their prevalence in industrial effluents and significant toxicological impacts. Lead is a neurotoxin particularly harmful to children, while cadmium, a known carcinogen, affects kidneys and bones [18]. Copper and zinc, though essential micronutrients, can be toxic in excess, causing organ damage and mineral imbalances [19]. Chromium, especially in its hexavalent form, is carcinogenic and can cause respiratory and dermal issues [20]. In aquatic ecosystems, these metals can bioaccumulate, leading to reduced growth, impaired reproduction, and increased mortality in organisms [21,22]. The World Health Organization's guidelines for heavy metal concentrations in sediment (Pb: 85 mg/kg, Cd: 0.8 mg/kg, Cu: 36 mg/kg, Cr: 100 mg/kg, Zn: 50 mg/kg) underscore the importance of monitoring these metals [23]. Their presence in the Balu River is of particular concern given the area's industrial activities, especially textile and dyeing factories [24,25].

Seasonal variations significantly influence heavy metal concentrations in water bodies. Factors such as temperature, rainfall, and runoff can alter metal concentrations throughout the year [26,27]. Understanding these seasonal dynamics is essential for comprehensive environmental monitoring and effective pollution management strategies. In the case of the Balu River, the recent relocation of tanneries and the establishment of new industrial zones necessitate ongoing assessment to evaluate the effectiveness of these measures in reducing pollution levels [28–30].

The Balu River, situated near Dhaka, receives substantial pollution from various industries, including textile and dyeing factories in Gazipur [24]. These industries discharge large volumes of wastewater containing a cocktail of chemicals, including heavy metals, oils, and hazardous pollutants [25,26]. The contamination of this aquatic system not only threatens the local ecosystem but also poses risks to human health through various exposure pathways.

To address these complex environmental challenges, it is crucial to conduct comprehensive research on sediment quality and metal contamination in river systems [6–9,31,32]. Such studies can provide valuable insights into the sources, distribution, and potential risks associated with heavy metal pollution. By employing advanced analytical techniques such as correlation and cluster analysis, researchers can better identify and classify pollutant sources, enabling more targeted and effective pollution control strategies [2,14,33]. This research aims to contribute to this body of knowledge by examining the seasonal dynamics of trace metal concentrations and hydrological parameters in the Balu River, Bangladesh, with the ultimate goal of informing sustainable water management practices and supporting efforts to achieve national and international environmental standards.

2. Materials and methods

2.1. Study area and data collection

This study focuses on the Balu River in Bangladesh, which flows for about 44 km through the marshes of Beel Belai and eastern Dhaka before entering the Shitalakshya River at Demra in the Dhaka District. The Balu River basin is characterized by a tropical monsoon climate, with distinct wet (June to October) and dry (November to May) seasons. The average annual rainfall in the region is approximately 2000 mm, with about 80% occurring during the monsoon season [34]. The area experiences hot and humid summers with temperatures reaching up to 35 °C, and mild winters with temperatures rarely dropping below 10 °C [35]. Topographically, the Balu River flows through the low-lying floodplains of the Ganges-Brahmaputra Delta, with an average elevation of 4–5 m above sea level [36]. The geology of the region is dominated by Quaternary alluvial deposits, consisting primarily of sand, silt, and clay [37]. Hydrogeologically, the area is characterized by a shallow aquifer system, with groundwater levels typically ranging from 1 to 5 m below the surface, fluctuating seasonally with rainfall and river levels [38]. The alluvial nature of the soil and shallow groundwater table make the region susceptible to both surface water pollution and groundwater contamination [39].

The Balu river’s width ranges from 100 to 200 m, with a depth of 3 to 4.5 m, which varies seasonally, particularly during monsoons [40,41]. Point sources (sewage from urban areas, industrial wastewater from concrete, tanneries, paint, and textile industries) and non-point sources (agricultural runoff) all contribute to pollution [42]. Ten sampling stations were deliberately placed over a 4.7 km section of the river based on surrounding industrial activity. Sediment samples were collected from the surface layer at these sites between February (non-monsoon) and August 2019 (monsoon), and the station names and surrounding industries are included in **Table 1** and **Figure 1**. Water level and discharge data were collected from both upstream (U/S) and downstream (D/S) locations during 2019 by the Institute of Water Modelling (IWM). Data was obtained at three-hour intervals to capture diurnal fluctuations as shown in **Figure 2**. Furthermore, rainfall data was collected from the Bangladesh Meteorological Department (BMD). Daily groundwater table (GWT) data was obtained from an existing well in Gulshan Station by the Bangladesh Water Development Board (BWDB).

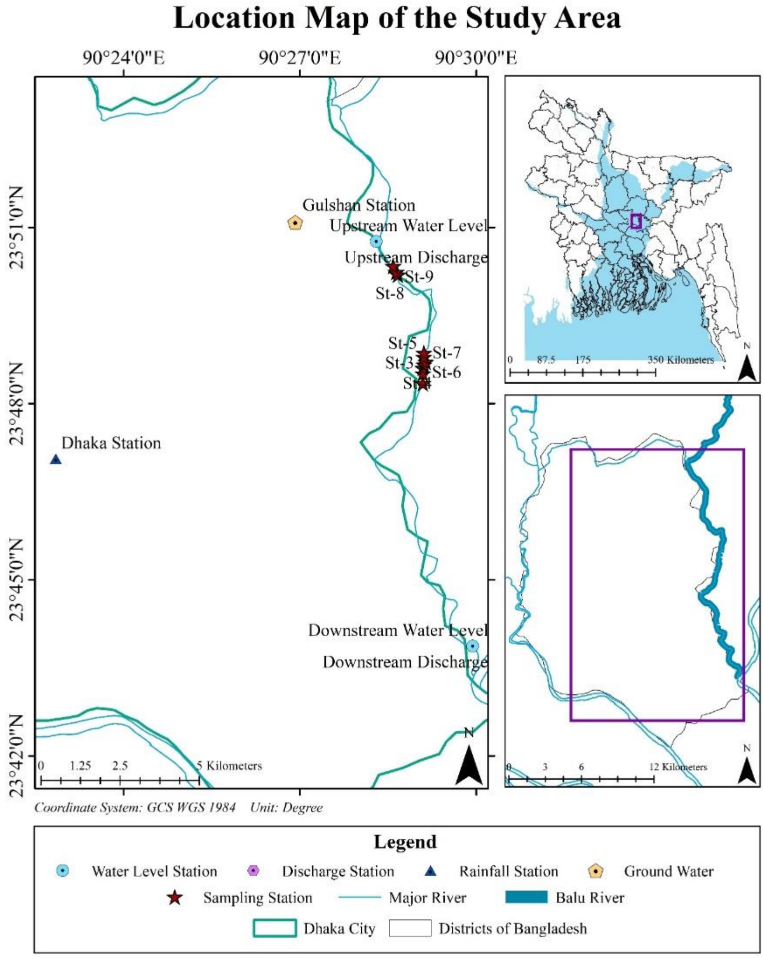


Figure 1. Location of the study area.

Table 1. Hydrological stations with other parameters and related information.

Data Sources	**Parameters with availability**	**Station name**	**Geographical location of the sampling stations**	
			Latitude (N)	**Longitude (E)**
Field Data	Trace Metal Concentration in Sediments (mg/kg) (01/02/2019; 01/08/2019)	St-1: Crown cement ready-mix concrete	23°48′20.6″	90°29′5.6″
		St-2: National development engineers - Balu bridge site office	23°48′30.7″	90°29′5.6″
		St-3: National development engineers ready mix concrete	23°48′36.3″	90°29′5.3″
		St-4: Jalshiri golf club	23°48′39.7″	90°29′6.7″
		St-5: Bashundhara ready-mix and construction industries limited - Plant office	23°48′42.5″	90°29′8.5″
		St-6: Bashundhara ready-mix and construction industries limited	23°48′47.4″	90°29′6.5″
		St-7: Property development limited ready-mix plant	23°48′51.8″	90°29′6.7″
		St-8: International cricket stadium – Construction site	23°50′11.5″	90°28′40.0″
		St-9: Balu bridge	23°50′14.3″	90°28′38.4″
		St-10: Biswas builders limited	23°50′20.5″	90°28′35.2″

Table 1. (*Continued*).

