Trace metals in water, sediment and fishes of the Ganges-Brahmaputra-Meghna Delta, Bangladesh: A Review

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Abstract

The Ganges-Brahmaputra-Meghna (GBM) Delta, a transboundary delta, is the world's largest delta which is believed to be contaminated with many pollutants including heavy metals. This study systematically reviewed heavy metal pollution in water, sediments and fish in different rivers of the GBM Delta, Bangladesh. This study evaluated total 12 heavy metals (Cr, Cd, Hg, As, Zn, Cu, Fe, Co, Pb, Ni, Mn and Ba) which are mostly reported in different rivers of the GBM Delta. Most of the heavy metals' mean concentration in water, sediments and fish exceeded the maximum permissible limits (MPLs) in the Buriganga, Bangshi, Dhaleshawri, Karnaphuli and Korotoa rivers because of direct or indirect discharge of significant levels of untreated industrial effluents, municipal sewage, domestic wastes and agricultural runoffs. However, the level of heavy metal contamination in water and sediments of the upper Ganges were below the MPLs. This might be caused by the effects of higher water flow in the river. The concentration of heavy metals in sediments and fish were reported much higher than waters as metals tend to deposit to the bottom of the water column and also accumulate in the fishes' tissues. We conclude that a few of the rivers of GBM delta are highly contaminated by heavy metals and there is potential risk concern for ecosystem and public health. This study recommends effective waste management strategies to control heavy metals pollution in different rivers of the GBM Delta in future.

Keyword: Heavy metal, Aquatic pollution, Transboundary delta, GBM river system, Bay of Bengal

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1. Introduction

Heavy metals in the aquatic environment have received worldwide attention because of their abundance, toxicity, persistence, accumulation behaviors and bio-magnification potential (Alloway 2013; Ali et al. 2016; Bhuyan et al. 2017). In recent decades, rapid urbanization and industrialization in developing countries have been responsible for increasing the metal pollution in aquatic ecosystems (Zhang et al. 2009; Ali et al. 2016; Xu et al. 2016; Proshad et al. 2018). Heavy metals are delivered from natural and anthropogenic sources into the waters; and ultimately accumulated in sediments. However, the concentration of heavy metals in water is much lower than sediments as metals tend to deposit in bottom of the water column (Wu et al. 2014).

The Ganges-Brahmaputra-Meghna (GBM) delta is one of the largest trans-boundary river systems covering a number of geographical regions with specific characteristics (Chowdhury and Ward 2004). The Ganges, Brahmaputra and Meghna rivers originate from the Gangotri glacier in the Himalayas mountain range, northern slope of the Himalayas in China and the Barak river in India, respectively. After entering Bangladesh, the Ganges (as Padma) and the Brahmaputra (as Jamuna) join at Daulatdia and flow as Ganges-Brahmaputra confluence, and later join with the Meghna before discharging into the Bay of Bengal (Fig. 1). Along its way, the Ganges, the Brahmaputra and the Meghna are joined by a number of tributaries to support one of the most fertile regions of the world and in Bangladesh, it occupies roughly 7% of the GBM delta (JRCB 2020).

The GBM delta is the world's most populated delta where around 670 million people depend on the river systems for their livelihoods (Whitehead 2018) and as a result, the delta is unequivocally influenced by anthropogenic activities such as urbanization and industrialization (Ericson et al. 2006). The GBM delta is the major source of water for households' activities, agriculture, industries and transport. According to BBS (2019), more than 46,291 small and large manufacturing industries have been established near the GBM or tributary rivers and in recent years, the pressure has increased manifolds due to continuous expansion of urbanization and industrialization. Annually on average, around 22.53 million tons of municipal solid wastes and 22×10^9 m^3 of industrial liquid wastes are produced in Bangladesh, of which collection coverage 20%, and the recycling rate is 0% (Waste Atlas 2020). As a result, large amounts of untreated industrial effluents are directly or indirectly discharged into low-lying lands and water bodies adjacent to the areas (Islam et al. 2015a) and ultimately have been washed into the surrounding rivers in the GBM delta of Bangladesh. In addition, agricultural runoff such as fertilizers, pesticides and insecticides mixed with rain or irrigation water and eventually drain into the GBM river system.

The GBM delta suffers heavy metal pollution due to several anthropogenic activities such as untreated industrial effluents, agricultural runoff, improper disposal of domestic waste, municipal sewage and so forth (Haque et al. 2019; Hossain et al. 2019). These heavy metals can cause severe pollution in water, sediments and foodstuffs which ultimately pose a threat on the surrounding ecosystems and overall environment. Most regional studies have focused on physiochemical parameters, water quality assessment and heavy metal pollution in a few tributaries or local rivers of Bangladesh in recent years (Ahmed et al. 2009a; Ahmad et al. 2010; Ahmed et al. 2015; Bhuiyan et al. 2015; Islam et al. 2015b; Ali et al. 2016; Haque et al. 2020). However, no systematic review on heavy metal pollution in water, sediments and fish of different rivers of GBM delta of Bangladesh has been attempted. This study aimed to review the heavy metal pollution in water, sediments and fish on the ecosystem of the GBM delta of Bangladesh.

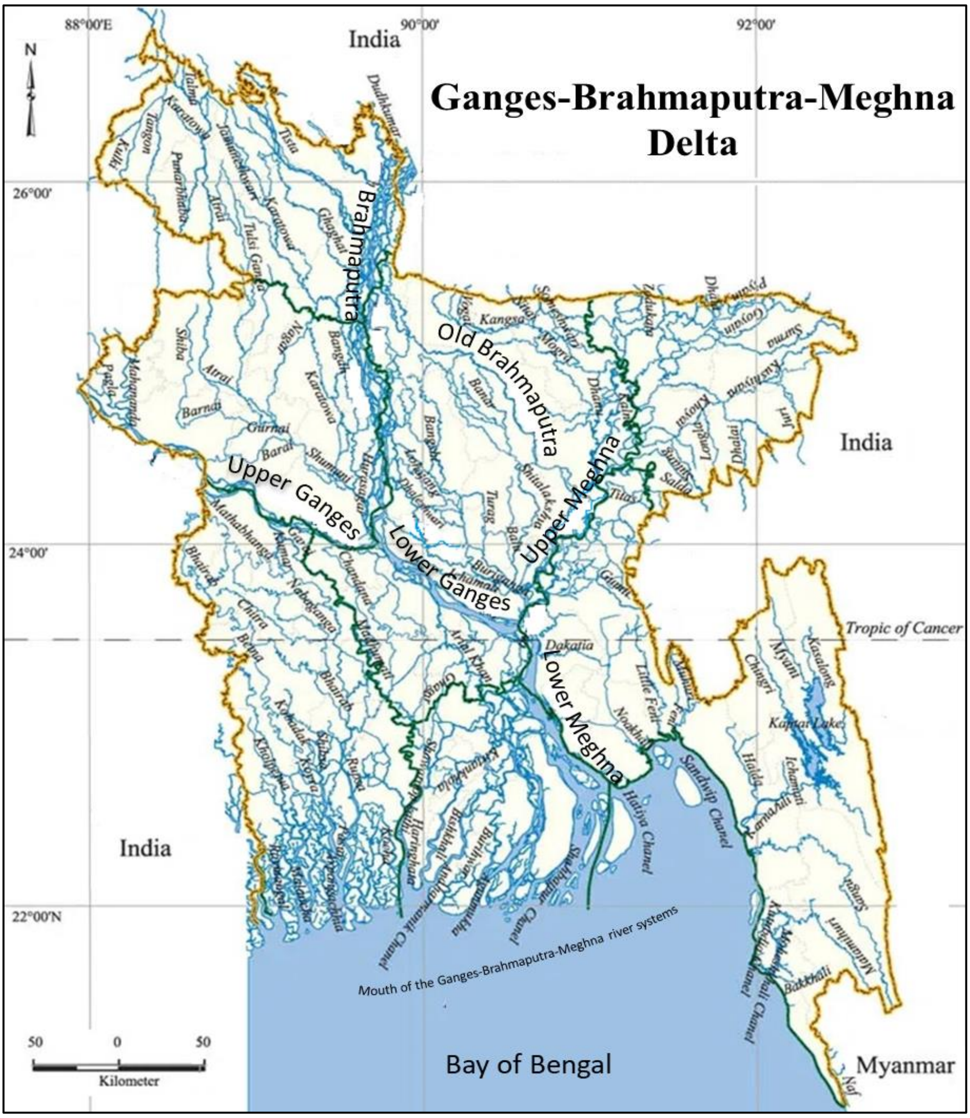

Fig. 1. Ganges-Brahmaputra-Meghna Delta, Bangladesh (modified from Banglapedia, 2014)

