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Review article

Urban river pollution in Bangladesh during last 40 years: potential public health and ecological risk, present policy, and future prospects toward smart water management

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ABSTRACT

River water is very much important for domestic, agriculture and industrial use in Bangladesh which is in critical condition from long time based on research data. During last 40 years, extreme pollution events occurred in peripheral rivers surrounding Dhaka city and Karnaphuli River in Chittagong city. Present data showed that other urban rivers are also in critical condition especially Korotoa, Teesta, Rupsha, Pashur and Padma. The pollutants flowing with water made a severe pollution in downstream areas of rivers. Metals concentrations in river water was found to be higher in dry season. Dissolve oxygen (DO) was nearly zero in Buriganga River and several points in Turag, Balu, Sitalakhya and Karnaphuli River. NO_3^-, NO_2^- and PO_4^{3-} pollution occurred in different rivers. Zn, Cu, Fe, Pb, Cd, Ni, Mn, As and Cr concentration was above drinking water standard in most of the river and some metals was even above irrigation standard in water from several rivers. Sediment data showed very much higher metal concentrations in most of the rivers especially peripheral rivers in Dhaka and Karnaphuli, Korotoa, Teesta, Rupsha and Meghna River. Metal concentrations in sediment was above US EPA threshold value in most of the rivers. Metal concentrations in fish and agricultural crops showed that bioaccumulations of metals had occurred. The concentration of metals showed the trend like: water<fish<sediment. Agricultural crops were found to contain toxic metals through polluted water irrigation. The calculated data of daily intake for the non-carcinogenic and carcinogenic showed that consumption of the contaminated foodstuff can cause serious health injuries.

1. Introduction

Water is a precious resource for living species on earth. Without water survival is impossible. Other planets have no water like earth so that living species cannot survive there. Out of 100% water on earth, 97% is reserved in Sea and Ocean which is saline and unusable normally. Only 3% water considered as fresh water and out of this 2% is stored as ice and glaciers which also unavailable water. The remaining 1% water stored in lake, canals and underground which is the only source of consumption [1]. Proper management and sustainable planning is very much needed to sustain life on earth. Before industrial revolution it was rare to think about water scarcity and water pollution. But after suffering many health hazards due to water pollution it was become prime concern [2]. In recent years, many developed countries like USA, Japan and South Korea developed efficient technology and national plan to ensure safe water to their citizens. However, developing and underdeveloped countries have serious water resource problem due to the lack of proper water resource management and Bangladesh is one of them [3, 4, 5].

Bangladesh has 238 major rivers. However, most of the rivers are small tributary of the major transboundary river Ganges, Brahmaputra and Meghna. Padma, Jomuna, Surma, Karnaphuli, Kushiyara, Tista, Dudhkumar, Dharla, Atrai, Mohananda, Dhaleshwari, Karatoya, Sitalakhya, Rupsa and Pasur are the well-known rivers around the country [5]. Bangladesh called riverine country because of these rivers. In earlier time, irrigation totally depends on this river water. However, due to sedimentation and pollution it became difficult to use river water for irrigation at present. So, farmers now highly depend on ground water [6]. Intensive exploitation of ground water also causes serious threat to living species by the decline of ground water table which causes accumulation of toxic materials with water [7]. Millions

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of peoples are now suffering from arsenic pollution in Bangladesh [8, 9, 10].

Most of the industries were established on the bank of the rivers. Thousands of tons of waste materials have been releasing into the river water every day [11]. There are rules and regulations but they do not obey it properly. Some industries have effluent treatment plant (ETP) but they do not like to run it due to high profit goal [12]. As a result, river water become toxic for living biota. Agricultural area close to the polluted river are affected as well [13]. Farmers using this polluted water for irrigation made the toxic materials to enter into the food chain and ultimately come to human. The poor usually use this polluted water for washing and cooking, which is very harmful [14, 15].

Rivers especially surrounding the city are becoming more polluted because of industrialization [16]. Buriganga, Turag, Balu and Sitalakhya are the surrounding rivers of capital city Dhaka, which are in severe condition at present [17]. Buriganga is called a dead river because of the quality of water. During summer season, the physical appearance of the water is dark black like burned Mobil [18, 19]. Karnaphuli River is affected severely by waste materials of Chittagong city. Hundreds of ship breaking industry situated on the Karnaphuli River bank area. Toxic liquids, oils and Mobil's and tons of iron materials were washed into the river water. This toxic water is used as irrigation water in many parts of the lower basin area [20, 21, 22].

According to Bangladesh Bureau of Statistics data, approximately 162.7 million peoples are living in Bangladesh. Only 59.8% of the total agricultural land (14.3 million ha.) is available to supply food to this huge population [23]. Farmers applied high dose of inorganic fertilizers, pesticides, herbicides and insecticides each year [24]. A portion of this materials is used by the crops but large portion is mixed with water and going down to the lower basins and finally into the rivers [24]. Due to high profit farmers use some chemicals in their crop which are band by government. Each year millions of tons of agricultural chemical enter into the country through illegal ways. These chemicals are primarily to meet farmers demand. However, the farmers do not know about the toxicity of these chemicals [25, 26]. In earlier times, there was lots of fish in the agricultural field and nearby catchment area. At present, the water quality becomes so much toxic due to the agricultural chemicals and there is no fish in this area [27].

The prime research goal of this article is to collect and analyze last 40 years available research data on river water quality in Bangladesh. Pollution source and trend will be discussed with appropriate figure and tables. Human health risk and ecological risk by river water pollution will be discussed based on metal consumption index, toxicity index and ecological risk index. Finally, future challenges will be discussed based on the present pollution scenario and necessary steps for sustainable water resources management will be suggested.

2. Industrialization in Bangladesh

Bangladesh has recently been upgraded from low income country (LIC) to lower-middle income country (LMIC) as per the World Bank's classification [16]. There is an aspiration to graduate from the LDC status to that of a middle income country by 2021 as per the United Nations' classification [28]. The country has posted the highest-ever gross domestic product (GDP) growth at 7.86 per cent in 2017–18 financial year. Accordingly, per capita income rose to US$1,751 in 2017–18 from US$1, 610 in the previous fiscal year [23]. In the past fiscal year, share of agriculture in the GDP was 13.82 per cent, while that of each industry and services sectors was 30.17 per cent and 56 per cent respectively [29]. The broad industry sector comprises (i) mining and quarrying (ii) manufacturing (iii) electricity, gas and water supply and (iv) construction activities. Large and medium scale industries are: Textile, Leather, Food products, Tobacco products, Pharmaceuticals and medicinal Chemical, Machinery and equipment, Paper & newsprints, Cement, Sugar, Chemicals and chemical products etc. [23, 30].

Industrialization began at a very slow pace in Bangladesh in the 1950s with the primary focus on agro-based industries such as jute, cotton and sugar. After independence in 1971, interest grew but it was not until the late 1970s that industrialization increased rapidly driven primarily by the ready-made garment (RMG) industry [30, 32]. Several government initiatives were also undertaken to promote industrial growth (Figure 1), including the establishment of industrial estates and export processing zones (EPZ). In the year of 2016–2017, the total number of registered textile industries are 4560. Around 220 tanneries, 2500 footwear making units and 90 large firms are now working with leather [33]. According to Bangladesh Association of Pharmaceutical Industries (BAPI) and Directorate General of Drug Administration (DGDA), approximately 257 licensed pharmaceutical manufacturers are operating in Bangladesh and about 150 are functional [34]. Bangladesh Chemical Industries Corporation (BCIC) operates six urea fertilizers, one ammonium sulphate, and two DAP (Diammonium Phosphate) plants. Karnaphuli Fertilizer Company Limited (KAFCO), a joint-venture between the government of Bangladesh and foreign companies, produces urea fertilizer and extra ammonia product for export [35]. There are a large number of other industries also operating in Bangladesh. Current industrial growth has clearly shown significant influences on national economy and development in Bangladesh.

3. Major rivers in Bangladesh

Bangladesh is a river based country. There are about 700 rivers including tributaries. Most of the rivers coming from India and entering northern part after that flowing across the country and fall in Bay of Bengal in the southern part of Bangladesh [36]. Rivers are the prime source of fish and agriculture [37]. Transportation through water way is very much important in several parts of the country. Every year these rivers deposited huge volume of silt which is very much fertile. In southern part, approximately 2.4 billion tons of sediment deposited by rivers and hoping that it will increase the surface area for settlement. However, riverbank erosion is a major problem at present. Additionally, sedimentation in the rivers causes flush flood in rainy season which hampered agriculture, settlements and lives extremely [31, 38, 39]. Figure 2 shows the distribution of major rivers in Bangladesh.

Rivers covered about 24140 km of total length and consisting several streams, canals, lakes, khals, beels and haors. Seasonal variation of temperature and rainfall truly make the river and tributaries magnificent. Arial Khan, Bangshi, Bhairab, Buriganga, Chitra, Dhaleshwari, Karatoya, Atrai, Karnaphuli, Kobadak, Purnarbhaba, Rupsa, Pasur and Tista are some river name in Bangladesh. However, four major river systems covered the whole country-a) Brahmaputra-Jomuna, b) Ganges-Padma, c) Surma- Meghna and d) Chittagong river system. Other rivers are tributaries and distributaries of this four major river system in Bangladesh [40, 41].