Data Sources	Parameters with availability	Station name	Geographical location of the sampling stations	
			Latitude (N)	**Longitude (E)**
BWDB (3 Hourly)	GW Table (m) (01/01/2019–31/12/2019)	Gulshan Station (Well ID: GT2626900)	23°51′06.1″	90°26′55.0″
IWM (3 Hourly)	Discharge (m^3/s) (01/01/2019–31/12/2019)	Balu Inflow (Station ID: 9878)	23°50′12.6″	90°28′12.6″
		Balu Outflow (Station ID: 29700)	23°43′32.0″	90°30′01.4″
	Water Level (mMSL) (01/01/2019–31/12/2019)	Balu Inflow (Station ID: 9000)	23°50′12.6″	90°28′12.6″
		Balu Outflow (Station ID: 27900)	23°43′32.0″	90°30′01.4″
BMD (Daily)	Rainfall (mm) (01/01/2019–31/12/2019)	Dhaka Station	23°46′49.8″	90°22′43.3″

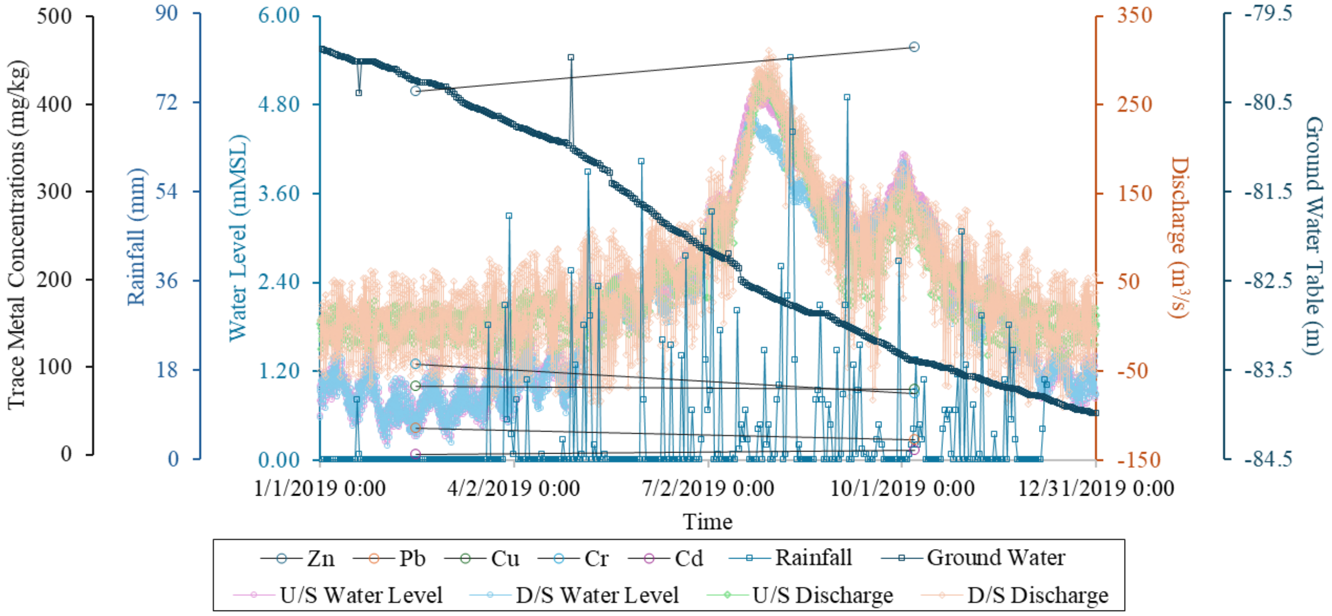


Figure 2. Temporal variations in trace metal concentrations, hydrological parameters, and water quality indicators for the Balu River (2019).

2.2. Hydrological analysis

Statistical analyses were performed on the collected hydrological data using R statistical software (version 4.0.3). One-sample t-tests and Wilcoxon Signed-Rank Tests were conducted to assess the significance of water level and discharge variations. The Shapiro-Wilk test was employed to evaluate the normality of data distribution. Time series analysis was performed using the ‘forecast’ package in R, with ARIMA models fitted to the data to identify trends and seasonal patterns. Model performance was evaluated using metrics such as R^2, Mean Squared Error (MSE), Root Mean Squared Error (RMSE), and Mean Absolute Percentage Error (MAPE).

2.3. Trace metal sampling and analysis

Sediment samples (n = 35, approximately 100 g each) were collected from ten sites along the Balu River basin in Bangladesh during both dry and wet seasons. Sampling locations, determined via mobile GPS and illustrated in **Figure 1**, included the river itself and nearby farmlands irrigated with its water, particularly near industrial discharge points. Samples were extracted to a depth of 55–60 cm using horizon sampling methods [43]. A stainless-steel Ekman grab sampler, cleaned between sites to prevent cross-contamination, was used to collect the top 2–3 cm of undisturbed sediment, which typically contains the highest pollutant concentrations [44,45]. Samples were immediately frozen and transferred to the Bangladesh Fisheries Research Institute laboratory in Chandpur for analysis. There, samples were thawed, homogenized, sieved through a 2 mm mesh, oven-dried at 105 ℃, and finely ground [46]. For digestion, 2 g of each sample was heated with water and concentrated H_2SO_4 in a Gerhardth test tube using a Gerhadt-Kieldathern digestion chamber (150 ℃ for 0.5 h, then 250 ℃ for 2 h) [47]. The digested samples were then transferred to 50 mL volumetric flasks, and metal concentrations (Zn, Pb, Cu, Cr, Cd) were determined using Atomic Absorption Spectroscopy (AAS) (Model No.120, Graphite Tube Atomizer). The following wavelengths were used: Zn (213.9 nm), Pb (283.3 nm), Cu (324.8 nm), Cr (357.9 nm), and Cd (228.8 nm). Standard curves (0–4 ppm) were used for calibration. To ensure analytical quality, the study used NIST’s SRM 3100 series via ICP-OES with an internal laboratory-developed method as a certified reference material. The recovery rates for all metals ranged from [e.g., 95% to 105%], which is within the acceptable range. The relative standard deviation for triplicate analyses was less than 5% for all metals. Additionally, blank samples were analyzed every 10 samples to check for potential contamination during the analytical process, and no significant contamination was observed.

2.4. Correlation analysis of trace metals

Correlation analyses were performed to examine the relationships between trace metal concentrations during wet and dry periods. Three different statistical methods were employed: Spearman rank correlation, Kendall’s tau, and Pearson correlation. These analyses were conducted using the ‘cor’ function in R, with significance tested at the 0.05 level. The use of multiple correlation methods allowed for a robust assessment of relationships, accounting for potential non-linearity and non-normality in the data.

2.5. Seasonal variation analysis

To assess seasonal variations in trace metal concentrations and hydrological parameters, data were segregated into dry (February) and wet (August) periods. Two-sample t-tests and Kolmogorov-Smirnov tests were performed to compare the distributions of metal concentrations between these periods. F-tests, Levene’s tests, and Bartlett’s tests were used to assess the equality of variances. These analyses were conducted using the ‘stats’ package in R. Percentage changes in concentrations and hydrological parameters between dry and wet periods were calculated to quantify seasonal variations.

2.6. Integrated analysis

The relationships between hydrological parameters and trace metal concentrations were explored using Gower coefficient analysis and partial correlation analysis. The Gower coefficient, calculated using the ‘cluster’ package in *R*, provided a measure of similarity between variables. Partial correlation analysis, performed using the ‘ppcor’ package, allowed for the examination of relationships between two variables while controlling for the effects of other variables. These methods provided insights into the complex interplay between hydrological conditions and trace metal dynamics in the river system.

2.7. Quality control and quality assurance

Rigorous quality control and quality assurance procedures were implemented throughout the study. For sample collection and handling, the study followed standardized protocols and collected field blanks and duplicate samples at a 10% rate. Laboratory analyses were performed in a certified facility using standard methods, with regular use of certified reference materials, method blanks, and internal standards. Data validation included ion balance calculations, conductivity balance checks, and statistical outlier detection. Multiple correlation methods were employed to ensure robust interpretation of relationships between variables. Where possible, the findings were compared with previous regional studies for external validation. These measures ensure the reliability and reproducibility of the results.

3. Results

3.1. Hydrological analysis of the Balu River

3.1.1. Statistical analysis of water levels and discharges

Statistical analysis of upstream (U/S) and downstream (D/S) water levels and discharges in the Balu River reveals significant variations and patterns (**Table 2**). The one-sample *t*-test shows high observed values (93.893 for U/S water level, 97.534 for D/S water level) compared to the critical value of 1.961, indicating statistically significant differences from hypothesized means. The Wilcoxon Signed-Rank Test further supports this, with large *V* values (4,244,241 for water levels, 3,927,833 and 3,676,565.5 for discharges) and *Z* scores exceeding 34, all suggesting significant deviations from central tendencies. The one-sample variance test reveals substantial variability, particularly in discharges, with chi-square values far exceeding the critical value of 3062.435. The Shapiro-Wilk test results (*W* values close to 1 and *p*-values < 0.0001) indicate that the data significantly deviates from a normal distribution for all parameters.

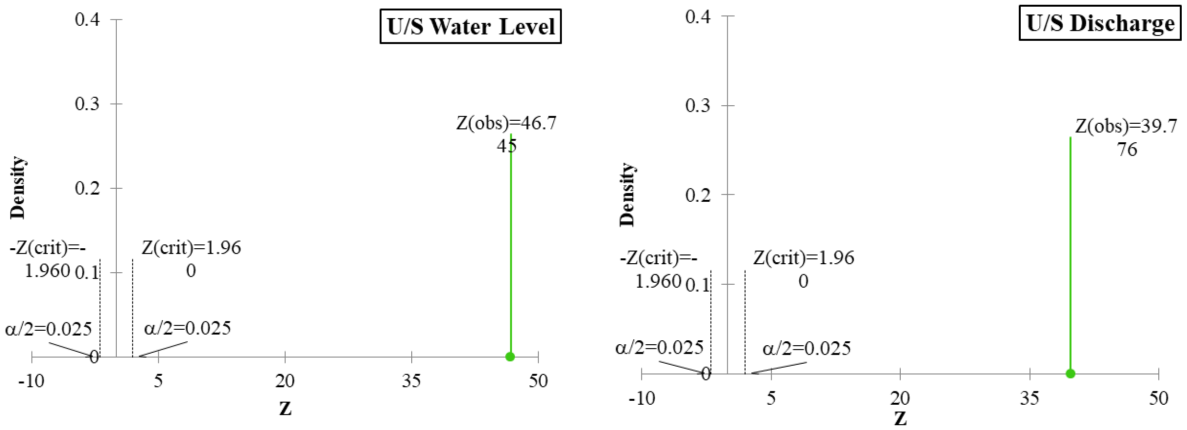
Table 2. Statistical analysis results for U/S and D/S water levels and discharges in the Balu River.

