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Layer-wise physicochemical and elemental distribution in an urban river water, Bangladesh: potential pollution, sources, and human health risk assessment†

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Buriganga is an economically important river located around the industrialized urban area of Dhaka City, Bangladesh. In this study, 17 water quality parameters (electrical conductivity, pH, total suspended solids, temperature, F^- , Cl^- , SO_4^{2-} , Cr, Ni, As, Cd, Hg, Cu, Pb, Fe, Mn, and Zn) of surface and deep waters of the Buriganga River were measured to assess the water quality, pollution level, elemental sources, and their potential ecological and human health risks. Comparing the concentrations of the analyzed parameters with the permissible standards, it was indicated that the water in Buriganga is unsafe for residential and recreational uses. Principal component and correlation analysis revealed that point and diffuse sources, such as the combustion of lubricant oils, fuel additives, exhaust fumes from vehicles, domestic wastewater, and inorganic fertilizers from agricultural fields, control the water quality. Regardless of depth, a higher degree of contamination and ecological risk was observed during the dry season, indicating a higher content of heavy metals in river water, which might impact the ecological balance in the future. Through ingestion, the hazard quotient (HQ) of As, Cd, Pb, and Hg and the hazard index (HI) values were higher than the risk threshold ($HQ > 1$). Total HI values for children in both residential and recreational water were higher than those for adults (1.04×10^1 and 1.73×10^0 for surface and deep water, respectively), indicating that children are more sensitive to elemental contamination. Total carcinogenic risks of Cr and As due to exposure to water were higher than the standard limit ($>1.0 \times 10^{-4}$), which indicated possible cancer risks to the inhabitants around the river. Therefore, regular monitoring of river water quality and sustainable management could be implemented to recover the polluted river water and keep it pollution-free in the future.

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Environmental significance

The accumulation of toxic metals in the riverine ecosystems can pose serious environmental problems. It is important to determine the intensity of pollution by inventorying the metal concentrations in water and their possible ecological and health risk. Surface and deep waters from one important urban river of Bangladesh have been used for metal analysis and ecological and health risk assessment. The major findings indicated that the river water of Buriganga is unsafe for residential and recreational uses and poses moderate to very high ecological risks and possible cancer risks to the inhabitants around the river. The outcome of the study will create awareness in society about the frequent utilization of polluted river water for various purposes.

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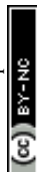
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1. Introduction

Researchers around the world are increasingly concerned about the deterioration of water quality and the presence of toxic elements in riverine water bodies.¹ Owing to their significant ecological toxicity, availability, extensive persistence, and bio-accumulation propensity, the toxic element contamination of waterways has become a widespread issue in recent years for human existence.²⁻⁴ The accessibility of potable, cooking, agricultural, recreational, residential, and manufacturing water is jeopardized by the high levels of toxic elements in river waters. In addition, the intake of fish and other aquatic foods sourced from polluted water environments often poses potential threats to the health of the environment and human beings as well.⁵⁻⁷ Toxic elements are primarily emitted by human activities, such as sewerage draining, the discharge of industrial waste and effluents, hospital waste dumping, unsustainable farming practices, unnecessary traffic activities, municipal waste disposal, and recreational operations. On the other hand, metals occur naturally in trace amounts and may enter aquatic ecosystems through the leaching of rocks, soil erosion, airborne dust, and forest fires.⁸⁻¹¹ River pollution has become an increasing threat due to government law enforcement weaknesses and a scarcity of frequent monitoring, particularly in developing nations like Bangladesh, where hundreds of manufacturers discharge waste materials into adjacent waterways.¹²⁻¹⁴ Nearly every day, a considerable volume of harmful effluents is poured into Bangladesh's lower land and water basins. The wastewater from various industries (located beside the river), such as battery manufacturing, garments, steel mills, and tanneries, is extremely toxic and reduces the oxygen levels in river water.¹⁵⁻¹⁷ As a consequence, essential and toxic elements are constantly precipitated and integrated into the water, polluting the aquatic habitat with heavy metals. Consequently, toxic elements in river water may have substantial negative consequences, affecting aquatic life, the natural ecology, water quality, and public health.^{18,19} Thus, studies have continued to analyze the hazards of toxic elements to public health, as well as their spatial and seasonal fluctuations in freshwater environments.

Because toxic elements are highly persistent and also have the capability to be hazardous to biological systems through bioaccumulation in food chains, they are of major concern for the aquatic ecosystem.²⁰⁻²³ Except for disrupting both surface and deep-water quality, trace metal bio-accumulation in the aquatic food chain is a threat to public health; thus, their potential exposure consequences on ecosystem integrity cannot be overlooked.^{24,25} Moreover, these toxic elements could build up in the body of a human through contact with the skin or ingestion of water with toxic elements and/or freshwater creatures. Long-term exposure to such toxic elements can lead to various diseases such as Parkinson's, sclerosis on the body surface, and prolonged cancer.^{12,18,26} Pollution of freshwater bodies of water, particularly rivers, has reached dangerous levels for human interaction, and this can be evaluated through heavy metal analysis in water.²⁷ However, regular monitoring of

river water quality is critical for maintaining environmental health and the achievement of sustainable development goals (SDGs) such as "Goal 6: Clean water and sanitation" and "Goal 14: Life below water" by dropping pollution and contamination.^{8,24,28-30} Thus, a thorough assessment of freshwater quality in terms of toxic metal contamination is critical for environmental and human health protection.

The Buriganga River, which flows from the Dhaleshwari near Kalatia, is a tide-influenced river that forms the western and southern borders of Dhaka city, the eco-political capital of Bangladesh.³¹ The river runs 11 km across Dhaka district and 7 km through Narayanganj district, with a little portion in Munshiganj. Some of the most prominent tourist sites in Dhaka, Bangladesh, such as Sadarghat (Buriganga River port), Ahsan Manzil Museum (architectural buildings), Tara Masjid (Islamic architecture), Lalbagh Fort (historical landmark), and Dhakeshwari Mandir (Bangladesh's National Temple), are situated on the bank or within a short distance of this river. A large number of tourists visit these locations for recreational purposes and approximately one million people live alongside the river. This increases the river's importance to residents and recreational users. The Buriganga River is vital for a wide variety of reasons, including several industrial activities, agricultural irrigation, fisheries, and recreational opportunities for residents and visitors alike. However, the river is severely polluted by a variety of sources, including but not limited to industrial wastewater, commercial waste, municipal wastewater, recreational activities, a variety of farming operations, navigational wastewater, and agricultural runoff.^{8,23,32}

Despite a government injunction and a High Court judgment, the majority of tanneries continue to pollute the Buriganga River. Rivers serve humans and other creatures in a number of ways, especially in impoverished countries like Bangladesh, where water sources are limited.³³ However, large volumes of pollutants such as toxic elements including As, Cd, Cr, Cu, Fe, Hg, Mn, Ni, Pb, and Zn are discharged into the riverine water bodies from various sources such as unplanned urbanization and rapid industrialization, which poses significant threats to the river ecosystems.^{25,34} Skin contact with river water while bathing and washing, as well as direct use of water for household purposes, is a potential route for toxic elements to enter the bodies of adult and child residents and recreationists.^{35,36} For years, the surface and deep waters of this river have been used by many restaurants and residences beside the river, resulting in trace element exposure. Therefore, an assessment of possible water quality deterioration factors is needed, and human health risks through ingestion and dermal contact (two common exposure routes) of water must be assessed for judicious management of river water.^{37,38} However, little is known about the potential health problems that the toxic elements in water may present to the residents of the Buriganga River.

The distribution and contamination of the river water by toxic elements have been depicted in previous studies.^{8,14,31} A recent study estimated the concentration of 48 metals in the surface water of the Buriganga River, targeting their seasonal variation, and found that the metals' concentration was lower in



the rainy season than in the winter.³⁹ Some of the most recent studies on the surface water of Buriganga River evaluated metal concentration, major anions, and cations as well as physico-chemical properties.^{40–43} However, no detailed study has been conducted yet on the layer-wise distribution (surface and deep waters) of toxic elements, major anions, and physical parameters in this urban river water with a focus on seasonal variation. Besides, no studies have highlighted the health risks to the residents who permanently live there or the recreationists who visit the historical places beside the studied Buriganga River. Therefore, the objectives of the current research are to (1) quantify and compare the levels of 17 water quality parameters including concerned elements (Cr, Ni, As, Cd, Hg, Cu, Pb, Fe, Mn, and Zn), anions (F^- , Cl^- , and SO_4^{2-}), and some physical parameters (electrical conductivity, pH, total suspended solids, and temperature) in both surface and deep waters of the river during dry and wet seasons, (2) identify the potential sources and factors that regulate the levels of toxic elements in the river, and (3) determine the human health risk of toxic elements in the river water by assessing the non-carcinogenic and carcinogenic risks for both adults and children who are residents and recreationists in the area.