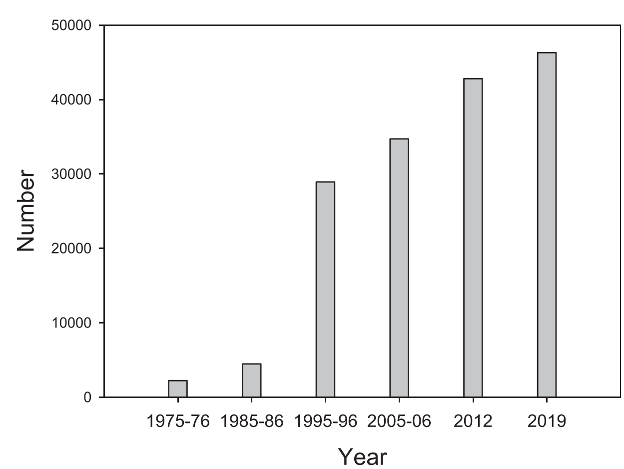

Figure 1. Number of industrial establishment per year.

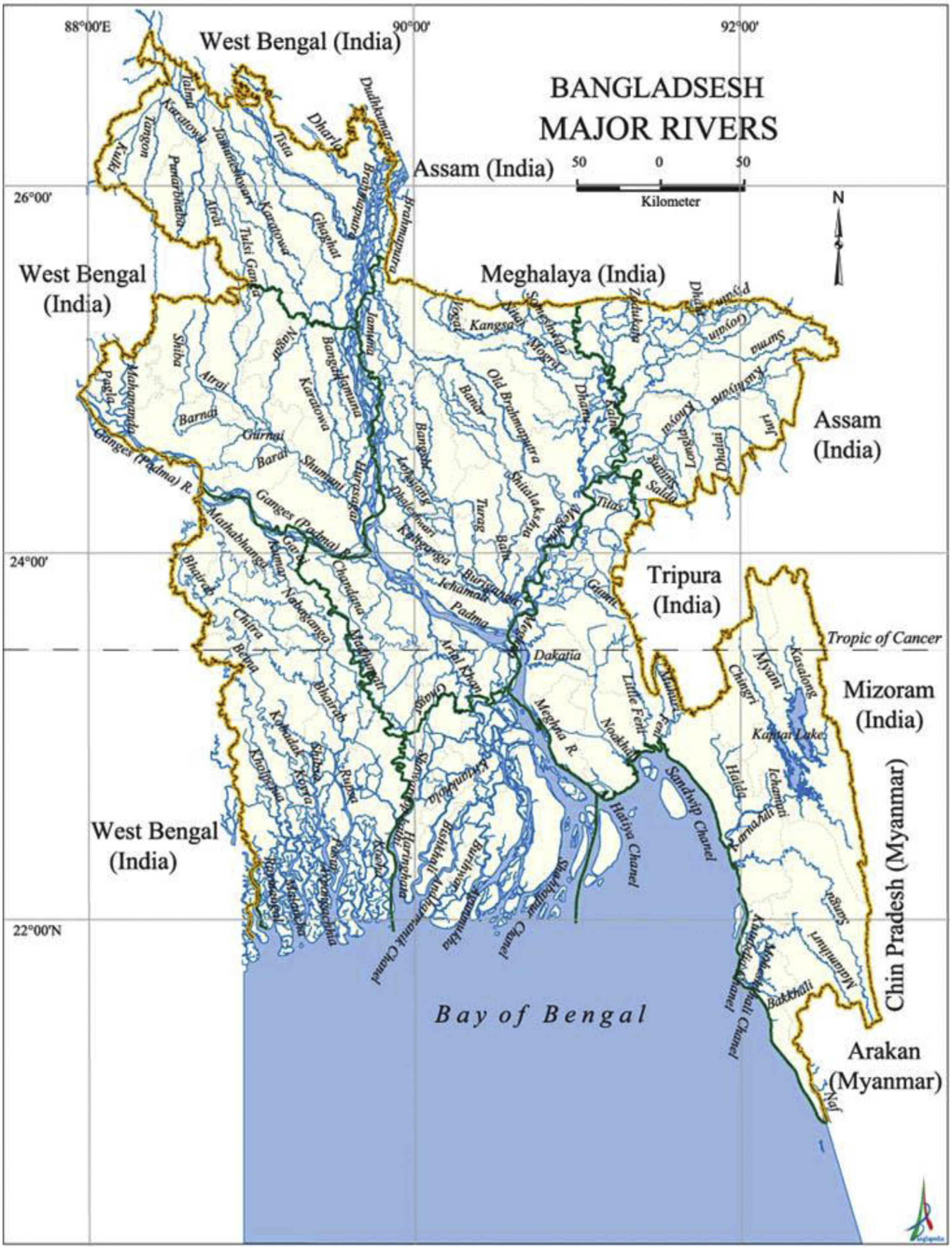

Figure 2. Major rivers of Bangladesh [40].

4. Sources of water pollution in Bangladesh

One of major concern of the growth of industrialization is environmental pollution load from each industrial sector which greatly affects the environment as well as public health [36, 42]. For example only tannery sectors produces approximately 20,000 m^3 of liquid waste and 232 tons of solid waste per day [43]. According to DoE (Department of Environment) report, textile industry produced 217 million cubic meter of wastewater in 2016 and estimated that it will increase to 349 million cubic meter in 2021 [13]. Dyeing, leather, sugar, pulp and paper industries are the major contributors of water pollutants [4]. Non-renewable local resource based industries include industries based on mineral resources such as limestone, hard rock, gravel, glass, sand and various types of clays. In this category, major polluters are the cement and fertilizer factories. Imported resource based industries includes textiles, pharmaceuticals, plastics, petroleum and metal works. Many of these are found to be highly polluting [44]. Figure 3 shows major sources of water pollution in Bangladesh. Open field dumping is the main process of solid and liquid waste treatment in Bangladesh. Liquid wastes are mixed with water and released to the drain and canals and ultimately to

Figure 3. Major sources of water pollution in Bangladesh.

the river. Household, Hospital, market and industrial wastes is dumped into the open field [45, 46]. Aerobic and anaerobic decomposition of wastes occurred continuously. During rainy season, soluble and insoluble waste materials are mixed with water and finally comes to the adjacent khals, canals and rivers [47].

Illiterate farmers apply higher amount of agrochemicals for rapid production in higher amount. Most of the chemicals are washed out with surface water and causes water pollution and health hazards [26]. Large amount of soaps, detergents, oils, medicines, and personal care products are accumulated in water and released as household effluent into the river. Bangladesh has approximately 600 hospitals all over the country [48]. A huge quantity of toxic solid and liquid waste are entered into the river water [45, 46]. Hundreds of launch and steamers transport passengers every day from Dhaka city to different destination. Different kinds of waste materials are thrown directly to the river water every day. These wastes pollute the river water and floating with river currents and settled down in the southern part of Bangladesh. However, there is lack of research data yet on water pollution by water vehicles. Big cities have many Bazars and markets on the bank of the rivers. Everyday several tons of organic waste products are dumped directly into the river water [49]. Frequent accidents by water vehicles in river that releases toxic liquids into the water, which causes severe threat to the flora and fauna of the river basin area [50].

Geologically surface and ground water in Bangladesh are facing pollution by higher concentrations of Fe and As [8, 51, 52, 53, 54, 55]. In addition, over extraction of ground water causes decline of ground water table which facilitate toxic metals especially Fe and As accumulation in ground water [56, 57, 58, 59]. Bangladesh is one of the top most country for air pollution [60]. Atmospheric deposition of toxic metals in agricultural field and surface water have significant influence on pollution [4, 60, 61, 62]. Urban rivers received higher amount of metals through atmospheric deposition each year. Newaz et al., 2020 found higher concentrations of heavy metals in roadside sediments [63]. Agricultural crops grown in urban roadside area accumulate higher amount of toxic metals [15, 49, 64, 65]. Furthermore, Bangladesh have almost 6000 registered and numerous unregistered brick field and most of them established on the river bank area. Brick fields are contributing river pollution tremendously in Bangladesh [66, 67, 68, 69, 70]. Geologically formed radioactive elements were found in soil, sand and sediment collected from Potenga sea beach Chittagong city [71].

Water and sediments containing higher concentrations of toxic materials deposited in lower basins in southern coastal regions in Bangladesh. River water pollution through these pollutants together with local pollutants in those rivers has become serious issue at present time.

5. River pollution in Bangladesh

5.1. Rivers surrounding the capital city, Dhaka

Industrial growth has led to increase in quantity of chemical materials used in industry, as well as in industrial facilities as raw materials. As a result, there is an increasing emission of organic and inorganic materials into the air, water and soil [49]. Although the problems occur in specific locations and regions, they are in fact global problems in that their frequency, magnitude, and potential effects are increasing rapidly [72]. Industrial wastes are known to adversely affect natural life by direct toxic action or indirectly through qualitative alterations in the character of the water [73]. The pollution from industrial effluents, urban and agricultural waste in some rivers and water bodies has reached alarming levels in Bangladesh [74].

Dhaka City, the capital of Bangladesh, is one of the most overcrowded cities in the world with a population of more than 16 million. It is located on the northern bank of the Buriganga River and is surrounded by some other rivers: the Turag, Dhaleshwari, Tongi Khal, Balu, and Sitalakhya (Figure 4). Most of the industries and factories are situated on the banks of these rivers or close to the river system [31]. Figure 4 shows the major rivers surrounding Dhaka city.

There are more than 7000 industries located mostly in three main areas of the Hazaribagh, Tejgaon and Dhaka-Narayanganj-Demra dam areas in Dhaka City beside these rivers [31, 75]. The rivers around Dhaka City are increasingly being polluted as a result of a huge volume of toxic wastes from industrial areas and sewage lines and also petroleum discharge from ships, launches, cargoes, boats, etc. [30, 35, 76].

