International Journal of Environmental Science and Technology
https://doi.org/10.1007/s13762-021-03434-8

ORIGINAL PAPER

How dynamic is the heavy metals pollution in the Buriganga River of Bangladesh? A spatiotemporal assessment based on environmental indices

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Received: 21 April 2020 / Revised: 18 May 2021 / Accepted: 2 June 2021

Abstract
Frequent discharge of heavy metals from textiles, tanneries and other anthropogenic sources occurs in Dhaka City, the capital of Bangladesh, contaminating the major rivers. Accumulation of heavy metals such as chromium (Cr), cadmium (Cd), lead (Pb), nickel (Ni) and zinc (Zn) in water, sediment, phytoplankton and fish species was investigated in Buriganga River, a major river of Dhaka City. Three different discharge points (Basila Bridge, Hazaribagh and Babu Bazar) were selected based on their proximity to heavy industrial discharges. Plant *Enhydra fluctuans*, phytoplankton *Lemnoideae* and fish species such as *Heteropneustes fossilis, Channa striata*, *Corica soborna* and *Wallago attu* of the Buriganga River were analyzed for heavy metals. Different environmental indices were determined (e.g., contamination factors, plant concentration factors, biomagnification factors, etc.), and correlations among concentrations in different compartments were obtained. Concentrations of Cr, Cd and Pb were above the toxicity reference values (TRV) for surface water quality standards applicable for aquatic life. Chromium (Cr) was found at very high levels 103 mg/kg in soil and 163 mg/kg in the plants in Hazaribagh tannery wastes discharge point. The biological samples had enough evidence for bioaccumulation of metals. Although environmental indices exhibited signs of improvement, evidence of higher level of metals in sediment, plants and fishes seemed alarming. Positive correlations among heavy metal concentrations in soil, water and plants indicate linear dependence of heavy metals accumulation from water and soil into the plants. This study emphasizes the necessity of controlling the point and nonpoint urban pollution sources discharging into the Buriganga River.

Keywords Buriganga River pollution · Heavy metal contamination · Sediment · Fish · Environmental indices

Introduction

Buriganga River is the major source of transportation routes, source of drinking water supply, recreation sites, flood control and drainage channel of Dhaka City, the capital of Bangladesh (Alam 2008). It plays an important role in Dhaka City's socioeconomic development. However, the industrial growth, rapid inconsiderate urbanization and population pressure of Dhaka City undesirably affect the environment, ecosystem as well as pollution transport in the Buriganga River. Discharges from the tanneries, dyeing and auxiliary industries and urban sewage system were the main sources of heavy metal contamination in the river water and sediment (Ahmad et al. 2010). Geochemical trap for heavy metals in fine-grained river sediment, depositional acceleration in the downstream and adsorption on clay surfaces further

Editorial responsibility: Anna Grobelak.

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Published online: 27 June 2021

increase the metal contamination (Islam et al. 2014). Mohiuddin et al. (2011) suggested industrial activity, atmospheric emission, leachates from defused batteries, metal plates and formation of complexes with organic matter as potential sources of sediment contamination of Buriganga River. Mohiuddin et al. (2015) suggested that 51-year- old Hazaribagh tannery, Dhaka-Demra-Naraynganj industrial zone and industries of Kamrangir Char are the major heavy metal pollution sources in Buriganga. Inequivalent maintenance of water quality and sanitation infrastructure with the population and urbanization growth also increased the contamination of rivers like Buriganga (Moniruzzaman et al. 2012). Regular discharge of domestic and industrial waste and wastewater with partial or no treatment and lack of regulation enforcement pollutes the river constantly increasing the level of pollutants in the water and other environmental compartments (soil/sediment, plants, phytoplankton, fishes, etc.) (Ahmed et al. 2012; Begum et al. 2012). There are limited engineering interventions to control point and nonpoint urban polluted runoff to the rivers around Dhaka City. Furthermore, the river transports huge amounts of sediments and waste substances from upstream of the river as well including domestic, agricultural and industrial wastes that contains various organic and inorganic pollutants.

Heavy metals, among those pollutants, have significant ecological and environmental impacts on the Buriganga River. Heavy metals can affect the cognitive growth of children; induce hypertension, osteotoxicity and cardiovascular, lungs and liver disease; impair function of the immune system; and may even cause cancer (Zhou et al. 2016). When ingested in excess, some heavy metals may cause acute aches in stomach and intestine as well as liver damage in addition to reduced immune system function and lower levels of high-density lipoproteins (Ekong et al. 2006; Harmanescu et al. 2011; Navas-Acien et al. 2004; Patrick 2003; Rahman et al. 2014). The concentrations of heavy metals in fishes and aquatic plants are mostly dependent upon metal concentrations in water and bottom soil/sediments (Ochieng et al. 2007). Pollution in a water body causes adverse impacts on the aquatic ecology, especially the fishes accumulate significant levels of heavy metals (Ali and Khan 2018). Thus, heavy metals, mostly persistent, toxic and bioaccumulative in the environment, pose severe risks to the ecological health especially to food chain and food safety (Ahmed et al. 2017; Wang et al. 2011; Zhou et al. 2016).

Heavy metals are frequently utilized in industrial manufacturing, operations, and daily consumables of Bangladesh. Surface water around the industrial zones is typically polluted with heavy metals (e.g., chromium (Cr), cadmium (Cd), mercury (Hg), lead (Pb), zinc (Zn) and copper (Cu)) posing health hazard for public and ecosystem in Bangladesh especially in the urban areas such as Dhaka City (Real et al. 2019; Real et al. 2017; Mohiuddin et al. 2015; Mohiuddin et al. 2011; Das et al. 2011; Islam et. al. 2006; Islam et al. 2018a; Simu et al. 2018). Furthermore, long-term accumulation of heavy metals in human body is possible through different exposure routes (water, direct contact, food, etc.). Fish being an important diet for the people of Dhaka City, consumption of fish is directly associated with heavy risk on health. Hence, human risks associated with food contamination and safety due to heavy metals mainly originating from rivers around Dhaka City are of major concerns for environmental researchers and regulators (Islam et al. 2018b; Simu et al. 2018; Nahar and Alam 2015; Banu et al. 2013). It is necessary to analyze not only the water quality but also every significant environmental compartments of the river system (e.g., sediment, phytoplankton, etc.) to assess the overall pollution level and its partitioning in the Buriganga River along with its subsequent impacts.

Previous studies have obtained varied concentrations of toxic heavy metals in Buriganga River during pre-monsoon, monsoon and post-monsoon seasons (Asaduzzaman et al. 2016; Saha and Hossain 2011; Das et al. 2011). Ranges of concentrations of Cr (0.54–0.62 mg/L), Cd (0.16–0.22 mg/L) and Pb (0.23–0.5 mg/L) have been reported in Buriganga River (Mohiuddin et al. 2011) exceeding their drinking water standards (0.05 mg/L for Cr, 0.005 mg/L for Cd and 0.05 mg/L for Pb) (ECR 1997). Significant levels of heavy metals such as Cr (> 150 mg/kg), Cd (> 1.5 mg/kg), Pb (> 100 mg/kg), Cu (> 300 mg/kg) and Zn (> 900 mg/kg) have been obtained in sediments of Buriganga River in different studies (Saha and Hossain 2011; Mohiuddin et al 2015). Highest Pb concentration in Buriganga River was reported in Chapila fish as 13.52 mg/kg and lowest Pb concentration in Tatkeni as 8.03 mg/kg (Ahmad et al. 2010). Moreover, heavy metals in fish varied widely in different seasons (Cr: 5.27–7.38 mg/kg, Cd: 0.73–1.25 mg/kg), Pb: 8.03–13.52 mg/kg, Cu: 4.19–6.94 mg/kg and Ni: 8.25–11.21 mg/kg) (Ahmad et al. 2010). Additionally, highest Cd concentration in Buriganga River was reported in Batashi fish as 1.25 mg/kg during monsoon season and lowest Cd concentration in Tatkeni as 0.73 mg/kg during post-monsoon season (Ahmad et al. 2010).

Different environmental indices such as contamination factor (CF), pollution level index (PLI), geo-accumulation index (I_{geo}), Carbon normalized sorption coefficient (Koc), plant concentration factor (PCF), bioconcentration factor (BCF), biota-sediment accumulation factor (BSAF), biomagnification factor (BMF), etc., can be utilized to evaluate the distribution of heavy metals at different compartments and severity of the pollution level in the river systems. Certain previous studies investigated these factors in characterizing different river environments (Mohiuddin et al. 2015; Saha and Hossain 2011; Rudnick and Gao, 2003; Muller 1981; Tomlinson et al. 1980); however, comprehensive investigation focusing on the interrelationship of pollutants in different environmental compartments in the Buriganga River is still lacking. Recent dredging of the river, removal of illegal structures/development along the bank of Buriganga and relocation of all the tannery and leather industries might have impact on the discharge of the toxic pollutants into the Buriganga River (Price and Price 2017). With the relocation, the pollution level in the Buriganga River is expected to reduce in course of time through natural recovery and cleansing phenomenon.