2. Methodology

2.1. Study area

Buriganga River is one of the most polluted rivers in Bangladesh and is located in the central region of the country. The depth of the Buriganga River varies from 7.6 meters up to 18 meters on average.⁴⁴ The studied river's biological and hydrological health has deteriorated to the point of death due to the undiscerning discarding of residential, municipal, and industrial pollutants and the lack of authorities to maintain the ecological health of the river.⁴⁵ The river Buriganga has a stream of water running through it during the rainy season (monsoon); however, there is no water flowing through it during the dry season (winter). As a result, the body of water becomes stagnant, and the direct discharge of waste from industries as well as households and medical facilities significantly raises the degree of pollution in it during the dry/winter season. To collect the surface and deep waters of the Buriganga River throughout the summer and winter seasons for this study, a total of 14 sample sites were chosen (Fig. 1). The sampling location was chosen based on the activities of numerous industries such as urban waste dumping and burning, electroplating, city waste sewerage lines, lead

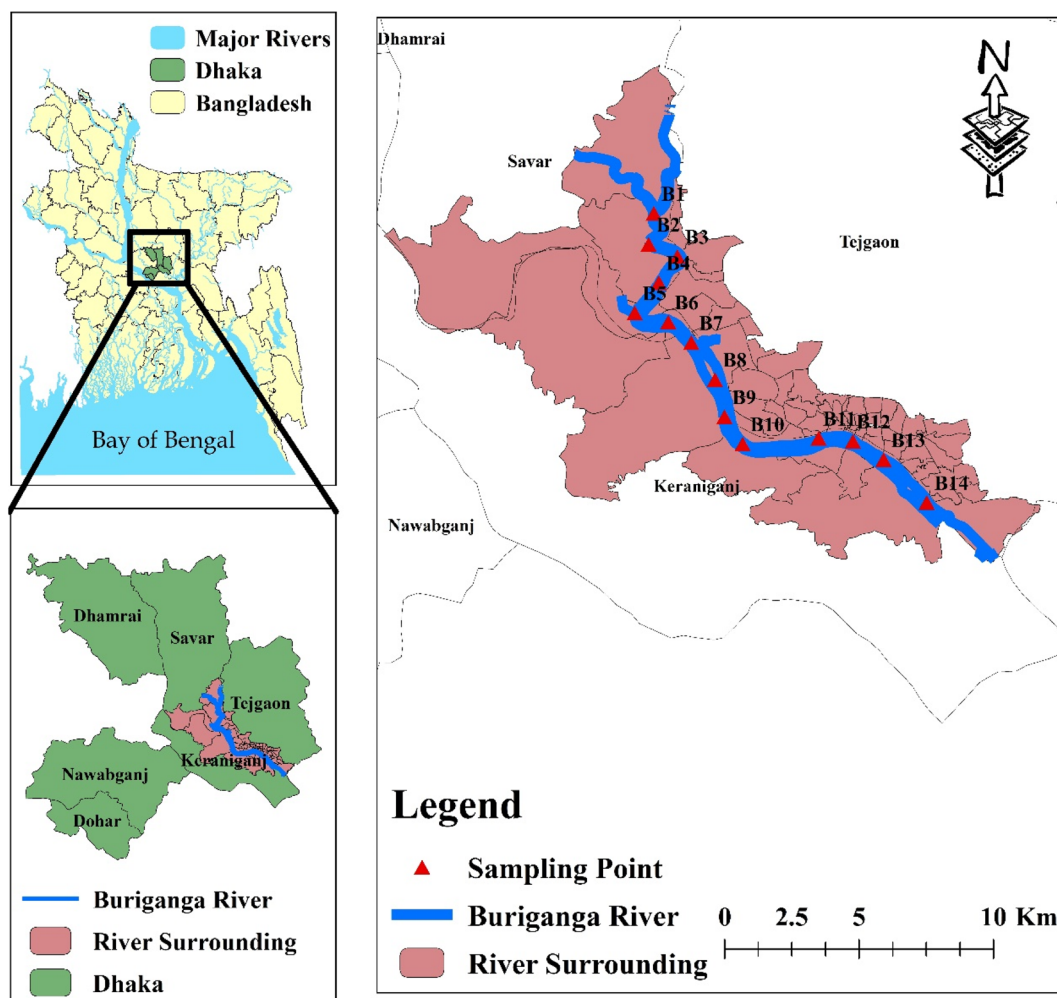


Fig. 1 Map of the study area of Buriganga river of Dhaka City urban area, Bangladesh.



smelting factories, leather tanning zones, distilleries, dyeing industries, textile, paper, glass, plastic, chemical, and battery manufacture, *etc.*

2.2. Sample collection and preservation

In this study, in total, 84 surface (0–20 cm) and 84 deep (400–800 cm) water samples were collected from 14 selected stations of the Buriganga River during the wet (July–August, 2021) and dry (February–March, 2022) seasons. The river water samples were collected directly in previously cleaned polypropylene bottles (500 mL), which were washed thoroughly with the sampling water before collecting the samples. For elemental analysis, the collected samples were immediately acidified with concentrated HNO_3 (2 mL L^{-1}), while an equal number of non-acidified samples were collected for the analysis of other parameters such as F^- , Cl^- , SO_4^{2-} , electrical conductivity (EC), pH, and total suspended solids (TSS). Water samples were collected and put in an ice chest before being transferred to the laboratory and kept in the refrigerator until chemical analysis.

2.3. Sample analysis and quality control

All samples were analyzed at an ISO/IEC 17025:2017 accredited laboratory (INARS, BCSIR, Dhaka, Bangladesh). However, the EC and pH of the river water samples were measured *in situ* during sample collection using a multimeter (Model: Sension™156, HACH, USA), which was calibrated with traceable standards. A calibrated thermometer was used to take water temperature readings on the spot as well. The EC, pH, and temperature of the water samples were measured directly by immersing the probes (for EC and pH) and thermometer (for temperature) into the water sample taken in a small beaker (100 mL) from both surface and deep waters separately. The surface water body was also checked directly for EC, pH, and temperature by immersing the respective probes into the water system to ensure the data quality. The TSS was determined gravimetrically in the laboratory.¹⁴ The collected non-acidified samples were vacuum filtered with $0.45 \mu\text{m}$ filter paper and taken in small sample vials to be used for F^- , Cl^- , and SO_4^{2-} analysis using an ion chromatograph (IC, Model: SIC10AVP, Shimadzu, Japan). Acidified water samples

were utilized for elemental analysis after filtration with Whatman No. 41 filter paper. The concentrations of As, Cd, Pb, Hg, Cr, Ni, Cu, Fe, Mn, and Zn were measured using an Atomic Absorption Spectrometer (AAS) with different arrangements and models of the instruments ((a) AA240FS, (b) GTA 120-AA240Z, and (c) SpectrAA 220, Varian, Australia). As and Hg were analyzed through VGA (vapor generation accessories)-77 by hydride vapor generation and cold vapor techniques, respectively. The concentrations of Cd, Pb, Cr, and Ni were determined through a graphite furnace, while Cu, Fe, Mn, and Zn were analyzed using an air-acetylene flame. NIST (National Institute of Standards and Technology) traceable certified reference materials (CRM) for individual elements and anions obtained from Fluka Analytical, Sigma-Aldrich, Germany, were employed for the preparation of calibration curves with high linearity ($r^2 = 0.9999$), and the concentration of each element and anion was determined against the respective individual calibration curve. The analysis accuracy and precision were guaranteed by repeated measurements of the CRM and the samples. The analysis of quality control standard, sample blank, and method blank was also performed sequentially. The spike recovery in the analysis of elements and anions using an AAS and IC, respectively, was within 97–102%. The limit of quantification (LOQ), the limit of detection (LOD), calibration range, and measurement uncertainty for the analyzed elements and anions are provided in ESI Table S1.† Further details about the analysis and quality control protocol employed in the analysis are described in our previous works (Fig. 2).^{14,46–49}

2.4. Environmental and ecological risk indices

The heavy metal evaluation index (HEI), degree of contamination (CD), and potential ecological risk (PER) indices were used to evaluate contamination levels for the studied metals. The details of these indices are described in ESI Table S2.†

2.5. Health risk assessment

Although the appearance of the Buriganga river water seems dark in color with a bad odor, some poor local people still use this water for their bathing and washing, which is an important health concern because metals from water systems can enter

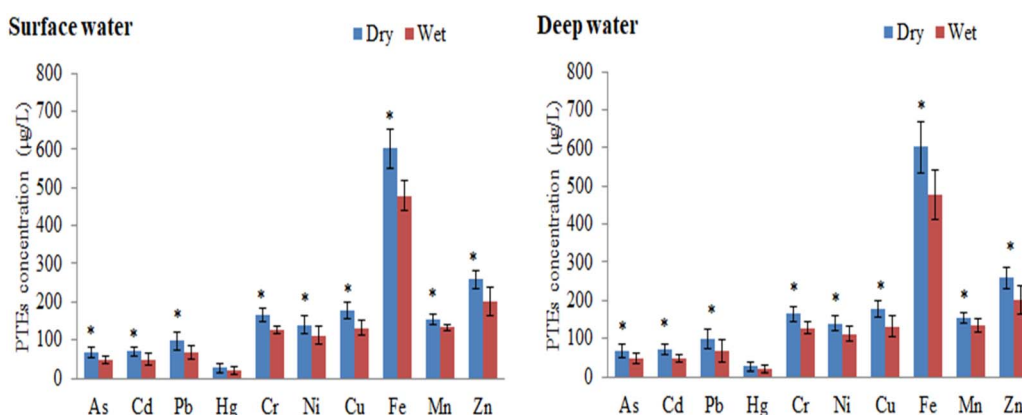


Fig. 2 Trace element concentration ($\mu\text{g L}^{-1}$) in surface and deep water samples of Buriganga River in Bangladesh. “*” indicates a statistically significant difference in TEs between the dry and wet seasons.



the human body through ingestion or skin contact, causing a health hazard. In this work, health risks associated with non-carcinogenic and carcinogenic effects of heavy metals through oral intake and dermal/skin contact with river water were calculated for both adult and child inhabitants following the guidelines of the USEPA.^{36,50,51} Non-carcinogenic risk parameters such as hazard quotient (HQ) and hazard index (HI) were calculated for the possible effects of non-carcinogenic risks of heavy metals *via* ingestion and skin contact using the following eqn (1)–(4).

$$HQ_{\text{ingestion}} = \frac{C_W \times IRW_{\text{res/rec}} \times EF_{\text{res/rec}} \times ED \times EV \times ET_{\text{res/rec}}}{BW \times AT_{\text{res/rec}} \times RfD_o \times 10^3} \quad (1)$$

$$HQ_{\text{dermal}} = \frac{C_W \times SA \times K_P \times ET_{\text{res/rec}} \times EV \times EF_{\text{res/rec}} \times ED}{BW \times AT_{\text{res/rec}} \times RfD_o \times GIABS \times 10^6} \quad (2)$$

Total HI was calculated by summing the HIs from each of the pathways.

$$HI = \sum HQs \quad (3)$$

$$THI = HI_{\text{ingestion}} + HI_{\text{dermal}} \quad (4)$$

The value of $HQ < 1$ represents no adverse health effects, while a value of $HI/THI > 1$ indicates that there may be non-carcinogenic effects from the close contact of metals.⁵²

Carcinogenic risk (CR) of human health defines the risk of cancer for an individual due to lifetime contact with As, Cr, and Pb and is calculated by eqn (5)–(10).