2. Methods

In this study, peer-reviewed scientific articles on heavy metal pollution and their environmental impacts in the Ganges-Brahmaputra-Meghna Delta of Bangladesh were reviewed. Google Scholar and Web of Science search engines were used with the following key words: 'metal pollution in water', 'metal pollution in sediment' and 'metal pollution in fish' in Bangladesh. A systematic review flowchart was shown in Fig. 2 for this study. This study excluded grey publications including published or unpublished theses, dissertations, reports, conference papers and working papers.

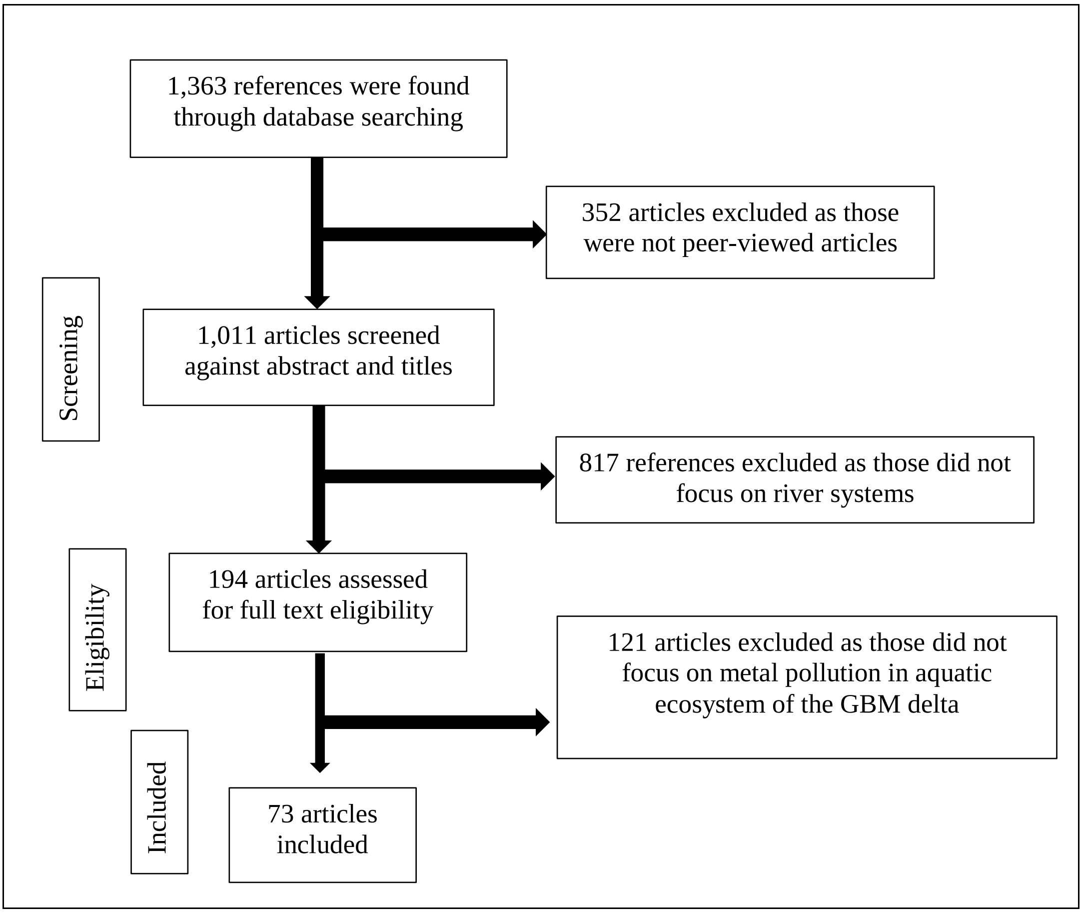

Fig. 2. A flowchart for reviewing heavy metal pollution in water, sediments and fishes of different rivers of the Ganges-Brahmapurta-Meghna delta of Bangladesh

3. Results

Heavy metal contamination in water, sediments and foodstuffs is a growing concern of environmental health risk around the world. A maximum of twelve (12) heavy metals were mostly reported in different rivers of the GBM delta. The contamination of heavy metals in waters, sediments and fishes of different rivers of the GBM delta are described below-

4. Heavy metals in surface water

Chromium (Cr) is one of the most health and environmentally concerning metals which found mostly in two oxidation states, Cr (III) and Cr (VI) in nature. According to WHO (2011) and Bangladesh standards (DPHE 2020), the maximum permissible limits (MPLs) of chromium in drinking water is 0.05 mg/L (Table 1). Among all of the studies, mean Cr concentration was found maximum in surface water of the Buriganga river (1.96±0.18 and 1.43±0.53 mg/L) in winter and summer respectively (Mohiuddin et al. 2011) followed by the Balu river (1.02±0.24 mg/L) (Hasan et al. 2014). Increasing discharge of industrial effluents, untreated domestic and municipal waste are responsible for higher concentration of Cr pollution in the surface water of the Buriganga and Balu rivers. However, the lowest mean concentration of Cr 0.0007 mg/L was reported in surface water of the upper Ganges river (Padma river) (Haque et al. 2020) because of higher water flow and distant pollution sources.

Cadmium (Cd), one of the most toxic heavy metals, occurs in natural environment (such as river) at a low level. But industrial effluents and agricultural runoff might increase the concentration of Cd in the environment. Most of the studies reported that mean concentration of Cd in water exceeded the MPL 0.003 mg/L (WHO 2011) except the Old Brahmaputra river (Bhuyan et al. 2019), Meghna estuary (Raknuzzaman et al. 2016), upper Ganges (Jolly et al. 2013 and Haque et al. 2020) and Pasur rivers (Ali et al. 2018). The highest concentration of Cd (0.22 mg/L) was found in the surface water of the Buriganga river in winter (Mohiuddin et al. 2011), whereas, the lowest value (0.00001 mg/L) was reported in the Meghna estuary, Bhola (Raknuzzaman et al. 2016).