	Parameters	**U/S water level**	**D/S water level**	**U/S discharge**	**D/S discharge**
One-Sample t-Test	95% confidence interval on the mean	[2.108, 2.198]	[2.011, 2.093]	[52.661, 57.777]	[54.616, 60.316]
	Difference	2.153	2.052	55.219	57.466
	t (Observed value)	93.893	97.534	42.327	39.538
	|*t*| (Critical value)	1.961			

Table 2. (*Continued*).

	Parameters	U/S water level	D/S water level	U/S discharge	D/S discharge
Wilcoxon Signed-Rank Test	*V*	4,244,241		3,927,833	3,676,565.500
	Z	46.745		39.776	34.241
One-Sample Variance Test	Variance	1.531	1.289	4956.194	6151.640
	95% confidence interval on the variance	[1.455, 1.612]	[1.225, 1.358]	[4711.113, 5221.005]	[5847.445, 6480.324]
	Chi-square (Observed value)	4455.616	3751.998	14,427,479.555	17,907,422.621
	|Chi-square| (Critical value)	3062.435			
	DF (Degrees of Freedom)	2911			
Shapiro-Wilk Test	*W*	0.979	0.982	0.880	0.948
	p-value (Two-tailed)	< 0.0001			

The Wilcoxon signed-rank test results for water levels and discharges in the Balu River reveal significant differences between paired observations at both upstream and downstream locations (**Figure 3**). All four parameters (U/S and D/S water levels and discharges) show observed Z-scores (Zobs) that far exceed the critical *Z*-values (Zcrit = ±1.960) at the $\alpha/2 = 0.025$ significance level. The U/S water level and D/S water level both have Zobs = 46.745, indicating identical statistical significance. The U/S discharge shows the highest Zobs of 39.776, while the D/S discharge has a Zobs of 34.241. These high *Z*-scores, all well above the critical value, provide strong evidence to reject the null hypothesis of no difference between paired observations. The consistency in high *Z*-scores across all parameters suggests that there are significant, non-random variations in both water levels and discharges throughout the river system. These results imply that the Balu River experiences substantial and statistically significant fluctuations in its hydrological characteristics, which could be attributed to factors such as seasonal changes, weather patterns, or anthropogenic influences affecting the river's flow regime.



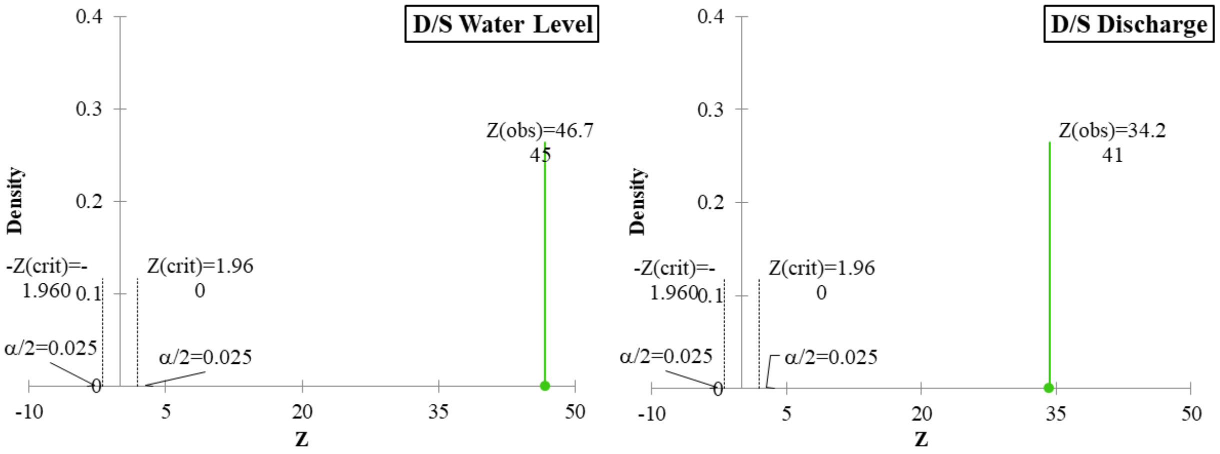


Figure 3. Wilcoxon signed-rank test results for upstream (U/S) and downstream (D/S) water levels and discharges in the Balu River, showing observed Z-scores and critical values.

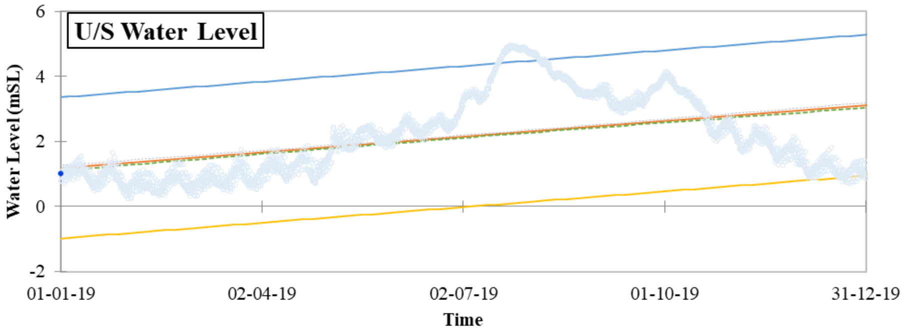
3.1.2. Descriptive statistics and time series analysis

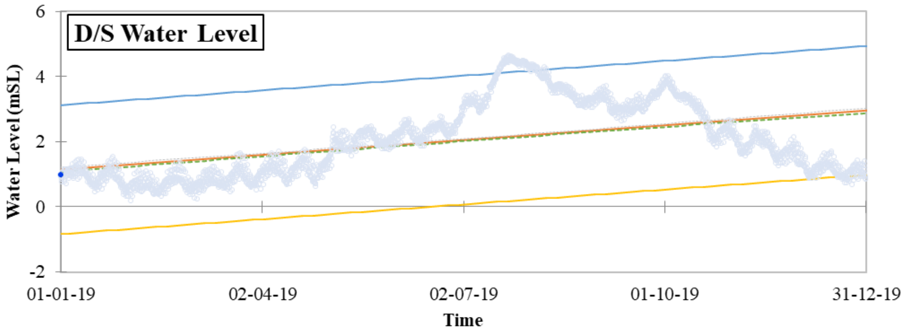
Descriptive statistics provide further insights into the river's hydrological characteristics (**Table 3**). Mean water levels are slightly higher upstream (2.15 m) than downstream (2.05 m), while mean discharge increases downstream from 55.20 m^3/s to 57.45 m^3/s. The range of values is considerable, with water levels varying by 4.71 m upstream and 4.45 m downstream, and discharges showing extreme fluctuations (326.48 m^3/s upstream, 401.98 m^3/s downstream). Notably, minimum discharge values are negative for both U/S and D/S (−41.34 m^3/s and −90.44 m^3/s respectively), potentially indicating reverse flow conditions or measurement errors. Standard deviations are relatively high, especially for discharges (70.38 m^3/s upstream, 78.41 m^3/s downstream), underscoring the river's dynamic nature. These results collectively paint a picture of a highly variable river system with complex flow patterns, suggesting the need for careful water management strategies and further investigation into the causes of extreme fluctuations and potential reverse flows.

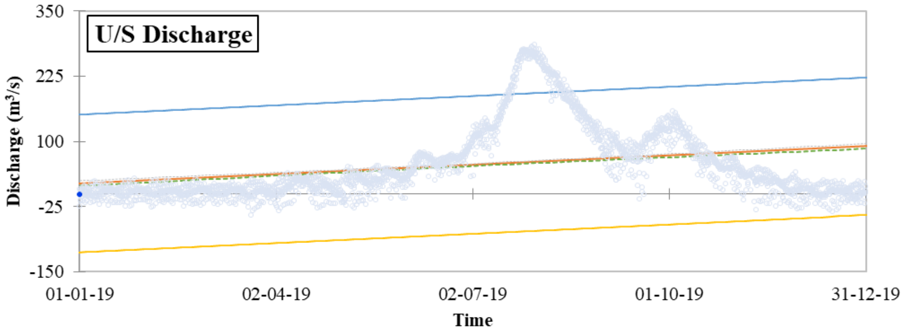
Table 3. Descriptive statistics for U/S and D/S water levels and discharges in the Balu River.

Parameters	U/S water level	D/S water level	U/S discharge	D/S discharge
Mean	2.15	2.05	55.20	57.45
Maximum	4.95	4.63	285.14	311.54
Minimum	0.24	0.18	−41.34	−90.44
Difference	4.71	4.45	326.48	401.98
Median	1.99	1.92	27.17	38.34
Standard deviation	1.24	1.14	70.38	78.41

The time series analysis of water levels and discharges in the Balu River reveals distinct seasonal patterns and overall increasing trends throughout 2019 for both upstream and downstream locations (**Figure 4**). All four parameters exhibit a general upward trajectory, with the most pronounced increases observed in discharge rates. The graphs clearly illustrate seasonal fluctuations, with peak water levels and discharges occurring around July–August, likely corresponding to the monsoon season. The model predictions (orange lines) closely follow the observed data trends, indicating a good fit. The 95% confidence intervals (dashed lines) for both the mean (gray) and observations (yellow) provide insight into the variability and uncertainty of the predictions. Notably, the confidence intervals widen towards the end of the year, suggesting increased uncertainty in long-term projections. The upstream and downstream patterns are similar, but downstream locations show slightly higher water levels and discharges, consistent with expected river dynamics. These results suggest that the Balu River experiences significant seasonal variations in water levels and discharges, with a general increasing trend over the year, potentially influenced by factors such as monsoon patterns, land use changes, or climate variations.