This study seeks to provide the baseline conditions of the Buriganga River while these major decisions have been implemented. The study evaluates the seasonal variation of heavy metals pollution in Buriganga River by measuring the concentrations of the heavy metals Cr, Cd, Pb, Ni and Zn in different parts of the river (e.g., water, sediment, plant, phytoplankton and aquatic life). This study further investigates the spatiotemporal variation of pollution in the Buriganga River while assessing the heavy metal pollutants' dynamics among different compartments of the river. It is imperative to note that this study does not address bacterial and organic pollution, which are allegedly in critical status in the Buriganga River. This study carefully determines the status of the river through different environmental indices such as contamination factor (CF), pollution level index (PLI), geo-accumulation index (I_{geo}), Carbon normalized sorption coefficient (Koc), plant concentration factor (PCF), bioconcentration factor (BCF), biota-sediment accumulation factor (BSAF) and biomagnification factor (BMF). It also demonstrates correlations among the concentrations in the different environmental compartments (water, soil, plants, phytoplankton, fish, etc.) using the principal component analysis (PCA). Furthermore, this present study provides foundation for future studies to be potentially focused on the recovery of Buriganga River and its ecosystem from pollution.

Materials and methods

Study area

The study area includes three specific and two supplementary locations along the Buriganga River stretch, each separated by at least 2 km distances from the nearest sampling location. The sampling locations are selected based on their proximities with the heavy metals pollution mainly affected by either uncontrolled industrial discharge or indiscriminate discharge of solid waste into the river. Figure 1 shows the river stretch studied with sampling points identified on a google map and Table 1 describes the sampling locations with coordinates along with the types of samples that are reported from the compartments of the respective locations. Sampling locations 'Basila Bridge (1)' and 'Babu Bazar (3)' are next to densely populated established areas with numerous industries, a power plant and a number of municipal runoff/sewer outlets. Sampling point 'Hazaribagh (2)' has hundreds of tanneries located on riverbanks with effluents being discharged into the Buriganga River without any proper treatment. Two supplementary locations are

Fig. 1 Sampling points along the Buriganga River for heavy metals analysis (1 = Basila Bridge, 2 = Hazaribagh, 3 = Babu Bazar, 4 = Sutrapur and 5 = Shyampur; 1, 2, 3: significant locations; 4, 5: supplementary locations) (the map was adopted from Google Search engine map)

Table 1 Sampling locations and types of samples collected at each location

Location	Coordinates	Sample types	Seasons
Basila Bridge (1) [upstream]	23.741876, 90.348666	Water, sediments, plant	Pre-monsoon, monsoon, post-monsoon
		Phytoplankton and fish	Pre-monsoon
Hazaribagh (2)	23.721844, 90.359202	Water, sediment, plant	Pre-monsoon, monsoon, post-monsoon
Babu Bazar (3)	23.70971, 90.40126	Water, sediments, plant	Pre-monsoon, monsoon, post-monsoon
Sutrapur (4)	23.70008, 90.41593	Water	Pre-monsoon
Shyampur (5) [downstream]	23.667659, 90.450283	Water	Pre-monsoon

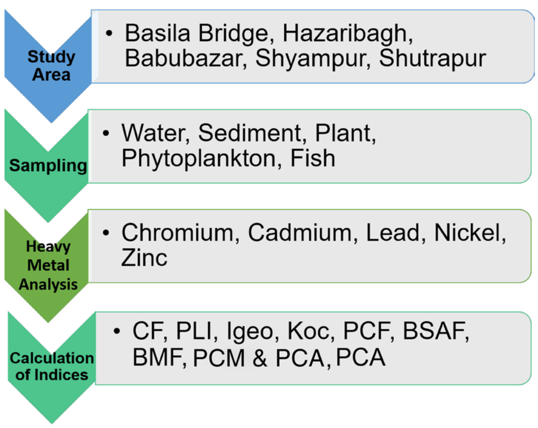

Fig. 2 Experimental design of this study conducted in Buriganga River

'Sutrapur (4)' and 'Shyampur (5)' further downstream of 'Babu Bazar (3).' These geographically important locations of Dhaka City would be able to provide a snapshot of environmental pollution at different compartments of the Buriganga River prelude to implementation of some major environmental actions implemented along the river. However, the tanneries are being relocated from these areas currently and this baseline study was conducted in different seasons of the year involving multiple sampling points in those locations. Extensive sample analysis was not conducted for Sutrapur and Shyampur areas as initial findings indicated Hazaribagh area as the major focus area of the study and showed higher level of pollution. Basila Bridge (upstream of Hazaribagh) and Babu Bazar (downstream of Hazaribagh) were selected to evaluate the extent of pollution from the major focus area. A flowchart in Fig. 2 shows the detailed experimental design performed in this study.

Sample collection

Water samples, collected in sampling bottles from just below the water surface and acidified with nitric acid, were stored at 4°C refrigerator for subsequent analysis of heavy metal contents (APHA 1998). Multiple rinsing of sample bottles (at least three times) with the river water was practiced before water collection for analysis. Grab sampler was utilized at each site to obtain soil/sediment samples at 0–30 cm depth from the bank of the river.

Enhydra fluctuens is one of the most available plants that grow beside the river. Additionally, previous study (Jolly et al. 2013) found that *Enhydra fluctuens* accumulate heavy metals. Hence, this plant was selected as an indicator of pollution level. So, *Enhydra fluctuens* (plant) were carefully separated from soil with their roots. Resealable plastic containers were utilized to store the plants after thoroughly rinsing them with deionized water. A phytoplankton net was utilized to collect phytoplankton (*Lemnoideae*) from the surface of the river. Fishermen caught the fishes [e.g., *Heteropneustes fossilis* (Shing), *Channa striata* (Shole), *Corica soborna* (Kachki) and *Wallago attu* (Boal)] that were analyzed in this study from Basila Bridge location of the Buriganga River due to their availability at the upstream. Several attempts were made to catch fish from the downstream points, i.e., Hazaribagh and Babu Bazar sampling points, but none of them succeeded. It was concluded that at the downstream of the river, the fish are rarely available. Heavy motorboat traffic in the downstream of the river starting from the Babu Bazar and associated disturbance and contamination (uncontrolled spilling of spent oils) may have negative impact on fish population. The fishes were immediately transported to laboratory, were cleaned carefully with water, and their weights were well documented prior to the laboratory analysis. Water, sediment, plant and phytoplankton samples from the locations of Basila Bridge (1), Hazaribagh (2) and Babu Bazar (3) were collected at three different time points to determine the seasonal variations of heavy metals concentrations (Table 1). Phytoplankton is the most common primary producer in the aquatic food web (Rahman et al. 2012b). Phytoplankton bioaccumulates metals and it is known to have some effect on biomagnification (Watras 1998; Chen and Folt 2005). Hence, it was taken into account for phytoplankton to be included in this study. As fish samples were collected from Basila Bridge, Phytoplankton samples were also collected from the same sampling point. A phytoplankton net was utilized to collect phytoplankton (*Lemnoideae*) from the surface of the river. All samples were collected between 6 and 8 am.

Laboratory analysis

The heavy metals Cr, Cd, Pb, Ni and Zn, selected for analysis in this study, are reported frequently and remain to be the most prevalent heavy metals in the Buriganga River. Hg was measured in the post-monsoon season only due to limitation of our analytical laboratory. Analysis of the samples from two of the supplementary areas, Sutrapur (4) and Shyampur (5), was conducted at pre-monsoon season only, mainly to identify the spread of the heavy metals pollution along Buriganga River beyond Babu Bazar (3). Careful transportation and storage of samples were ensured from the river to the laboratory in an ice chest. Atomic absorption spectrophotometer (Shimadzu, AAS—6800 model), employing atomic absorption and flame photometry techniques, was utilized to measure the concentrations of heavy metals in different compartments of the Buriganga River (Isaac and Kerber 1971). Later on, the fishes were dried at a higher temperature of about 101–105°C. Dry ashing technique proposed by Issac and Kerber (1971) was followed for the digestion of fish sample. First, fish flesh was separated and dried in an oven at 65 °C for 48 h followed by heating at 250 °C for 30 min. Again the dried sample was made to ash for 4 h at 480 °C in a muffle furnace. After bringing the sample temperature down to the room temperature, 2 ml of 5 M nitric acid was added and the sample was placed in a cool furnace followed by heating at 400 °C for 15 min. After cooling it down, 2 ml of 38% HCL and 5 ml of 2 M HCl were added and swirled. The digested solution was filtered using 0.45 µm Millipore filter paper.

Distribution of heavy metals among different media (compartments) and calculation of environmental indices of Buriganga River

The concentrations of different heavy metals vary both spatially and seasonally. The concentration profiles in water, soil/sediment and plants along the Buriganga River show how heavy metals are partitioned at different phases along the changes in the river flow. The pollution of environmental compartments and accumulation of heavy metals in soil, plants, water and aquatic biota were further evaluated by different environmental indices describing the fate and transport of heavy metals in the riverbanks. The indices are indicative of the degree of heavy metal contamination in the river with their spatial and seasonal distribution. The environmental indices are described below:

Contamination factor (CF_{metals})

Contamination factor (CF_{metals}) is calculated as the ratio between the concentrations of each metal to the background concentrations in sediments (background value from continental upper crust) in sediment (Tomlinson et al. 1980),

$$CF_{metals} = C_{metal}/C_{background}$$

There are four grades of CF values to monitor temporal variation of metal pollution in a particular location (Islam et al. 2015). CF value is unitless. The four grades are (a) CF value < 1 is considered low degree, (b) CF value between $1 \leq CF < 3$ is considered moderate degree, (c) CF value between $3 \leq CF < 6$ is reported as considerable degree, and CF values above 6 is considered very high degree of pollution ($CF \geq 6$) (Real et al. 2019). Thus, the CF values can indicate the historical enrichment of specific metal in sediments.