Table 1. Mean (±sd) heavy metal concentration (mg/L) in surface water of different rivers of the Ganges-Brahmaputra-Megha Delta, Bangladesh

Study location	Concentrations (mg/L)												References	Quality assurance
	Cr	Cd	Hg	As	Zn	Cu	Fe	Co	Pb	Ni	Mn	Ba		
Balu river	1.02±0.24	-	-	-	0.38±0.08	0.16±0.04	0.16±0.02	-	-	-	-	-	Hasan et al. 2014 ws	CRM used
	-	-	-	-	0.05±0.02	0.08±0.04	0.04±0.02	-	-	-	-	-	Hasan et al. 2014 rs	
Bangshi river	0.11±0.03	0.01±0	-	0.02±0	3.01±0.62	0.89±0.14	-	-	0.09±0.02	0.03±0.01	0.08±0.01		Rahman et al. 2014	SRM used
Buriganga river	0.587±0.0441	0.009±0.001	-	-	-	0.163±0.033	-	-	0.065±0.004	0.008±0.001	-	-	Ahmad et al. 2010	SRM used
	1.43±0.53	0.16±0.04	-	0.24±0.03	0.26±0.05	1.71±0.14	-	0.09±0.01	0.50±0.06	0.15±0.02	-	-	Mohiuddin et al. 2011 SS	CRM used
	1.96±0.18	0.22±0	-	0.40±0.19	0.22±0.03	2.74±0.01	-	0.10±0.01	0.23±0.06	0.17±0.02	-	-	Mohiuddin et al. 2011 WS	
Dhaleshawri river	0.441±0.0425	0.006±0.001	-	-	-	0.154±0.030	-	-	0.05±0.019	0.007±0.001	-	-	Ahmed et al. 2009a	SRM used
	0.13±0.007	0.001±0	-	-	-	ND	-	-	0.201±0.076	-	-	-	Ahmed et al. 2012 dw	Not specified
Halda river	0.06	0.03	0.003	-	0.35	0.10	-	0.05	0.07	0.41	0.16	-	Bhuyan and Bakar 2017	Not specified
Karnaphuli river	0.069±0.016	0.006±0.003	-	0.023±0.007	-	-	-	-	0.009±0.005	-	-	-	Ali et al. 2016 SS	CRM used
	0.086±0.017	0.010±0.004	-	0.034±0.009	-	-	-	-	0.016±0.006	-	0.126±0.002	0.019±0.001	Ali et al. 2016 WS	
Khiru river	-	0.175±0.34	-	-	0.006±0.003	0.004±0.001	-	-	0.011±0.008	-	0.095±0.11	-	Rashid et al. 2012	Not specified
Korotoa river	0.073±0.027	0.008±0.006	-	0.037±0.024	-	0.061±0.028	-	-	0.027±0.015	0.032±0.019	-	-	Islam et al. 2015b SS	CRM used
	0.083±0.027	0.011±0.008	-	0.046±0027	-	0.073±0.033	-	-	0.035±0.019	0.039±0.023	-	-	Islam et al. 2015b WS	
Meghna estuary	0.011±0.001	0.00001±0	-	0.002±0	0.005±0.008	0.01±0.013	-	-	0.005±0.001	0.01±0001	-	-	Raknuzzaman et al. 2016	CRM used
Meghna river	0.034±0.023	0.003±0.001	-	-	0.036±0.031	-	1.022±0.410	-	BDL	BDL	0.008±0.008	-	Hasan et al. 2015	Not specified
	0.02	0.018	-	-	0.04	0.027	1.93	0.009	0.01	0.155	0.26	-	Bhuyan et al. 2017	Calibration curve used

Old Brahmaputra river	0.01	0.001	0.001	-	0.01	0.12	-	0.2	0.11	0.44	1.44	-	Bhuyan et al. 2019	Calibration curve used
Pasur river	0.044±0.015	0.001±0.001	-	0.008±0.003	-	-	-	-	0.02±0.009	-	-	-	Ali et al. 2018[ss]	Calibration curve used
	0.053±0.015	0.002±0.001	-	0.011±0.004	-	-	-	-	0.027±0.01	-	-	-	Ali et al. 2018[ws]	
Upper Ganges river (Padma)	0.003	0.002	-	0.001	0.007	0.02	0.199	-	0.001	0.008	0.015	-	Jolly et al. 2013	Calibration curve used
	0.038±0.043	0.005±0.004	-	0.003±0.002	0.03±0.035	0.012±0.013	-	-	0.009±0.009	0.004±0.002	-	-	Haque et al. 2019	Not specified
	0.0007	0.0001	-	0.002	0.089	0.006	0.080	-	0.002	0.005	0.0001	0.172	Haque et al. 2020	SRM used
Surma river	0.04±0	-	-	-	0.004±0.001	0.04±0	1.83±0.93	-	0.01±0	-	-	-	Alam et al.2007 [ms]	Not specified
	0.04±0	-	-	-	1.154±0.247	0.04±0	0.33±0.07	-	0.01±0	-	-	-	Alam et al. 2007[ds]	
Turag river	0.027±0.017	-	-	-	0.078±0.02	0.016±0.005	0.227±0.061	-	0.014±0.004	0.015±0.004	0.175±0.05	0.07±0.014	Zakir et al. 2006	SRM used except Fe
MPL	0.05	0.005	0.001	0.05	5	1	0.3-1	-	0.05	0.1	0.1	1	DPHE 2020	
	0.05	0.003	-	0.01	3	2	0.3	0.1	0.01	0.02	0.1	0.7	WHO 2011	

Note: MPL=maximum permissible limit, ss=summer season. ws=winter season, rs=rainy season, ds=dry season, ms=monsoon season, BDL= beyond detection limit, ND=not detected, SRM/CRM= standard/certified reference materials

Analysis of the data confirmed that the concentration of Zinc (Zn) remained within the MPL of DPHE (2020) and WHO (2011) except the reported value of 3.01±0.62 mg/L in the Bangshi river (Rahman et al. 2014) (Table 1). However, the recorded concentration of Zn was much lower (0.004±0.001 mg/L) in the Surma river (Alam et al. 2007) during the monsoon because of dilution of river water.

The mean concentration of copper (Cu) in surface waters of different rivers of the GBM delta ranged between 0.004 to 2.74±0.01 mg/L (Table 1). The MPL of Cu was 1 mg/L and 2 mg/L recommended by DPHE (2020) and WHO (2011), respectively. The highest concentration of Cu (2.74±0.01 mg/L) was reported in the water of the Buriganga river (Mohiuddin et al. 2011) in winter because of direct discharge of industrial effluents and domestic waste in the river.

Arsenic (As) is less available in surface water because it absorbs to sediment along with Fe (Ahmed et al. 2016). This study showed that most of the available studies reported the mean concentration of As was above the MPL (0.01 mg/L) of WHO (2011) for drinking water except the Meghna estuary (Raknuzzaman et al. 2016), Pasur river (Ali et al. 2018) and the upper Ganges river (Jolly et al. 2013; Haque et al. 2019 and 2020). The highest recorded value of As was 0.40±0.19 mg/L in the Buriganga river (Mohiuddin et al. 2011) which was higher than the standard limit (0.05 mg/L) set by the government of Bangladesh (DPHE 2020).

Iron (Fe), an essential trace element, is mostly found in the Earth's crust. The maximum concentration of Fe (1.93 mg/L) and (1.83±0.93 mg/L) was reported in surface water of the Meghna river (Bhuyan et al. 2017) and Surma river (Hasan et al. 2015) respectively which were higher than the threshold limit set by DPHE (2020) and WHO (2011). The lowest value of Fe 0.04±0.02 mg/L and 0.08 mg/L was reported in the Balu river (Hasan et al. 2014) and the upper Ganges river (Haque et al. 2020) which was much lower than the MPL set by different parties (Table 1).

Lead (Pb) is a ubiquitous metal and raises substantial public health concern as it is increasingly reported in the natural environment around the world. The MPL set by WHO and Bangladesh government for Pb in drinking water is 0.01 mg/L and 0.05 mg/L respectively. The concentration of Pb in different rivers of the GBM delta ranged between BDL to 0.50±0.06 mg/L (Table 1). The highest concentration of Pb (0.50±0.06 mg/L and 0.23±0.06 mg/L) was reported in the Burignga river in summer and winter season respectively (Mohiuddin et al. 2011). Increasing discharge of industrial effluents might be responsible for the highest level of Pb contamination in the Buriganga river.

Nickel (Ni) is an important trace metal for the organ development. The concentration of Ni in surface water ranged between BDL to 0.44 mg/L (Table 1). The MPL of Ni in drinking water is 0.1 mg/L (DPHE 2020) and 0.02 mg/L (WHO 2011). The highest concentration of Ni (0.44 mg/L) was recorded in the Old Brahmaputra river (Bhuyan et al. 2019) which was higher than the MPL set by DPHE (2020) and WHO (2011).