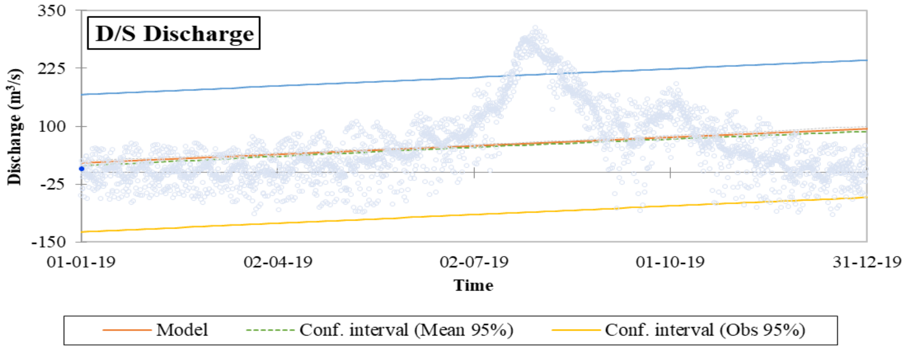


Figure 4. Time series analysis of water levels and discharges in the Balu River for upstream (U/S) and downstream (D/S) locations during 2019, showing observed data, model predictions, and confidence intervals.

3.1.3. Model performance and trend analysis

The model performance metrics for U/S and D/S water levels and discharges in the Balu River reveal moderate to weak predictive capabilities (**Table 4**). The R^2 and Adjusted R^2 values are low across all parameters, ranging from 0.08 to 0.21, indicating that the models explain only a small portion of the variance in the data. Mean Squared Error (MSE) and Root Mean Squared Error (RMSE) values are notably high, especially for discharge measurements (RMSE of 67.33 and 75.44 for U/S and D/S discharges respectively), suggesting significant deviations between predicted and observed values. The Mean Absolute Percentage Error (MAPE) is particularly high for U/S Discharge (1147.20%), indicating poor model accuracy. Durbin-Watson (DW) statistics close to 0 for water levels and discharges suggest positive autocorrelation in the residuals. The Akaike Information Criterion (AIC) and Schwarz Bayesian Criterion (SBC) values are lower for water level models compared to discharge models, indicating relatively better fit for water level predictions. The high Press statistics, especially for discharges, further confirm the models' limited predictive power.

Table 4. Model performance metrics and additional parameters for U/S and D/S water levels and discharges in the Balu River.

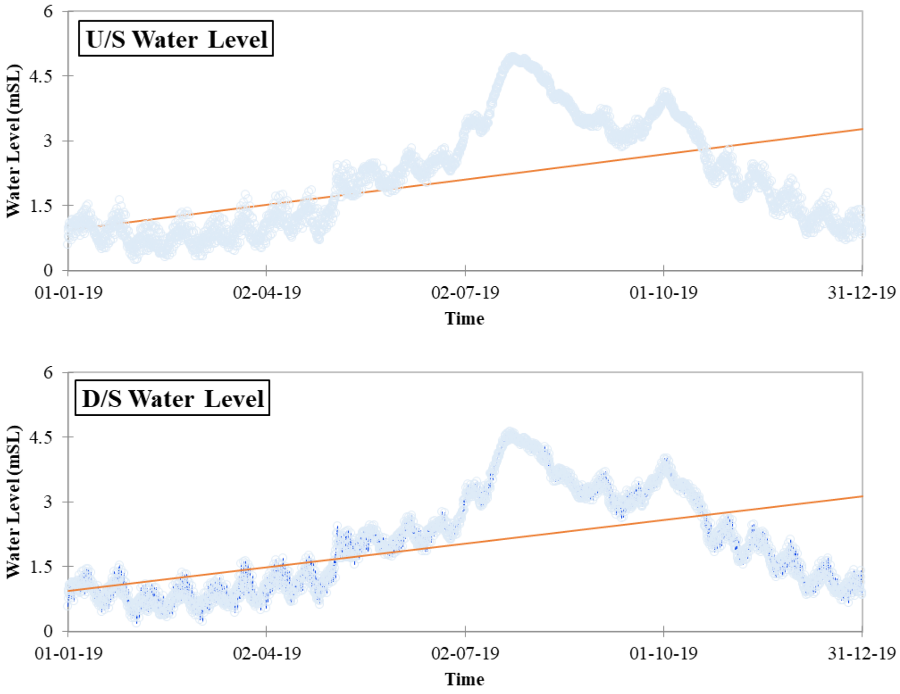
Parameters	U/S water level	D/S water level	U/S discharge	D/S discharge
Observations	2913.00			
Sum of Weights	2913.00			
DF	2910.00			
R^2	0.20	0.21	0.09	0.08
Adjusted R^2	0.20	0.21	0.09	0.07
MSE	1.22	1.02	4533.10	5691.01
RMSE	1.11	1.01	67.33	75.44
MAPE	59.17	55.75	1147.20	512.87
DW	0.01	0.02	0.06	0.33
Cp	2.00	2.00	2.00	2.00
AIC	584.53	46.97	24,518.60	25,181.03

Table 4. (*Continued*).

Parameters	**U/S water level**	**D/S water level**	**U/S discharge**	**D/S discharge**
SBC	596.48	58.92	24,530.55	25,192.98
PC	0.80	0.79	0.92	0.93
Press	3559.36	2959.42	13,206,404.69	16,580,400.05
Q^2	0.20	0.21	0.08	0.07

DF: Degrees of Freedom; R^2: Coefficient of Determination; MSE: Mean Squared Error; RMSE: Root Mean Squared Error; MAPE: Mean Absolute Percentage Error; DW: Durbin-Watson statistic; Cp: Mallows' Cp; AIC: Akaike Information Criterion; SBC: Schwarz Bayesian Criterion; PC: Prediction Criterion; Press: Predicted Residual Sum of Squares; Q^2: Predictive Squared Correlation.

The time series analysis of water level and discharge data for both upstream (U/S) and downstream (D/S) locations in the Balu River reveals seasonal patterns and trends throughout 2019 (**Table 4, Figure 5**). All four parameters (U/S and D/S water levels and discharges) show a general increasing trend from January to December, with Sen's slopes ranging from 0.006 to 0.202 (**Table 5**). The most pronounced increase is observed in D/S discharge (slope = 0.202). Kendall's Tau values (0.207 to 0.334) indicate weak to moderate positive correlations between time and the measured parameters, suggesting a consistent but not strong upward trend. The graphs clearly illustrate seasonal fluctuations, with peak water levels and discharges occurring around July–August, likely corresponding to the monsoon season. However, the *p*-values (0.291 to 0.453) for all parameters are greater than 0.05, indicating that these trends are not statistically significant at the 95% confidence level. This suggests that while there are observable patterns and increases in water levels and discharges over the year, these changes could be due to natural variability rather than a definitive long-term trend. The high variance (Var(S)) values further support the considerable fluctuations observed in the data throughout the year.



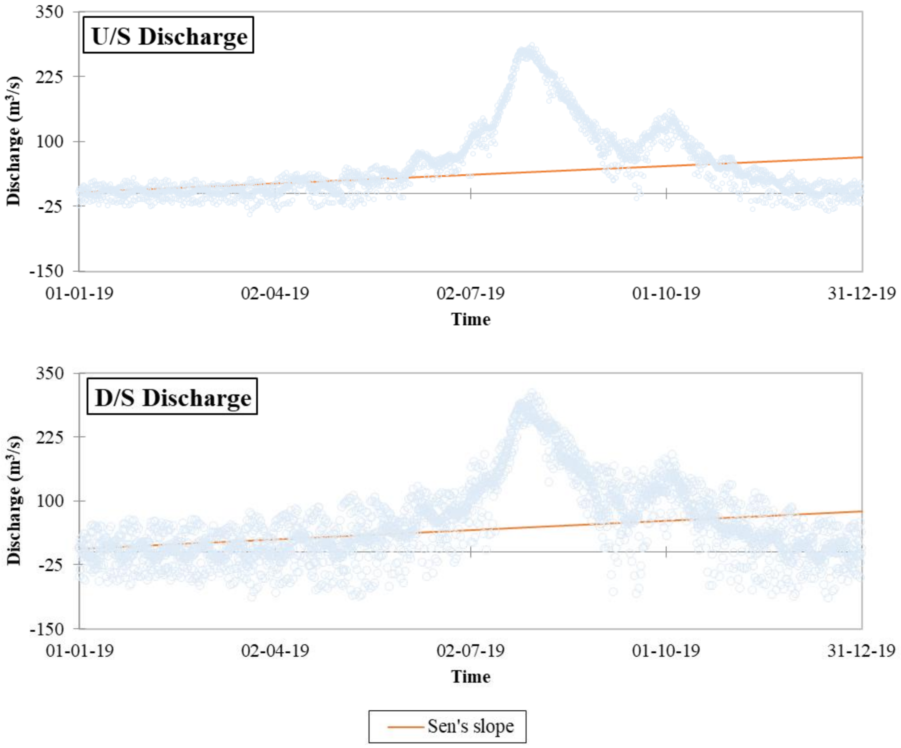


Figure 5. M-K analysis of water levels and discharges in the Balu River for upstream (U/S) and downstream (D/S) locations during 2019, showing Sen's slope.

Table 5. Statistical parameters and correlation analysis for U/S and D/S water levels and discharges in the Balu River.