Pollution level index (PLI)

This parameter is determined for each location by taking inverse root of the multiplied value of contamination factors (CF) of all metals analyzed in a particular location (Tomlinson et al. 1980),

$$PLI = \sqrt[n]{\left(CF_1 \times CF_2 \times CF_3 \times \cdots \times CF_n\right)}$$

PLI value is unitless. The PLI value of 0 represents perfect environmental condition. When PLI varies between 0 and 1, it confirms the baseline levels of pollutants and PLI value above 1 confirms gradual negative impact on the site and estuarine quality.

Geo-accumulation index (I_{geo})

Geo-accumulation index (I_{geo}) is determined by calculating log 2-based ratio of measured heavy metals concentration with 1.5 × background concentration as shown in the following equation (Muller 1969)

$$I_{geo} = \log_2 \left(C_n/1.5B_n\right)$$

where Cn = Measured concentration of heavy metal in the sediment.

B_n = Geochemical background concentration in continental upper crust of element n. The multiplier 1.5 is utilized to account for probable variations of the background concentration due to lithological variations.

I_{geo} value is unitless. The I_{geo} value below 0 represents practically uncontaminated (PU) environmental condition with $0 \le I_{geo} \le 1$ indicating uncontaminated to moderately uncontaminated environmental condition (UMC), $1 \le I_{geo} \le 2$ indicating moderately contaminated condition (MC), $2 \le I_{geo} \le 3$ indicating moderately to heavily contaminated condition (MHC), $3 \le I_{geo} \le 4$ indicating heavily contaminated condition (HC), $3 \le I_{geo} \le 4$ indicating heavily contaminated condition (HC), $4 \le I_{geo} \le 5$ indicating heavily to extremely contaminated condition (HEC) and $4 \le I_{geo} \le 5$ indicating heavily to extremely contaminated condition (HEC) and I_{geo} above 5 indicating extremely contaminated (EC) environmental condition, respectively (Förstner et al. 1993).

Carbon normalized sorption coefficient (Koc)

Carbon normalized sorption coefficient (Koc) is the ratio of concentrations of heavy metals in the organic carbon of the soil with concentrations of heavy metals in water as shown below (Piwoni and Keeley, 1990):

$$\begin{aligned} K_{oc} &= (\text{Concentration in the organic carbon of soil}/\text{Concentration in water})/\text{fraction organic carbon} \\ &= \left(C_{soil}/C_{water}\right)/f_{oc} \end{aligned}$$

The unit of K_{oc} is L/kg. Higher Carbon normalized sorption coefficient (Koc) indicates higher sorption of metals with organic carbon in the soil compared to concentrations in water phase. Mean fraction of organic carbon which has been estimated for Buriganga River sediment was obtained from Mohiuddin et al. 2015.

Plant concentration factor (PCF)

The plant concentration factor (PCF), also known as transfer factor or transfer coefficient which confirms human exposure to metals through food chain, is the ratio of heavy metals concentrations in plants compared to heavy metals concentrations in soil calculated as shown below (Kananke et al. 2015; Real et al. 2019):

$$\text{PCF} = C_{plant}/C_{soil}$$

where C_{plant} and C_{soil} represent the heavy metal concentrations in extracts of plants and soils (dry weight basis), respectively (Kananke et al. 2015). PCF value is unitless. Relatively lower value of PCF confirms strong metals sorption to colloids of soils, whereas relatively higher values of PCF confirm less available metals in soils and high absorbed metals in plants (Alloway and David 1997).

Bioconcentration factor (BCF)

Bioconcentration factor (BCF) is defined by the ratio of the concentration of a chemical of concern in the organism (mg/kg) and the concentration of that chemical in water (mg/L) (Kravitz et al. 2000). BCF is utilized to identify bioaccumulative substances and it provides estimation for target metals concentrations ranges for a water body in order to keep the concentration of the contaminant below acceptable/tolerable daily intake (Schäfer et al. 2015).

$$\text{BCF} = C_{organism}/C_{water}$$

The unit of BCF is L/kg. Substances are bioaccumulative with a BCF > 2000 L/kg and very bioaccumulative with BCF > 5000 L/kg according to EU regulation 253/2011 (Schäfer et al. 2015; EU Commission regulation 2011) in the context of assessing persistent, bioaccumulative and toxic substances as well as very persistent and very bioaccumulative substances. Chemicals have low bioaccumulation when their BCFs are less than 1000 L/kg (OECD 1981).

Biota-sediment accumulation factor (BSAF)

Biota-sediment accumulation factor (BSAF) is the ratio of bioconcentration factor (BCF) and Carbon normalized sorption coefficient (Koc) (van der Oost et al. 2003) as shown below:

$$\begin{aligned} \text{B}SAF &= \text{B}io - concentrationfactor/\text{Carbon normalized} \\ &\quad sorptioncoefficient(Koc) = \text{BCF}/K_{oc} \end{aligned}$$

BSAF value is unitless. Higher BSAF values are indicative of higher heavy metals accumulation in the biota phase compared to heavy metals partitioning with the sediment.

Biomagnification factor (BMF)

Biomagnification factor (BMF) is the ratio between chemical concentrations in the organism and concentration of the chemical in the diet of the organisms (Beyer and Bizuik 2009; Real et al. 2019). Biomagnification brings out the effect of the toxic substance concentrating via food chain. BMF value is unitless. Bioaccumulation is a sum of the effects of bioconcentration and biomagnification.

$$\text{BMF} = \frac{\text{Chemical concentration in the organism, } C_b}{\text{Concentration of the chemical in the diet of the organisms , } C_a}$$

Cumulative BMF = BMF_1 * BMF_2 * …………*BMF_i l, where 1, 2,… i, etc., represents the different trophic levels.

Statistical analysis and principal component analysis

The interrelationship and interdependence of heavy metal concentrations in different compartments of Buriganga River have been evaluated by principal component analysis (PCA) and Pearson's correlation matrix (PCM). These analyses have been conducted with XLTAT 2017 Software. The correlation analysis method describes the relationship among different parameters (Eriksson et al. 2013). The high correlation coefficient (near + 1 or − 1) indicates very close relationship between two variables. The correlation among two variables are termed as 'very high' when r value is between 0.90 and 1, the correlation is termed as 'high' when r value is between 0.70 and 0.90, and it is termed as 'moderate' when r value is between 0.5 and 0.7 (Hinkle et al. 2003). A correlation coefficient value near zero indicates no relationship between the two variables at a significant level of 0.05% level (Alghobar and Suresha 2015).

Results and discussion

Distribution of heavy metals in Buriganga River water

A comprehensive representation of heavy metal levels in river water, sediment and plant samples for the considered locations along the river during different seasons is provided in Fig. 3. Bar charts indicate the concentration levels and the boxes below the river profile indicates the sources of pollution in each location. The allowable levels of different heavy metals in water, sediment and plants that have been established by different regulatory entities are shown at the bottom of Fig. 3.

The extensively studied heavy metals of this study, chromium (Cr), cadmium (Cd), lead (Pb), nickel (Ni), zinc (Zn) and mercury (Hg), ranged widely in concentrations and seasonally as shown in Table S1. Concentrations of these heavy metals ranged from below detection limit (BDL) to 0.224 mg/L for Cr, BDL to 0.0014 mg/L for Cd, BDL to 0.024 mg/L for Pb, 0.008 to 0.027 mg/L for Ni and 0.02 to 0.12 mg/L for Zn, respectively. Hg concentrations varied from 0.013 to 0.27 mg/L. The mean heavy metals concentration could be ordered in a descending trend as Hg > Cr > Zn > Pb > Ni > Cd. Cr was measured at an alarming level of 0.224 mg/L at Hazaribagh, which is five times higher than allowable toxicity limit (ECR, 97). Cr concentrations in water at the Basila Bridge and Babu Bazar were low compared to those in Hazaribagh location (pre-monsoon: 0.022 and 0.007 mg/L and post-monsoon: BDL and 0.079 mg/L, respectively) while those were highest in Hazaribagh in all three seasons (pre-monsoon: 0.224 mg/L, monsoon: 0.0485 mg/L and post-monsoon: 0.087 mg/L (Fig. 3, Table S1). The tannery industries of the Hazaribagh area had the general practice to utilize Cr in their leather processing and the spent metals ultimately became part of the discharge stream into the river. Previous studies reported similar and comparable levels of Cr in Buriganga River water which continues to be a threat for the river ecosystem (Sarkar et al. 2015). Though these concentrations are below Safe Drinking Water Act (SDWA) standard value of 0.1 mg/L except pre-monsoon level at Hazaribagh, most of the levels exceed the TRV value of 0.011 mg/L.

Cadmium (Cd) concentrations in water at Basila Bridge were not detectable in pre-monsoon and were very low in monsoon season in all three locations (0.0009 mg/kg in Basila and Hazaribagh, 0.0014 mg/kg in Babu Bazar) (Fig. 3, Table S1). All these concentrations were below SDWA standard value of 0.005 mg/L and TRV value of 0.002 mg/L. Lead (Pb) concentrations in water at the Basila Bridge and Babu Bazar were higher in Pre-monsoon and monsoon seasons (pre-monsoon: Basila = 0.02 mg/L, Babu Bazar = 0.016 mg/L; monsoon: Basila = Babu Bazar = 0.015 mg/L) and non-detectable in post-monsoon season (Fig. 3, Table S1) while in Hazaribagh, the concentrations were highest and consistent in pre-monsoon and monsoon seasons (pre-monsoon and monsoon: 0.024 mg/L). Thus, all pre-monsoon and monsoon seasonal ranges for Pb were higher than TRV value of 0.003 mg/L and SDWA standard of 0.015 mg/L.