Manganese (Mn) occurs naturally and can be released into water bodies of rivers through surface runoff from agricultural fields. The MPL of Mn is 0.1 mg/L for drinking water recommended by WHO (2011). The highest concentration of Mn (1.44 mg/L) was reported in surface water of the Old Brahmaputra river (Bhuyan et al. 2019), whereas, the lowest value (0.0001 mg/L) was recorded in the upper Ganges river (Haque et al. 2020).

A very few studies were found for mercury (Hg), cobalt (Co) and barium (Ba) pollution in surface water of different rivers of the GBM delta. A few studies were reported Hg pollution in surface water of the GBM delta such as Bhuyan et al. (2019) and Bhuyan and Bakar (2017) who reported that Hg concentration was 0.001 mg/L in the old Brahmaputra river and 0.003 mg/L in the Halda river respectively. The concentration of Co was ranged between 0.009 to 0.2 mg/L (Table 1) but there has no recommended standard value for Co in drinking water by the government of Bangladesh. The concentration of Ba in surface water in the available studies were below the recommended value of DPHE (2020) and WHO (2011).

5. Heavy metals in sediments

The maximum concentration of Cr (788 mg/kg dw) was recorded in sediment of the Buriganga river (Tamim et al. 2016) which was 31 times higher than the MPL of sediment 25 mg/kg set by WHO (2004) and USEPA (1999) (Table 2). In the same river, the value was 177.53±30.19 mg/kg in 2010 (Ahmad et al. 2010), 510.70 mg/kg and 709.40 mg/kg in summer and winter season in 2011 respectively (Mohiuddin et al. 2011). The concentration of Cr in the Buriganga river dramatically increased over two years because of direct discharge of industrial effluents into the river. The lowest concentration of Cr (6.6 mg/kg) was reported in the Old Brahmaputra river (Bhuyan et al. 2019). It was also found that the concentration of Cr was higher in winter than summer in the Buriganga, Karnaphuli, Paira, Pasur and Rupsa rivers (Table 2) due to lower water flow during winter which could assist to accumulate the heavy metals in sediment (Islam et al. 2015a). In case of the Ganges river, the upper Ganges showed lower concentration of Cr 24.23±10.21 mg/kg (Hossain et al. 2019) than the lower Ganges 49.68±17.08 mg/kg (Hossain et al. 2019) and 98 mg/kg (Datta and Subramanian 1998) due to higher water flow in the upper Ganges.

The concentration of Cd in sediment was ranged from 0.04 mg/kg in the Halda river (Bhuyan and Bakar 2017) to 5.88 mg/kg in the Buriganga river (Mohiuddin et al. 2011). Most studies showed lower concentration of Cd in different rivers of the GBM delta than the recommended value of WHO (2004) (Table 2). However, the concentration of Cd in the Buriganga, Dhaleshawri, Karnaphuli, Korotoa and Rupsa rivers all exceeded the MPL (0.6 mg/kg) set by USEPA (1999) and CCME (1998).

The concentration of Zn in the sediments of different rivers of GBM delta was comparatively lower than the MPL set by different parties (Table 2) except the Buriganga, Turag, Bangshi and Shitalakhya rivers. The highest value 958.15 mg/kg was recorded in the Buriganga river in winter (Mohiuddin et al. 2011). In case of the Turag river, the value was 128 mg/kg in 2006 (Zakir et al. 2006) which had increased to 780 mg/kg in 2020 (Khan et al. 2020b). Various anthropogenic activities such as extreme road traffic, domestic and industrial sewages might be the cause of the highest level of Zn contamination in Turag river (Khan et al. 2020b).

Most of the studies showed that Cu concentration in sediment was higher than the recommended value of 35.7 mg/kg set by CCME (1998) except the Halda, Old Brahmaputra, Meghna and Ganges rivers (Table 2). The highest concentration of Cu (238.45 mg/kg) was reported in the Buriganga river (Mohiuddin et al. 2011) and lowest value (2.45±2.28 mg/kg) was found in the upper Ganges river (Hossain et al. 2019).

The concentration of As in sediment was higher than the MPL 5.9 mg/kg set by CCME (1998) except the Feni river estuary and Ganges river (Table 2). The highest value 27±17 mg/kg was reported in sediments of the Korotoa river (Islam et al. 2017) and lowest value 0.85 mg/kg was found in the Feni river estuary (Islam et al. 2018).

Table 2. Mean (±sd) heavy metal concentration (mg/kg dw) in sediment of different rivers of the Ganges-Brahmaputra-Meghna Delta, Bangladesh

Study location	Concentration (mg/kg)												References	Quality assurance
	Cr	Cd	Hg	As	Zn	Cu	Fe	Co	Pb	Ni	Mn	Ba		
Bangshi river	114.42±17.21	0.67±0.19	-	1.71±0.82	111.38±20.98	28.66±7.85	-	-	56.47±15.81	20.33±8.06	461.90±56.88	-	Rahman et al. 2014	SRM used
Buriganga river	177.53±30.19	3.33±0.77	-	-	-	27.85±3.56	-	-	69.75±4.13	200.45±29.21	-	-	Ahmad et al. 2010	SRM used
	510.70	4.68	-	13.75	712.95	238.45	-	30.45	474.85	113.35	-	-	Mohiuddin et al. 2011 SS	CRM used
	709.40	5.88	-	15.75	958.15	224.55	-	35.35	477.85	137.35	-	-	Mohiuddin et al. 2011 WS	
	788	-	0.092	7.1	101	45	25000	10.5	25	-	508	458	Tamim et al. 2016	SRM used
Dhaleshawri river	117.56±19.57	3.23±0.61	-	-	-	44.05±14.93	-	-	64.22±3.80	186.06±33.27	-	-	Ahmed et al. 2009a	SRM used
	27.39±1.29	2.08±0.01	-	-	-	37.45±0.33	-	-	15.79±1.25	-	-	-	Ahmed et al. 2012 dw	Not specified
Feni river estuary	35.28	-	0.71	0.85	-	-	-	-	6.47	33.27	37.85	-	Islam et al. 2018	SRM used
Halda river	8.84	0.04	0.001	-	79.58	5.90	-	4.92	8.80	16.97	139.5	-	Bhuyan and Bakar 2017	Not specified
Khiru river	-	1.86±1.94	-	-	103.23±17.71	31.02±29.64	-	-	5.33±3.83	-	29.94±14.56	-	Rashid et al. 2012	Not specified
Upper Ganges (Padma)	38.91	-	-	3.57	49.16	10.64	21483	-	11.70	13.98	415	-	Jolly et al. 2013	Calibration curve used
	24.23±10.21	-	-	4.01±0.67	28.44±5.76	2.45±2.28	-	-	17.55±2.03	9.12±3.97	-	287.92±41.62	Hossain et al. 2019	SRM used
Lower Ganges (Padma)	98	-	-	-	76	25	-	-	17	28	1075	275	Datta and Subramanian 1998	Geostandard RM used
	49.68±17.08	-	-	4.08±0.73	36.22±6.19	3.48±2.38	-	-	15.97±3.59	13.92±3.86	-	308.06±53.24	Hossain et al. 2019	SRM used
Ganges river (Padma)	77.73±24.24	0.13±0.02	-	-	-	29.94±12.52	-	14.94±3.36	24.24±2.73	37.26±13.19	-	-	Khan et al. 2020a	Geochemical RM used
Karnaphuli river	70.06±30.93	1.51±0.64	-	16.79±4.70	-	-	-	-	-	-	-	-	Ali et al. 2016 SS	CRM used
	92.11±33.16	2.50±0.85	-	23.81±6.39	-	-	-	-	-	-	-	-	Ali et al. 2016 WS	
Korotoa river	118±50	1.5±0.77	-	27±17	-	82±26	-	-	63±16	103±43	-	-	Islam et al. 2017	SRM used
Meghna river	138	-	-	-	98	32	-	-	26	33	1174	261	Datta and Subramanian 1998	Geostandard RM used
	31.74±14.94	0.23±0.16	-	-	79.02±50.15	-	1281.42±37.90	-	9.47±12.38	76.11±63.80	442.59±198.82	-	Hasan et al. 2015	Not specified