The Buriganga and linked rivers (Turag, Tongi Khal, Balu, Sitalakkhya and Dhaleswari) receives about 60,000 m^3/day of toxic wastes discharged mainly from nine major industrial clusters (Tongi, Hazaribagh, Tejgaon, Tarabo, Narayanganj, Savar, Gazipur, DEPZ, Ghorashal) [77]. Bangladesh Poribesh Andolon (BAPA) reported that a total of 6000 tons of liquid waste is dumped into the Buriganga every day, half of which comes from Hazaribagh tanneries [78, 79]. Another study revealed that Hazaribagh tanneries generate 7.7 million litre of liquid waste and 88 million tons of solid waste everyday [80]. Moreover, at least 7000 tons of solid wastes are generated in and around the Dhaka City Corporation area every day [81]. Household pipelines are connected

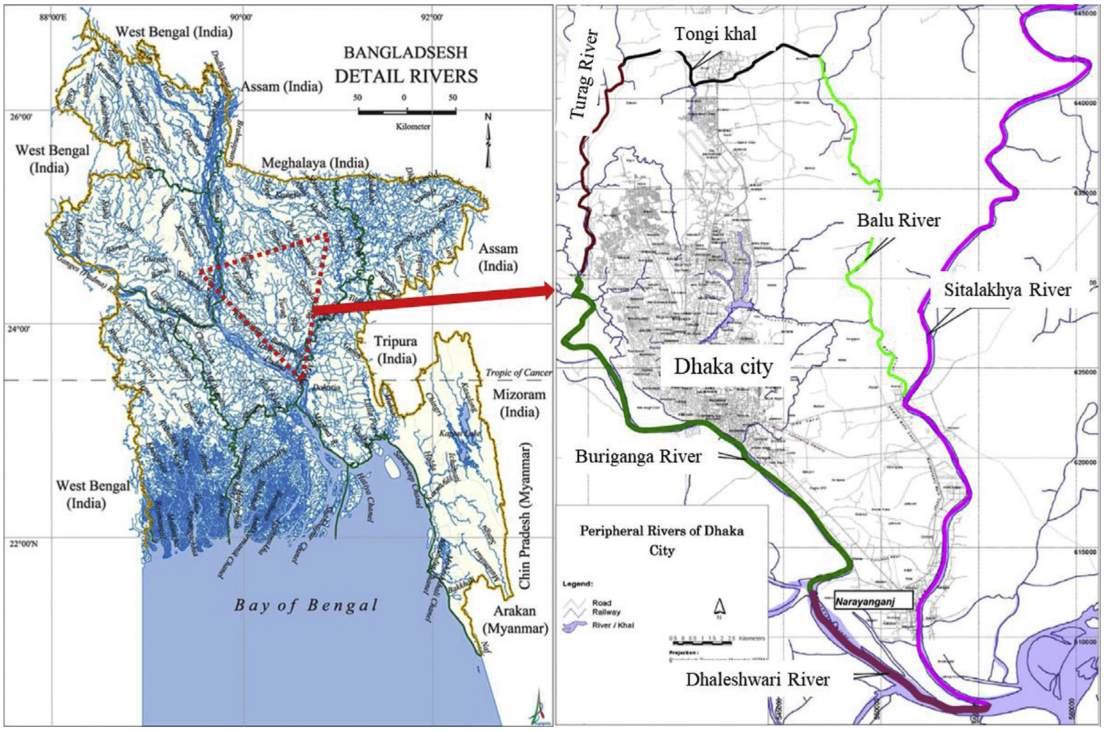

Figure 4. Dhaka city surrounded by different rivers [40].

Figure 5. Appearance of Buriganga river water in dry season.

to drains and this drains are directly connected to the different canals and khals which finally fall down the river. Personal care products, oils and high load of organics comes with these household used water. Furthermore, Thousands of water vehicles transport peoples and things into Dhaka city everyday through the surrounding river, which pollute the river in an alarming rate [12, 36, 42].

5.1.1. Buriganga river pollution

In dry season, the color of the river water is dark black and looks like burned engine gasoline (Figure 5). Most of the physicochemical characteristics exceeds WHO water standards (different standard values listed in table S1). Figure S1 showing changes of some parameters during last 40 years based on published research data. In 2000, dissolve oxygen was 2 mg/L [82] which turned zero in 2019.

Biochemical oxygen demand (BOD), total dissolved solids (TDS) and chemical oxygen demand (COD) changes abruptly. It might be due to the variations of different factors like, sample collection procedure, time of sample collection and location of sample collections. However, most of research data showed that extreme river pollution events are occurring in Buriganga river basin area [83].

River water is become toxic with heavy metals especially Pb, Cd and Cr (figure S2 and Tables 1 and 2). Based on last 40 year trend analysis, extreme pollution events occurred in some specific time period and that time river water became highly toxic comparing with drinking and irrigation water recommendations. Sediment samples showed higher concentration of toxic metals. This can be ascribed to that the high organic materials in the river water might be settled down with toxic metals (Table 3). In certain research, fish samples from Buriganga River showed higher concentrations of toxic metals. Though most of the data were under DoE recommended safe limit continuous consumption might causes serious health hazards [84]. Besides that, existing research data were limited to some physical and chemical analysis on the river water, sediment and fish. Extensive research on organic pollutants, personal care products, pharmaceutical products etc. is required urgently to see the details river quality which is very much needed for smart water management [85]. Based on the research data, it is clear that Buriganga River is in serious threat and if this continue, not only people but also the flora and fauna may suffer seriously [86, 87].

Akbor et al., 2020 analysed 13 elements in water and sediment of Buriganga River. They calculated geoaccumulation index (Igeo), contamination factor (CF), potential ecological risk index, pollution load index (PLI), heavy metal evaluation index (HEI), heavy metal pollution index and Nemerow index (NI). Based on the data, Buriganga River is highly polluted with heavy metals [88].

Table 1. Physicochemical characteristics of water from different surface waterbodies in Bangladesh.

River	pH	EC (μS/cm)	DO (mg/L)	BOD (mg/L)	COD (mg/L)	Coliform (CFU/ml)	TDS (mg/L)	Cl^-(mg/L)	NO_3^- (mg/L)	NO_2^- (mg/L)	PO_4^{3-} (mg/L)	Research Year	Reference
Brahmaputra	7.75	351.12	4.47	1.02	-	-	178.54	-	-	-	-	2013–2014	[137]
	7.12–8.9	76–190	4.3–8.3	-	-	-	34.5–80	14.2–85.2	1.13–1.30		0.01–0.03	2014–2015	[138]
	7.45–7.65	348–355	3.20–3.70	3.6–4.2	-	-	205–220	-	-	-	-	2016	[102]
Buriganga	-	-	-	25.58–36.87	-	-	175–259.5	-	0.43–0.91	0.22–0.37	1.08–2.32	2006–2007	[139]
	7.41	660.56	0.85	34.50	60.12	-	-	-			0.53	2008–2009	[140]
	7.3	619–620	-	-	40	216–360	440	-	0.2–1	0.02–0.2	2	2010	[141]
	6.5–7.6	0.57–2.24	-	-	96–151	-	-	-	1.91–8.41		6.07–10.2	2010	[142]
	6.7–7.9	-	0–3.4	1.5–15.3	-	5–102	-	-	0.6–5.6	-	-	2011	[143]
	7.13 ± 0.20	344.27 ± 241.04	-	-	26.92 ± 11.53	227.67 ± 55.10	-	-	0.78 ± 0.20	0.10 ± 0.04	1.03 ± 0.85	2011	[144]
	7.1–9.8	830–1990	0.45–3.5	41–151	17–185	-	620–1260	-	-	-	-	2011–2012	[75]
	6.8–8.8	-	0.8–4.8	0.1–1.9	216–336	-	3.2–9.72	0–0.3	-	-	-	2012–2013	[145]
	4.05–7.18	555.3–853.25	2.41–4.7	38.9–65.38	91.61–129.22	-	169.03–1015.1	-	-	-	-	2014–2015	[110]
	6.04–8.02	94.95–1362	0–3.47	15–275	64–405	-	124–1719	-	1.70–14.30	-	1.58–15.45	2015	[146]
	7.57–7.64	1096–1117	-	109–163	185–381	-	-	-	-	-	-	2016	[103]
	6.24–7.63	604–1101	0.62–2.74	21.40–63.20	-	-	112–587	-	-	-	-	2016	[147]
	7.31	928.9	-	-	-	-	-	79	0.0254	0.058	2.22	2016	[148]
	-	-	1.73–2.36	13.68–22.8	22–30		280–303				5.6–7.3	2017	[149]
	-	-	0-<1	35–55	60–90	8–160		40–80	1.5–3		0.4	2019	[150]
Turag	7.4–7.5	566–593	-	-	25–45	220–340	402–419	-	1–2	0.1	1.5–2	2010	[141]
	6.6–7.98	160–1107	0.11–6.8	10–180	21–220	-	100–580	-	-	-	-	2010	[93]
	7.73 ± 0.37	296.91 ± 251.83	-	-	82.83 ± 56.38	190.33 ± 80.06	-	-	7.87 ± 7.41	0.42 ± 0.29	1.45 ± 1.03	2011	[144]
	6.9–9.1	790–2850	0.45–3.20	56–179	5–177	-	650–1510	-	-	-	-	2011–2012	[75]
	6.18–7.46	35–150	0.6–3.9	0.4–1.9	-	-	203–902	-	-	-	-	2013	[151]
	7.40–7.79	276–303	-	-	-	-	181.7–194.5	-	-	-	-	2014	[89]
	5.86–7.28	354.5–488.75	3.49–5.2	42.34–55.92	102.6–181.7	-	109.61–196.7	-	-	-	-	2014–2015	[110]
	7.5–8.2	0.0325–0.0535	-	-	-	-	225.4–356.2	-	-	-	-	2015	[146]
	-	-	-	-	-	-	-	-	1–4.87	0.218–1.25	9.9–26.10	2015	[152]
	6.35–6.75	1850–2120	3.75–4.10	2.90–3.30	-	-	3460–4145	-	-	-	-	2015	[98]
	7.24–7.61	425–2277	1.22–3.66	-2.44–0.86	-	-	239–1349	-	-	-	-	2016	[103]
	-	340–610	2.32–6.28	13–73	-	-	582–655	-	-	-	-	2016	[153]
Balu		118.6–715.1	1.04–2.77	6.56–8.06	-	-	69.81–87.3	-	-	-	-	2008	[100]
	6.89–7.33	-	0.33–2.12	-	-	-	982–1308	-	-	-	-	2012	[99]
	7.58–8.35	996–1099	-	102–149	204.8–307.2	-	-	-	-	-	-	2012	[154]
	6.42–6.68	12.8–35.1	-	-	-	-	-	-	0.97–3.13	-	7.07–16.87	2013	[155]
	6.92–8.02	-	1.51–4.45	0.6–11	-	-	10.17–18.83	-	-	-	-	2015	[101]
	7.10–7.35	1012–1130	1.40–2.10	18–24	-	-	705–722	-	-	-	-	2016	[102]
Sitalakhya	-	-	0.07–7.52	0.4–28.8	1–61	-	-	-	0.2–1.8	-	0.08–2.8	2008	[105]
	7.2–9	503–1672			120	180	357–1118	-	1	0.02–1	0.15–2	2010	[141]
	7.54 ± 0.46	488.58 ± 519.32	-	-	56.42 ± 55.33	171.67 ± 33.29	-	-	2.30 ± 2.12	0.04 ± 0.02	0.74 ± 0.51	2011	[156]
	7.22–7.32	-	2.32–3.08	30–140	130–280	-	743–858	-	-	-	-	2011–2012	[12]
	6.5–8.3	720–1920	0.6–3.8	44–146	14–172	-	475–1180	-	-	-	-	2011–2012	[75]
	6.9–8	121–1167	0.5–3.5	-	80–480	-	80–754	-	-	-	-	2012–2013	[106]
	6.7–7.25	986–2321	1.2–3.12	25.12–35.12	89.72–118.1	-	639.1–1171	-	-	-	-	2014–2015	[110]
	7.4–7.7	443–1175	1.3–2.63	0.55–1.3	-	-	269–573	-	-	-	-	2015	[111]
	6.5–7.6	108–478		6–12	-	-	54–245	3.54–9.91	-	-	-	2017–2018	[107]