$$CR_{\text{ingestion}} = \frac{C_W \times IFW_{\text{res/rec}} \times CSF_0}{AT \times 10^3} \quad (5)$$

$$IFW_{\text{res/rec}} = \frac{EF_{\text{res/rec}} \times ED_a \times IRW_{\text{res/rec-a}}}{BW_a} + \frac{EF_{\text{res/rec}} \times ED_c \times IRW_{\text{res/rec-c}}}{BW_c} \quad (6)$$

$$CR_{\text{dermal}} = \frac{C_W \times K_P \times 0.001 \times ET_{\text{event-res/rec}} \times DFW_{\text{res/rec}} \times CSF_0}{AT \times GIABS \times 10^3} \quad (7)$$

$$ET_{\text{event-res/rec}} = \frac{ET_{\text{res/rec-a}} \times ED_a + ET_{\text{res/rec-c}} \times ED_c}{ED} \quad (8)$$

$$DFW_{\text{res/rec}} = \frac{EV_a \times EF_{\text{res/rec}} \times ED_a \times SA_a}{BW_a} + \frac{EF_{\text{res/rec}} \times EV_c \times IRW_{\text{res/rec-c}} \times ED_c}{BW_c} \quad (9)$$

Total cancer risk (TCR) was calculated by the sum of CRs from oral and skin contact.

$$TCR = CR_{\text{ingestion}} + CR_{\text{dermal}} \quad (10)$$

Units and values of the parameters used in the above equations associated with the carcinogenic and non-carcinogenic risks, oral reference dose (RfD_o), gastrointestinal absorption (GIABS), dermal permeability constant (K_P), and oral slope factor (CSF_0) are presented in ESI Tables S3 and S4.†

2.6. Statistical analysis

SPSS software (version 28, USA) was used to analyze the estimated water quality parameters. Means, standard deviations, and inferential statistics of measured data of water quality parameters were calculated to evaluate the data dispersion. Additionally, multivariate statistics, namely, principal component analysis (PCA) and Pearson correlation matrix were used to identify the sources of water quality controlling factors.¹²

3. Results and discussion

3.1. Physical and chemical properties of the surface and deep waters

The physical and chemical parameters of Buriganga River water during the wet and dry seasons are summarized in Table 1. In both surface and deep waters, F^- , Cl^- , and SO_4^{2-} showed higher concentrations in the dry season compared to the wet season. However, in a deep-water sample, a significantly higher concentration of SO_4^{2-} was observed compared to surface water. Water samples collected during the dry season had a significantly higher EC value than those collected during the wet season, which could be attributed to the dilution effect of river water caused by the wet season's high rainfall. However, in the wet season, higher TSS was reported, which is attributable to the influence of waste materials from agricultural runoff beside the river along with industrial discharge.^{2,53} Furthermore, the concentrations of EC and TSS in the surface water were found to be higher than in deep water since suspended and ionic matter from anthropogenic sources mostly comes first at the water's surface. The temperature of the Buriganga River water fluctuated with temporal variations. In the dry season, the mean (\pm SD) pH of surface and deep waters was 5.86 ± 0.49 and 5.80 ± 0.52 , respectively; in the wet season, the pH of surface and deep waters was 5.66 ± 0.50 and 5.61 ± 0.50 , respectively, indicating slightly acidic water in both seasons. The lower pH levels at some sampling sites could be attributed to the inputs of untreated wastewater from industries and domestic uses.¹⁵ Interestingly, the lower pH and higher TSS in river water might be attributed to higher concentrations of anions (F^- , Cl^- , and SO_4^{2-}), possible anaerobic conditions in water resulting in acidic substances, particularly from organic wastes, and potential adsorption of cations on the suspended organic and inorganic substances.^{54,55} Other elements including topography, hydrology, land outflow, rainfall, and industrial emissions (solid or liquid waste) may have had an important impact on the alteration of physicochemical qualities of the surface and deep waters of the Buriganga river.²⁴

The layer-wise concentrations ($\mu\text{g L}^{-1}$) of metals in river water for both dry and wet seasons are summarized in Table 2. Table 3 compares the studied metals of the Buriganga River to





Table 1 Physicochemical parameters in surface water samples from the Buriganga River in Bangladesh (mean \pm SD, from each station, $n = 3$)

Sites	F ⁻ (mg L ⁻¹)		Cl ⁻ (mg L ⁻¹)		SO ₄ ²⁻ (mg L ⁻¹)		EC (ms m ⁻¹)		pH		TSS (mg L ⁻¹)		Temperature (°C)	
	Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet
Surface water														
B1	0.11	0.09	6.61	6.23	3.51	3.34	40.5	18.9	5.22	6.13	326	398	23.5	28.1
B2	0.21	0.15	7.5	7.01	3.89	3.52	33.2	13.7	6.13	5.16	319	333	24.2	30.3
B3	0.23	0.17	7.31	7.21	4.33	3.84	33.7	24.8	6.05	6.03	256	310	25.5	30.7
B4	0.33	0.22	5.16	5.1	4.25	3.87	33.5	26.3	6.84	6.25	261	299	22.3	30.3
B5	0.22	0.16	7.02	6.29	4.28	3.89	47.2	25.2	5.77	5.36	265	302	24.1	28.7
B6	0.32	0.31	8.01	7.12	3.69	3.36	53.3	18.8	6.27	6.27	365	381	26.2	29.8
B7	0.37	0.31	7.73	6.91	4.29	3.07	52.1	27.5	6.14	6.11	289	301	24.3	30.5
B8	0.19	0.09	7.12	6.33	4.63	3.38	41.6	19.1	5.93	5.56	389	395	22.1	30.4
B9	0.13	0.07	6.18	6.01	3.42	3.13	39.3	28.2	6.18	6.13	412	486	23.3	30.2
B10	0.22	0.12	7.19	6.59	4.26	4.15	48.2	33.5	5.58	5.85	403	412	23.1	30.5
B11	0.24	0.14	6.69	6.09	4.06	3.11	38.3	23.5	6.08	5.15	313	312	23.5	28.5
B12	0.26	0.16	7.15	6.22	4.22	4.14	43.2	33.4	5.38	5.05	303	333	23.6	29.2
B13	0.27	0.12	7.79	6.99	4.29	3.95	41.1	35.5	5.22	5.01	411	387	23.3	30.1
B14	0.28	0.18	7.67	6.51	4.26	4.05	40.3	30.5	5.18	5.15	376	402	23.9	30.1
Mean \pm SD	0.24 \pm 0.07 ^a	0.16 \pm 0.07	7.08 \pm 0.75 ^a	6.47 \pm 0.56	4.10 \pm 0.35 ^a	3.63 \pm 0.40	41.8 \pm 6.46 ^a	25.6 \pm 6.42	5.86 \pm 0.49	5.66 \pm 0.50	335 \pm 57.1	361 \pm 56.2 ^a	23.8 \pm 1.1	29.8 \pm 0.84 ^a
Deep water														
B1	0.21	0.18	6.13	5.75	3.11	3.15	35.2	26.2	5.65	5.45	322	329	21.5	26.4
B2	0.08	0.06	6.22	5.87	3.72	3.33	31.1	19.9	5.06	5.07	353	369	22.2	25.4
B3	0.17	0.16	6.31	6.14	4.14	4.12	33.3	25.2	6.12	6.01	290	368	21.4	27.6
B4	0.17	0.13	7.02	7.03	4.71	3.52	41.3	26.7	6.05	6.02	251	295	22.7	25.3
B5	0.18	0.13	6.89	6.34	3.13	3.21	30.5	23.1	6.01	5.08	321	340	24.5	26.1
B6	0.16	0.15	7.07	6.36	4.35	3.87	41.1	27.5	5.07	5.11	257	253	23.7	24.4
B7	0.22	0.21	6.69	6.29	4.19	3.69	38.4	25.5	5.35	5.03	221	285	24.2	25.5
B8	0.24	0.18	5.56	5.73	3.93	3.45	39.2	29.3	6.21	6.22	310	376	24.1	27.6
B9	0.13	0.15	7.12	6.14	4.42	4.14	34.5	22.2	6.12	6.07	316	350	22.1	25.5
B10	0.09	0.07	7.84	7.31	4.64	4.12	33.4	23.2	5.55	5.56	332	366	22.2	26.3
B11	0.19	0.17	7.11	6.33	4.65	3.81	36.6	13.8	6.55	6.57	302	372	21.2	26.9
B12	0.08	0.07	6.99	6.51	4.25	3.22	30.4	23.5	6.51	5.59	330	365	22.5	28.3
B13	0.15	0.17	6.49	7.01	4.04	3.38	37.7	23.7	5.85	5.58	298	331	22.9	27.5
B14	0.18	0.17	6.68	7.05	4.11	3.91	38.4	25.1	5.05	5.16	312	372	22.7	26.7
Mean \pm SD	0.16 \pm 0.05	0.14 \pm 0.05	6.72 \pm 0.56	6.42 \pm 0.51	4.10 \pm 0.50 ^a	3.64 \pm 0.36	35.8 \pm 3.73 ^a	23.9 \pm 3.75	5.80 \pm 0.52	5.61 \pm 0.50	301 \pm 35.9	341 \pm 38.4 ^a	22.7 \pm 1.1	26.4 \pm 1.1 ^a

^a Indicates statistically significant difference between dry and wet seasons for the parameters ($p < 0.05$).