Parameters	**U/S water level**	**D/S water level**	**U/S discharge**	**D/S discharge**
Sen's Slope	0.006	0.006	0.183	0.202
Kendall's Tau	0.331	0.334	0.255	0.207
S	1,403,852	1,414,997	1,083,133	879,963
Var(S)	1,796,649,599,551	1,799,449,752,747	1,363,072,147,460	1,374,017,901,114
p-value (Two-tailed)	0.295	0.291	0.354	0.453

3.2. Trace metal analysis

3.2.1. Correlation analysis of trace metals

The Pearson correlation matrix reveals distinct patterns of trace metal associations in the Balu River during wet and dry periods (**Table 6**, S1–S2). In the wet period, strong positive correlations are observed between Zn and Cr ($r = 0.742$), as well as Cu and Cr ($r = 0.870$), suggesting common sources or similar environmental behaviors for these metals during rainy conditions. Conversely, the dry period shows weaker correlations overall, with the strongest being between Zn and Cr ($r = 0.539$). Notably, Cd exhibits weak to moderate negative correlations with most other metals in both periods, indicating its unique behavior. The p-values demonstrate that many of these correlations are statistically significant ($p < 0.05$), particularly in the wet period. The coefficients of determination (R^2) further support these findings, with the wet period showing stronger relationships, especially for the Zn-Cr and Cu-Cr pairs. These results suggest that metal dynamics in the river are significantly influenced by seasonal factors, with stronger interrelationships during wet periods, possibly due to increased runoff and mobilization of pollutants. The distinct behavior of Cd implies it may have different sources or environmental pathways compared to the other metals studied.

Table 6. Pearson correlation matrices of trace metal concentrations for wet and dry periods.

Wet period	**Zn**	**Pb**	**Cu**	**Cr**	**Cd**
Zn	**1**	0.501	0.554	**0.742**	−0.148
Pb	0.501	**1**	0.141	0.401	−0.309
Cu	0.554	0.141	**1**	**0.870**	0.176
Cr	**0.742**	0.401	**0.870**	**1**	−0.131
Cd	−0.148	−0.309	0.176	−0.131	**1**
Dry Period	**Zn**	**Pb**	**Cu**	**Cr**	**Cd**
Zn	**1**	0.209	0.574	0.539	0.063
Pb	0.209	**1**	−0.058	−0.171	−0.295
Cu	0.574	−0.058	**1**	0.291	0.481
Cr	0.539	−0.171	0.291	**1**	0.212
Cd	0.063	−0.295	0.481	0.212	**1**

Values in bold are different from 0 with a significance level alpha = 0.05.

Table 7. Spearman correlation matrices of trace metal concentrations for wet and dry periods.

Wet period	**Zn**	**Pb**	**Cu**	**Cr**	**Cd**
Zn	**1**	0.503	0.638	**0.784**	−0.212
Pb	0.503	**1**	0.286	0.620	−0.321
Cu	0.638	0.286	**1**	**0.802**	0.067
Cr	**0.784**	0.620	**0.802**	**1**	−0.170
Cd	−0.212	−0.321	0.067	−0.170	**1**
Dry Period	**Zn**	**Pb**	**Cu**	**Cr**	**Cd**
Zn	**1**	0.164	0.479	0.539	−0.006
Pb	0.164	**1**	−0.115	−0.055	−0.321
Cu	0.479	−0.115	**1**	0.273	0.455
Cr	0.539	−0.055	0.273	**1**	−0.091
Cd	−0.006	−0.321	0.455	−0.091	**1**

Values in bold are different from 0 with a significance level alpha = 0.05.

The Spearman correlation analysis reveals distinct patterns of trace metal associations in the Balu River across wet and dry periods (**Table 7**, S3–S4). During the wet period, strong positive correlations are observed between Zn and Cr (rho = 0.784), Zn and Cu (rho = 0.658), and Cu and Cr (rho = 0.802), all statistically significant (p < 0.05). This suggests common sources or similar environmental behaviors for these metals during rainy conditions. In contrast, the dry period shows generally weaker correlations, with the strongest being between Zn and Cu (rho = 0.479). Notably, Cd exhibits weak to moderate negative correlations with most other metals in the wet period but shows positive correlations in the dry period, particularly with Cu (rho = 0.455). The coefficients of determination (*R^2*) further support these findings, with higher values in the wet period, especially for Zn-Cr and Cu-Cr pairs. These results indicate that metal dynamics in the river are significantly influenced by seasonal factors, with stronger interrelationships during wet periods, possibly due to increased runoff and mobilization of pollutants. The seasonal shift in Cd's behavior implies it may have different sources or environmental pathways compared to the other metals, which vary with hydrological conditions.

The Kendall correlation analysis reveals distinct patterns of trace metal associations in the Balu River between wet and dry periods (**Table 8**, S5–S6). During the wet period, strong positive correlations are observed between Zn and Cr (τ = 0.584), Cu and Cr (τ = 0.659), and Zn and Cu (τ = 0.560), all statistically significant ($p < 0.05$). This suggests common sources or similar environmental behaviors for these metals during rainy conditions. In contrast, the dry period shows generally weaker correlations, with the strongest being between Zn and Cr (τ = 0.467). Notably, Cd exhibits weak negative correlations with most other metals in the wet period but shows slight positive correlations in the dry period. The coefficients of determination (R^2) further support these findings, with higher values in the wet period, especially for the Zn-Cr and Cu-Cr pairs. These results indicate that metal dynamics in the river are significantly influenced by seasonal factors, with stronger interrelationships during wet periods, possibly due to increased runoff and mobilization of pollutants. The seasonal shift in Cd's behavior implies it may have different sources or environmental pathways compared to the other metals, which vary with hydrological conditions. The Kendall correlation results generally align with the previous Spearman analysis, providing robust evidence for these seasonal metal interaction patterns.

Table 8. Kendall correlation matrices of trace metal concentrations for wet and dry periods.

Wet period	**Zn**	**Pb**	**Cu**	**Cr**	**Cd**
Zn	**1**	0.378	0.360	**0.584**	−0.200
Pb	0.378	**1**	0.180	0.405	−0.200
Cu	0.360	0.180	**1**	**0.659**	0.090
Cr	**0.584**	0.405	**0.659**	**1**	−0.135
Cd	−0.200	−0.200	0.090	−0.135	**1**
Dry Period	**Zn**	**Pb**	**Cu**	**Cr**	**Cd**
Zn	**1**	0.111	0.378	0.467	0.022
Pb	0.111	**1**	−0.067	−0.156	−0.244
Cu	0.378	−0.067	**1**	0.289	0.378
Cr	0.467	−0.156	0.289	**1**	−0.067
Cd	0.022	−0.244	0.378	−0.067	**1**

Values in bold are different from 0 with a significance level alpha = 0.05.

3.2.2. Statistical analysis of trace metal concentrations

The statistical analysis of trace metal concentrations in the Balu River reveals significant variations between dry and wet periods for certain metals (**Table 9**). The T-test results show significant differences ($p < 0.05$) for Zn, Pb, and Cd, with Zn and

Cd exhibiting particularly low *p*-values ($p < 0.0001$). The 95% confidence intervals for the differences between means do not include zero for these metals, further supporting the significance of the seasonal variations. Notably, Cd shows the largest standardized difference (*t*-value) of 7.101, indicating a substantial change in concentration between dry and wet periods.

Table 9. Statistical analysis of trace metal concentrations in the Balu River: T-test, Kolmogorov-Smirnov, Fisher's F-test, Levene's test, Bartlett test, and Mann-Whitney test results.

***T*-test**					
	Zn	**Pb**	**Cu**	**Cr**	**Cd**
95% confidence interval on the difference between the means	[−70.463, 168.959]	[−17.278, −8.913]	[−25.764, 17.687]	[−58.328, −9.206]	[1.039, 6.558]
Difference	49.248	−13.096	−4.039	−33.767	3.799
t (Observed value)	0.864	−6.578	−0.391	−2.888	2.892
|t| (Critical value)	2.101				
DF	18				
p-value (Two-tailed)	0.399	< 0.0001	0.701	0.010	0.010
Kolmogorov-Smirnov test					
	Zn	Pb	Cu	Cr	Cd
D	0.300	0.900	0.300	0.600	0.600
p-value (Two-tailed)	0.759	0.001	0.759	0.055	0.055
Fisher's F-test					
	Zn	Pb	Cu	Cr	Cd
95% confidence interval on the ratio of variances	[1.304, 21.140]	[0.524, 8.501]	[0.238, 3.852]	[0.181, 2.927]	[13.344, 216.282]
Ratio	5.251	2.111	0.957	0.727	53.72
F (Observed value)	5.251	2.111	0.957	0.727	53.72
F (Critical value)	4.026				
DF1	9.000				
DF2	9.000				
p-value (Two-tailed)	0.021	0.281	0.949	0.643	< 0.0001
Levene's test					
F (Observed value)	4.611	1.209	0.020	0.695	17.481
F (Critical value)	4.414				
DF1	1.000				
DF2	18.000				
p-value (Two-tailed)	0.046	0.286	0.889	0.415	0.001
Bartlett's test					
Chi-square (Observed value)	5.293	1.164	0.004	0.216	22.462
Chi-square (Critical value)	3.841				
DF	1.000				
p-value (Two-tailed)	0.021	0.281	0.949	0.642	< 0.0001

Table 9. (*Continued*).