(continued on next page)

Table 1 (*continued*)

River	pH	EC (μS/cm)	DO (mg/L)	BOD (mg/L)	COD (mg/L)	Coliform (CFU/ml)	TDS (mg/L)	Cl^-(mg/L)	NO_3^- (mg/L)	NO_2^- (mg/L)	PO_4^{3-} (mg/L)	Research Year	Reference
Tu-Ba-Bu RC	7.12–8.26	277–1115	0.16–2.36	-	-	-	184.1–580	74–325	0.3–78.1	-	1.2–13.7	2017–2018	[19]
Meghna	6.07–8.01	61.30–182.20	4.66–8.35	1.20–10.10	20.84–114.62	-	-	-	-	-	-	2014	[116]
Surma	5.86–6.86	759–850	3.5–7.2	0.6–1.8	1–2.6	11–182.5	38.46–1478.9	-	-	-	-	2001–2003	[157]
Dhalai Beel	9.05–9.41	1.38–2.51	2.71–3.58	81.91–103.97	133–215	-	1136–1340	387–446	-	-	-	2012	[158]
Bangshi	8.11–9.17	0.93–1.67	3.74–4.43	42.77–69.75	17–38	-	880–1035	147–281	-	-	-	2012	[158]
Karnaphuli	6.36–9.86	90–45600	0–7.91	0.21–9.17	11.39–179.87	-	45–20000	2.09–13147.70	0–1.63	0–5.18	-	2008–2009	[126]
	6.2–7	552–31340	0.10–3	160–370	350–755	-	292–18530	-	-	-	-	2003; 2008	[130]
	-	-	-	15.50–630	20.80–832	-	-	-	0.20–1.50	0.10–0.80	0.50–45	2013	[129]
	6.8–7.9	3020–20500	1.50–5.20	168–380	322–765	-	1963–15262	13.88–41.35	-	-	-	2016	[128]
Halda	7.03–8.60	72–414	3.02–9.90	0.70–5.08	14.78–49.28	-	30–200	2.41–73.50	0.00	0–0.87	-	2008–2009	[126]
	6.3–7.3	110–524	0.93–5.15	30–545	43–983	-	-	12–56	-	-	-	2015–2016	[132]
	7.10–8.80	-	3.35–4.70	0.055–5	-	-	-	8.4–69.30	0.12–3.10	-	0.06–0.16	2016	[133]
	7.08–7.65	96.1–218	5.90–8.40	0.30–2.80	24–96	-	45.5–104.1	25–54.5	-	-	0.13–0.38	2018	[135]
Sangu	7.66	270.90	5.83	2.24	-	-	135.32	14.35	0.25	0.01	-	2008–2009	[126]
Kaptai lake	7.90	85.87	6.85	1.27	-	-	41.33	3.96	0.44	0.01	-	2008–2009	[126]
Matamuhuri	7.71	237.50	5.64	3.60	-	-	118.55	13.88	0.00	0.00	-	2008–2009	[126]
Naf	7.73	49300.00	7.56	6.92	-	-	24700.00	21720.92	0.00	0.00	-	2008–2009	[126]
Bakkhali	9.55	353.00	6.96	7.40	-	-	171.00	62.96	0.00	0.00	-	2008–2009	[126]
Kasalong	7.69	235.90	5.36	2.34	-	-	117.70	8.61	0.00	0.00	-	2008–2009	[126]
Chingri	7.31	170.90	4.91	2.79	-	-	85.50	6.70	0.00	0.00	-	2008–2009	[126]
Bhairab	6.56–8.07	173–1329	3.5–6.5	-	-	-	-	15.37–460.85	0.66–14.47	-	-	2015–2016	[159]
Rupsa	7.0–8.18	193–4120	4.0–5.6	-	-	-		22.25–1311.65	1.52–30.72	-	-	2015–2016	[159]
	8.1–9.0	13730–20470	-	-	-	-	6900–11000	444–724	-	-	-	2016–2017	[160]
Mayur	6.88–7.34	770–1670	-	-	-	-	600–1100	0.018–0.069	0.979–23.887	-	-	2012	[161]
SW-DEPZ	8.2–10.6	590–6600	0–2.8	38–377	136–937	-	710–8570	128–1290	-	-	-	2013	[162]
SW-Savar	6.02–8.46	214.00–3036.67	0.92–7.96	10.67–162.33	6.00–145.06	-	106.00–1539.00	3.84–402.04	0.02–12.19	1.12–12.03		2010–2011	[163]
DW-Rajshahi	5.45–7.01	1152–1589	0–2	<1-112	12–261	-	920–1200	-	0.2–1.8	0.004–0.796	-	2007	[164]
CMADW-Dinajpur	6–7.5	120–380	10.45–16.24	8.2–27.7	187–292	-	-	-	-	-	-	2010	[165]
CMASW-Dinajpur	5.78–7.92	223–653	4–5.78	-	-	-	-	2.21–10.80	0–0.88	-	-	2009	[166]
MWS-Mymensingh	7.33 ± 0.12	1049 ± 78	1.73 ± 0.3	124 ± 12.76	181 ± 25.66	-	522 ± 26		3.13 ± 0.38	0.022 ± 0.004	-	2007–2010	[167]
RNPPA-GW	6.20–7.40	552.00–969.00	2.40–3.60	0.00–58.00	552.00–969.00	-	-	0.32–70.80	0.00–527.80	0.00–24.18	-	2017	[168]
Rajakhali Canal	8.1–8.8	-	0–9.7	-	-	-	334–951	-	-	0.22–0.40	0.045–0.915	2011	[49]

Note: SW- Surface water; DW- Drain water; GW-Ground water; CMASW- Coal mining area surface water; CMADW- Coal mining area drainage water; DEPZ-Dhaka export processing zone; MWS- Municipal wastewater of sewerage; RNPPA- Ruppur nuclear power plant area; Tu-Ba-Bu RC- Turag-Balu-Buriganga river channel.

Table 2. Heavy metals concentration in water from different surface waterbodies in Bangladesh.