Lower Meghna river	78.63±5.47	0.13±0.02	-	-	-	22.48±2.51	-	13.88±1.52	21.61±1.00	36.21±3.46	-	-	Khan et al. 2020a	Geochemical RM used
Brahmaputra river	110	-	-	-	83	28	-	-	19	33	776	300	Datta and Subramanian 1998	Geostandard RM used
	103±8.63	0.13±0.01	-	-	-	40.20±2.92	-	18.33±1.06	24.29±0.76	53.97±3.31	-	-	Khan et al. 2020a	Geochemical RM used
Old Brahmaputra river	6.6	0.48	0.001	-	52.7	6.2	-	4.1	7.6	12.8	126.2	-	Bhuyan et al. 2019	Calibration curve used
Paira river	32±12	0.5±0	-	9±8	-	27±16	-	-	21±12	34±19	-	-	Islam et al. 2015a[ss]	CRM used
	57±22	0.9±0	-	13±8	-	40±12	-	-	29±16	35±18	-	-	Islam et al. 2015a[ws]	
Pasur river	44.89±16.71	1.33±0.69	-	8.87±3.84	-	-	-	-	21.90±12.29	-	-	-	Ali et al. 2018[ss]	Calibration curve used
	57.70±18.54	2.10±0.75	-	12.40±4.16	-	-	-	-	33.60±13.82	-	-	-	Ali et al. 2018[ws]	
Rupsa river	18.71±6.1	2.72±1.7	-	7.02±3.3	-	48.28±17.7	-	-	22.90±12.1	34.47±27.7	-	-	Proshad et al. 2019[ss]	CRM used
	31.81±10.4	4.83±3.0	-	11.59±5.44	-	89.32±32.9	-	-	42.23±22.4	50.33±40.4	-	-	Proshad et al. 2019[ws]	
Shitalakhya river	74.82	-	-	14.02	200.59	143.69	38697.37	13.73	-	-	-	-	Islam et al. 2016	Not specified
Turag river	100	-	-	-	128	51.8	43246	-	25.7	43.4	953	293	Zakir et al. 2006	SRM used except Fe
	70±30	-	-	-	780±2181	-	-	12.0±4.7	-	-	768±1183	415±92	Khan et al. 2020b	SRM used
	43.02±18.31	0.28±0.33	-	-	139.48±42.48	50.40±5.62	-	-	32.78±3.32	-	-	-	Banu et al. 2013	Not specified
Sediment quality guideline (MPL)	25	0.6	-	-	110	-	30	-	40	16	30	-	USEPA 1999	
	37.3	0.6	0.17	5.9	123	35.7	ND	ND	35	ND	ND	ND	CCME 1998	

Note: MPL=maximum permissible limit, ND=no data available, dw=dry weight basis,
Note: ss=summer season. ws=winter season, SRM/CRM= standard/certified reference materials

Most available studies reported a higher concentration of Fe than the MPL (30 mg/kg) set by USEPA (1999) in sediment of different rivers of the GBM delta (Table 2). The highest concentration (43,246 mg/kg) was recorded in the Turag river (Zakir et al. 2006) followed by 38,697.37 mg/kg in the Shitalakhya river (Islam et al. 2016) and 25,000 mg/kg in the Buriganga river (Tamim et al. 2016).

The concentration of Pb in sediments of the Buriganga, Bangshi, Dhaleshawri and Korotoa rivers exceeded the MPL set by USEPA (1999) and CCME (1998) (Table 2) while rest of the reported values of heavy metals in different rivers of the GBM delta were below the MPL. The highest value 477.85 mg/kg and 474.85 mg/kg was reported in the Buriganga river in winter and summer respectively (Mohiuddin et al. 2011). The lowest value 6.47 mg/kg was recorded in the Feni river estuary (Islam et al. 2018). The concentration of Pb in the Pasur river (33.60±13.82 mg/kg) (Ali et al. 2018) and the Rupsa river (42.23±22.4 mg/kg) (Proshad et al. 2019) in winter exceeded the threshold limit set by CCME (1998) than summer.

The concentration of Ni in sediment of different rivers was ranged from 9.12±3.97 mg/kg in the upper Ganges river (Hossain et al. 2019) to 200.45±29.21 mg/kg in the Buriganga river (Ahmad et al. 2010). The MPL of Ni in sediment was set 16 mg/kg (USEPA 1999). The value of Ni in sediment of the Old Brahmaputra river (Bhuyan et al. 2019) and both of the upper and lower Ganges (Hossain et al. 2019) was below the MPLs set by different parties (Table 2).

The concentration of Mn in sediments of different rivers of the GBM delta was higher than the MPL 30 mg/kg (USEPA 1999) except the Khiru river (Rashid et al. 2012). The highest value 1,075 mg/kg was recorded in the lower Ganges (Datta and Subramanian 1998). In case of the Khiru river, the concentration (29.94±14.56 mg/kg) was almost aligned with the MPL (Rashid et al. 2012).

The maximum and minimum value of Hg in sediments was 0.7 mg/kg in the Feni river estuary (Islam et al. 2018) and 0.001 mg/kg in Old Brahmaputra river (Bhuyan et al. 2019) and Halda river (Bhuyan and Bakar 2017). The highest concentration of Co 35.35 mg/kg and 30.45 mg/kg was found in sediments of the Buriganga river in winter and summer respectively (Mohiuddin et al. 2011) and the lowest value (4.1 mg/kg) was recorded in the Old Brahmaputra river (Bhuyan et al. 2019). The maximum and minimum concentration of Ba was reported in the Buriganga river (458 mg/kg) (Tamim et al. 2016) and the Meghna river (261 mg/kg) (Datta and Subramanian 1998).

6. Heavy metals in fish muscle tissue

Elevated heavy metal concentrations in the aquatic environment can increase the risk of aquatic food consumption as metals can be accumulated in foodstuffs from surrounding environments such as waters and sediments (Sun et al. 2018). In different rivers of the GBM delta, a total of seven (7) heavy metals (Cr, Cd, As, Zn, Cu, Pb and Ni) were reviewed in eight important fish species which are mostly consumed in Bangladesh.

A wide range of heavy metal concentrations were observed in muscle tissue of different fish species in different rivers of the GBM delta (Table 3). Some studies also reported heavy metals in whole fish and different parts of the body such as gill, liver, kidney and intestine of fish in different rivers of the GBM delta (Table S1). In case of *Tenualosa ilisha* (Hilsa shad), the concentration of Pb and As exceeded the international threshold limit (0.2 mg/kg and 1 mg/kg, respectively) in the Karnaphuli (Ali et al. 2019), Paira (Islam and Habibullah-Al-Mamun 2017), upper Ganges (Mortuza and Al-Misned 2015) and Meghna (Bhuyan et al. 2016; Ahmed et al. 2019) rivers (Table 3). The highest concentration of Zn (82.468±16.34 mg/kg dw) in *T. ilisha* was recorded in the upper Ganges river (Mortuza and Al-Misned 2015). The possible reason of higher Zn accumulation in the fish muscles of *T. ilisha* in the upper Ganges might be the variety of anthropogenic activities that occur in the regions characterized by the disposal of raw sewage materials and household garbage (Khanom et al. 2020). However, the value of Cr and Ni in *T. ilisha* was below the MPL (FAO/WHO 2002). In the upper and lower Meghna, most of the metals concentrations except As and Pb in *T. ilisha* were below the threshold limits (Bhuyan et al. 2016; Ahmed et al. 2019).