***T*-test**					
	Zn	**Pb**	**Cu**	**Cr**	**Cd**
Mann-Whitney test					
U	51	2	43	17	89
U (standardized)	0.000				
Expected value	50.000				
Variance (U)	175.000	175.000	174.868	174.868	175.000
p-value (Two-tailed)	0.971	< 0.0001	0.616	0.011	0.002

The Kolmogorov-Smirnov test results corroborate these findings, showing significant differences in the distribution of Zn, Pb, and Cd concentrations between seasons ($p < 0.05$) (**Table 9**). The F-test for equality of variances indicates significant differences in variability for Zn and Cd ($p < 0.05$), suggesting not only changes in mean concentrations but also in the spread of values between dry and wet periods. Levene's test, which is less sensitive to non-normality, confirms the variance heterogeneity for Cd ($p = 0.001$) (**Table 9**). The Bartlett's test results align with these findings, particularly highlighting the strong heterogeneity in Cd concentrations ($p < 0.0001$). These comprehensive statistical analyses collectively suggest that Zn, Pb, and especially Cd concentrations in the Balu River are significantly influenced by seasonal factors, potentially due to variations in runoff, precipitation patterns, or seasonal anthropogenic activities affecting the river system.

The univariate clustering analysis of trace metals in the Balu River reveals distinct patterns between dry and wet seasons (**Tables 10** and **11**). During the dry season, zinc (Zn) shows the highest concentration (mean: 398.0 µg/L), followed by chromium (Cr) and copper (Cu), while cadmium (Cd) has the lowest concentration (mean: 1.0 µg/L). The wet season exhibits a similar order but with generally lower concentrations, particularly for Zn (mean: 304.0 µg/L). Notably, the clustering results indicate higher variability in metal concentrations during the dry season, as evidenced by larger ranges and standard deviations. For instance, Zn's range in the dry season (252.5–535.5 µg/L) is wider than in the wet season (235.0–373.0 µg/L). The clustering also reveals potential outliers, particularly for Cr and Cu in both seasons. These results suggest significant seasonal variations in trace metal concentrations, with the dry season characterized by higher concentrations and greater variability. This pattern could be attributed to factors such as reduced dilution during low flow periods, increased anthropogenic inputs, or changes in biogeochemical processes between seasons. The clustering analysis provides valuable insights for understanding metal pollution dynamics in the Balu River and can inform targeted environmental management strategies.

Table 10. Univariate clustering results for trace metals in the Balu River during dry season.

Dry season	**Zn**			**Pb**				**Cu**				**Cr**			**Cd**				
Class	1	2	3	1	2	3	4	1	2	3	4	1	2	3	1	2	3	4	5
Objects	6	3	1	4	3	2	1	5	1	2	2	5	4	1	1	1	6	1	1
Sum of weights	6	3	1	4	3	2	1	5	1	2	2	5	4	1	1	1	6	1	1
Within-class variance	536.2	456.6	0	1.5	0.3	0.4	0	24.4	0	0.2	194.9	26.4	122.4	0	0	0	0	0	0
Minimum distance to centroid	0.2	6.2	0	0.4	0.1	0.4	0	2	0	0.3	9.9	0.3	4.7	0	0	0	0.1	0	0
Average distance to centroid	17.9	15.8	0	1	0.4	0.4	0	3.9	0	0.3	9.9	3.4	9	0	0	0	0.1	0	0
Maximum distance to centroid	35.2	23.8	0	1.5	0.6	0.4	0	7.7	0	0.3	9.9	7.6	13.3	0	0	0	0.2	0	0
	St1	St4	St7	St1	St2	St3	St5	St1	St3	St4	St6	St1	St3	St4	St1	St2	St3	St4	St7
	St2	St5		St4	St9	St7		St2		St7	St10	St2	St6				St5		
	St3	St10		St6	St10			St5				St5	St7				St6		
	St6			St8				St8				St8	St10				St8		
	St8							St9				St9					St 9		
	St9																St10		

Table 11. Univariate clustering results for trace metals in the Balu River during wet season.

Wet Season	**Zn**				**Pb**					**Cu**				**Cr**					**Cd**			
Class	1	2	3	4	1	2	3	4	5	1	2	3	4	1	2	3	4	5	1	2	3	4
Objects	5	3	1	1	6	1	1	1	1	5	1	2	2	4	1	2	2	1	1	2	6	1
Sum of weights	5	3	1	1	6	1	1	1	1	5	1	2	2	4	1	2	2	1	1	2	6	1
Within-class variance	823.9	1172.3	0	0	1.7	0	0	0	0	75	0	5.1	6.8	26.5	0	4.6	70	0	0	0.9	1.1	0
Minimum distance to centroid	3.3	8.3	0	0	0.3	0	0	0	0	0.1	0	1.6	1.8	1	0	1.5	5.9	0	0	0.7	0.1	0
Average distance to centroid	19.8	25.1	0	0	0.9	0	0	0	0	6	0	1.6	1.8	3.6	0	1.5	5.9	0	0	0.7	0.8	0
Maximum distance to centroid	49.5	37.6	0	0	2	0	0	0	0	15	0	1.6	1.8	7.2	0	1.5	5.9	0	0	0.7	1.4	0
	St1	St4	St7	St10	St1	St2	St5	St9	St10	St1	St4	St5	St7	St1	St4	St5	St7	St10	St1	St2	St3	St4
	St2	St5			St3					St2		St10	St9	St2		St8	St9			St7	St5	
	St3	St9			St4					St3				St3							St6	
	St6				St6					St6				St6							St8	
	St8				St7					St8											St9	
					St8																St10	

The cumulative distribution plots in **Figure 6** compare trace metal concentrations (Zn, Pb, Cu, Cr, and Cd) between dry and wet periods in the Balu River using the Two-sample Kolmogorov-Smirnov test/Two-tailed test. For zinc (Zn), lead (Pb), and copper (Cu), the distributions show some separation between dry and wet periods, indicating potential seasonal variations in concentrations. Chromium (Cr) exhibits a more pronounced difference, with the dry period curve generally higher than the wet period, suggesting higher Cr levels during dry conditions. Cadmium (Cd) shows the most striking contrast, with the wet period curve rising much more steeply than the dry period, implying significantly higher Cd concentrations during wet periods. These results suggest that trace metal concentrations in the Balu River vary seasonally, with different metals exhibiting distinct patterns between dry and wet periods. These variations may be attributed to factors such as changes in river flow, runoff patterns, or seasonal differences in anthropogenic activities affecting the river.

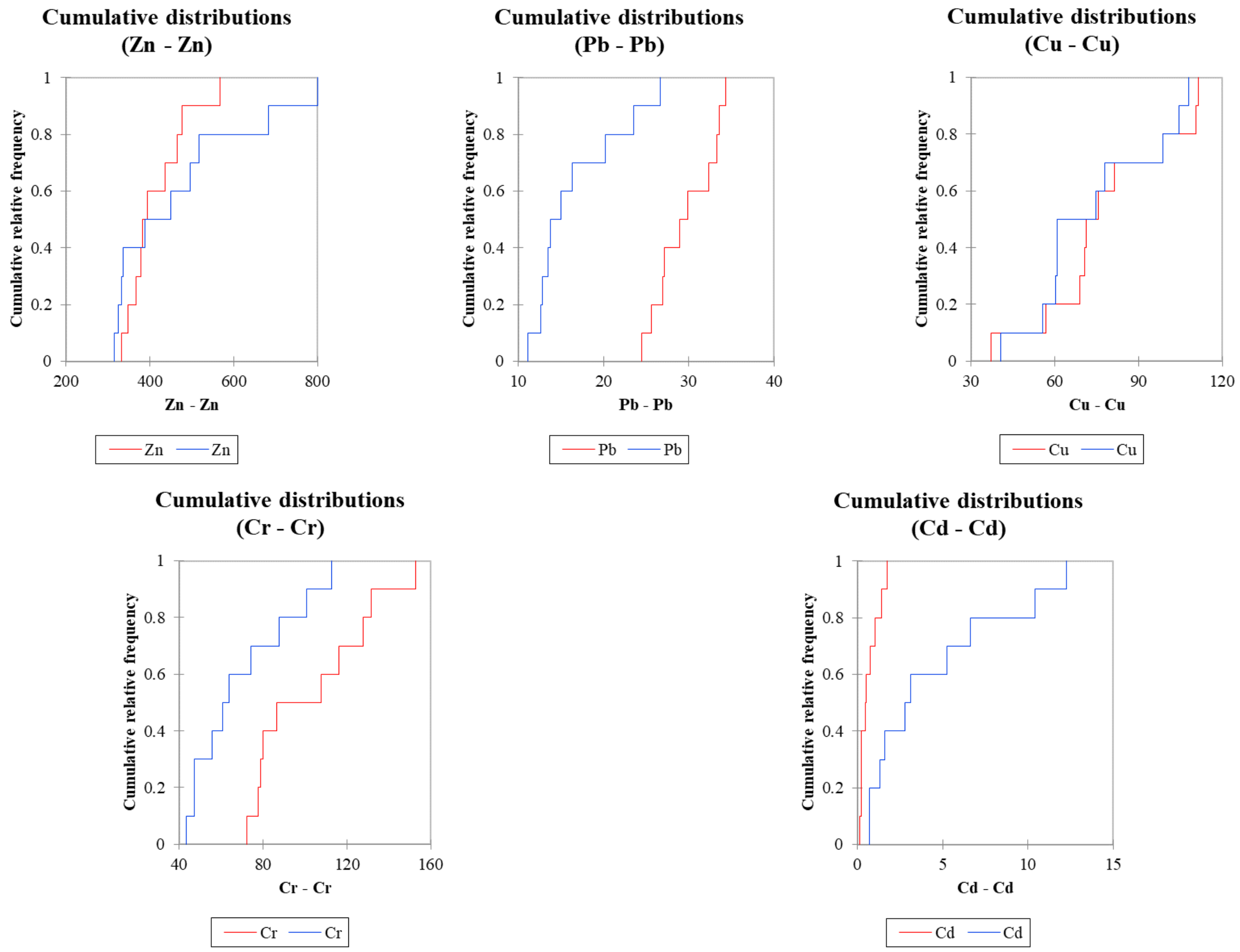


Figure 6. Kolmogorov-Smirnov test between dry and wet period trace metals concentrations in Balu River.