River	Fe (μg/L)	Cu (μg/L)	Ni (μg/L)	Mn (μg/L)	Zn (μg/L)	Pb (μg/L)	Co (μg/L)	Cd (μg/L)	Hg (μg/L)	Cr (μg/L)	As (μg/L)	Research Year	Reference
Brahmaputra	-	987–2134	-	-	1456–3045	56–145	-	0–16	-	0–7.9	-	2014–2015	[138]
	-	30–200	20–800	0–2500	0	0–210	0–30	0	0	0	-	2015–2016	[72]
	-	0.00	32–36	-	18–32	17–24	-	8–12	-	9–12	-	2016	[102]
Buriganga	-	1220–2760	120–210	-	190–420	130–590	50–120	110–240	-	820–2660	180–780	2009	[169]
	-	107.38–201.29	7.15–10.32	-	-	58.17–72.45	-	7.08–12.33	-	489.27–645.26	-	2010	[170]
	90–2200	100–990	90–400	60–310	110–900	100–210	90–400	30–90	-	12–180	5–220	2010	[142]
	-	-	-	-	-	15310–22440	-	0	53–70	40888–60092	4270–7080	2013	[171]
	20683–39313	25–81	-	<740-1560	167–427	-	5–19	-	-	-	-	2013	[162]
	740–1790	31–215	17–41	-	338–1021	49–112	-	-	10–52	12–48	-	2014–2015	[110]
	470–2830	-	-	-	950–2759	0.563–1.296	-	470–900	0.959–8.003	470–830	-	2016	[103]
	170	-	-	230	53	280	-	-	-	-	18	2016	[148]
	0.678–12.779	0.375–9.053	0.218–3.177	0–96.590	2.269–19.916	0.004–0.158	0.022–0.883	0–0.072	0–0.024	0.099–3.175	0.722–5.834	2017–2018	[172]
	-	-	-	-	1000–4000	1	-	-	<1	2–270	-	2019	[150]
Turag	90–310	0–25	0–23	110–280	49–121	0–0.019	-	-	-	0–55	-	2005	[173]
	-	-	-	-	0.04–0.45	2.29–18.62	-	0.043–2	0.12–1.45	-	1.15–4.8	2010	[93]
	1400–3290	50–100	-	-	80–190	10–90	-	0–7	-	-	-	2012	[154]
	2100–3050	143–1341	17–21	-	331–561	33–80	-	-	7–16	31–103	-	2014–2015	[110]
	770–14790	1–90	1–28	350–920	60–300	100–630	-	0	-	230–470	-	2014	[89]
	950–1120	380–560	-	-	-	52–62	-	6.2–7.5	-	-	-	2015	[98]
Balu	1790–50150	3–20	<10-19	28–730	8–76	<18-28	<4-54	<3-3	-	<4-8	-	2004–2005	[174]
	-	8–11	40–47	-	75–85	29–35	-	15–25	-	15–21	-	2016	[102]
	270–556	-	-	-	200–485	7.5–38.1	-	0.62–2.23	22.1–60.6	1.44–2.34	-	2016	[103]
	950	-	-	-	-	7.6	-	0.56	-	200	-	2018	[175]
Sitalakhya	1–8	3–12	<10–23	29–197	7–36	<18–22	<4–8	<3–3	-	<4–9	-	2004–2005	[109]
	-	0–3	-	-	0–20	0–4	-	110–170	-	-	-	2011–2012	[12]
	-	16–143.4	144.1–513	-	48.1–130	-	-	6.5–15.2	-	37.1–102.3	-	2012–2013	[106]
	530–1730	14–1010	22–34	-	17–81	9–45	-	-	1–42	34–61	-	2014–2015	[110]
	-	24	-	-	817	6.5	-	4.40	5.70	6.9	-	2015	[112]
	-	20–27	-	-	-	20–27	-	5–9	-	-	-	2015	[111]
	1002.20	-	24.60	192.20	83.80	15.60	-	1.84	-	56.80	8.38	2017–2018	[37]
Tu-Ba-Bu RC	0.678–92.734	0.375–9.053	0.218–3.177	0–532.978	2.269–19.916	0.004–0.158	0.022–0.883	0–0.072	0–1.69	0.099–6.470	0.722–5.834	2017–2018	[19]
Dhaleshwari	-	98–188	5–9	-	-	38–63	-	5–8	-	378–501	-	2001–2002	[114]
Bangshi	-	650–1130	13–37	59–103	2130–4020	68–122	-	5–10	-	72–157	9–25	2012	[158]
Dhalai Beel	-	1080–1460	36–58	77–124	2810–4170	91–173	-	5–8	-	43–89	27–39	2012	[158]
Meghna	467.6–1598.7	-	0	0.3–25	10.0–112.2	0	-	1.2–7.1	-	6.3–73.7	-	2014	[116]
	180–3680	27	10–300	20–500	40 (mean)	10 (mean)	-	18 (mean)	-	20 (mean)	-	2015–2016	[117]
	1139.68	-	5.00	18.82	36.46	4.40	-	3.04	-	14.54	11.32	2017–2018	[37]
Surma	280–3160	4.2	-	-	1443.1	13	-	-	-	40	-	2001–2003	[157]
Karnaphuli	20025–42203	372–973	356–865	498–1372	472–1186	405–1195	-	90–217	-	421–925	-	1997–1998	[176]
	60–3240	10–30	-	0–920	10–40	0–20	-	0	-	0–10	-	2008–2009	[126]
	4630 ± 2035	320 ± 80	-	-	660 ± 319	250 ± 85	-	30 ± 8	-	-	-	2010	[127]
	2060 ± 1456	50 ± 28	-	120 ± 43	280 ± 139	140 ± 31	-	10 ± 2	-	250 ± 68	-	2013	[129]
	-	-	-	-	-	5.29–27.45	-	2.54–18.34	-	46.09–112.43	13.31–53.87	2014–2015	[121]
	40–600		60–130	10–80	20–80	-	-	-	-	-	-	2016	[128]
Halda	250–5940	0–70	-	122–930	40–800	0–70	-	0	-	-	-	2008–2009	[126]
Khiru	-	4.33	-	167	6.57	22.1	-	127.57	-	0–10	-	2008–2009	[177]
Korotoa	-	23–119	9.3–71	-	-	8–64	-	0.9–22	-	33–126	10–92	2013	[178]
	436	-	6.68	162	50.96	4.66	-	11.60	-	6.30	1.86	2017–2018	[37]

(continued on next page)

Table 2 (*continued*)

River	Fe (μg/L)	Cu (μg/L)	Ni (μg/L)	Mn (μg/L)	Zn (μg/L)	Pb (μg/L)	Co (μg/L)	Cd (μg/L)	Hg (μg/L)	Cr (μg/L)	As (μg/L)	Research Year	Reference
Teesta	9238	-	4.44	676	46	4.80	-	4.66	-	3.34	1.78	2017–2018	[37]
Rupsha	770 ± 380	-	-	83 ± 18	47 ± 24	17 ± 17	-	-	-	-	-	2010	[179]
	6970–45640	<100-280	<100-140	200–2190	<50-630	<100-150	-	<1	-	<5-4330	-	2016–2017	[160]
		2.13–11.14	0.04–14.51			1.54–14.90		0.21–2.55		3.19–16.59	3.13–10.97	2016–2017	[180]
	976	-	18.70	288.46	68.40	18.40	-	6.50	-	45.20	3.52	2017–2018	[37]
	-	1320	48	88	3680	136	-	8	-	58	27	2019	[181]
Pasur	2062	-	21.40	65.40	33.80	26.60	-	9.80	-	40	12.34	2017–2018	[37]
SW-DEPZ	-	143–397	36–100	-	248–2230	-	-	-	-	13–64	4–11	2013	[162]
SW-DEPZ	4130–5530	1350–2880	130–290	-	490–1690	140–300	-	20–80	-	290–530		2005–2006	[182]
DW-Rajshahi	800–6950	20–60	<20-30	-	-	310–1030	-	3–8	-	<20-120	<3-47	2007	[164]
CMADW-Dinajpur	1720–8370	<27- 900	<29- 800	80–440	130–780	<10- 500	-	-	-	<72	<28	2010	[165]
CMASW-Dinajpur	580–2000	2540–16730	8480–27860	22900–162940	7500–149270	1600–10180	-	3350–4970	-	2830–4510	300–500	2009	[166]
RNPPA-GW	76.50–496.70	1.18–9.96	-	0.48–2.04	-	0.18–2.44	-	0–0.19	-	1.29–4.02	0.90–498.35	2017	[168]
MWS-Mymensingh	480 ± 70	9.5 ± 3	-	410 ± 50	30 ± 10	17 ± 8	-	1.35 ± 9	-	-	-	2007–2010	[167]

Note: SW- Surface water; DW- Drain water; GW-Ground water; CMASW- Coal mining area surface water; CMADW- Coal mining area drainage water; DEPZ-Dhaka export processing zone; MWS- Municipal wastewater of sewerage; RNPPA- Ruppur nuclear power plant area; Tu-Ba-Bu RC- Turag-Balu-Buriganga river channel.

5.1.2. Turag river pollution

Turag River is in north-western side of Dhaka city (Figure 4). The river water quality is affected by untreated industrial effluents, washed materials from agricultural fields and municipal sewage from the slum area [89]. Most of the textile industries were established on this area. Farmers using inorganic fertilizers, pesticides and herbicides in their agricultural land live close to Turag River. In rainy season, all the waste materials are washed with water and ultimately come to the river [90]. Due to the extensive pollution, Turag River is in ecologically critical state declared by DoE in 2009 [91]. Upstream river water quality was found extremely poor because of high volume industry in that area [92]. The river water is used for irrigation to grow crops which farmers selling in the markets. Therefore, there are possibilities to suffer serious health condition of those who is eating regularly vegetables, fish and rice grown in this area. Research data proved that the crops grown in this area contain toxic metals. Bioaccumulation of toxic metals into the flora and fauna of Turag River occurred which may hamper human health seriously [84, 90].

The color of the river water is dark black in dry season and have bad smell of the water. pH varied differently because at some source points, basic effluent was discharged into the river water and some source points discharged acidic effluent. As a result pH is balanced for the river water. DO of the river water is found to be below the DoE recommended standards, which is very much harmful for flora and fauna in the river (figure S3). Some researchers found higher values of BOD, COD, TDS and metals in the river water (Tables 1 and 2) [90, 93, 94]. Higher concentrations of toxic metals were found in sediments (Table 3) and fish samples from the river [94, 95]. Toxicity assessment of river water based on metal concentrations (figure S4) found that the river became toxic and very much harmful for human health and living biota [19].