Most of the heavy metals concentration in *Gudusia chapra* (Indian river shad) in the Bangshi river (Rahman et al. 2012) and the Karnaphuli river (Ali et al. 2019) exceeded the MPLs recommended by different parties (Table 3). This might be because of massive industrialization and urbanization on the bank of the rivers and surrounding areas leading to the discharging of untreated industrial effluents and domestic waste. However, the concentration of Cr in *G. chapra* in the Bangshi river (0.595 mg/kg dw) (Rahman et al. 2012), Karnaphuli (0.84 mg/kg) (Ali et al. 2019), Padma (0.645±0.149 mg/kg) (Khanom et al. 2020) and Rupsa (0.022±0.008 mg/kg) (Samad et al. 2015) rivers was below the MPLs (Table 3).

In *Colisa fasciatus* (Banded gourami), the values of Cr, Pb and Ni in the Buriganga, Shitalakhya and Turag (Islam et al. 2015c) rivers exceeded the MPLs set by international parties (Table 3). But in the same rivers, the concentration of Cd, As and Cu in muscles of *C. fasciatus* was below the recommended MPLs. The highest value of Cr (4.5±0.24 mg/kg) and Ni (3.0±0.04 mg/kg) was reported in muscle of *C. fasciatus* in the Buriganga river (Islam et al. 2015c). The measured high concentrations of Cd and Ni in the fish muscle of *C. fasciatus* of the Buriganga river might be due to the untreated wastewater discharged from various industries such as dyeing, batteries, metal processing and tanneries (Rahman et al. 2012). The concentration of Cd and Cu was reported below the MPL in the Buriganga, Korotoa, Paira, Shitalakhya and Turag rivers (Table 3).

The concentration of Cr and Pb in *Channa punctatus* (Spotted snakehead) in the Buriganga, Shitalakhya and Turag rivers exceeded the MPL recommended by different parties (Table 3). In the Khiru river (Rashid et al. 2012) and the Paira river (Islam and Habibullah-Al-Mamun 2017), most of the heavy metals concentration except Zn were below the MPL. The concentration of Cu (5.5±0.35 mg/kg) in *C. punctatus* in the Buriganga river (Islam et al. 2015c) was higher than the available studies of the same species in different rivers and it exceeded the MPLs (4.5 mg/kg) (FAO/WHO 2002).

Most of the heavy metals in *Channa striatus* striped snakehead in the Korotoa and Paira rivers (except Pb and Ni) were below the MPL (Table 3). The mean concentration of Ni was reported 1.2±1.5 mg/kg in the Korotoa river (Islam et al. 2017) and 0.911±0.30 mg/kg in the Paira river (Islam and Habibullah-Al-Mamun 2017).

Table 3. Mean (±sd) heavy metal concentration (mg/kg ww, otherwise mentioned) in fish (muscle) of different rivers of the Ganges-Brahmaputra-Meghna Delta, Bangladesh

Fish scientific name (common name)	Study locations	Concentration (mg/kg ww)								References	Quality assurance
		Cr	Cd	As	Zn	Cu	Pb	Ni	Hg		
Tenualosa ilisha (Hilsa shad)	Karnaphuli river	0.65	0.15	1.22	-	-	0.67	-		Ali et al. 2019	CRM used
	Paira river	0.481±0.22	0.171±0.19	0.511±0.18	-	1.11±0.57	0.511±0.47	0.541±0.44		Islam and Habibullah-Al-Manun 2017	SRM used
	Upper Ganges river	0.925±0.32	0.034±0.001	10.507±4.57	82.468±16.34	4.949±1.421	0.55±0.07	0.347±0.065		Mortuza and Al -Misned 2015 ^{dw}	CRM used
	Upper Meghna river	0.05	0.092	-	11.31	1.21	0.67	0.084		Bhuyan et al. 2016 ^{dw}	Calibration curve used
	Lower Meghna river	0.64	0.10	0.82	-	4.06	3.33	-		Ahmed et al. 2019 ^{dw}	SRM used
Gudusia chapra (Indian river shad)	Bangshi river	0.595	0.15	2.74	53.645	15.465	3.05	1.82		Rahman et al. 2012 ^{dw}	SRM used
	Karnaphuli river	0.84	0.11	1.73	-	-	0.82	-		Ali et al. 2019	CRM used
	Padma river	0.645±0.149	0.031±0.026	-	14.367±3.851	12.632±2.939	0.375±0.156	-		Khanom et al. 2020	Calibration curve used
	Rupsa river	0.022±0.008	-	-	1.162±0.173	0.133±0.037	0.027±0.013	0.037±0.009		Samad et al. 2015	Not specified
Colisa fasciatus (Banded gourami)	Buriganga river	4.5±0.24	0.049±0.018	0.28±0.01	-	4.1±0.56	2.5±0.26	3.0±0.04		Islam et al. 2015c	CRM used
	Korotoa river	0.24±0.32	0.04±0.4	0.59±0.37	-	0.81±0.86	0.27±0.33	1.5±1.3		Islam et al. 2017	SRM used
	Paira river	0.701±0.33	0.0191±0.011	0.181±0.022	-	1.1±0.51	0.521±0.30	0.591±0.36		Islam and Habibullah -Al-Manun 2017	SRM used
	Shitalakhya river	3.6±0.42	0.014±0.002	0.37±0.04	-	3.0±0.48	1.3±0.36	1.8±0.67		Islam et al. 2015c	CRM used
	Turag river	2.9±0.67	0.015±0.002	0.29±0.11	-	3.7±0.38	1.5±0.05	2.5±0.20		Islam et al. 2015c	
Channa punctatus (Spotted snakehead)	Buriganga river	3.5±0.47	0.044±0.014	0.30±0.03	-	5.5±0.35	1.4±0.16	2.9±0.02		Islam et al. 2015c	
	Korotoa river	0.17±0.13	0.032±0.03	0.54±0.35	-	0.78±0.39	0.52±0.50	0.89±0.62		Islam et al. 2017	SRM used
	Khiru river	-	0.001±0.002	0.0004±0.0007	86.96±35.20	3.46±0.85	0.001±0.002	-		Rashid et al. 2012	Not specified
	Paira river	0.741±0.13	0.0191±0.011	0.181±0.018	-	1.21±0.42	0.471±0.25	0.491±0.27		Islam and Habibullah -Al-Manun 2017	SRM used
	Shitalakhya river	2.3±0.26	0.036±0.009	0.28±0.05	-	4.2±0.5	0.64±0.26	0.69±0.28		Islam et al. 2015c	CRM used
	Turag river	2.5±0.55	0.011±0.003	0.25±0.02	-	1.9±0.35	0.63±0.12	0.44±0.08		Islam et al. 2015c	
	Upper Meghna river	1.12	0.13	0.42	1.23	0.59	0.16	-		Sarkar et al. 2020	CRM used