Nickel (Ni) concentrations in water at the Basila Bridge were low compared to other locations of the Buriganga River in all three seasons (pre-monsoon: 0.018 mg/L, monsoon: BDL and post-monsoon: 0.008 mg/L) (Fig. 3, Table S1). The highest level for Ni was obtained in the Hazaribagh area in pre-monsoon and post-monsoon seasons (pre-monsoon: 0.027 mg/L, monsoon: BDL and post-monsoon: 0.014 mg/L). All concentrations were lower than TRV of 0.052 mg/L.

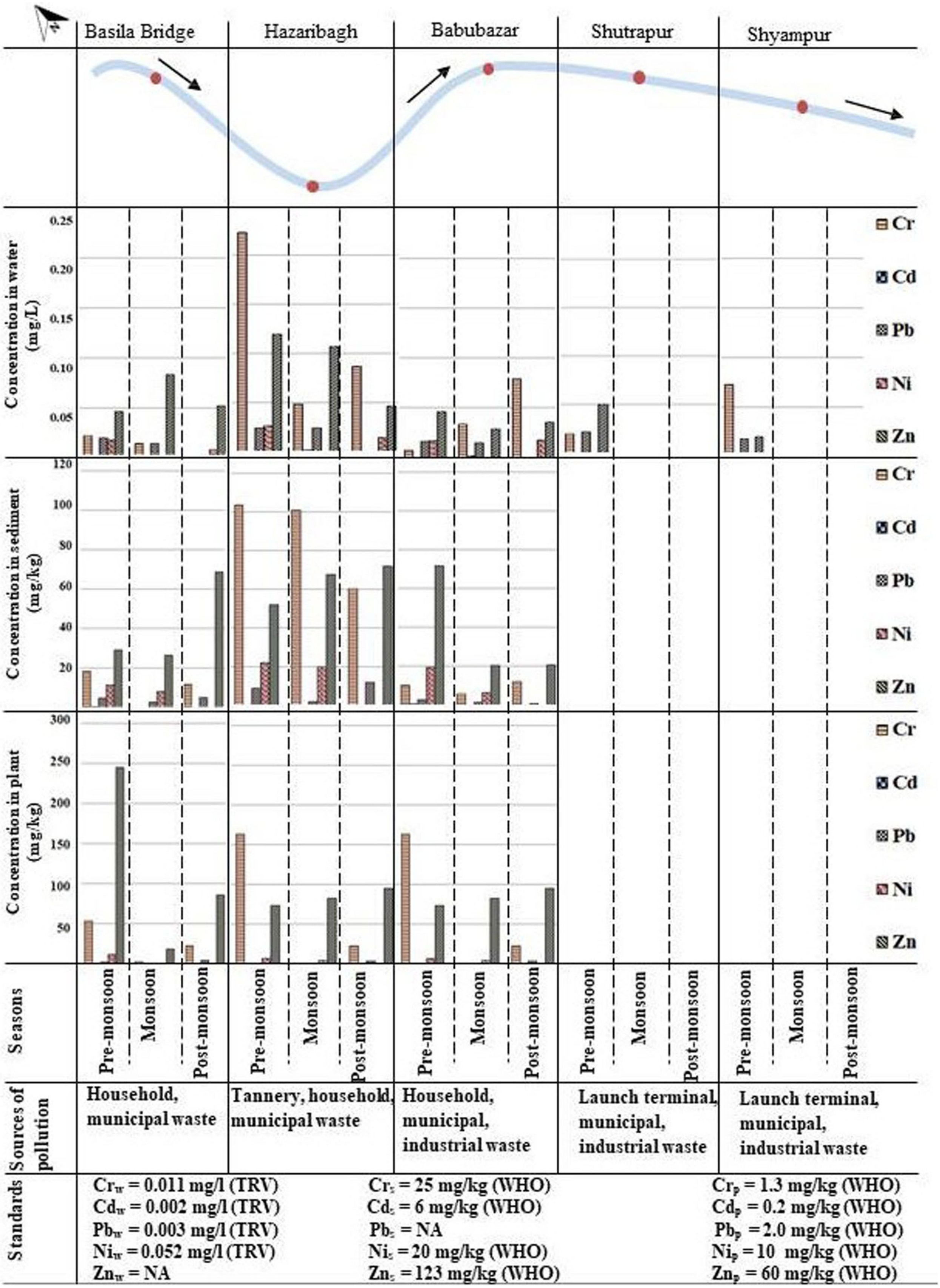

Fig. 3 Seasonal and spatial variation of heavy metal concentrations in Buriganga River

Zinc (Zn) concentrations in water at the Basila Bridge were pre-monsoon- 0.046 mg/L, monsoon- 0.083 mg/L and post-monsoon- 0.052 mg/L) while in Hazaribagh Zn concentrations in water were the highest in all three seasons (pre-monsoon: 0.12 mg/L, monsoon: 0.11 mg/L and post-monsoon: 0.05 mg/L), but Zn concentrations were lower than SDWA standard during all seasons (Fig. 3, Table S1) in the mentioned as well as Babu Bazar areas.

Distribution of heavy metals in Buriganga River sediments

The spatial and seasonal variations of the heavy metals concentrations in sediments of Buriganga River are shown in Table S2. The mean heavy metals concentrations of sediments had higher levels of Cr concentrations followed by Zn, Ni, Pb and Cd. Cr was absorbed significantly in the soil/sediment as well in all locations with 103.58 mg/kg during pre-monsoon, 100.9 mg/kg during monsoon and 60.2 mg/kg during post-monsoon season at Hazaribagh. Cr absorbed in sediment was always higher at Hazaribagh than the recommended concentrations of Cr in soil by World Health Organization (WHO) (25 mg/Kg), United States Environmental Protection Agency (USEPA) (25 mg/Kg) and Canadian Council of Ministers of the Environment (CCME) (37.3 mg/kg) in all three seasons (Fig. 3, Table S2) (WHO 1996; USEPA 1999; CCME 1999). The Cr concentrations in sediment samples had a mean value of 40.27 mg/kg with concentrations ranging from BDL to 103.58 mg/kg. The major leather industrial development of Hazaribagh area with its untreated leather tanning wastes containing Cr used to get discharged to Buriganga River and might have caused higher level of Cr (Mohiuddin et al. 2015).

Cadmium (Cd) concentration was the lowest ranging from BDL to 0.16 mg/kg out of five metals investigated in the sediments being much lower than WHO and USEPA recommended levels of 6 mg/kg and 0.6 mg/kg respectively (Fig. 3, Table S2) (WHO 1996; USEPA 1999). Hazaribagh sediments also had the highest concentrations for Pb and Ni. Pb was significantly adsorbed into soil/sediments of the Buriganga river during all seasons (4.54 mg/kg, monsoon: 2.52 and post-monsoon: 5 mg/kg in Basila and in Hazaribagh with 8.89 mg/kg during pre-monsoon, 2 mg/kg during monsoon and 12 mg/kg during post-monsoon season). The post-monsoon Pb level shows significant transport of Pb via sediment transport downstream of the Buriganga River from the Basila Bridge area. Pb absorbed in soil was always lower than USEPA (1999) (40 mg/kg) recommended concentrations of Pb in soil in all three seasons (Fig. 3, Table S2). The Pb adsorbed to sediment started decreasing at monsoon and then further increasing at post-monsoon season indicating the effects of higher flow and some sediment transport during monsoon season. Pb was absorbed significantly at a lower rate in Babu Bazar in the soil/sediment compared to the other areas. Average Ni concentration exceeded the sediment quality guideline recommended by USEPA (1999) (16 mg/kg) and WHO (1996) levels (20 mg/kg). Ni was absorbed significantly in the soil/sediment in the pre-monsoon and monsoon season as well at Hazaribagh with 21.93 mg/kg during pre-monsoon, 20.13 mg/kg during monsoon season. (Fig. 3, Table S2). Furthermore, the post-monsoon Ni level (BDL) shows significant transport of Ni via sediment transport downstream of the Buriganga River in the Hazaribagh area. Other locations did not contain Ni in the soil above standard levels. Zn was adsorbed to soil/sediments of the Buriganga river at the following levels: pre-monsoon season (29.1 mg/kg), monsoon (26.2 mg/kg) and post-monsoon (68.6 mg/kg) at Basila and 51.8 mg/kg during pre-monsoon, 67.6 mg/kg during monsoon and 71.9 mg/kg during post-monsoon season at Hazaribagh. Babu Bazar had lower concentrations than the levels in the other locations. The higher level of sediment transport downstream during monsoon season decreased the level of Zn (adsorbed to sediment in the upstream and increased the sediment Zn in the downstream). Zn adsorbed to soil at all locations in all seasons was relatively lower than WHO (1996) (123 mg/kg), USEPA (1999) (110 mg/kg) and CCME (1999) (123 mg/kg) recommended levels (Fig. 3, Table S2). Overall, the levels of three pollutants Cd, Pb and Zn analyzed in the sediments were lower than the permissible limits for sediment. But Cr level in the sediments was higher than the permissible limits for sediment (USEPA 1999).

Distribution of heavy metals in Buriganga riverside plants

Heavy metal levels in the plant species *Enhydra fluctuens* collected from the Buriganga riverbank at different seasons (pre-monsoon, monsoon and post-monsoon) are shown in Table S3. The mean heavy metals concentrations appeared as Zn > Cr > Ni > Pb > Cd in the descending order. The highest level of Cr (163.1 mg/kg), observed at Hazaribagh area, could again be attributed to the unregulated wastewater discharge from tannery industries in the Hazaribagh location. It is directly correlated to higher level of Cr in the sediment (103.58 mg/kg) in the pre-monsoon season showing high plant intake which exceeds the WHO recommended level of 1.3 mg/kg. But the plant Cr concentrations during monsoon season (0.95 mg/kg) was comparatively lower (< WHO level of 1.3 mg/kg) though the sediment concentrations were high (100.9 mg/kg) (Fig. 3, Table S2, Table S3).