5.1.3. Balu river pollution

A tributary of Sitalakhya River flows through different wetlands of Beels and Belai and meet finally Sitalakhya River at Demra. It is connected to Turag River through Tongi Khal in the northern part of Dhaka city. Several khals and canals (Tongi Khal, Norai Khal and Rampura Khal) connected with Balu River. Industries discharged their untreated and partially treated toxic effluents into the khals and canals, which eventually flowed into the Balu River [96, 97]. River water is affected by the effluents from Tongi industrial zone, textile industry, pharmaceutical industry, food industry, soap and detergent industry, metal industry, dying industry etc. Municipal waste and wastes from agricultural fields comes to Balu River as well. Due to higher pollution activity in Balu River, DoE declared that it was ecologically critical state river in 2009 [98].

Dissolve oxygen is almost zero which affect tremendously the flora and fauna of Balu River [99]. Some researchers found higher concentrations of TDS, BOD COD and metals in water (figure S5 and S6) [100, 101, 102, 103]. Based on the available data it is confirmed that pollution events have occurred in that area and contaminates the river continuously. The pollutant analysis data of Tejgoan-Rampura Khal, Tongi Khal and Norai Khal which ultimately fallen down into Balu River showed that these channels transported high load of pollutants into Balu River [19]. Pollutant concentrations in sediments (Table 3) were several fold higher than water and higher then USEPA recommended standard concentrations [12]. Water from these channels and Balu River are only source of irrigation in that area. As a results crops are affected by different toxic materials (Tables 1 and 2).

5.1.4. Sitalakhya river pollution

Most prominent rivers are originated from old Brahmaputra River in Bangladesh. Sitalakhya River flows across the eastern side of Dhaka city and meets Meghna River at Kolagachi, Munsiganj. It receives water from Balu River and Dhaleshwari River (Buriganga River ends in this

Table 3. Heavy metals (**mg/kg**) in sediment of different rivers.

River	Fe	Zn	Cu	Pb	Cd	As	Cr	Ni	Mn	Research Year	References
Brahmaputra	-	52.7	6.2	7.6	0.48	-	6.6	12.8	126.2	2015–2016	[72]
Buriganga	-	-	21.75–32.54	64.71–77.13	2.36–4.25	-	118.63–218.39	147.06–258.17	-	2010	[170]
	9480–15435	45.45–60.50	39–85.2	50.12–80.20	4.2–11.28	11.82–19.25	1019–1884	35–59	368–692	2010	[142]
	11943–14129	148.4–803.8	88.3–650.3	13.1–85.6	0.5–7	-	106.9–279.8	79.5–278.4	2257–7409	2014	[183]
Dhaleshwari	-	-	31.53–76.52	58.19–70.26	2.11–4.14	-	95.76–141.27	135.02–231.44	-	2001–2002	[114]
	-	-	37.450	15.797	2.083	-	27.393	-	-	2010–2011	[115]
Balu	-	304.67	99	41	12.4	-	-	-	-	2011–2012	[12]
Sitalakhya	21451.81–70598.76	77.09–631.36	19.78–501.77	-	-	12.63–14.99	63.47–83.29	-	-	2016	[113]
Turag	-	36200–47505	29.10–69.10	15.30–31.70	-	-	66–138	27.70–59.5	768–1025	2005	[173]
	-	94.60–190.10	46.30–60	28.30–36.40	0.00–0.80	-	32–75.50	-	-	2006–2010	[95]
	10413–14455	119.4–548.9	30.6–72.3	13.1–24.6	0.2–3.6		109.1–231.7	108–221.6	2512–7964	2014	[184]
T-B-S	-	-	65–405	45–1846	8–29	12–58	112–2471	139–606	-	2012	[185]
Meghna	1207.23–1324.51	29.414–204.76	-	0.4059–44.855	0.09–0.69	-	12.656–56.95	28.245–218.85	168.737–789.510	2014	[116]
	737–2385	-	-	6.98	0.00–0.53	-	1.27–6.81	-	-	2015–2016	[117]
Karnaphuli	832.40	16.30	1.22	4.96	0.24	-	0.76	-	15.30	2013	[129]
	-	-	-	21.98–73.42	0.63–3.56	11.56–35.48	37.23–160.32	-	-	2014–2015	[121]
Bakkhali	-	93.51–106.38	27.18–41.76	21.28–32.08	0.16–0.36	-	-	-	-	2012	[136]
Sangu	-	22.8–112.5	2.23–39.80	12–33.42	0.00	2.1–2.9	9.52–31.40	15.6–79.7	-	2017	[134]
Khiru	-	88.11–103.23	31.02–41.42	5.33–6.15	1.86–2.41	-	-	-	27.07–29.94	2008–2009	[177]
Feni	-	-	-	0.36–14.04	-	0.13–2.27	13.91–41.74	8.56–41.86	17.92–46.01	2016–2017	[186]
Rupsha	-	121.35	31.95	62.40	0.56	2.22	67.72	31.34	508.38	2019	[181]
	-	-	18.66–151.84	80.67–95.48	0.94–13.25	3.61–24.21	12.69–52.19	4.42–151.48	-	2016–2017	[187]
Korotoa	-	19.5–123	0.00–34.1	5.94–99.99	9.38–13.13	-	2.75–20.95	5.58–12.18	-	2011	[188]
	-	-	35–118	36–83	0.26–2.80	2.6–52	55–183	37–163	-	2013	[178]
Upstream	1792–67200	91–220.71	1.7–34	21.7–97.20	0.23–2.20	1.8–9.5	9.05–106.51	10.20–507	289.8–3459	2017–2018	[189]
Midstream	1275–51317	54.97–631.4	19.8–201.8	6.41–78.90	0.17–1.84	3.89–9	25.95–83.30	37.51–567.8	374.5–1098	2017–2018	[189]
Downstream	19500–49000	58.1–234.6	2.1–63.5	5.48–42.3	0.39–4.07	3.89–9.0	48.6–82.4	4.42–92.6	267–780	2017–2018	[189]
Paira	-	-	10–65	9.1–58	0.15–1.6	2.6–29	17–93	13–63	-	2012	[190]
Pasur	19006.067–22947.993	-	6.33–21.31	1.035–12.20	-	-	15.083–20.877	19.59–21.39	-	2013	[191]
US EPA-SV	-	110.00	16.00	31.00	0.60	6.00	26.00	16.00	-	2017–2018	[189]

Note: T-B-S- Turag-Buriganga-Sitalakhya; US EPA-SV- United States Environmental Protection Agency-Standard Value.

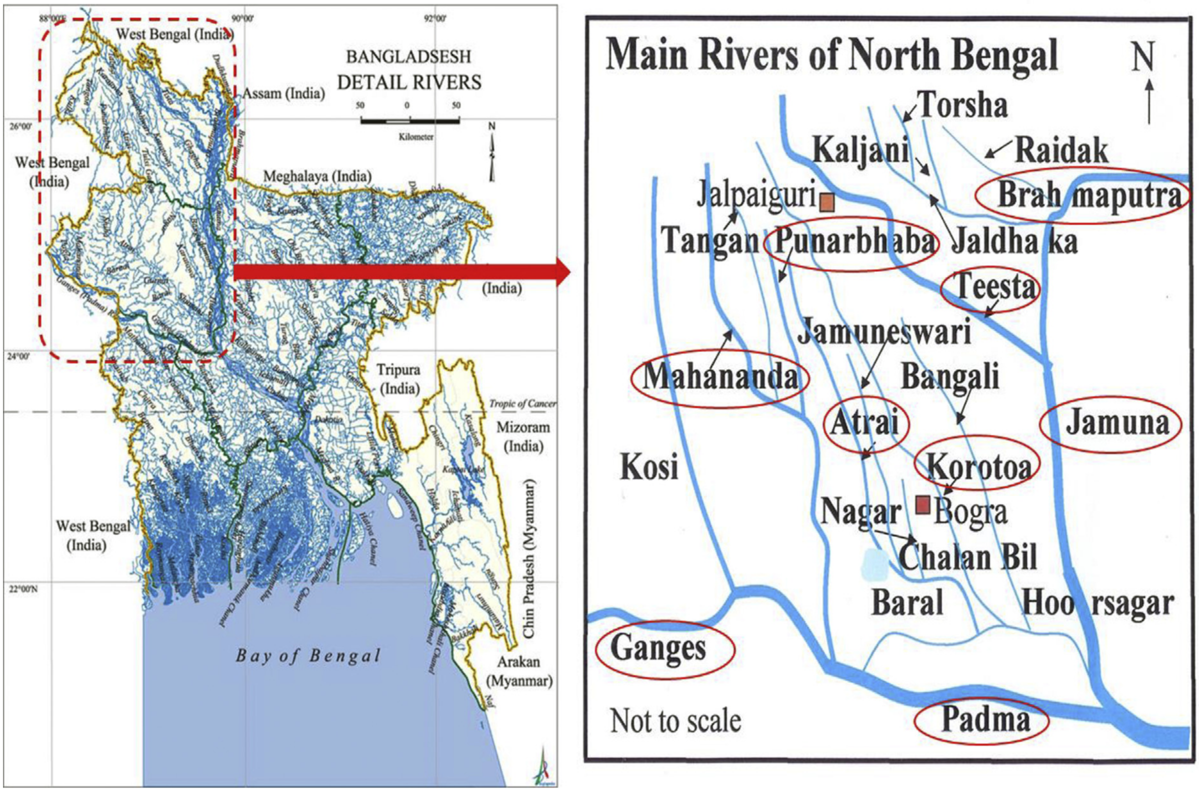

Figure 6. Major rivers in northern area, Bangladesh.

river) [104]. Several industries were situated on the riverbank area through the channel especially in Narayanganj district where the density of industry is high. Water vehicles and cargos are using this waterways to communicate Chandpur and Chittagong district. The river is also affected by Narsingdhi district. Sitalakhya River water is the prime source of water for cooking, drinking, bathing, washing, irrigation and industrial use. Textile, cement, fertilizer, pulp and paper, sugar mill, jute etc. industries situated on the riverbank area affects tremendously the quality of Sitalakhya River water (Tables 1 and 2). Besides, the pollutant loads were also coming from Balu River and Dhaleshwari River [37, 105, 106, 107]. The drinking water treatment plant in Saidabad receives raw water from Sitalakhya River close to Demra ghat. Research data found that the treatment plant had been faced severe problem due to river pollution and suggested that the current water intake point is not safe due to presence of toxic pollutants and microbial loads [108].