Table 2 Trace element concentration ($\mu\text{g L}^{-1}$) in the water samples of Buriganga river in Bangladesh (mean \pm SD, from each station, $n = 3$)

As	Cd		Pb		Hg		Cr		Ni		Cu		Fe		Mn		Zn	
Sites	Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet
Surface water																		
B1	70.1	55.4	71.5	57.3	91.1	60.0	16.5	15.7	177	122	130	95	155	113	550	490	169	152
B2	77.8	30.8	75.5	45.1	99.4	39.5	16.5	13.0	156	132	142	107	154	145	573	447	167	156
B3	66.9	44.9	77.2	33.3	83.5	41.8	13.5	12.7	149	116	146	117	152	134	588	393	146	139
B4	55.1	41.1	65.1	25.6	61.7	47.8	25.9	22.1	174	126	133	120	178	136	566	460	153	148
B5	86.7	63.5	78.8	55.1	79.2	44.1	25.1	13.9	185	142	135	83	189	126	594	487	167	152
B6	51.8	44.0	65.3	48.3	79.0	56.7	17.7	15.5	148	117	148	122	205	155	601	510	142	132
B7	82.0	47.1	55.2	44.0	57.8	59.6	17.3	14.8	169	147	161	139	207	134	554	459	150	135
B8	78.8	44.4	75.2	41.0	74.8	56.9	28.7	15.5	144	125	114	82	167	146	670	513	157	136
B9	77.3	32.9	88.3	44.2	108	71.1	29.6	17.3	145	134	123	110	192	176	626	533	167	158
B10	78.1	33.6	85.1	48.9	106	75.9	29.7	26.5	168	141	164	123	188	157	652	544	175	152
B11	95.4	43.1	92.1	47.1	112	88.1	35.7	22.2	188	141	173	132	210	144	656	440	188	152
B12	88.7	59.9	90.5	59.9	122	91.3	41.2	35.6	192	135	172	145	196	136	670	482	179	149
B13	96.3	55.7	95.6	88.0	136	87.7	45.8	30.1	188	133	189	154	200	166	697	500	183	142
B14	81.8	55.8	91.8	76.6	129	89.0	44.4	34.2	192	141	183	144	214	178	689	500	190	137
Mean	77.6 \pm 13.2 ^a	46.6 \pm 10.3	79.1 \pm 12.1 ^a	51.0 \pm 16.1	95.6 \pm 24.3 ^a	65.0 \pm 18.8	27.7 \pm 10.8	20.7 \pm 8.0	170 \pm 18.3 ^a	132 \pm 9.8	151 \pm 23.0 ^a	120 \pm 22.5	186 \pm 21.6 ^a	146 \pm 18.7	620 \pm 51.4 ^a	483 \pm 40.0	167 \pm 15.5 ^a	146 \pm 8.7
Deep water																		
B1	51.1	33.2	56.2	39.0	73.3	43.3	13.9	11.5	133	86.6	105	83.9	141	104	490	368	128	103
B2	42.0	29.9	47.0	41.5	74.0	33.3	14.9	10.0	150	111	120	87.0	150	112	534	432	159	121
B3	55.6	33.9	59.0	47.3	76.3	38.7	13.8	9.9	142	109	112	83.0	149	109	579	446	133	109
B4	53.3	40.5	65.4	51.2	76.2	39.4	15.5	13.5	176	126	123	116	172	118	532	399	151	126
B5	54.4	41.2	78.7	39.7	74.4	51.3	14.5	13.7	185	135	128	78.9	184	123	539	479	161	138
B6	55.2	47.8	65.1	46.7	79.9	68.4	17.2	15.9	132	120	124	115	179	138	679	504	140	123
B7	43.9	27.1	56.2	53.3	85.8	64.9	17.0	15.6	154	135	154	129	160	109	523	401	149	128
B8	65.6	38.9	74.1	32.2	99.9	46.0	27.8	15.4	175	127	147	117	166	116	637	428	152	139
B9	82.4	54.3	56.1	42.3	98.8	67.7	28.8	17.8	168	136	137	110	189	127	698	529	162	130
B10	81.1	65.6	84.3	58.9	96.6	66.1	39.2	26.6	173	145	157	128	174	116	637	522	151	146
B11	85.4	69.7	77.8	55.5	121	87.9	41.8	32.8	178	131	162	133	186	139	661	552	175	168
B12	92.6	63.7	84.0	49.8	116	99.0	45.0	31.7	187	135	154	121	211	175	632	513	165	152
B13	77.9	55.4	88.3	61.0	138	112	41.4	34.6	189	142	155	130	204	178	619	563	158	143
B14	89.3	64.3	89.9	63.3	151	123	37.8	32.1	175	156	169	138	208	188	659	555	176	144
Mean	66.4 \pm 17.7 ^a	47.5 \pm 14.5	70.2 \pm 14.0 ^a	48.7 \pm 9.2	97.2 \pm 25.5 ^a	67.2 \pm 28.6	26.3 \pm 12.4	20.1 \pm 9.3	165 \pm 19.6 ^a	128 \pm 17.4	139 \pm 20.3 ^a	112 \pm 20.5	177 \pm 22.1 ^a	132 \pm 28.1	601 \pm 67.0 ^a	478 \pm 65.0	154 \pm 14.2 ^a	134 \pm 17.2

^a Indicates statistically significant difference between dry and wet seasons for the parameters ($P < 0.05$).

those of other national and international rivers. Significant variations in metal concentrations were observed among the sampling sites and seasons. The variation of metal concentrations in any riverine ecosystem may have been influenced by the geomorphological setting, land runoff, and domestic-industrial discharges.^{12,56} The mean concentrations of the studied metals in the Buriganga River followed the descending order of Fe > Zn > Cu > Mn > Cr > Ni > Pb > Cd > As > Hg. Higher levels of metals were observed in the dry season than in the wet season, owing to decreased water flow during the dry season, which may have helped to accumulate metals in the river water.⁵⁷ In this study, concentrations of studied metals in surface water are clearly higher than in deep water, which indicated that elements after release from the sources quickly mixed with the surface water. Moreover, regardless of the seasons, the examined metals showed higher concentrations in the downstream locations of the studied river (Table 2). Water flow in the river with industrial effluents and wastewater discharge channels with sampling points may be related to variations in metal

concentrations along the riverways.⁵⁸ However, the main reasons for higher metal input at various sampling sites in the Dhaka megacity include industrial discharges, municipal wastewater, domestic garbage, and urban runoff.¹⁵ Table 3 also reveals the comparison of the minimum, maximum, and mean concentrations of these metals in both seasons (dry and wet) with the Bangladesh drinking water standards⁵⁹ and⁶⁰ drinking water guideline values. The results revealed that most of the water quality parameters exceeded the standard guidelines,^{59,60} indicating severe contamination of the surface and deep waters of the Buriganga River.

In surface water, the maximum concentration of As was found at site B13 ($96.3 \mu\text{g L}^{-1}$) in the dry season, followed by site B5 ($63.5 \mu\text{g L}^{-1}$) in the wet season. Considering both seasons, the maximum concentrations of As were found at sites B12 ($92.6 \mu\text{g L}^{-1}$) and B11 ($69.7 \mu\text{g L}^{-1}$) in deep water (Table 2). The use of As-contaminated pesticides in agricultural areas, the use of chromate copper arsenate to treat wood, the burning of coal for electricity, and the mining of silt from the whole system of the

Table 3 Comparison of the concentrations of trace elements in this study with international guidelines and other freshwater rivers (unit in $\mu\text{g L}^{-1}$)^a

Locations	As	Cd	Pb	Hg	Cr	Ni	Cu	Fe	Mn	Zn	References
Buriganga River, Bangladesh (present study)											
Surface water (dry season)	Mean 77.6	79.1	95.6	27.7	169.6	142.7	186.2	620	166.7	272.5	This study
Surface water (wet season)	Mean 46.6	51.0	65.0	20.7	131.4	119.6	146.2	483	1086.4	229.9	This study
Deep water (dry season)	Mean 66.4	70.2	97.2	26.3	165	139	176.6	601	154.2	259.0	This study
Deep water (wet season)	Mean 47.5	48.7	67.2	20.1	128.2	112.1	132.3	478	133.7	201.0	This study
Other rivers in Bangladesh and other countries for comparison											
Shitalakhya River, Bangladesh	Mean NA	2.9	4.4	3.6	4.2	NA	20.1	NA	NA	632	2
Old Brahmaputra River, Bangladesh	Mean NA	1.0	110	1.0	10	440	120	NA	1440	10	71
Turag River, Bangladesh	Range 11.8–19.3	0.21–0.30	3.73–4.50	NA	11.1–16.0	12.9–18.9	12.3–41.7	NA	NA	NA	66
Karnaphuli River, Bangladesh	Mean NA	0.01	0.14	NA	0.25	NA	0.05	NA	0.12	0.28	72
Buriganga River, Bangladesh	Mean NA	59	112	NA	114	NA	150	NA	157	332	78
Balu River, Bangladesh	Mean NA	13.7	1.0	NA	NA	NA	6.0	NA	NA	10.1	73
Bangshi River, Bangladesh	Mean NA	1.2	13.5	NA	NA	NA	70.0	NA	NA	210.0	74
Subarnarekha River, India	Mean NA	NA	NA	NA	0.89	25.2	16.6	134	12	NA	97
Damodar River, India	Mean NA	9	10	NA	16	52	18	NA	33	89	75
Ganges River, India	Mean 0.634	0.220	0.567	NA	1.851	0.485	0.642	0.033	NA	2.611	69
Meric-Ergene River, Turkey	Mean 3.51	0.046	0.51	NA	13.76	9.06	4.30	NA	26.3	8.18	67
Tigris River, Turkey	Mean 0.63	0.044	2.82	NA	25.41	24.54	17.10	158.16		12.01	68
Catalan River, Spain	Mean 2.9	1.2	2.2	NA	2.4	2.7	1.3		NA	1.9	70
Hawkesbury-Nepean River, Australia	Mean NA	0.045	0.111	NA	NA	0.26	0.81	268	52	0.88	76
Trinity River, USA	Mean NA	0.008	0.026	NA	NA	2.07	1.15	5.8	4.15	NA	77
Freshwater quality criteria for protection of aquatic life											
USEPA, CMC, acute	0.34	0.0018	0.082	0.0014	0.016	470	NA	NA	NA	0.12	65
USEPA, CCC, chronic	0.15	0.00072	0.0032	0.00077	0.011	52	NA	NA	NA	0.12	65
Drinking water quality criteria											
Drinking Water Standard Board (DWSB)	0.05	0.005	0.05	0.001	0.05	100	1	0.3–1.0	0.1	5	59
European Community	0.01	0.005	0.01	0.001	0.05	20	2	0.2	0.05	NA	63
WHO	0.01	0.003	0.01	0.006	0.05	70	2	NA	0.5	3	60
USEPA	MCLG 0.0	0.005	0.0	0.002	0.1	NA	1.3	NA	NA	NA	64
USEPA	MCL 0.01	0.005	0.015	0.002	0.1	NA	NA	NA	NA	NA	64

^a NA = data not available, CMC = criterion maximum concentration; CCC = criterion continuous concentration; MCLG = maximum contaminant level goal; MCL = maximum contaminant level.



studied river sites might all be contributing factors to the existence of a greater concentration of As.^{61,62} In comparison to several drinking water quality criteria, the As level in water samples was significantly higher than that recommended by Drinking Water Standard Board (DWSB), European Community (EuC), World Health Organization (WHO), Maximum Contaminant Level Goal (MCLG), and Maximum Contaminant Level (MCL) regardless of season^{59,60,63,64} (Table 3). The results of the current study were compared with freshwater quality criteria, and the level of As was observed to be several orders of magnitude greater than the water quality permissible standards established by the USEPA.⁶⁵ Arsenic concentrations in the current study's water samples were compared to those of other relevant studies at the national and international levels, and the As value was clearly higher than those of the rivers of Turag,⁶⁶ Meriç-Ergene River,⁶⁷ the Tigris River,⁶⁸ the Ganges River,⁶⁹ and the Catalan River⁷⁰ (Table 3).