It might be possible that the collected plant sample was grown on the sediments containing comparatively lower concentration of Cr that might have been transported from uncontaminated areas from upstream. Again, post-monsoon Cr concentration (22.5 mg/kg) in the plant was higher than the WHO recommended level of 1.3 mg/kg. The plant Cr concentration in post-monsoon season (22.5 mg/kg) is almost 8 times lower compared to plant Cr concentration in the pre-monsoon season (163.1 mg/kg) (Fig. 3, Table S3). Similar to the concentration level patterns in water and sediments, concentration level of Cr in plants also showed a seasonal pattern decreasing from pre-monsoon to post-monsoon period while the trend was not so evident for the other metals. Cd is an extremely toxic element for organisms and the Cd concentration in normal plants from uncontaminated soils usually range from 0.05 to 0.2 mg/kg (Peng et al. 2008). Cd exhibited minimal accumulation among the metals. Low level of Cd was detected in the plant during pre-monsoon season (0.31 mg/kg in Basila, 0.23 mg/kg in Hazaribagh and 0.32 mg/kg in Babu Bazar) which in fact, is higher than the allowable WHO limit of 0.2 mg/kg (FAO/WHO 1976).

Plants grown on the sediments of the Buriganga River showed significantly higher level of Pb at Basila at pre-monsoon (1.29 mg/kg) and post-monsoon seasons (4.0 mg/kg) which correlated well with higher level of sediment Pb concentrations during pre-monsoon (4.54 mg/kg) and post-monsoon (5 mg/kg) seasons. The concentrations in the plants for pre-monsoon and post-monsoon seasons exceeded the allowable CODEX Alimentarius Commission limit of 0.3 mg/kg but did not exceed the allowable WHO limit of 2 mg/kg. Plant Pb concentrations in the post-monsoon season at Hazaribagh were the highest (3 mg/kg) compared to the other seasons (CODEX Alimentarius Commission 1989, WHO 1996). It is directly correlated to higher level of Pb in the sediment (12 mg/kg) in the post-monsoon season showing high plant intake which exceeds the WHO recommended level of 2 mg/kg. Plant Pb concentrations in the post-monsoon season at Babu Bazar were the highest (6 mg/kg) compared to any location and season. In the pre-monsoon season, it was 3.19 mg/kg. Hence, average Pb content (2.98 mg/kg) in present study is higher than the permissible limit.

The highest level of Ni in plant was observed at Babu Bazar (27.75 mg/kg). Plant samples exceeded the WHO permissible limit for Ni (10 mg/kg) (WHO, 1996; Real et al. 2019). Plants grown on the sediments of the Buriganga River at Basila showed higher level of Ni at pre-monsoon (11.42 mg/kg) and monsoon season (0.66 mg/kg) which correlated well with higher level of sediment Ni concentrations during pre-monsoon (11.4 mg/kg) and post-monsoon (7.9 mg/kg) seasons. Ni concentrations in the plants for pre-monsoon season exceeded the allowable WHO (1996) limit of 10 mg/kg but Ni concentrations in the plants for monsoon and post-monsoon season were below WHO limit. Plant Ni concentrations during any of the seasons at Hazaribagh were not significant.

Concentration of Zn is the highest in the plants among the metals and that of Cd is the lowest which is supported by the study conducted by Zhang et al. (2010). The highest concentration of Zn (244.60 mg/kg) was found in Basila Bridge during pre-monsoon season and post-monsoon season concentration was 85.77 mg/kg which correlated well with higher level of sediment Zn concentrations during pre-monsoon (29.11 mg/kg) and post-monsoon (68.55 mg/kg) seasons at Basila. Relatively low level of Zn was detected in the plant during monsoon season (18.68 mg/kg) probably due to low level of Zn in soil/sediment (26.19 mg/kg) (Fig. 3, Table S3). It might be possible that the plants grown during monsoon season were located at higher elevation with minimally contaminated soil. Zn concentrations in the plants for pre- and post-monsoon seasons exceeded the allowable WHO limit of 60 mg/kg (WHO 1996). Plant Zn

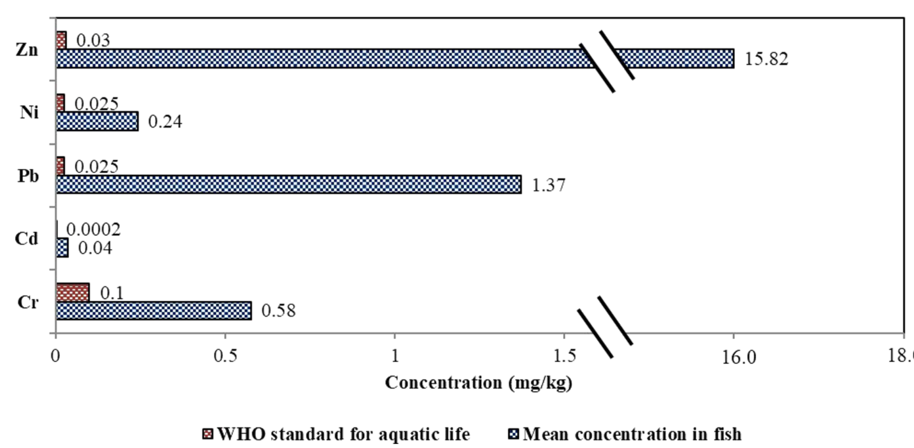

Fig. 4 Mean concentration (mg/kg) of heavy metals in fish

concentrations at Hazaribagh increased over time (pre-monsoon 73.2 mg/kg, monsoon 82.5 mg/kg and 94.6 mg/kg). It is directly correlated with higher level of Zn in the sediment (pre-monsoon 51.8 mg/kg, monsoon 67.6 mg/kg and 71.9 mg/kg). Plant Zn concentrations at Babu Bazar were comparatively lower (pre-monsoon: 49.4 mg/kg, monsoon: 68.3 mg/kg and post-monsoon: 89.4 mg/kg) compared to any other location and season (Dghaim et al. 2015; El-Rjoob et al. 2008). *Enhydra fluctuens* evidently possesses superior ability to accumulate the heavy metals which is an indication of phytoremediation.

Distribution of heavy metals in Buriganga River fish species

Aquatic species in the Buriganga River have endured the adverse impacts of the discharge of untreated industrial and domestic waste for a long time now. The heavy metals concentrations in various fish species found in Buriganga River were investigated extensively on the pre-monsoon season in Basila Bridge location. The concentrations are summarized in Table S4. The mean concentration of heavy metals in fish species and WHO standards for aquatic life for associated metals are illustrated in Fig. 4 (Sudhira and Kumar 2000)**.** The concentrations of chromium (Cr) in the muscle of fish were BDL to 1.04 mg/kg, which is higher than the concentrations observed in other studies (Saei-Dehkordi et al. 2011; Yılmaz et al. 2010) but also less than reported (1.56 and 7.38 mg/kg, respectively) in other studies (Begum et al. 2013; Ahmad et al. 2010). Pollutants measured in *Corica soborna* exhibited the highest level of Cr (1.04 mg/kg) and those in *Heteropneustes fossilis* exhibited the lowest level (0.29 mg/kg) (Table S4).

The highest levels of cadmium (Cd) were observed in *Heteropneustes fossilis* (0.03–0.04 mg/kg). (Table S4). No Cd was detected in the muscle tissue in most of the fish samples (Fig. 4, Table S4). Permissible limit of Cd for fish is 0.05 mg/kg set by CODEX Alimentarius Commission (1989) (Real et al. 2019). Cd in fish sample from the Buriganga River was below the permissible limit, but long period of accumulation of Cd in fish might pose health hazards. The presence of Cd in the sediment of all three locations indicates anthropogenic input of Cd from sewage, manure and phosphate fertilizer application. The highest level of Pb was found in *Corica soborna* (2.92 mg/kg) and the lowest in *Wallago attu* (BDL) (Table S4). Since lead (Pb) content in *Heteropneustes fossilis* corresponded to 1.04 mg/kg, careful attention should be given to edible fish species in Buriganga River. Sediments could be the major source of lead contamination in *Heteropneustes fossilis*, a bottom living fish.

Nickel (Ni) concentrations found in fish in this study were BDL to 0.26 mg/kg. These values were much lower than the reported value of Sharif et al. (1993), Rahman et al. (2012a, b), Ahmad et al. (2010) and Amin et al. (2011). Concentration levels of Ni in fish species of Buriganga River were below the established safe level of 5.5 mg/kg set by Western Australian Food and Drug Regulations (Plaskett and Potter, 1979). In the present investigation, Zn concentrations in fish species varied from 5.77 to 32.35 mg/kg. The previous study conducted in Buriganga River showed higher Zn concentrations in fish (Begum et al. 2013). Several studies that investigated other rivers in Bangladesh had obtained higher levels of Zn compared to this present study (Sharif et al. 1993; Amin et al. 2011; Rahman et al. 2014; Real et al. 2019). The highest level of Zn was found in *Wallago attu* (Boal) (32.35 mg/kg) and the lowest in *Heteropneustes fossilis* (Shing) (5.77 mg/kg). It is expected that the concentrations of all the metals under consideration in the fish species will be lower in the monsoon and post-monsoon season showing similar trends of respective metals in water, sediment and plant samples.