Channa striatus (Striped snakehead)	Korotoa river	0.13±0.22	0.02±0.02	0.43±0.42	-	0.69±0.56	0.25±0.23	1.2±1.5		Islam et al. 2017	SRM used
	Paira river	0.691±0.17	0.021±0.01	0.251±0.06	-	0.971±0.72	0.781±0.27	0.911±0.30		Islam and Habibullah -Al-Manun 2017	SRM used
Heteropneustes fossilis (Stinging catfish)	Buriganga river	2.8±0.93	0.34±0.01	0.341±0.04	-	6.0±1.1	1.4±0.10	3.0±0.018		Islam et al. 2015c	CRM used
	Korotoa river	0.46±0.48	0.23±0.33	1.7±1.0	-	1.6±1.0	0.82±1.0	2.6±0.4		Islam et al. 2017	SRM used
	Paira river	0.971±0.26	0.0161±0.012	0.271±0.059	-	0.911±0.59	0.921±0.32	1.01±0.20		Islam and Habibullah -Al-Manun 2017	SRM used
	Shitalakhya	2.9±0.64	0.24±0.01	0.37±0.07	-	5.8±0.20	1.2±0.29	1.5±0.12		Islam et al. 2015c	CRM used
	Turag river	2.4±0.25	0.026±0.004	0.28±0.02	-	5.1±0.67	1.3±0.08	1.1±0.16		Islam et al. 2015c	
	Upper Meghna river	1.30	0.25	0.14	1.10	1.22	0.85	-		Sarkar et al. 2020	CRM used
Glossogobius giuris (Tank goby)	Khiru river	-	0.004±0.009	0.0006±0.0007	95.06±28.78	2.95±0.94	0.001±0.002	-		Rashid et al. 2012	Not specified
	Rupsa river	0.017±0.009	-	-	0.713±0.134	0.124±0.045	0.018±0.015	0.024±0.006		Samad et al. 2015	Not specified
Pseudeutropius atherinoides (Indian Potasi)	Bangshi river	0.96	0.28	2.76	58.38	9.34	2.35	0.88		Rahman et al. 2012 [dw]	SRM used
	Korotoa river	0.17±0.20	0.031±0.03	0.44±0.26	-	0.71±0.30	0.60±0.32	0.77±0.66		Islam et al. 2017	SRM used
Lates calcarifer (Barramundi)	Lower Meghna river	1.19	0.15	1.48	-	6.62	4.63	-		Ahmed et al. 2019 [dw]	SRM used
Silonia silondia (Silond catfish)		0.95	0.16	1.43	-	6.26	4.42	-			
Clupisoma garua (Garu Bacha)		0.77	0.13	1.21	-	5.83	4.07	-			
Otolithoides pama (Pama croaker)		0.65	0.09	0.84	-	4.43	3.37	-			
Rhinomugil corsula (Corsula mullet)		0.62	0.10	0.79	-	3.83	2.91	-			
Ailia coila (Gangetic ailia)		0.62	0.10	0.75	-	3.77	2.76	-			
Sperata aor (Long whiskered catfish)	Dhaleshawri river	1.37±0.37	0.17±0.13	-	-	18.23±0.52	0.17±0.13	-		Ahmed et al. 2012 [dw]	Not specified
MPL	Food safety guideline	1	-	1	30	4.5	-	0.8		FAO/WHO 2002	
			0.05				0.2			FAO 2003	

Note: MPL=maximum permissible limit, ww= wet weight basis, dw= dry weight basis, SRM/CRM= standard/certified reference materials

The concentrations of Cr, Cu, Pb and Ni in muscle of *Heteropneustes fossilis* (Stinging catfish) in the Buriganga, Shitalakhya and Turag rivers were higher than the MPL (Table 3). The reported values of Cd, Cu, Pb and Ni in *H. fossilis* were also higher in the Buriganga river than the available records of the same species in different rivers (Table 3). The highest level of Cr was reported in the Shitalakhya river (2.9±0.64 mg/kg) followed by the Buriganga river (2.8±0.93 mg/kg) (Islam et al. 2015c).

Most of the heavy metals except Zn in *Glossogobius giuris* (Tank goby) in the Khiru and Rupsa rivers were below the MPL (Table 3). The highest concentration of Zn was 95.06±28.78 mg/kg reported in the Khiru river (Rashid et al. 2012) which exceeded the MPL. However, in the case of *Pseudeutropius atherinoides* (Indian Potasi), most of the heavy metals except Cr concentration exceeded the MPL in the Bangshi river (Rahman et al. 2012). In contrast, all heavy metals except Pb concentration in *P. atherinoides* was below the threshold limit in the Korotoa river (Islam et al. 2017).

7. Discussion

Heavy metal pollution in any ecosystem is a significant concern due to their toxicity, long-term persistence and subsequent bio-accumulation (Ahmed et al. 2009a). Among various pollutants, heavy metals can be concentrated and bio-magnified along the food chain, producing a severe toxic effect in surrounding environment depending on considerable distances from the source of pollution because of their non-biodegradable nature (Kahlon et al. 2018).

Based on our review, it was found that the level of heavy metal contamination in waters, sediments and fish were different in different rivers of the GBM delta. The level of metal contamination in different rivers water was comparatively lower than the sediments because of heavy metals deposition to the sediments rather than floating in water (Wu et al. 2014). The measured high concentrations of heavy metal in different rivers depended on the anthropogenic activities as well as natural sources. For example, due to massive untreated wastewater discharged from various industries such as dyeing, battery production, metal processing and tanneries in the Buriganga river, the level of heavy metals contamination was higher in waters and sediments of the river (Mohiuddin et al. 2011; Islam et al. 2015c). Most of the heavy metals contamination in water and sediments of the upper Ganges were below the MPL which might be because of higher water flow and less industrial pollution in the upper Ganges (Hossain et al. 2019; Haque et al. 2020).

This study found that most of the rivers of the GBM delta were polluted by heavy metals to some extent. The rivers which flow through the dense industrial areas were comparatively more polluted than others. However, the level of contamination of all heavy metals was not similar in different rivers. The waters of the Buriganga, Bangshi, Dhaleshawri, Halda and Karnaphuli rivers were polluted by Cr, Cd and Pb. On the other hand, the concentration of Zn, Cu, Ni and Mn along with Cr, Cd and Pb were reported higher than the MPL in sediments of the Buriganga, Bangshi, Dhaleshawri, Karnaphuli, Korotoa, Paira, Rupsa Shitalakhya and Turag rivers. This might be because of site inputs from anthropogenic activities like dyeing and printing, textiles, electroplating, storage batteries, oil refineries, ship breaking activities and tanneries (Ahmed et al. 2010; Rahman et al. 2012).

Some metals are essential for aquatic living organisms at low concentrations such as Cr, Zn, Fe, Mn, Co, Mo and Cu. An organism can uptake these heavy metals directly from the water or with food particles and then these metals bind to different parts of the body. Moreover, those heavy metals which deposited in aquatic sediments are accumulated in the body of aquatic organisms living in these sediments to varying degrees (Kim and Kang 2015). But these heavy metals could induce or exacerbate toxic effects if they exceed the MPL and affect the development of any aquatic organism or can be transmitted to the trophic level of the food chain (e.g., phytoplankton, zooplankton and fish) (Atici et al. 2010; Bere et al. 2012; Stankovic et al. 2014). Their subsequent bioaccumulation into the food chain and bio-magnification at the highest trophic level result in disruption of the biogeochemical cycles of the ecosystem and pose a health risk for those who consume them.

This study found that there were inter-specific differences in levels of metal contamination in fish muscles of different rivers of the GBM delta. This differences might be due to different habitat types, feeding habits, trophic level, metabolic rate, age and size of the fish, and the level of metal pollution in the vicinity (Burger and Gochfeld 2005; Ahmed et al. 2010; Jia et al. 2017). The metal accumulation might be different depending on which zone of water the fish lives in and the geographical locations. For example, the bottom living fish associated with sediments accumulate more heavy metals than pelagic or mid water living species (Gupta et al. 2009; Monikh et al. 2012). Moreover, bioaccumulation and bio-magnification of heavy metals in carnivorous fishes is comparatively higher than herbivorous and omnivorous fish (Hosseini et al. 2015). However, most of the available studies on heavy metal accumulation in fish muscles in different rivers of the GBM delta failed to explain the responses. In contrast, most studies reported that level of metal pollution in the vicinity and individual species accumulation rate might be responsible for the difference of metal contamination in fish muscles of different species (Ahmed et al. 2010; Islam and Habibullah-Al-Mamun 2017; Sarkar et al. 2020).