The highest concentration of Cd was found in surface water at the B13 site (95.6 and 88.0 $\mu\text{g L}^{-1}$ in the dry and wet seasons, respectively), followed by deep water at the B14 site (89.9 and 63.3 $\mu\text{g L}^{-1}$ in dry and wet seasons, respectively) (Table 2). Higher levels of Cd in the Buriganga River's water could be linked to industrial activities, air emissions, and Cd-plated substances.⁵⁶ Furthermore, greater Cd levels could be attributed to variations in river water availability, where water intake to the river is primarily urban and there is a scarcity of regular water from natural sources, preventing pollutants from mixing with natural water.² The mean Cd levels in both water samples exceeded the criterion maximum concentration (CMC) and criterion continuous concentration (CCC) limits recognized by the USEPA,⁶⁵ implying that toxic metals, especially Cd, in river water may pose a substantial risk to the surrounding ecosystems (Table 3). In the current investigation, Cd content in both surface and deep waters was significantly greater than some guidelines such as DWSB, EuC, WHO, MCLG, and MCL, despite the seasons, when compared to various standards for drinking water quality.^{59,60,63,64} When comparing the Cd concentrations in this study with those of the other studies, it was discovered that Cd was substantially higher than those found in the waters of some of the other rivers such as Shitalakhya,² Old Brahmaputra,⁷¹ Turag,⁶⁶ Karnaphuli,⁷² Balu,⁷³ Bangshi,⁷⁴ Damodar,⁷⁵ Catalan,⁷⁰ Hawkesbury-Nepean,⁷⁶ and Trinity River,⁷⁷ but apparently similar to those found in the Buriganga River.⁷⁸

Among the sampling sites, B13 showed the highest level of Pb ($\mu\text{g L}^{-1}$) in the surface water (136 and 91.3 during the dry and wet seasons, respectively), whereas the highest levels of Pb ($\mu\text{g L}^{-1}$) were detected at B13 (138 in the dry season) and B14 (123 in the wet season) in deep water samples (Table 2). The increased Pb concentration in the current study river could be attributable to garbage discharged by neighboring battery and textile companies, dyeing industry lead-based dyes, or PVC-containing plastic toys.^{8,9} The first and most troubling component in Bangladesh is Pb, which was found in water samples to be expressively higher than the acceptable limits for drinking water, such as DWSB, EuC, WHO, MCLG, and MCL,^{59,60,63,64} and aquatic life, such as CMC and CCC,⁶⁵ as well as in other studies in Bangladesh^{2,66,71–74} and other countries^{70,75–77} (Table 3).

However, exceptionally high Pb concentration was found in the Buriganga River,⁷⁸ which is expected to be comparable to the current study, and could be owing to various sources at the study sites, such as gasoline, metropolitan runoffs, and deposition of lead-containing materials from the atmosphere.¹⁸

During the dry and wet seasons, the maximum Hg concentrations were detected in surface water at the B13 site (45.8 $\mu\text{g L}^{-1}$) and the B12 site (35.6 $\mu\text{g L}^{-1}$). The highest level of Hg was reported at site B12 (45.0 $\mu\text{g L}^{-1}$ in the dry season) and site B13 (34.6 $\mu\text{g L}^{-1}$ in the wet season) in the deep-water samples (Table 2). Hg concentrations in water samples were found to be significantly higher than the freshwater quality criteria (CMC and CCC recommendation values) as well as other drinking water standards^{59,60,63–65} (Table 3). Mercury levels in groundwater and surface water are typically less than 0.5 $\mu\text{g L}^{-1}$, while higher levels in groundwater may result from local mineral deposits.⁶⁰ Mercury can also be found in non-ionic organic molecules, as well as in other organic and inorganic compounds. Mercury enters the riverine aquatic environment through a variety of routes. Depositions from the atmosphere can directly introduce inorganic forms into reservoirs.⁷⁹ Hg(II) and CH_3Hg , on the other hand, are carried into water reservoirs by surface runoff and leaching from higher levels of a soil profile to groundwater, which are then recycled into surface waters.⁸⁰ Mercury adsorption and desorption processes in the aquatic environment play an important role in mercury distribution in different aquatic components. These systems are also necessary for the distribution, transformation, and uptake of Hg by living organisms in bodies of water.⁸¹ The mean concentration of Hg was found to be considerably higher than that of the numerous earlier studies conducted in Bangladesh, such as in the Shitalakhya River² and Old Brahmaputra River.⁷¹

The highest value of Cr was observed at B12 and B14 sites (192 $\mu\text{g L}^{-1}$ in the dry season), while B10, B11, and B14 sites were recorded as the top Cr-rich sites in the wet season (141 $\mu\text{g L}^{-1}$) (Table 2). In contrast, a greater level of Cr in deep water was found at sites B13 (189 $\mu\text{g L}^{-1}$) and B14 (156 $\mu\text{g L}^{-1}$). Concentrations of Cr in water samples from the study area were found to be substantially higher than the CMC and CCC standards for aquatic life protection established by the USEPA.⁶⁵ The current study's Cr level was compared to numerous drinking water quality criteria, and it was confirmed that Cr levels were higher than the recommended values of the standards such as DWSB, EuC, WHO, MCLG, and MCL.^{59,60,63,64} The presence of higher levels of Cr in water samples could be due to the effects of untreated wastewater from tanneries on the Buriganga River's west bank (Hazariabagh area of Dhaka City).⁸ In addition, pigment production, electroplating a thin layer of chromium onto a metal object, and different preservatives for wood processing may have a direct influence on raising Cr levels in the studied river.² Hence, the waste and effluents emitted by these enterprises are most likely to blame for the higher Cr levels found in the exposed water samples. Furthermore, earlier literature demonstrating worldwide increasing Cr concentrations was accessible from a number of scientists, including Kabir *et al.*,² Islam *et al.*,⁶⁶ Bhuiyan *et al.*,⁷¹ Islam *et al.*,⁷² and Carafa *et al.*⁷⁰ (Table 3).



In surface water, the maximum concentration ($\mu\text{g L}^{-1}$) of Ni was observed at the B13 site (189 and 154 during the dry and wet seasons, respectively). In deep water, the highest concentration of Ni ($\mu\text{g L}^{-1}$) was found at the B14 site (169 and 138, dry and wet seasons, respectively) (Table 2). However, Ni concentrations were prominent and deliberately higher than the various drinking water reference levels, for instance, DWSB, EuC, and WHO.^{59,60,63} Moreover, water samples of the Buriganga River showed lower and higher amounts of Ni contents when compared to USEPA-CMC and CCC values (Table 3), respectively, documented by USEPA.⁶⁵ Although motor oils contain tiny amounts of Ni, the combustion of diesel fuel is the primary source of Ni in urban street dust, and as a result, the urban runoff would be a significant Ni source in nearby surface and deep waters. Accidental spills of Ni-containing items, municipal and industrial waste, and lithogenic causes are all possible sources of Ni in the urban aquatic environment.³⁷ Nickel concentrations in water samples were significantly lower in previous studies^{66,70,75–77} than in this study, but significantly higher concentration was reported by Bhuiyan *et al.*⁷¹ than the current measured concentrations (Table 3).

For the dry and wet seasons, the greatest concentrations ($\mu\text{g L}^{-1}$) of Cu in surface water were reported at the B14 site (214 and 178). The highest concentration of Cu in deep water was observed at sites B12 and B14 (211 and 188 $\mu\text{g L}^{-1}$ during the dry and wet seasons, respectively) (Table 2). All of the Cu contents in all of the water samples collected across the study area were much higher than the DWSB, EuC, WHO, and MCLG standards^{59,60,63,64} (Table 3). In the current study, an elevated level of Cu could be due to the sorption and desorption, leaching of contaminants, and leakage of sewage from the urban runoff.^{2,8} The Cu concentration in water of the current study was higher than that of earlier Bangladeshi research^{2,66,71–74} and other countries^{70,75–77} (Table 3).

The maximum concentration of Fe in the Buriganga River surface water was determined to be 697 $\mu\text{g L}^{-1}$ at the B13 site during the dry season, but it dropped to 544 $\mu\text{g L}^{-1}$ at the B10 site during the wet season. The highest concentration (698 $\mu\text{g L}^{-1}$) of Fe was found in deep water at the B8 site during the dry season, followed by 563 $\mu\text{g L}^{-1}$ at the B13 site during the wet season (Table 2). The Fe concentration in the Buriganga River deep water is higher than that in the surface water in this study, and it is always the highest for both seasons and each site. The average Fe content in this investigation was a hundred times greater than DWSB and EuC norms^{59,63} (Table 3). When the Fe concentrations in this study were compared to those in previous studies, it was determined that they were much greater than those of the aquatic environments like Tigris River,⁶⁸ Hawkesbury-Nepean,⁷⁶ and the Trinity River⁷⁷ (Table 3). The largest Fe concentrations in both water samples are most likely due to the accumulation of rock minerals by the effects of storms, corrosion, wind, and waves, electroplating and smelting activities at the banks of the river, and wastewater application to the river-side agricultural fields.⁸

In both the dry and wet seasons, the highest level of Mn in surface water was found at sites B14 (190 $\mu\text{g L}^{-1}$) and B9 (158 $\mu\text{g L}^{-1}$), respectively, followed by B14 (176 $\mu\text{g L}^{-1}$) and B11 (168 $\mu\text{g L}^{-1}$) locations in deep water, respectively (Table 2). It was revealed that the current study's Mn concentration level was extensively greater than DWSB, EuC, and WHO norms^{59,60,63} (Table 3). Mn concentrations in the current study's waters were compared to those in other studies conducted in Bangladesh and other countries, and it was discovered that the current study's Mn concentration was higher than that in the other studies,^{72,75–77} it was also interestingly lower than that of Bhuiyan *et al.*,⁷¹ and it was expectedly parallel to that of Bhuiyan *et al.*⁷⁸ (Table 3). Manganese may be present in water due to natural sources (rock and soil weathering), extraction of other geological minerals from the earth, and industrial discharges of untreated waste.²³

In the Buriganga River, the second highest concentration in surface water was Zn found at the B9 site, with maximum concentrations of 320 and 293 $\mu\text{g L}^{-1}$ during the dry and wet seasons, respectively (Table 2). However, the maximum Zn level was found in deep water at the B12 site (299 and 259 $\mu\text{g L}^{-1}$ in the dry and wet seasons, respectively) (Table 2). The mean value of Zn in samples exceeded the USEPA's⁶⁵ CMC and CCC standards, indicating that Zn in river water posed a significant threat to the riverine ecosystems (Table 3). When compared to various drinking water quality criteria, the Zn level in water was significantly higher than that recommended by DWSB and WHO, regardless of season.^{59,60} Other researchers observed higher levels of Zn in water samples, such as Kabir *et al.*² and Bhuiyan *et al.*;⁷⁸ in contrast, lower levels of Zn were found in other investigations^{70–76} than the present study (Table 3). Zn concentrations varied from location to location and season to season, which could be attributed to changes in water flow, industrial settlement, drainage networks, and waste from agricultural runoff at the sampling sites.² Moreover, increased anthropogenic activities like brick manufacturing, dredging, power production, transporting industrial emissions, galvanizing, refining, sludge disposal, and energy production also raise the concentration of Zn in the Buriganga River water.