Overall status of the river

The findings on each heavy metal distribution across water, sediment and plants in three primary locations along Buriganga River linking with the associated seasonal variations essentially facilitated the overall evaluation of the river. Lower Cr concentration observed in all different compartments of the environment indicates significant improvement with regard to Cr discharge in both Basila and Babu Bazar area. In monsoon and post-monsoon seasons, Cr concentrations might be of concern at some compartments (water, plant) at Babu Bazar. However, higher Cr concentration is reported in all different compartments of the environment indicating no significant improvement of Cr level in the Hazaribagh area yet. Based on the residence time of Cr in lake water, it may take 18 years for Cr in water to naturally attenuate if further discharge from the point sources or upstream can be prevented (Schmidt and Andren 1984). Needless to say, the mass of Cr might be potentially transported to other environmental compartments mostly in sediment (Cary 1982). It has already further accumulated in fishes and plants of the river.

Lower Cd concentration is reported in all different compartments of the environment. Comparison with past studies on Cd in different environmental compartments reveal a reductions of Cd level in all the environmental compartments of Buriganga River (Saha and Hossain 2011; Islam et al. 2018b). However, Cd uptake by plants mainly in Basila and Babu Bazar might be of concern as

Table 2 Contamination factors and PLI values (unitless)

Sample location		Cr	Cd	Pb	Ni	Zn	PLI
Basila Bridge (upstream)	Pre-monsoon	0.20	0.52	0.27	0.24	0.43	0.311
	Monsoon	0.01	0.05	0.15	0.17	0.39	0.079
	Post-monsoon	0.13	0.05	0.29	0.01	1.02	0.121
Hazaribagh	Pre-monsoon	1.13	0.77	0.52	0.47	0.77	0.695
	Monsoon	1.10	0.05	0.12	0.43	1.01	0.310
	Post-monsoon	0.65	N/A	0.71	0.01	1.07	0.284
Babu Bazar	Pre-monsoon	0.11	1.80	0.16	0.41	1.07	0.423
	Monsoon	0.06	0.05	0.07	0.13	0.30	0.099
	Post-monsoon	0.13	N/A	0.03	0.01	0.31	0.062
Mean	0.39	0.54	0.26	0.21	0.71		
CUC*(mg/kg)	92	0.09	17	47	67		

*CUC Continental upper crust; Rudnick and Gao (2003)

Table 3 Plant concentration factors (unitless)

PCF (plant concentration factor)						
Sample location		Cr	Cd	Pb	Ni	Zn
Basila Bridge (upstream)	Pre-monsoon	2.89	6.65	0.28	1.00	8.40
	Monsoon	4.27	4.99	0.02	0.08	0.71
	Post-monsoon	1.97	N/A	0.80	0.11	1.25
Hazaribagh	Pre-monsoon	1.57	3.36	0.04	0.29	1.41
	Monsoon	0.01	4.99	0.02	0.19	1.22
	Post-monsoon	0.37	N/A	0.25	0.11	1.32
Babu Bazar	Pre-monsoon	0.24	2.30	1.21	0.18	0.69
	Monsoon	4.18	4.99	0.03	4.51	3.37
	Post-monsoon	2.08	N/A	12.00	0.11	4.35
Mean	1.96	4.55	1.63	0.73	2.53	

Table 4 I_{geo} values (unitless)

Sample location	Period	Cr	Cd	Pb	Ni	Zn
Basila Bridge (upstream)	Pre-monsoon	−0.57	−0.16	−0.45	−0.49	−0.24
	Monsoon	−2.10	−1.16	−0.70	−0.65	−0.28
	Post-monsoon	−0.78	−1.16	−0.41	−1.76	0.13
Hazaribagh	Pre-monsoon	0.18	0.01	−0.16	−0.21	0.01
	Monsoon	0.17	−1.16	−0.80	−0.24	0.13
	Post-monsoon	−0.06	N/A	−0.03	−1.76	0.16
Babu Bazar	Pre-monsoon	−0.83	0.38	−0.68	−0.26	0.15
	Monsoon	−1.10	−1.16	−1.00	−0.76	−0.39
	Post-monsoon	−0.77	N/A	−1.41	−1.76	−0.39

Cd efficiently bioaccumulates in all trophic categories of food chain (Jarup 2002).

Overall, higher Pb concentration is reported in all different compartments of the environment showing no significant reduction in the level of Pb mainly in the Babu Bazar area especially during pre-monsoon and monsoon seasons, in fact, levels of Pb might be of concern at some compartments (water, plant) at Babu Bazar. Spatial and seasonal variation of Pb level in environmental compartments indicates that the contamination is coming from urban runoff. Discharges from various point and non-point sources may vary seasonally leading to these variations in concentrations.

Although lower level of Ni concentration is reported in water, compared to the previous studies it is observed that Ni concentration in water increased slightly over

Table 5 Carbon normalized sorption coefficient (Koc) (L/kg)

log Koc (L/kg)						
Sample location		Cr	Cd	Pb	Ni	Zn
Basila Bridge (upstream)	Pre-monsoon	4.04	4.60	3.47	3.91	3.91
	Monsoon	2.71	1.83	3.35	N/A	3.61
	Post-monsoon	5.33	N/A	4.65	3.00	4.23
Hazaribagh	Pre-monsoon	3.78	4.00	3.68	4.02	3.75
	Monsoon	4.43	1.83	3.03	N/A	3.91
	Post-monsoon	3.95	N/A	5.03	2.76	4.31
Babu Bazar	Pre-monsoon	4.27	4.37	3.33	4.17	4.30
	Monsoon	3.34	1.63	3.05	N/A	3.97
	Post-monsoon	3.29	N/A	3.65	2.67	3.88

Table 6 Biota-sediment accumulation factors (unitless) for relevant metals in selected locations

Source/species		Cr	Pb	Zn
Primary producers	*Lemnoideae* (Mean)	2.41E-02	3.01E-02	9.98E-02
Primary consumers	*Corica soborna* (Kachki)	4.35E-03	4.54E-03	1.74E-01
Secondary consumers	*Channa striata* (Shole)	3.26E-03	1.62E-03	1.37E-01
	Heteropneustes fossilis (Shing)	1.20E-03	1.07E-03	4.25E-02
Tertiary consumer	*Wallago attu* (Boal)	0.0	0.0	179.6

time (Ahmad et al. 2010; Mohiuddin et al. 2011). Though the sediment was not contaminated with Ni at Babu Bazar, the desorption process might have taken place to release Ni from sediment to water over longer period of time. Evidence of Ni uptake by plants has been reported previously (ATSDR 2005). Ni concentrations in plant during the pre-monsoon season at Babu Bazar were significantly lower compared to post-monsoon season. Ni transport via sediment downstream of Hazaribagh showed higher Ni concentrations in plant at monsoon (27.75 mg/kg) exceeding the WHO (1996) recommended level of 10 mg/kg (Fig. 3, Table S3). Overall, low level of Ni is reported in all different compartments of the environment demonstrating that Ni is not a major concern in the area.

Evaluation of Buriganga River status based on environmental indices and associated correlations

The heavy metals concentrations in the water are of concern especially for potable and non-potable use at Basila Bridge. But the environmental indices clearly show that the soil/sediments and fishes are not contaminated extensively by heavy metals. Tables 2, 3, 4, 5 and 6 show the comprehensive listing of the estimated values for contamination factors (CF), pollution load index (PLI), geo-accumulation index (I_{geo}), Carbon normalized sorption coefficient (Koc), plant concentration factors (PCF) and biota-sediment adsorption factors (BSAF), respectively, for all the seasons and selected locations. Overall, contamination from all pollutants (except Zn) in the Hazaribagh area is at alarming level in all environmental compartments. However, heavy metals contamination in the Babu Bazar area is not at alarming level in most of the environmental compartments.

Contamination factors (CF) of Cr, Cd, Pb, Ni and Zn at different seasons varied from 0.01 to 1.13, 0.05 to 1.80, 0.03 to 0.71 and 0.01 to 0.41 and 0.30 to 1.07, respectively. Sediment contamination is considered low degree (CF < 1) for Cr at Basila Bridge and Babu Bazar in all seasons but considered moderate degree (CF > 1) at Hazaribagh in pre-monsoon (1.13) and monsoon seasons (1.10). Cd contamination in sediment is considered low degree (CF < 1) at Basila Bridge and in Hazaribagh in all seasons but considered moderate degree (CF > 1) at Babu Bazar in pre-monsoon season (1.80). Contamination of sediment by Pb and Ni is considered low degree (CF < 1) at all locations in all seasons. CF values of most seasons (pre-monsoon and monsoon) for Zn at Basila Bridge and most seasons (monsoon and post-monsoon) at Babu Bazar, and pre-monsoon season at Hazaribagh is below 1, indicating low degree sediment contamination. However, moderate degree pollution (CF > 1) at post-monsoon season (1.02) at Basila Bridge, monsoon (1.01) and post-monsoon (1.07) seasons at Hazaribagh, and pre-monsoon season (1.07) at Babu Bazar indicate moderate degree of Zn pollution. Overall higher CF values are observed at pre-monsoon compared to the monsoon and post-monsoon period for most of the metals probably due to dilution effects during higher flow and contaminated sediment transport during monsoon season. In general, the mean contamination factors (CFs) of the metals were below 1 indicating low degree of contamination and it followed descending order of: Zn > Cd > Cr > Pb > Ni (Table 2).