To review the heavy metal concentrations in water, sediments and fish, special focus was given to explore the methods thoroughly as outputs might be different in different methods. This study suggested to use those articles carefully which did not specify any standard experimental design such as standard reference materials or blanks to validate the analysis methods or to ensure quality of the outputs. Different methods of heavy metal analysis such as atomic absorption spectrophotometer (AAS) (e.g., flame AAS, cold vapor AAS, etc.) and inductively coupled plasma mass spectrometer (ICP-MS) (e.g., high resolution ICP-MS, multi-collector ICP-MS, etc.) might provide different results as they work in different ways. However, this study included both methods while comparing the metal contamination in different rivers. This study suggests a standardization of the methods of measurement and appropriate experimental design and analysis of samples for future comparisons of waters, sediments and fishes in different rivers of the GBM delta to be valid.

The level of heavy metal accumulation in different body parts of a fish is not same. Generally the bioaccumulation of heavy metals in muscle is much lower than other body parts such as gills, scales or livers (see Table 3 and Table S1) (Ahmed et al. 2009b). In addition, the metal accumulation in different species are not equal; being dependent on the species' ecological niche, feeding habits, swimming behavior and metabolic activities (Kalay et al. 1999). Moreover, the concentration of heavy metals in a particular species might be different depending on age and size. For example, the old fish of a particular species generally accumulated higher level of heavy metals than younger ones in a constant environment where the aquatic environment is contaminated with heavy metals (Farkas et al. 2003). However, there is controversy against this general statement as young individuals with higher metabolic activities and ingestion rates were proven to accumulate more heavy metals than older ones (Liu et al. 2015). This study recommended to use fish data cautiously based on life-history comparisons while comparing the heavy metal concentration in different species in different rivers of the GBM delta.

A few of the rivers of the GBM delta were highly contaminated by heavy metals to some extent which indicated that there is significant potential health risk of the heavy metals though some of the metals concentration in water, sediments and fish were below the MPL. Since most of the heavy metals were generated from anthropogenic activities, regular monitoring should be performed in different rivers of the GBM delta to reduce and control indiscriminate dumping of industrial effluents, municipal sewage and domestic waste without proper treatment. A national waste management inventory should be established to reduce water pollution.

8. Conclusions

Based on the review, this study concluded that a few of the rivers and tributaries of the GBM delta are highly polluted by a number of heavy metals. Both natural and anthropogenic activities such as discharge of untreated industrial effluents, domestic waste, agricultural runoff, municipal wastewater, etc. are likely responsible for the heavy metal pollution in the GBM delta. Some of the heavy metals concentration in water, sediment and fish in the Buriganga, Bangshi, Dhaleshawri, Karnaphuli, Korotoa, Paira, Rupsa, Shitalakhya and Turag rivers exceeded the MPL recommended by Bangladesh government and different international parties. Though some of the heavy metals concentration in water, sediments and fish in different rivers of the GBM delta were within the MPL, there is still potential risk concern for ecosystem and human health if control of anthropogenic inputs is not improved. This study also concluded that most of the rivers of GBM delta are partly contaminated by heavy metals and in coming years, the level of contamination will be more higher due to increasing pressure of industrialization and urbanization if proper waste management plans and regulations should not be taken to reduce the heavy metal exposure to safe level into the rivers of the GBM delta.

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Table S1. Mean (±sd) heavy metal concentration (mg/kg ww, otherwise mentioned) in whole fish and different parts of the body in different rivers of the Ganges-Brahmaputra-Meghna Delta, Bangladesh

Study locations	Sample type	Fish scientific name	Concentration (mg/kg ww)								References	Quality assurance
			Cr	Cd	As	Zn	Cu	Pb	Ni	Hg		
Buriganga river	Whole fish	*Puntius ticto*	5.54±1.52	0.02±0	0.32±0.01	203.58±12.85	11.52±3.34	3.05±0.09	1.65±0.27	-	Ahmed et al. 2016	CRM used
		Puntius sophore	4.33±1.35	0.02±0	0.19±0.01	248.20±14.63	9.04±1.57	3.16±0.08	1.21±0.30	-		
		Puntius chola	3.57±1.60	0.01±0	0.17±0	292.13±19.75	6.86±1.11	2.32±0.08	1.00±0.52	-		
		Labeo rohita	18.84±1.72	0.04±0	0.73±0.03	251.69±18.17	18.77±2.18	6.98±0.23	6.64±0.24	-		
		Glossogobius giuris	5.13±0.96	0.01±0	0.20±0.01	194.68±12.57	5.90±0.50	1.77±-.10	0.73±0.19	-		
		Ailia coila	2.93±0.37	0.02±0	0.10±0.01	99.49±6.39	5.57±0.92	0.47±0.03	0.36±0.10	-		
		Gagata youssoufi	2.09±1.18	0.01±0	0.08±0	185.59±8.04	4.39±0.49	0.54±0.01	0.45±0.21	-		
		Mastacembelus pancalus	7.18±1.38	0.01±0	0.22±0.01	165.10±9.28	11.66±1.48	3.17±0.07	1.60±0.17	-		
		Glossogobius giuris	6.42±0.55	0.87±0.08	-	-	5.03±0.90	9.91±1.40	9.74±1.32	-	Ahmad et al. 2010[dw]	SRM used
		Gudusia Chapra	6.31±1.05	0.98±0.13	-	-	4.99±1.17	10.92±2.31	9.10±0.63	-		
		Cirrhinus reba	6.99±0.21	0.87±0.22	-	-	4.33±0.88	8.94±0.80	9.61±0.84	-		
		Channa punctatus	5.66±0.24	0.88±0.08	-	-	5.31±0.06	9.11±1.10	9.85±0.36	-		
		Mystus vittatus	5.67±0.53	1.13±0.04	-	-	4.31±0.84	11.68±1.24	9.41±0.65	-		
		Pseudeutropius atherinoides	6.62±0.63	1.10±0.21	-	-	4.85±0.37	9.18±0.32	9.15±1.02	-		
Dhaleshawri river	Gill	*Sperata aor*	2.15±0.69	0.31±0.02	-	-	15.83±0.55	47.62±6.26	-	-	Ahmed et al. 2012[dw]	Not specified
	Kidney		2.15±1.21	0.41±0.05	-	-	93.06±0.65	11.77±4.99	-	-		
	Liver		ND	0.09±0.01	-	-	14.29±0.51	ND	-	-		
	Whole fish	*Glossogobius giuris*	8.84±1.74	0.66±0.03	-	-	6.19±0.82	6.33±1.35	7.03±2.00	-	Ahmed et al. 2009a[dw]	SRM used
		Trypauchen vagina	9.30±1.79	0.56±0.07	-	-	6.98±1.49	6.88±0.62	7.46±1.01	-		

Meghna river	Intestine	*Glossogobius giuris*	22.9	20.2	8.5	-	-	50.3	83.5	11.8	Ahmed et al. 2009b	SRM used
		Clupisoma garua	26.8	6.5	11.4	-	-	852.8	104.2	12.2		
		Channa striatus	146	37.2	ND	-	-	231.8	86.4	5.4		
	Gill	*Glossogobius giuris*	17.7	ND	12.9	-	-	314	37.6	7.6		
		Clupisoma garua	22.1	ND	7.7	-	-	247.9	116.9	2		
		Channa striatus	74.9	3.1	10.7	-	-	313.7	46.2	26.3		
	Liver	*Glossogobius giuris*	15.1	11.1	11.3	-	-	375.4	32.3	5.8		
		Clupisoma garua	12.2	9.3	9.7	-	-	595.8	ND	ND		
		Channa striatus	252.4	73.6	ND	-	-	323.4	186.3	11.5		
MPL	Food safety guideline		1	-	1	30	4.5	-	0.8		FAO/WHO 2002	
				0.05				0.2			FAO 2003	

Note: MPL=maximum permissible limit, ww= wet weight basis, dw= dry weight basis, SRM/CRM= standard/certified reference materials