The correlation analyses of trace metal concentrations during wet and dry periods revealed distinct patterns across three different statistical methods: Spearman, Kendall, and Pearson correlations (**Tables 12–14,** S7–S12). During the wet period, strong positive correlations ($p < 0.05$) were consistently observed between Cr and Cu (Spearman: 0.802, Kendall: 0.659, Pearson: 0.870), as well as between Cr and Zn (Spearman: 0.784, Kendall: 0.584, Pearson: 0.742). Additionally, Zn showed a significant positive correlation with Cu across all methods. Pb exhibited moderate positive correlations with Zn and Cr in the Spearman analysis, but these relationships were less pronounced in the Kendall and Pearson correlations.

Table 12. Pearson correlation matrix of hydrological parameters in the Balu River.

Variables	Ground water	Rainfall	U/S discharge	D/S discharge	U/S water level	D/S water level
Ground water	**1**	−0.138	**0.279**	**0.287**	**0.416**	**0.426**
Rainfall	−0.138	**1**	0.000	0.001	−0.016	−0.024

U/S discharge	**0.279**	0.000	**1**	**0.999**	**0.933**	**0.915**

Table 12. (*Continued*).

Variables	Ground water	Rainfall	U/S discharge	D/S discharge	U/S water level	D/S water level
D/S discharge	**0.287**	0.001	**0.999**	**1**	**0.936**	**0.917**
U/S water level	**0.416**	−0.016	**0.933**	**0.936**	**1**	**0.998**
D/S water level	**0.426**	−0.024	**0.915**	**0.917**	**0.998**	**1**

Values in bold are different from 0 with a significance level alpha = 0.05.

Table 13. Spearman correlation matrix of hydrological parameters in the Balu River.

Variables	Ground water	Rainfall	U/S discharge	D/S discharge	U/S water level	D/S water level
Ground water	**1**	−0.118	0.137	0.137	0.165	0.164
Rainfall	−0.118	**1**	−0.046	−0.045	−0.073	−0.077
U/S discharge	0.137	−0.046	**1**	**0.997**	**0.975**	**0.964**
D/S discharge	0.137	−0.045	**0.997**	**1**	**0.974**	**0.963**
U/S water level	0.165	−0.073	**0.975**	**0.974**	**1**	**0.997**
D/S water level	0.164	−0.077	**0.964**	**0.963**	**0.997**	**1**

Values in bold are different from 0 with a significance level alpha = 0.05.

Table 14. Kendall correlation matrix of hydrological parameters in the Balu River.

Variables	Ground water	Rainfall	U/S discharge	D/S discharge	U/S water level	D/S water level
Ground water	**1**	−0.072	0.040	0.038	0.076	0.077
Rainfall	−0.072	**1**	−0.032	−0.033	−0.049	−0.050
U/S discharge	0.040	−0.032	**1**	**0.964**	**0.867**	**0.837**
D/S discharge	0.038	−0.033	**0.964**	**1**	**0.861**	**0.831**
U/S water level	0.076	−0.049	**0.867**	**0.861**	**1**	**0.969**
D/S water level	0.077	−0.050	**0.837**	**0.831**	**0.969**	**1**

Values in bold are different from 0 with a significance level alpha = 0.05.

In contrast, the dry period demonstrated weaker and fewer significant correlations among the trace metals. The most notable relationship during the dry period was between Cu and Cd, which showed a moderate positive correlation in the Spearman (0.455) and Pearson (0.481) analyses, though this was not reflected in the Kendall correlation. Zn maintained weak to moderate positive correlations with Cu and Cr across all methods during the dry period. Interestingly, Pb showed weak negative correlations with Cu and Cr in the dry period, a pattern not observed in the wet period. These results suggest that the relationships between trace metal concentrations are more pronounced and generally more positively correlated during wet periods compared to dry periods, indicating potential differences in metal behavior or sources between these two environmental conditions.

The Gower coefficient and partial correlation analyses of hydrological parameters in the Balu River reveal both similarities and differences in their relationships (**Tables 15** and **16**). The Gower coefficient shows strong correlations between U/S and D/S discharge (0.964), as well as between U/S and D/S water levels (0.999), indicating high similarity in these paired measurements. Interestingly, rainfall exhibits strong correlations with water levels (0.855 and 0.854) in the Gower analysis. However, the partial correlation analysis presents a different picture, highlighting the relationships between variables when controlling for others. It shows a very strong correlation between U/S and D/S discharge (0.980) and between U/S and D/S water levels (0.998), consistent with the Gower results. Yet, it reveals weak or negative correlations for most other parameter pairs, suggesting that many apparent relationships in the Gower analysis may be indirect. Notably, the strong rainfall-water level relationship observed in the Gower analysis disappears in the partial correlation, implying that this connection may be mediated by other factors. These results underscore the complex interplay of hydrological parameters in the Balu River, where direct relationships between discharge measurements and water levels are robust, but other parameter interactions are more nuanced and potentially influenced by confounding variables.

Table 15. Gower coefficient correlation matrix of hydrological parameters in the Balu River.

Variables	Ground water	Rainfall	U/S discharge	D/S discharge	U/S water level	D/S water level
Ground water	**1**	0.339	0.496	0.491	0.200	0.199
Rainfall	0.339	**1**	0.408	0.379	0.855	0.854
U/S discharge	0.496	0.408	**1**	**0.964**	0.347	0.345
D/S discharge	0.491	0.379	**0.964**	**1**	0.318	0.317
U/S water level	0.200	0.855	0.347	0.318	**1**	**0.999**
D/S water level	0.199	0.854	0.345	0.317	**0.999**	**1**

Values in bold are different from 0 with a significance level alpha = 0.05.

Table 16. Partial correlation coefficient matrix of hydrological parameters in the Balu River.

Variables	Ground water	Rainfall	U/S discharge	D/S discharge	U/S water level	D/S water level
Ground water	**1**	−0.168	−0.149	0.089	0.144	−0.116
Rainfall	−0.168	**1**	−0.019	−0.019	0.205	−0.205
U/S discharge	−0.149	−0.019	**1**	**0.980**	−0.256	0.253
D/S discharge	0.089	−0.019	**0.980**	**1**	0.426	−0.418
U/S water level	0.144	0.205	−0.256	0.426	**1**	**0.998**
D/S water level	−0.116	−0.205	0.253	−0.418	**0.998**	**1**

Values in bold are different from 0 with a significance level alpha = 0.05.

3.3. Integrated analysis of hydrological parameters and trace metals

3.3.1. Correlation analysis of hydrological parameters

The probability plots for Ground Water Table (GWT) and Rainfall in the Balu River basin reveal distinct patterns in data distribution and their deviation from theoretical normal distribution (**Figure 7**). For the GWT, the observed data (pink line) closely follows the theoretical normal distribution (dashed line) between the 10th and 90th percentiles, indicating a generally normal distribution within this range. However, deviations are noticeable at the extremes, particularly below the 10th percentile (79.8 units) and above the 90th percentile (83.7 units), suggesting some skewness in the tails of the distribution. The rainfall data shows a more pronounced deviation from normality, with a clear S-shaped curve indicating non-normal distribution. This curve suggests that rainfall data is likely skewed, with a higher frequency of lower rainfall amounts and fewer extreme high rainfall events. The stark difference between GWT and rainfall distributions implies that while groundwater levels maintain a relatively stable, near-normal distribution, rainfall patterns are more variable and potentially influenced by extreme events. These findings have important implications for water resource management in the basin, indicating the need for different approaches in modeling and predicting groundwater levels versus rainfall patterns.

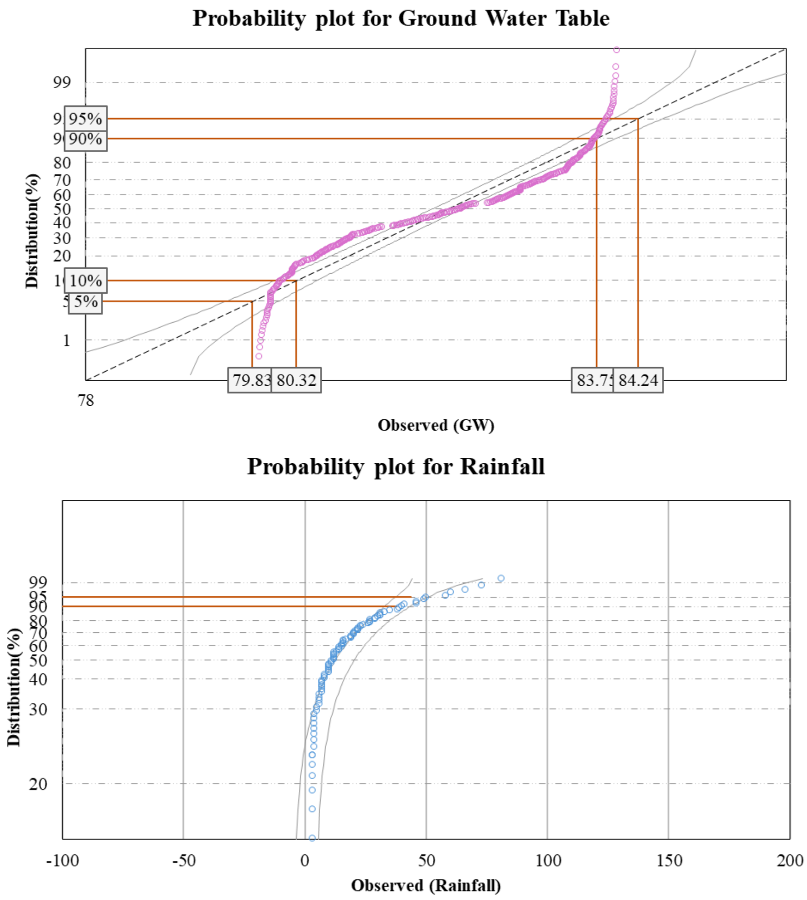


Figure 7. Probability plots for Ground Water Table and Rainfall in the Balu River, showing observed data distribution and theoretical normal distribution.