The pollution load index (PLI), calculated for all heavy metals combined, showed seasonal variation with 0.31 (pre-monsoon), 0.08 (monsoon) and 0.12 (post-monsoon) at Basila Bridge; 0.69 (pre-monsoon), 0.31 (monsoon) and 0.28 (post-monsoon) at Hazaribagh as well as 0.69 (pre-monsoon), 0.31 (monsoon) and 0.28 (post-monsoon) at Babu Bazar, respectively. All locations at different seasons showed baseline level (PLI: 0–1) of heavy metals concentrations while pre-monsoon season showing higher level of pollution (Table 2). The PLI values obtained for Buriganga River ranged from 0.062 to 0.695 indicate low degree of sediment contamination. However, Mohiuddin et al. (2011) and Mohiuddin et al. (2015) investigated on Buriganga River and obtained high degree of sediment contamination (PLI ranged from 4.90 to 29.4) in 2011 and low to high degree of sediment contamination (PLI ranged from 1.61 to 7.51) suggesting evidence of reduction in metal contamination of sediment over time in Buriganga River. In fact, the PLI values of this study further indicate that sediments of Buriganga River are less contaminated than some rivers and lakes in India and Japan (Prinju and Narayana, 2006; Chaparro et al. 2008, 2011; Mohiuddin et al. 2010; Suresh et al. 2012). Nevertheless, while the river might be self-recovering to certain extent due to the

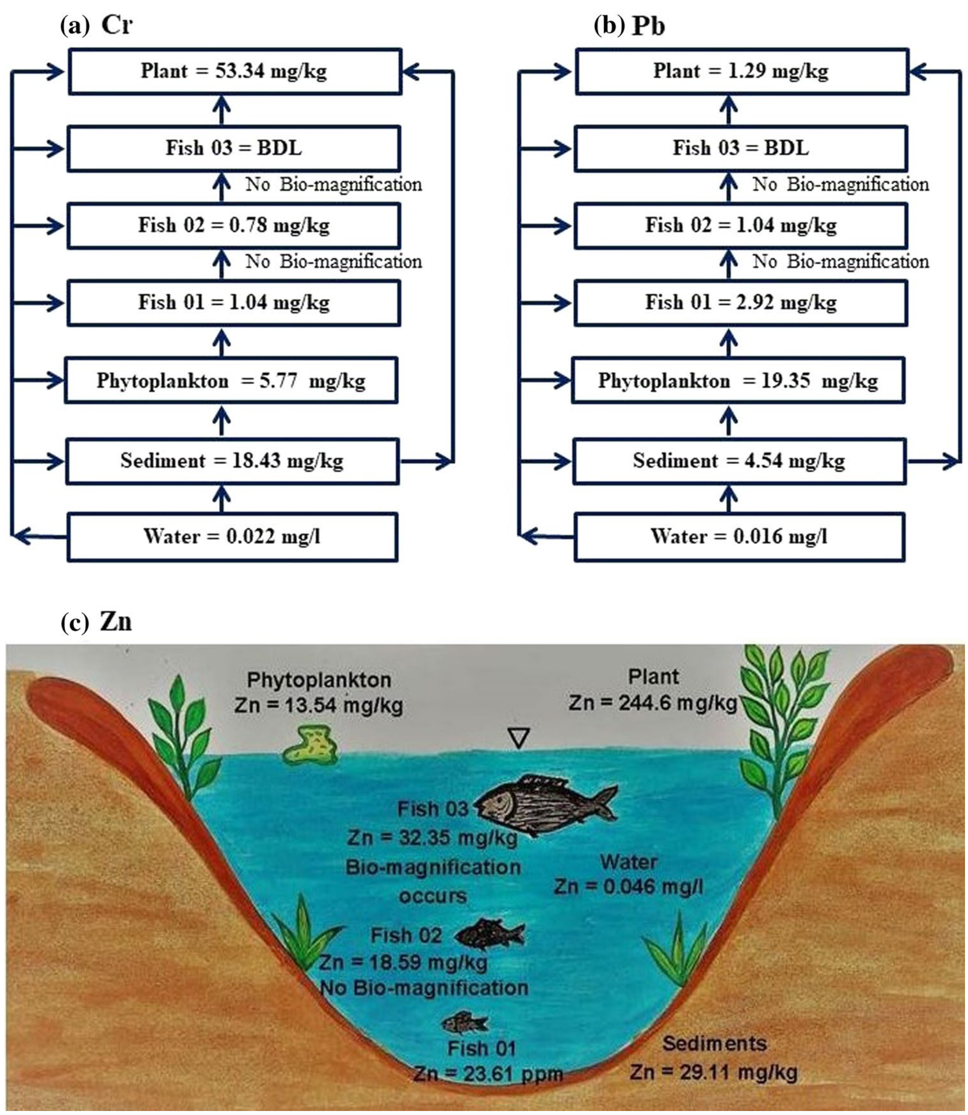

Fig. 5 Biomagnification of **a** Cr, **b** Pb and **c** Zn

relocation of industries, significant rehabilitation will still be required for Buriganga River.

Geo-accumulation index (I_{geo}) values summarized in Table 4 indicates negligible I_{geo} for most of the metals in all seasons and locations indicating practically uncontaminated (UC) to moderately uncontaminated (UMC) environmental condition of the sediment. Log(K_{oc}) values for all of the metals higher than 1 at all locations indicate higher level of metals in soil relative to metals concentration in water (Table 5) and PCF values higher than 1 indicate higher plant uptake of metals from the soil (Table 4).

Biota-sediment accumulation factor (BSAF), bioconcentration factor (BCF) and biomagnification factor (BMF) for Cr, Pb and Zn were measured only at Basila Bridge. BSAF for Cr and Pb were highest in the primary producers compared to primary, secondary and tertiary consumers (Table 6). It shows that biota accumulation of Cr and Pb decreases in higher-level species. Cr and Pb got bioconcentrated in the primary producers, primary consumers and secondary consumers in descending order as expected. However, Zn shows completely different trend of accumulation by increasing in higher-level species. Zn got bioconcentrated in the primary producers (BCF of 294.3 L/kg), primary consumers (BCF of 513.3 L/kg), secondary consumers (BCF of 404.1 and 125.4 L/kg) and tertiary consumers (BCF of 703.3 L/kg). Cr and Pb did not get biomagnified during pre-monsoon season (BMF < 1) (Fig. 5, Table S5). There is no indication of biomagnification of Cr and Pb along the terrestrial food chain but biomagnification of Zn is possible (Cary 1982; Cardwell et al. 2013). In this study, Zn is the only metal that got biomagnified during pre-monsoon season (BMF = 2.4) (Fig. 5, Table S5).

Thus, the environmental indices show that though the water is polluted with several heavy metals especially Cr, the soil/sediments and fishes are not contaminated extensively by Cd and Ni complying with the findings that Cd and Ni adsorbed to soil at Basila Bridge was relatively lower than WHO (1996) and USEPA (1999) recommended levels of 6 mg/kg and 0.6 mg/kg for Cd while 20 mg/kg and 16 mg/kg for Ni in all seasons (Fig. 3, Table S2). Plant uptake behavior of Cr clearly shows that it is probable to have higher level of Cr in the fish samples of Hazaribagh and Babu Bazar area though sediment concentrations are not of major concern at Basila Bridge area. However, water and plant are contaminated extensively by Pb. Hence, concentration levels of Pb in

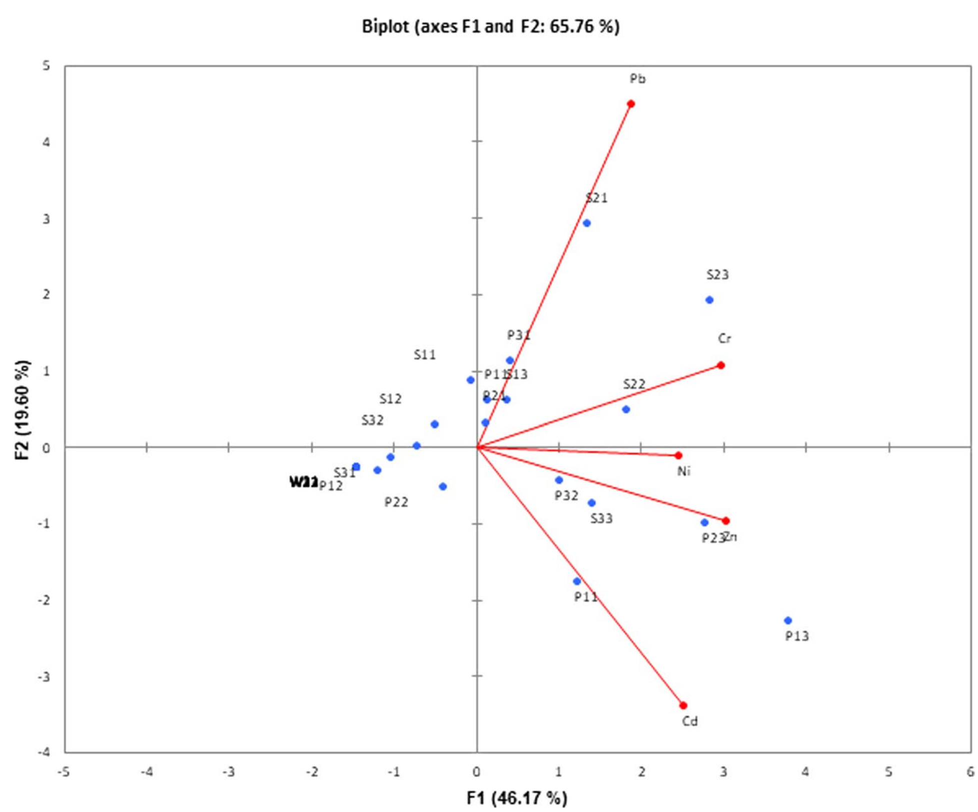

Fig. 6 Biplot from principal component analysis on the metals (Pb, Cr, Ni, Zn, Cd) for plant (P), soil (S) and water (W). Sample ID 'ij' indicates sample from ith location (i = 1–3; 1 = Basila; 2 = Hazaribagh; 3 = Babu Bazar) and jth sampling period (j = 1–3; 1 = pre-monsoon; 2 = monsoon; 3 = post-monsoon)

the water and plant are of concern at Basila Bridge in all seasons. Soil/sediments and fishes are contaminated by Zn complying with the findings that Zn is adsorbed into soil/sediments at Basila Bridge. Although Zn is not a carcinogenic compound, its concentration level is of a concern in all different compartments of Buriganga River at Basila Bridge.