3.2. Source analysis of metals

To determine the interrelationship and potential sources of metals, Pearson's correlation analysis and principal component analysis (PCA) using varimax rotation with Kaiser normalization were used. The results are presented in Tables S5–S8 and Fig. S1–S4.†

In the wet season for surface and deep-water data of metals, PCA extracted four and two components (eigenvalues > 1.0) specifying 83.2 and 80.6% of the total variance, respectively. For surface water, the PC1 explained 42.1% of the total variance and was loaded with Pb, Hg, Ni, and Zn. According to Table S4,† Pb was strongly correlated with Hg ($r = 0.85$) and Zn ($r = 0.773$). Ni correlated moderately with Hg ($r = 0.85$) and Pb ($r = 0.85$). A similar association among these metals means that they may have originated from similar sources such as vehicular pollution. Tire abrasion, combustion of lubricants, fuel additives, and the fumes of vehicles are responsible for releasing these elements in urban areas.^{82,83} The PC2 accounted for 17.9% of the total variance and was loaded with Cu, Fe, and Zn. Cu showed a moderate correlation with Fe ($r = 0.587$) and Zn ($r = 0.627$). Municipal



wastewater and landfill leachate together with natural sources (such as weathering of parent rock) may be responsible for releasing these elements into the surface water.^{84–86} The PC3 explained 12.6% of the total variance and was loaded by As and Cd and moderate correlation was observed among these two elements ($r = 0.575$) in correlation analysis, demonstrating the agricultural effluents as a source for As and Cd. Arsenic can be found in insecticides, herbicides, and pesticides.⁸⁷ Cadmium can also be released into the river by overusing Cd-based fertilizers.^{88,89} The PC4 was found to be loaded with Cr and Mn, and it explained 10.4% of the total variance. There was no correlation between Cr and Mn and other metals, indicating that these two metals may have originated from unlike sources.⁹⁰

In deep water, the PC1 explained 69.5% of the total variance and was associated with Cd, Pb, As, Hg, Cu, Ni, Fe, and Zn. In correlation analysis, As showed strong correlations with Pb ($r = 0.760$), Hg ($r = 0.879$), and Fe ($r = 0.797$). Cd showed a strong correlation with Pb ($r = 0.723$), Hg ($r = 0.733$), and Ni ($r = 0.705$), whereas Pb showed a strong correlation with Hg ($r = 0.921$), Ni ($r = 0.733$), Cu ($r = 0.927$), Fe ($r = 0.799$) and Zn ($r = 0.737$). In addition, a moderate correlation was found for As with Cd ($r = 0.591$), Cr ($r = 0.519$), Ni ($r = 0.643$), Cu ($r = 0.690$), and Zn ($r = 0.591$), and for other element pairs such as Cd and Cu ($r = 0.595$), Cd and Fe ($r = 0.580$), Cr and Ni ($r = 0.564$), Cr and Fe ($r = 0.511$), Ni and Cu ($r = 0.576$), Ni and Fe ($r = 0.539$), Ni and Zn ($r = 0.504$), and Fe and Zn ($r = 0.634$). The sources of these metals in PC1 are the same as the sources of the metals in surface water in PC1, PC2, and PC3. This is due to the hydraulic characteristics of the river flow, the turbulence of the flow, and secondary flows (especially in river bends). Hence, these elements may be derived from a mixture of vehicular, agricultural, and municipal waste and wastewater. The component PC2 was loaded by As, Cr, Ni, Fe, and Mn and explained 11.0% of the total variance. Arsenic had strong correlations with Fe ($r = 0.869$) and Mn ($r = 0.799$). Manganese is also strongly correlated with Fe ($r = 0.714$). There was a moderate correlation between As and Cr ($r = 0.519$), As and Ni ($r = 0.643$), Cr and Fe ($r = 0.511$), Ni and Fe ($r = 0.539$), and Ni and Mn ($r = 0.687$). These elements have been linked to geochemical activities or the sink function of river sediment in terms of metal release into the water column.⁹¹ Chromium is moderately correlated with Mn ($r = 0.620$), indicating the discharge of industrial wastewater.

In the dry season, two components were extracted for both surface and deep waters, explaining 77.9 and 82.7% of the total variance, respectively. For surface water, the first component (PC1) explained 62.5% of the total variance and was loaded with Cd, Pb, As, Hg, Mn, Fe, and Zn. A strong correlation was found between As and Mn ($r = 0.754$), Cd and Pb ($r = 0.919$), Cd and Hg ($r = 0.797$), Cd and Fe ($r = 0.816$), Cd and Mn ($r = 0.836$), Pb and Hg ($r = 0.769$), Pb and Fe ($r = 0.753$), Pb and Mn ($r = 0.849$), Hg and Fe ($r = 0.886$), and Hg and Mn ($r = 0.799$). In addition, a moderate correlation was observed for As with Cd ($r = 0.655$), Pb ($r = 0.754$), Hg ($r = 0.627$) and Fe ($r = 0.571$), Zn with Cd ($r = 0.694$), Fe ($r = 0.550$), Pb ($r = 0.697$), and Mn with Zn ($r = 0.524$). These metals may be associated with a mixture of traffic-related pollution and agricultural effluents, demonstrating a combination of PC1 and PC3 in the wet season. The second component

(PC2) was specified by Hg, Cr, Cu, Ni, and Mn and composed 15.4% of the total variance. Manganese showed a strong correlation with Hg ($r = 0.799$) and Cr ($r = 0.799$). There was a moderate correlation between Hg and Cr ($r = 0.628$), Hg and Ni ($r = 0.620$), Hg and Cu ($r = 0.600$), Cr and Ni ($r = 0.676$), As and Pb ($r = 0.754$), Ni and Cu ($r = 0.629$), and Ni and Mn ($r = 0.594$). These metals might be related to a mixture of industrial and municipal wastewater, landfill leachate, and natural sources. PC2 in the dry season can be representative of the combination of PC2 and PC4 in the wet season.

For deep water, the first component (PC1) explained 70.9% of the total variance and was specified by As, Cd, Pb, Hg, Cr, Ni, Cu, and Mn. According to the correlation analysis provided in ESI Table S8,[†] both strong and moderate correlations were observed between these metals. The sources of these elements in PC1 are the same as the sources of the surface water in PC1, revealing vehicular pollution, municipal waste and wastewater, and agricultural effluents. The second component (PC2) was explained by As, Pb, Hg, Cu, Fe, and Zn and determined by 11.7% of the total variance. Arsenic exhibited a strong correlation with other elements in this PC, indicating natural sources

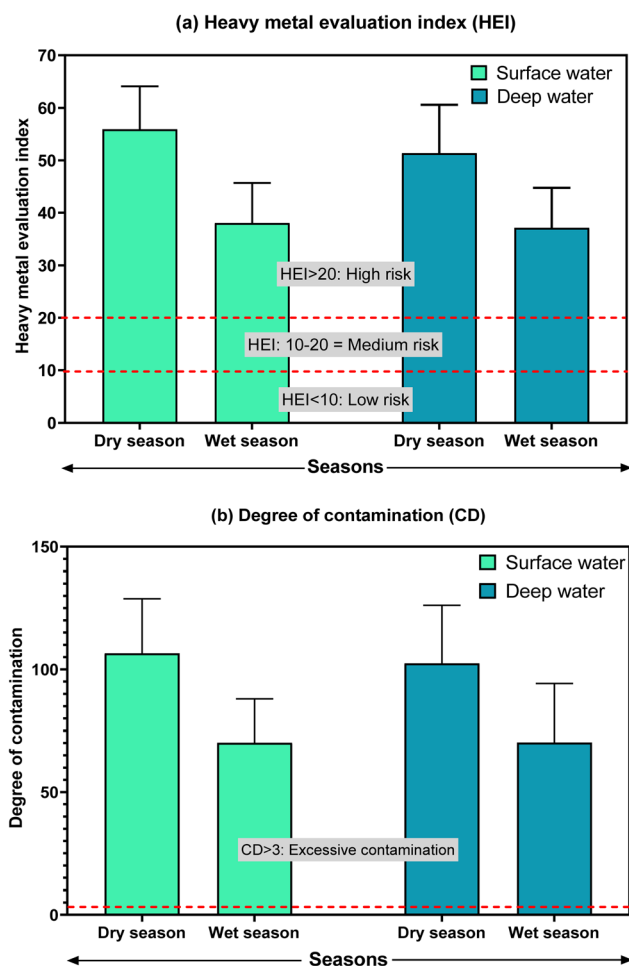


Fig. 3 Heavy metal evaluation index (HEI) and degree of contamination (CD) in the surface and deep waters of the Buriganga River during dry and wet seasons.



for these elements, which could be derived from river bed sediment.^{92–94} In addition, the strong correlation between Hg and Cr ($r = 0.727$) can be justified by the discharge of industrial wastewater. PCA results indicate that the source of metal attribution was mainly anthropogenic actions such as chemical fertilizing, industrial waste, raw materials from households and agro-fields, and so on.