3.3.2. Seasonal variations in trace metals and hydrological parameters

The analysis of trace metal concentrations and hydrological parameters in the Balu River revealed significant variations between the dry (February) and wet (August) periods of 2019 (**Table 17**). Most notably, zinc (Zn) and cadmium (Cd) concentrations increased by 11.86% and 554.52% respectively, while lead (Pb), copper (Cu), and chromium (Cr) decreased by 44.15%, 5.16%, and 32.72%. These changes coincided with substantial increases in hydrological parameters, particularly upstream and downstream water levels (862.68% and 752.92% increase) and discharge rates. Groundwater levels showed a modest 3.22% increase. The dramatic rise in discharge and water levels, coupled with the occurrence of rainfall in the wet period, indicates a major shift in hydrological conditions. The contrasting behavior of metal concentrations suggests complex interactions between hydrological factors and metal mobilization or dilution processes. While the dilution effect is evident for Pb, Cu, and Cr, the significant increases in Zn and especially Cd concentrations warrant further investigation into potential sources or mobilization mechanisms during wet periods. These results highlight the need for more frequent sampling to better understand the seasonal dynamics of metal concentrations in relation to hydrological changes in the Balu River.

Table 17. Comparison of trace metal concentrations (mg/kg) and hydrological parameters in the Balu River between dry and wet periods (2019).

Parameters	Dry period (01 February 2019)	Wet period (01 August 2019)	Difference
Zinc (Zn)	415.36	464.61	11.86% increase
Lead (Pb)	29.66	16.57	44.15% decrease
Copper (Cu)	78.32	74.28	5.16% decrease
Chromium (Cr)	103.19	69.43	32.72% decrease
Cadmium (Cd)	0.69	4.49	554.52% increase
Ground water (m)	80.11	82.69	3.22% increase
Rainfall (mm)	0.00	1.00	Rainfall Occurred
U/S discharge (m^3/s)	0.62	261.08	Increased
D/S discharge (m^3/s)	−1.65	269.02	Increased
U/S water level (mMSL)	0.49	4.72	862.68% increase
D/S water level (mMSL)	0.50	4.28	752.92% increase

4. Discussion

The present study reveals significant seasonal variations in trace metal concentrations and hydrological parameters in the Balu River, Bangladesh. The findings indicate complex interactions between metal pollution and hydrological factors, which are crucial for understanding the river's ecosystem health and managing water resources effectively.

The observed increase in zinc (Zn) and cadmium (Cd) concentrations during the wet season, coupled with decreases in lead (Pb), copper (Cu), and chromium (Cr), suggests a nuanced relationship between metal mobilization and hydrological changes. This pattern aligns with the findings of Banu et al. [38] who reported higher metal concentrations in the dry season for most metals, except for specific cases. The dramatic increase in Cd concentration (554.52%) during the wet season is particularly concerning and warrants further investigation. This surge could be attributed to increased runoff from agricultural areas or industrial effluents, as suggested by Hossain et al. [48], who found elevated Cd levels in fish from the Turag-Tongi-Balu river system.

The substantial increases in water levels and discharge rates during the wet season (over 750% for both parameters) highlight the river's dynamic hydrology. These findings are consistent with the observations of Atiq et al. [49], who noted that pollutant concentrations in the Balu River are generally higher during the non-monsoon period due to lower water flow. However, the results show that this pattern doesn't hold true for all metals, particularly Zn and Cd. This discrepancy underscores the complex nature of metal behavior in aquatic systems and suggests that factors beyond simple dilution effects are at play.

The correlation analyses between trace metals reveal stronger relationships during the wet period, especially for Cr-Cu, Cr-Zn, and Zn-Cu pairs. These findings support the observations of Islam et al. [50], who noted that heavy metal contamination varies according to the nature of the sites and the intensity of industrial and agricultural runoff. The weaker correlations observed during the dry period suggest that point sources of pollution may have a more dominant influence when river flow is reduced. This aligns with the conclusions of Hasan et al. [51], who found that water pollution in the Balu River is generally more severe during the dry season due to reduced dilution.

The strong positive correlations observed between Cr-Cu, Cr-Zn, and Zn-Cu pairs during the wet season provide valuable insights into the dynamic behavior of these metals in the Balu River ecosystem. The consistent correlation across Spearman, Kendall, and Pearson analyses suggests a robust relationship that may be attributed to similar sources or shared geochemical behavior. For instance, the strong Cr-Cu correlation (Spearman: 0.802, Pearson: 0.870) could indicate a common industrial source, such as tanneries or metal plating facilities, which are known to release both metals [52,53]. The Cr-Zn and Zn-Cu correlations might reflect the influence of urban runoff, as these metals are often associated with vehicular emissions and wear of galvanized structures [54,55]. The weaker correlations observed during the dry season suggest that the behavior and sources of these metals may be altered under different hydrological conditions. This seasonal variation in metal relationships could be explained by changes in pH, redox conditions, or the relative contributions of point and non-point pollution sources [56,57]. The stronger correlations during the wet season may indicate enhanced mobilization and co-transport of these metals during high-flow periods, possibly due to resuspension of contaminated sediments or increased industrial discharge [58]. These findings highlight the need for season-specific pollution management strategies and underscore the importance of considering metal interactions in environmental risk assessments.

The integrated analysis of hydrological parameters and trace metals provides valuable insights into the river's pollution dynamics. The strong correlations between upstream and downstream discharge and water levels, as revealed by both Gower coefficient and partial correlation analyses, indicate a well-connected river system. However, the weak or negative correlations between rainfall and other parameters in the partial correlation analysis suggest that the relationship between precipitation and river pollution is not straightforward. This complexity is reflected in the findings of Roy et al. [59], who recommended maintaining appropriate distances for waste dumping sites and strict implementation of effluent treatment regulations to mitigate pollution.

The results highlight the urgent need for comprehensive water quality management strategies in the Balu River basin. The seasonal variations in metal concentrations and their relationships with hydrological parameters underscore the importance of tailored approaches for different seasons. As Sami and Sikder [60] emphasized, reviving the Balu River is not just a matter of healing the waterway but also of rejuvenating Dhaka itself. Implementing robust conservation strategies, as suggested by Bhuiyan et al. [61], such as stricter industrial discharge regulations, effective effluent treatment, and control of both point and non-point pollution sources, is crucial for improving the river's health.

Future research should focus on more frequent sampling to capture the fine-scale dynamics of metal concentrations in relation to hydrological changes. Additionally, investigating the sources and pathways of Cd pollution, given its alarming increase during the wet season, should be a priority. The potential for microplastic pollution, as highlighted by Odora et al. [40], adds another dimension to the complexity of the Balu River's environmental challenges. Integrating these various aspects of pollution and hydrology will be essential for developing a holistic understanding of the river ecosystem and implementing effective restoration measures. Authors should discuss the results and how they can be interpreted from the perspective of previous studies and of the working hypotheses. The findings and their implications should be discussed in the broadest context possible. Future research directions may also be highlighted.

5. Conclusion

This study provides comprehensive insights into the seasonal dynamics of trace metal concentrations and hydrological parameters in the Balu River, Bangladesh. The findings reveal significant seasonal variations in metal pollution, with zinc and cadmium showing marked increases during the wet season, while lead, copper, and chromium concentrations decreased. These changes coincided with substantial increases in water levels and discharge rates, highlighting the complex interplay between hydrological factors and metal mobilization. The dramatic increase in cadmium concentrations (554.52%) during the wet season is particularly concerning due to its potential toxic effects on aquatic life and human health.

The exceptionally high increase in cadmium and the contrasting behavior of different metals during wet and dry seasons highlight the complex dynamics of pollution in this urban river system. These findings go beyond general expectations and provide crucial, site-specific data for targeted environmental management. The results demonstrate that even in a monsoon-affected region, the patterns and magnitudes of seasonal metal pollution can vary significantly and unpredictably, necessitating continuous, detailed monitoring and adaptive management strategies.

This research has significant impacts at multiple levels. Globally, it contributes to understanding seasonal dynamics of trace metal pollution in monsoon-affected urban river systems. Nationally, it informs environmental policies and water management strategies across Bangladesh, particularly highlighting the critical issue of cadmium pollution. Locally, our findings have immediate implications for the management of the Balu River basin and surrounding urban areas of Dhaka, providing a scientific basis for targeted remediation efforts, urban planning, and public health initiatives.

These results underscore the need for season-specific water quality management strategies and more rigorous monitoring of industrial effluents and agricultural runoff. The findings support the implementation of stricter regulations on industrial discharges, improved effluent treatment practices, and better control of both point and non-point pollution sources.

Future research should focus on more frequent sampling to capture fine-scale dynamics of metal concentrations, investigation of cadmium pollution sources, and integration of microplastic pollution studies. Ultimately, the revitalization of the Balu River is crucial not only for the health of the aquatic ecosystem but also for the sustainable development of Dhaka and its surrounding areas. This study provides a foundation for evidence-based policy-making and conservation efforts aimed at improving the ecological status of this vital water resource, taking into account the complex seasonal dynamics of pollutant behavior in monsoon-affected urban river systems.

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