Dissolve oxygen concentrations was found to be almost zero in some points during dry season in Sitalakhya River. BOD COD and TDS values are within the DoE recommended standard for surface water (figure S7). However, comparing with past data, it is confirmed that pollution events had been occurred on this designated river basin area. As it is connected with the upper polluted river, it receives heavy loads of pollutants each year through this connecting rivers. Higher concentrations of Cu, Ni, Cr, As and Fe (figure S8) was found during dry season in Sitalakhya River water which were higher than DoE recommended standard concentrations for surface water (Tables 1 and 2) [12, 37, 106, 109, 110, 111, 112]. Heavy metal concentrations in sediment was found above US EPA safe limit (Table 3) [113]. Direct consumption of river water can cause serious health hazard. Besides, transfer of toxic metals into fish and crops (through irrigation) may ultimately come to human body [86].

5.1.5. Dhaleshwari river pollution

Dhaleshwari River is receiving higher pollution load from upper Buriganga River and transporting it into Sitalakhya River in the lower region and finally merged with Meghna River. This river is the Distributary River of Jomuna River. There are two branches: South branch named Kaliganga and North branch named Dhaleshwari. They merged in Manikganj and flow through the central part of Bangladesh [104]. Higher concentrations of Cr was found in river water, which exceeds FAO irrigation water standards (Table 2) [114]. The concentrations of Cr, Ni, Cu, Pb and Cd in sediment sample from Dhaleshwari River were found to be above US EPA threshold value (Table 3) [114, 115].

5.1.6. Meghna river pollution

Meghna River is one of the three that form Ganges Delta which is the largest Delta on earth. Meghna River is a part of Surma-Meghna River system and Meghna is formed in Kishoreganj district in Bangladesh and ended up in the Bay of Bengal across the country. Meghna River meets Surma, Kushiyara, Padma and Sitalakhya River and receives sediment and contaminants from these rivers. Agriculture and fishery in Bangladesh depends on this river. Several industries established in different parts of the river also use river water continuously. The river water was also affected by both agricultural and industrial activities. From Table 2, the concentration of Fe, Cr, Mn, Ni and Cd exceeds WHO recommended maximum limit for drinking water and Ni, Mn and Cd exceeds FAO irrigation standard values [37, 116, 117]. The concentrations of Zn, Pb, Cd, Cr and Ni in Meghna River sediment (Table 3) was found to be higher than US EPA threshold value in several points [116, 117]. Elevated levels of heavy metal concentrations in water, sediment and fishes were found in several locations of Meghna River [118].

The research data proved that, Buriganga, Turag, Balu and Sitalakhya Rivers had been affected seriously by urbanization and industrialization. Due to higher pollution rate, this rivers are declared to be ecologically

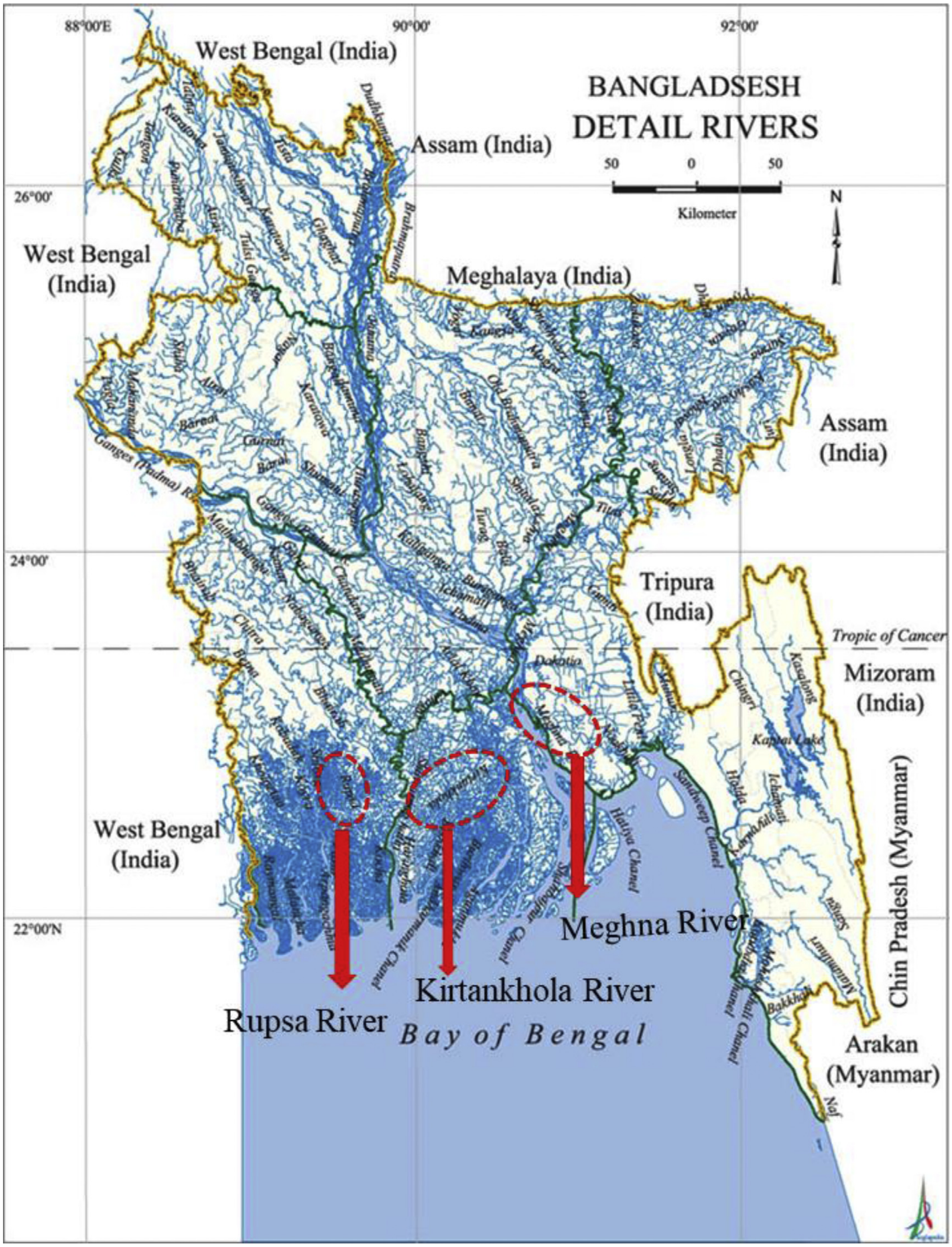

Figure 7. Major rivers in southern area, Bangladesh.

critical river by DoE in 2009. In some research, concentrations of different physicochemical parameters and metals in surface water, sub-surface water and sediment were analysed and found the concentration trend were like surface<sub-surface<sediment [100, 119]. Bio-accumulation of toxic metals into fish samples has been occurred which is alarming for human consumption. At least 78% of Dhaka city dwellers use ground water for household needs and other 22% of water supply is from surface water [120]. Some research data found that due to heavy pollution in surrounding rivers, ground water is seriously affected and water samples from some area showed higher metal concentrations [7, 120]. Dhaleshwari and Meghna River receives pollutants from upper boundary rivers. In addition, anthropogenic activity in Dhaleshwari and Meghna River also affects excessively river water and sediment quality. The most alarming thing is till date all the research were only based on some conventional parameters like pH, DO, BOD, COD, TDS and some metals. Microbial analysis, organic pollutant analysis, personal care products, pharmaceutical products and other toxic pollutant analysis are overlooked.

5.2. Rivers affected by port city, Chittagong

5.2.1. Karnaphuli River pollution

Karnaphuli River is one of the largest river in Chittagong region. Chittagong city is also called port city because national and international transports for export and import products using the Karnaphuli River in Chittagong. Karnaphuli River is in south-eastern side of Bangladesh and flows through Chittagong hill tracts and Chittagong into the Bay of Bengal [38, 121]. River water is used for household activity, irrigation and industrial purpose, which is highly polluted in recent years [21, 79].

The river is affected by oil refinery, dying, textile, tannery industry, spinning mill, steel industry, fertilizer industry, cotton industry, paper and rayon mill, cement industry, bitumen plant, soap and detergent factory, DDT and insect killer production plant, paint manufacturing, naval and merchant ship, and ship recycling industry etc. [20, 122]. Higher concentrations of organic contaminant was found in atmospheric air in Chittagong ship breaking area [123]. Oil and grease concentrations was high in Karnaphuli River sediment [124]. Geoaccumulation value (I_{geo}) for Ti, Zr, Y, Rb, Fe and Zn in sediments from ship breaking area showed sediment is changed from unpolluted to moderately polluted for this elements [125].