3.3. Pollution level and ecological risks

The cumulative pollution level of the water in Buriganga River was estimated using the heavy metal evaluation index (HEI) and degree of contamination (CD) for the studied metals in this study, which is depicted in Fig. 3. The HEI and CD both indicated a high risk and excessive degree of contamination of the

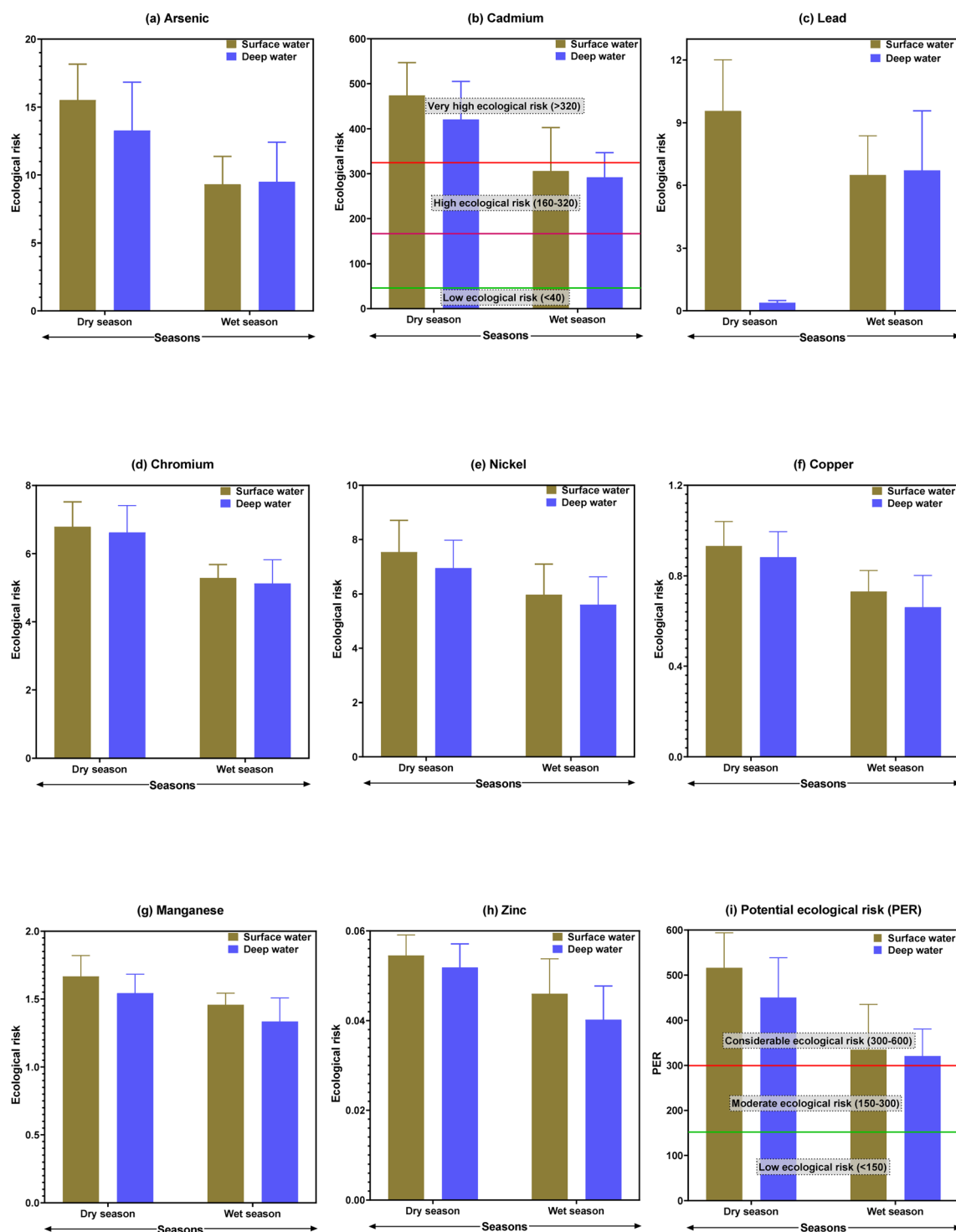


Fig. 4 Ecological risks of metals in surface and deep waters from Buriganga River during dry and wet seasons.



river water in both depths regardless of the seasons. Apparently, there were higher risks and contamination in the surface water during the dry season, where, during the dry season, the HEI was 55.9 ± 8.15 in surface water and 51.4 ± 9.24 in deep water. The highest HEI was observed at site B13 (HEI = 69) in the surface water during the dry season, followed by 67 at B14 in the deep water during the dry season. A similar pattern was also found for CD values, indicating the most polluted location at B13 and B14 in the Buriganga River arising from estimated metals in water (ESI Table S9†). Apparently, the upstream of the Buriganga River is less polluted than the downstream, which might be associated with higher urban, industrial, and other anthropogenic activities in the downstream areas.

Ecological risks of individual metals and their cumulative ecological risks are provided in Fig. 4. Most of the studied metals have no ecological risks as the values were less than 40, except for Cd. During the dry season, Cd in surface and deep waters indicated a very high ecological risk (>320), with average values of 474.5 and 420.9, respectively. The highest ecological risk for Cd was found at B13 (ecological risk value of 573.6), followed by B11 (552.6) in the surface water (ESI Table S10†). However, the potential ecological risk (PER) indicated considerable ecological risks both in the surface and deep waters of the Buriganga River during both seasons. Similar to the pollution level, higher ecological risk was observed during the dry season in the surface water. A very high ecological risk (>600) was observed at B11 (ecological risk value of 602.0), B13

(ecological risk value of 626.3), and B14 (ecological risk value of 600.0) in the surface water, while at these points, in the deep water, a considerable ecological risk was observed during the dry season (ESI Table S11†). In line with the pollution and contamination levels, higher ecological risks were observed for the downstream sites of the Buriganga River. As the PER indicated a moderate to very high ecological risk in different locations in the Buriganga River during different seasons at different water depths, there is a big matter of concern, particularly in the very high ecological risk points that may face stress and possibly a matter of extinction of various aquatic species in Buriganga River. Besides, if the pollution from metals continues it will affect the ecological balance in the long run.

3.4. Health risk appraisal

Non-carcinogenic and carcinogenic risks such as HQ, HI, and CR from oral intake and skin contact with water from the Buriganga River are presented in Tables 4 and 5. As shown by the highest HQ values for the examined inhabitants through the ingestion of water (Tables 4 and 5), arsenic contributed 40 and 39% of the total health risk in surface and deep waters, respectively, for both the adult and child receptors (Tables 4 and 5). Previous studies, however, have found a high non-carcinogenic risk of As for residents *via* oral intake of water.^{92,95} In the case of surface water samples, Hg also had high HQ values of 2.26×10^0 and 1.56×10^{-1} for residential and

Table 4 Non-carcinogenic (HQ, HI, and THI) and carcinogenic (CR and TCR) risks from trace elements in the surface water of the Buriganga River for residential and recreational receptors^a

Elements	Non-carcinogenic risks for adults			Non-carcinogenic risks for child			Carcinogenic risks for adults		
	HQ ingestion	HQ dermal	THI	HQ ingestion	HQ dermal	THI	CR ingestion	CR dermal	TCR
Residential									
As	3.87×10^0	3.04×10^{-2}	3.90×10^0	5.57×10^0	4.55×10^{-2}	5.62×10^0	1.31×10^{-3}	6.99×10^{-6}	1.32×10^{-3}
Cd	1.22×10^0	9.57×10^{-4}	1.22×10^0	1.75×10^0	1.43×10^{-3}	1.75×10^0			
Pb	1.07×10^0	8.43×10^{-4}	1.07×10^0	1.54×10^0	1.26×10^{-3}	1.55×10^0	9.60×10^{-6}	5.12×10^{-8}	9.65×10^{-6}
Hg	2.26×10^0	1.78×10^{-2}	2.28×10^0	3.25×10^0	2.66×10^{-2}	3.28×10^0			
Cr	9.41×10^{-1}	5.92×10^{-1}	1.53×10^0	1.35×10^0	8.84×10^{-1}	2.24×10^0	1.06×10^{-3}	4.53×10^{-4}	1.51×10^{-3}
Ni	1.26×10^{-1}	4.97×10^{-3}	1.31×10^{-1}	1.82×10^{-1}	7.43×10^{-3}	1.90×10^{-1}			
Cu	7.77×10^{-2}	6.11×10^{-4}	7.83×10^{-2}	1.12×10^{-1}	9.13×10^{-4}	1.13×10^{-1}			
Fe	1.47×10^{-2}	1.16×10^{-4}	1.49×10^{-2}	2.12×10^{-2}	1.73×10^{-4}	2.14×10^{-2}			
Mn	1.22×10^{-1}	2.39×10^{-2}	1.46×10^{-1}	1.75×10^{-1}	3.57×10^{-2}	2.11×10^{-1}			
Zn	1.57×10^{-2}	7.39×10^{-5}	1.57×10^{-2}	2.25×10^{-2}	1.10×10^{-4}	2.27×10^{-2}			
HI	9.72×10^0	6.71×10^{-1}	1.04×10^1	1.40×10^1	1.00×10^0	1.50×10^1	2.38×10^{-3}	4.60×10^{-4}	2.84×10^{-3}
Recreational									
As	2.67×10^{-1}	4.78×10^{-2}	3.15×10^{-1}	1.36×10^0	7.22×10^{-2}	1.43×10^0	8.69×10^{-5}	8.93×10^{-6}	9.58×10^{-5}
Cd	8.40×10^{-2}	1.50×10^{-3}	8.55×10^{-2}	4.28×10^{-1}	2.27×10^{-3}	4.30×10^{-1}			
Pb	7.41×10^{-2}	1.32×10^{-3}	7.54×10^{-2}	3.77×10^{-1}	2.00×10^{-3}	3.79×10^{-1}	6.37×10^{-7}	6.54×10^{-8}	7.02×10^{-7}
Hg	1.56×10^{-1}	2.79×10^{-2}	1.84×10^{-1}	7.95×10^{-1}	4.22×10^{-2}	8.37×10^{-1}			
Cr	6.50×10^{-2}	9.29×10^{-1}	9.94×10^{-1}	3.31×10^{-1}	1.40×10^0	1.73×10^0	1.13×10^{-5}	2.89×10^{-4}	3.01×10^{-4}
Ni	8.74×10^{-3}	7.80×10^{-3}	1.65×10^{-2}	4.45×10^{-2}	1.18×10^{-2}	5.63×10^{-2}			
Cu	5.37×10^{-3}	9.59×10^{-4}	6.32×10^{-3}	2.73×10^{-2}	1.45×10^{-3}	2.88×10^{-2}			
Fe	1.02×10^{-3}	1.82×10^{-4}	1.20×10^{-3}	5.18×10^{-3}	2.75×10^{-4}	5.46×10^{-3}			
Mn	8.40×10^{-3}	3.75×10^{-2}	4.59×10^{-2}	4.28×10^{-2}	5.67×10^{-2}	9.95×10^{-2}			
Zn	1.08×10^{-3}	1.16×10^{-4}	1.20×10^{-3}	5.51×10^{-3}	1.75×10^{-4}	5.68×10^{-3}			
HI	6.71×10^{-1}	1.05×10^0	1.73×10^0	3.42×10^0	1.59×10^0	5.01×10^0	9.88×10^{-5}	2.98×10^{-4}	3.97×10^{-4}

^a Bold figures indicate that the risk level of TEs is higher than 1.0 (HQ/HI/THI > 1.0).