Correlation and principal component analysis (PCA) among compartmental concentrations of heavy metals

The relationship among heavy metal concentrations between water–soil–plant was reported and the full correlation matrix for all heavy metal levels for the locations and compartments can be obtained in Supplementary Information (Table S6). Correlation analysis of heavy metal concentrations in different media of Buriganga River (at $\alpha = 0.05$, where α is significant level) indicated that very strong correlation exists between Cr (water) and Cr (plant) [$r = 0.866$, $p = 0.003$], Pb (water) and Ni (soil) [$r = 0.909$, $p = 0.001$], Cd (soil) and Cd (plant) [$r = 0.902$, $p = 0.001$], whereas strong negative correlation exists between Cd (water) and Zn (water) [$r = -0.835$, $p = 0.005$], Pb (water) and Pb (plant) [$r = -0.794$, $p = 0.011$]. Moderate correlation exists between Cr (water) and Cr (soil) [$r = 0.715$, $p = 0.030$], Ni (water) and Cr (soil) [$r = 0.767$, $p = 0.016$], Ni (water) and Ni (soil) [$r = 0.676$, $p = 0.046$], Zn (water) and Cr (plant) [$r = 0.705$, $p = 0.034$]. Correlation (Pearson) analysis between remaining heavy metals in different compartments showed no statistical significance ($p > 0.05$). The negative correlation between Cd (water) and Zn (water) suggests inverse relationship between the metals. Multiple sources of heavy metals are responsible for the pollution as the elements in water did not show any positive correlation with each other (Bastami et al. 2012). The industrial along with municipal and urban activities near the river especially tannery waste/wastewater with sewage disposal to Buriganga River contributed to the overall pollution as significant correlation was reported between metal concentrations in the water and in the soil (Avila-Perez et al. 1999). The positive significant correlations between Cr (water) and Cr (plant), Cd (soil) and Cd (plant), Pb (water) and Pb (plant) indicate linear dependence of heavy metals accumulation from water and soil into the plants, *Enhydra fluctuens*. In addition, positive correlation between Zn (water) and Cr (plant) suggests that the process of concentration of Zn in water and Cr in plant may be cooperative.

The biplot of principal component analysis (PCA) is shown in Fig. 6 where first 2 components explain 65.74% of the data set. The symbols W, P and S represents water, plant and soil, respectively, where first subscript of W, P and S represents locations of the sample collection (where, 1 = Basila Bridge, 2 = Hazaribagh. 3 = Babu Bazar) and second subscript represents different seasons (where, 1 = pre-monsoon, 2 = monsoon and 3 = post-monsoon). The outcomes suggest that the plant samples are mostly located in positive side of principal component 1 (PC1) signifying strong influence from most of the heavy metals. River water samples (W22) [Hazaribagh during monsoon season] that have the lowest content of heavy metals are grouped in the negative side of the two PCs representing their decreased influence on the heavy metal compartmentalization. From evaluation of the biplot (Fig. 6), soil samples S21 [Hazaribagh at pre-monsoon season] are strongly characterized by Pb while plant samples P11 [Basila at pre-monsoon season], P21 [Hazaribagh at pre-monsoon season], P31 [Babu Bazar at pre-monsoon season] and soil samples S13 [Basila at post-monsoon season] are characterized by Pb at low levels. Soil samples S22 [Hazaribagh at monsoon season] and S23 [Hazaribagh at post-monsoon season] can be evaluated to be moderately characterized by Cr. Plant samples P23 [Hazaribagh at post-monsoon season] are strongly characterized by Zn whereas plant sample P32 [Babu Bazar at monsoon season] and soil sample S33 [Babu Bazar at post-monsoon season] are influenced at low levels by Zn. Plant sample P33 [Babu Bazar at post-monsoon season] is moderately characterized by Cd while plant sample P13 [Basila at post-monsoon season] is influenced at low levels by both Cd and Zn. None of the samples seem to be influenced by Ni to any degree. Water samples of the river at any location or any season could not be characterized by any of the heavy metals under consideration.

Conclusion

This study reports the presence of several heavy metals at different compartments of Buriganga River with higher concentrations of certain metals above regulatory limits. It investigated the status and dynamic pattern of pollution from selected relevant heavy metals at different compartments of Buriganga River of Dhaka City. Among the five metals (chromium-Cr, cadmium-Cd, lead-Pb, nickel-Ni and zinc-Zn) that were extensively investigated in this study, the chromium-Cr, cadmium-Cd and lead-Pb pollution in the Buriganga seem to be of significant concern and need continuous thorough investigation. Ni and Zn contamination is not of major concern for Buriganga River according to this study. The chromium (Cr), cadmium (Cd) and lead (Pb) pollution is concentrated at Basila Bridge and Hazaribagh area. The major exposure route of pollution in Buriganga is allegedly through water as findings demonstrate higher level of pollution from Cr, Cd and Pb in the water. However, concentration of heavy metals in sediments are apprehended to be potentially masked through deeper sediment burial, and meanwhile, sediments at certain stretches of Buriganga might also be recovering from heavy metal pollution, to be optimistic.

Sediment pollution was mainly described by different indices such as CF, PLI, I_{geo}, etc. Contamination factors were found to be very low (CF < 1) indicating minimum degree of contamination in the three major locations and three seasons. PLI values of Buriganga River ranged from 0.040 to 0.395 with an average of 0.221 in the sediments of the three sites at different seasons, indicating no major level of sediment pollution (no pollution). Again, it does not correlate well with water concentrations of the pollutants indicating the requirement for extensive study and collection of sediment samples from deeper levels in the Buriganga River. Furthermore, the calculated index of geo-accumulation (I_{geo}) measured contamination intensity of heavy metals in the sediments of the Buriganga River. I_{geo} values for the studied trace metals revealed a zero-class representing uncontaminated sediment quality. However, the K_{oc} values are higher indicating higher amount of metals partitioned into organic carbon of sediments. Plant concentration factor (PCF) values indicate that there were significant absorption of heavy metals by plants from the soils. The plant, *Enhydra fluctuens*, absorbed higher levels of Cr, Cd and Pb from the soil compared to the other metals studied. Plants did not exhibit any major transfer of Ni in their tissue.

There is major evidence of bioaccumulation of all metals as shown by bioconcentration factors. But BCF values were less than 2000 L/kg indicating that the heavy metals were not persistent and not very bioaccumulative according to EU regulation. *Lemnoideae* accumulated cadmium much higher than the other metals as per BCF values for Cd. None of the toxic heavy metals were biomagnified (Cr, Cd and Pb). Zn was biomagnified (BMF = 2.14) which is not of significant concern for the Buriganga River. Thus, Cr, Cd and Pb pollution in the Buriganga is of significant concern in the water phase. Although the desired quality of water for Buriganga cannot be allegedly evidenced in this study, however, the results indicate some extent of improvements in sediment quality. An in-depth sediment study will be required to reveal and confirm the findings. The water quality of the Buriganga River in Dhaka showed signs of improvement to some extent though not to the expected level since the relocation of the tanneries of Hazaribagh began. This study sets up a foundation emphasizing the importance of frequent monitoring of the river systems and its compartments in a city such as Dhaka that is continuously undergoing rapid industrial expansion and urbanization issues. Based on the findings of this study, continuous assessment on waste loads and pollutant concentrations requires to be carried out for Buriganga River with a view to benchmarking the major steps being enforced to mitigate the water pollution in Dhaka City.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s13762-021-03434-8.

Acknowledgements The authors acknowledge the contribution of Dr. Arifur Rahman of Jacobs Engineering Group Inc., Texas, USA, on principal component analysis.

Author contributions All listed authors attest that all authors contributed significantly to create this manuscript. All authors confirm that the manuscript was carefully read and approved by all listed authors. All authors further confirm that the order of authors listed in the manuscript has been approved.

Funding Funding for the project was allocated annually for two years from the research grant of the Institute of Energy, Environment, Research and Development (IEERD) at the University of Asia Pacific, Dhaka, Bangladesh.

Availability of data and material (data transparency) The datasets generated and/or analyzed during this work are available in the main manuscript and in the form of supplementary tables that is submitted along the manuscript.

Code availability (software application or custom code) XLSTAT software was used for statistical analysis. No code was developed or required to develop by the authors for data analysis.

Declarations

Conflict of interest The authors confirm that there are no known conflict of interest associated with this publication. No financial support for this work has influenced its outcome.

Ethical approval The authors confirm that this research activity does not involve human or animal as a subject matter.

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