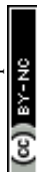


Table 5 Non-carcinogenic (HQ, HI and THI) and carcinogenic (CR and TCR) risks from trace elements in the deep water of the Buriganga River for residential and recreational receptors^a

Elements	Non-carcinogenic risks for adult			Non-carcinogenic risks for child			Carcinogenic risks		
	HQ ingestion	HQ dermal	THI	HQ ingestion	HQ dermal	THI	CR ingestion	CR dermal	TCR
Residential receptor									
As	3.55×10^0	2.79×10^{-2}	3.58×10^0	5.11×10^0	4.17×10^{-2}	5.16×10^0	1.20×10^{-3}	6.41×10^{-6}	1.21×10^{-3}
Cd	1.11×10^0	8.74×10^{-4}	1.11×10^0	1.60×10^0	1.31×10^{-3}	1.60×10^0			
Pb	1.10×10^0	8.64×10^{-4}	1.10×10^0	1.58×10^0	1.29×10^{-3}	1.58×10^0	9.83×10^{-6}	5.24×10^{-8}	9.88×10^{-6}
Hg	2.17×10^0	1.71×10^{-2}	2.19×10^0	3.12×10^0	2.55×10^{-2}	3.15×10^0			
Cr	9.16×10^{-1}	5.76×10^{-1}	1.49×10^0	1.32×10^0	8.60×10^{-1}	2.18×10^0	1.03×10^{-3}	4.40×10^{-4}	1.47×10^{-3}
Ni	1.17×10^{-1}	4.62×10^{-3}	1.22×10^{-1}	1.69×10^{-1}	6.90×10^{-3}	1.76×10^{-1}			
Cu	7.22×10^{-2}	5.68×10^{-4}	7.28×10^{-2}	1.04×10^{-1}	8.49×10^{-4}	1.05×10^{-1}			
Fe	1.44×10^{-2}	1.13×10^{-4}	1.45×10^{-2}	2.08×10^{-2}	1.69×10^{-4}	2.09×10^{-2}			
Mn	1.12×10^{-1}	2.21×10^{-2}	1.34×10^{-1}	1.62×10^{-1}	3.30×10^{-2}	1.94×10^{-1}			
Zn	1.43×10^{-2}	6.76×10^{-5}	1.44×10^{-2}	2.06×10^{-2}	1.01×10^{-4}	2.07×10^{-2}			
HI	9.18×10^0	6.50×10^{-1}	9.83×10^0	1.32×10^1	9.71×10^{-1}	1.42×10^1	2.24×10^{-3}	4.47×10^{-4}	2.69×10^{-3}
Recreational receptor									
As	2.45×10^{-1}	4.38×10^{-2}	2.89×10^{-1}	1.25×10^0	6.62×10^{-2}	1.31×10^0	7.97×10^{-5}	1.62×10^{-5}	9.59×10^{-5}
Cd	7.67×10^{-2}	1.37×10^{-3}	7.81×10^{-2}	3.91×10^{-1}	2.07×10^{-3}	3.93×10^{-1}			
Pb	7.59×10^{-2}	1.36×10^{-3}	7.72×10^{-2}	3.86×10^{-1}	2.05×10^{-3}	3.88×10^{-1}	6.52×10^{-7}	6.70×10^{-8}	7.19×10^{-7}
Hg	1.50×10^{-1}	2.68×10^{-2}	1.77×10^{-1}	7.63×10^{-1}	4.05×10^{-2}	8.03×10^{-1}			
Cr	6.32×10^{-2}	9.04×10^{-1}	9.67×10^{-1}	3.22×10^{-1}	1.37×10^0	1.69×10^0	1.08×10^{-5}	2.81×10^{-4}	2.92×10^{-4}
Ni	8.11×10^{-3}	7.24×10^{-3}	1.54×10^{-2}	4.13×10^{-2}	1.09×10^{-2}	5.22×10^{-2}			
Cu	4.99×10^{-3}	8.91×10^{-4}	5.88×10^{-3}	2.54×10^{-2}	1.35×10^{-3}	2.67×10^{-2}			
Fe	9.96×10^{-4}	1.78×10^{-4}	1.17×10^{-3}	5.07×10^{-3}	2.69×10^{-4}	5.34×10^{-3}			
Mn	7.75×10^{-3}	3.46×10^{-2}	4.24×10^{-2}	3.94×10^{-2}	5.23×10^{-2}	9.18×10^{-2}			
Zn	9.90×10^{-4}	1.06×10^{-4}	1.10×10^{-3}	5.04×10^{-3}	1.60×10^{-4}	5.20×10^{-3}			
HI	6.34×10^{-1}	1.02×10^0	1.65×10^0	3.23×10^0	1.54×10^0	4.77×10^0	9.12×10^{-5}	2.98×10^{-4}	3.89×10^{-4}

^a Bold figures indicate that the risk level of TEs is higher than 1.0 (HQ/HI/THI > 1.0).

recreational receptors, respectively, which contributed 23% of the total risk (HI) (Table 3). Like surface water, Hg also showed elevated values of HQ of 2.17×10^0 and 1.50×10^{-1} for residential and recreational receptors, respectively, which contributed 24% of the total risk in the deep-water case (Table 5). The HQ values of As and Hg from ingestion and dermal exposure pathways were higher than the risk threshold (10^{-4}), indicating that these two elements can cause serious adverse effects on health in residential and recreational adult and child receptors. Considering the health risks for adults and children through oral intake of water, the following descending order of As > Hg > Cd > Pb > Cr > Ni > Mn > Cu > Fe > Zn was found.

Through the dermal pathway, the highest HQ value was obtained for Cr, which contributed 88 and 89%, respectively (Tables 4 and 5). The calculated values of HQ for Cr were higher than those of the studies of Li and Zhang⁹⁶ and Giri and Singh.⁹⁷ From dermal contact, HQ values for the studied elements were lower than the threshold limit (HQ < 1), indicating a lower risk through this pathway. Through ingestion from the surface and deep waters, HI values were higher than the threshold limit (HI > 1) for adults only, whereas for recreational HI values, they were higher than the threshold limit (HI > 1) for both adults and children, indicating that oral intake is more severe than dermal contact with water. The assessment of health risks in the current study from the surface and deep waters by ingestion and dermal contact for adults and children is in agreement with the previous studies.^{92,98–100}

The total carcinogenic risk of As and Cr exceeded the USEPA standard limit (1×10^{-4}) for the adult and child residents only, indicating that residential receptors were more susceptible to lifetime cancer risk by water intake or contact with their skin. Three elements As, Pb, and Cr were used for CR calculation with Cr having the main contributor to the TCR (CR_{ingestion} + CR_{dermal}) via ingestion and dermal pathways (Tables 4 and 5). The TCR value of As in water for residents was (1.32×10^{-3}), which was higher than the acceptable limit (1×10^{-4}), and the current study is in agreement with the previous studies.^{96,98,101,102}

3.5. Policy implications for sustainable management of river water

This study is an in-depth monitoring of trace elements in an urban river's surface and deep waters, which will assist Bangladeshi policymakers in identifying and deciding on projects in urban regions. They will benefit from the current study by knowing the information and applying it to their decision-making plan, which they will appraise. It will be carried out as part of a development project that will aid in assessing surface and subsurface water quality in Bangladesh. This study is focused on a small amount of the urban river in Bangladesh, which acts as a small step to investigate the impacts of urban activities on the pollution of trace elements in surface and deep waters and the associated risk to human health. A more advanced study could be carried out based on Bangladeshi



conditions on the source and factors affecting water quality linked to public health, social acceptability, and sustainability. Further study is, therefore, suggested to examine the impact of poor water quality on individuals and the agricultural sector.

4. Conclusions

In summary, the water quality of the studied Buriganga River, located around the industrialized urban area of Dhaka, Bangladesh, is highly deteriorated due to a lack of proper management. Herein, the elemental concentrations of As, Cd, Cr, Cu, Fe, Hg, Mn, Ni, Pb, and Zn were measured in both surface and deep waters of the river and the obtained concentrations exceeded the safe limits in the water, indicating the contamination of river water. According to the PCA analysis, mostly municipal wastewater and landfill leachate, together with natural sources, were responsible factors for the deterioration of the water quality of the Buriganga River. The potential ecological risk (PER) showed moderate to very high ecological risk in both seasons at different water depths. Health risk assessment revealed that the total hazard index values of As, Cd, Pb, Hg, and Cr in surface and deep waters for both groups of people (adults and children) exceeded the risk threshold, which indicates that there is a possible threat to their health. The carcinogenic risk values of As and Cr in surface water and deep water were a little bit higher than the standard limit (1×10^{-4}). This shows that there may be carcinogenic and non-carcinogenic risks in the study area of the river. Furthermore, the analyses showed that children are vulnerable to toxic elements. The study found that, in addition to natural sources, anthropogenic activities such as industrial processes, farm waste disposal, and coal burning were the most prevalent causes of the elevated elemental concentrations in the study area. Depositing harmful elements into adjacent water sources or river water without taking the required corrective action should be prohibited. Toxic element levels in the research area need to be treated and keep an eye on all time monitoring.

Conflicts of interest

The authors declare that they do not have any competing interests that could have appeared to influence the work reported in this paper.

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