Based on research data present water quality of Karnaphuli River is not good [126, 127, 128, 129]. Most of the physicochemical characteristics are below the DoE recommended standard for drinking and surface water quality. Due to lower concentration of DO and increasing BOD and COD value (Table 1), the river water is becoming unsafe for human consumption and flora and fauna in Karnaphuli River [128, 129, 130]. In figure S9 and S10, certain peak points might be due to some extreme pollution events occurred on that designated time. EC and Cl^- value showed that the river water is saline. That is why the water chemistry for different pollutants might be different here. Water contains less amount of metals which might be deposited into the sediment. However, some researchers found higher levels of metal concentration around the adjoining points where khals and canals are connected with the river [49]. This proved that river pollution is occurring continuously. According to Kibria et al., in 2016 Karnaphuli River and coastal area of Bay of Bengal is highly polluted with U, Pb, Ni, Hg, Cu, Cr and Cd (Table 2). They identified the pollution 'hotspots' and the source of these metals (industrial, agricultural and domestic) [131]. Table 3 shows that sediments of Karnaphuli River is highly polluted with As, Cr, Pb and Cd, which is above US EPA threshold value [121, 129].

Halda, Bakkhali, Sangu, Matamuhuri, Naf, Kasalong and Chingri River was found to be affected by anthropogenic activity (Tables 1, 2, and 3) [126, 132, 133, 134, 135]. Dissolve oxygen (DO) concentrations was found <4 in Halda River [126, 132]. In addition, Fe and Mn concentrations in river water exceeded the FAO safe limit for irrigation water [126]. In Bakkhali River sediment, Cu and Pb concentration was greater than US EPA threshold value [136]. Sangu River originated from Myanmar contains higher concentrations of Zn, Cu, Pb, Cr and Ni, which is exceeded the maximum safe limits [134].

5.3. River pollution in northern area of Bangladesh

Korotoa, Teesta, Atrai and Padma River are affected by different cities and agricultural activities in that area (Figure 6). As, Cr, Cd, Pb, Mn, Ni and Fe concentrations in Korotoa River water was found to be above WHO recommended drinking water standards. Besides that, Cr and Cd concentration were above FAO recommended safe limit for irrigation water (Table 2) [37, 178]. The maximum concentrations of Cr, Ni, Cu, As, Cd and Pb in Korotoa River sediment was found 183, 163, 118, 52, 2.8 and 83 mg/kg respectively. Based on the calculated pollution load index value (PLI), the sediments in Korotoa River were highly contaminated (PLI>1) especially for Pb, Cd and Cr. Besides that, As and Cd was found high (CF>1) degree contaminant based on contamination factor (CF) calculated value. Enrichment factor (EF) analysis data proved that Korotoa River is affected by anthropogenic activity. Textile industry, steel industry, leaded gasoline, tanning,

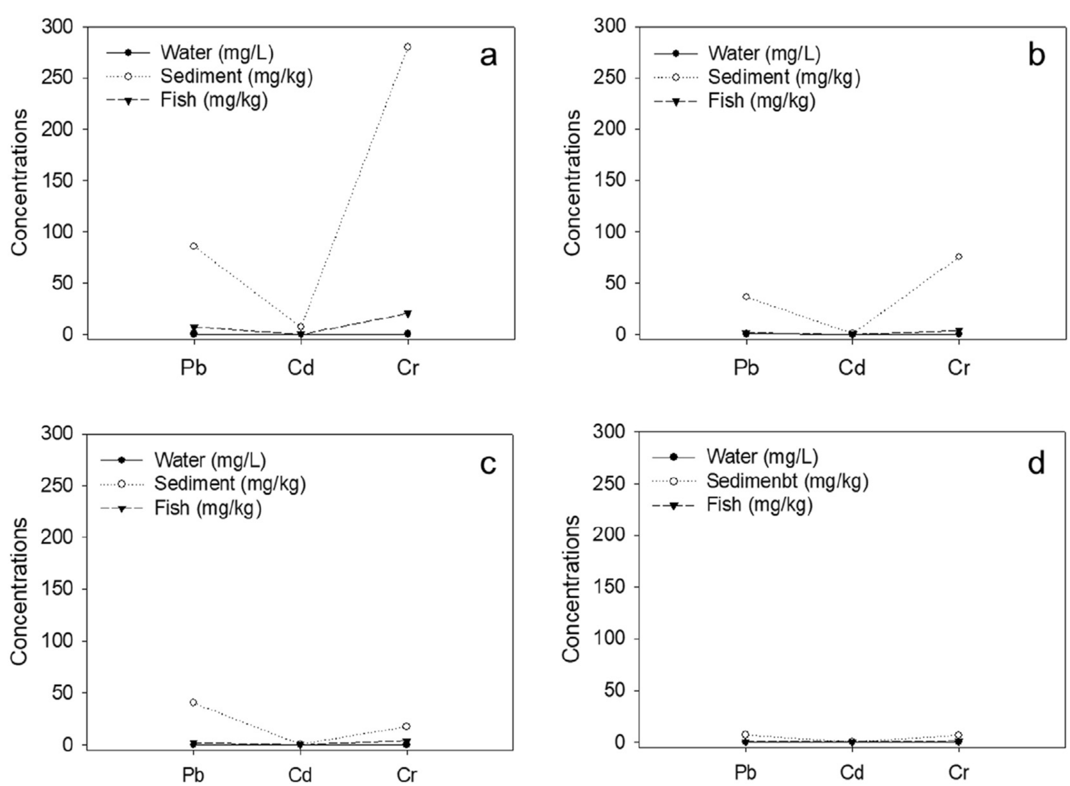

Figure 8. Pb, Cd and Cr concentrations in water, sediment and fish samples. Sampling points and time of sample collection are not considered in this figure. Available published data by different researchers and research organisations are used to (Maximum/Average data taken) show the accumulation of metals into fish body. [(Buriganga River (a), Turag River (b), Sitalakhya River (c) and Meghna River (d)].

municipal waste, agrochemicals and atmospheric deposition might be the causes of pollution [178, 188, 189]. The concentrations of Zn, Cu, Pb, Cd, As, Cr and Ni in sediments (Table 3) of Korotoa River exceeds US EPA recommended safe limit indicating higher rate of pollution in that river.

Teesta River coming from Sikkim, India flows across different northern cities (Rangpur and Bogura) and finally is mixed with Jomuna River in Bangladesh. Islam et al., 2020 found higher heavy metal concentrations in river water. The concentration of Cd was found to be above WHO recommended drinking water standard while Fe and Mn concentrations was above FAO recommended irrigation water standards (Table 2) [37]. Islam et al., 2020 first time used positive matrix factorization (PMF) receptor model to identify the source of pollutant and sediment pollution in upstream, midstream and downstream rivers (Teesta, Korotoa-Sitalakhya, Meghna-Rupsha and Pasur River) in Bangladesh. Risk indices and geoaccumulation index (I_{geo}) data showed that the river sediment is highly polluted with Cd. Research data found that Cr posed strong co-occurrence network with Ni, Fe and Mn. Based on the model data, four factors were identified for river sediment pollution: a) agricultural source (for Cu and As); b) industrial source (for Ni and Mn); c) anthropogenic point source (for Cd); and d) mixed source (for Fe and Cr) [189]. The water quality and sediment quality data showed that Teesta River was affected by receiving heavy load of pollutants. Some researchers found radioactive and heavy elements in Teesta River water which poses higher cancer risk in that area [192].

Padma River flowing beside the Rajshahi city receives pollutant loads through drains, khals and canals from city. Acute deforestation is occurring in this area. Open waste dumping, sewerage line, industrial effluents and domestic water continuously affect the river water quality. Besides, inorganic fertilizers, pesticides, insecticides washed out from agricultural field comes to river water [193]. This river coming from India enters Bangladesh in Chapainababganj. It flows through several districts and finally meets Meghna River in Chandpur [38]. Haque et al., 2018 found higher coliform and *Vibrio cholera* counts in river water during summer season [194]. Zn, Cu, Pb, Cd, Mn and Cr concentration in popular fish species from Padma River was analysed and found that continuous consumption of fishes from Padma River may cause serious health injuries [195].

5.4. Rivers pollution in the southern area of Bangladesh

Lower basin of Meghna River, Kirtankhola River, Rupsa River and the tributary and distributary rivers, canals and khals are affected by unplanned urbanization and industrialization in cities on the river bank area (Figure 7). Southern rivers close to Bay of Bengal contain saline water in major parts. During rainy season, saline water intrusion occurs frequently in this region [196]. Public perceptions is that the salinity intrusion is now more frequent thing in that region. It might be due to the climate change effect on that region. Natural disasters like Aila, Sidr, Fani causes severe damage on crops, plantations and households. Most important the after effect is that huge area is suffering salinity problem. The ecology of this region was affected by these natural hazards and anthropogenic activities [9].

Kirtankhola River is receiving higher amount of pollution loads through different khals and canal in Barisal city. Household used water, sewerage lines, industrial effluents and huge organic loads from the city are directly coming to the river. There are many Hospitals in this city which produce sensitive waste every day. In addition, the city corporation generates huge amount of wastes every day. All of these wastes are directly dumped in open field named Moilakhola. There is no operating waste management process to handle sensitive wastes. Therefore, in rainy season, water take these pollutants into Kirtankhola River. Brick kiln, cement industry, pharmaceutical industry, food industry, textile industry and water vehicles were continuously polluting Kirtankhola River [197]. Rupsha River in Khulna, Padma River in Rajshahi face similar pollution problem now. In addition, pollutants from upper rivers also flow in with river water and finally go down the Bay of Bengal. Electrical conductivity, total suspended solids, turbidity, nitrate and phosphate concentrations of Kirtankhola River water was found to be higher than permissible standards for drinking water by Anjuman Ara Rajonee in 2017 [198]. Ground water quality is largely dependent on saline surface water quality. Water quality in upper aquifer is affected largely by saline water and arsenic than deep aquifer. Barisal area is also suffering natural arsenic problem in ground water [199]. Due to lack of research data on metals and other organic and inorganic pollutants, it is very difficult to explain the quality of the Kirtankhola River water.

Rupsha River is flowing south-western area of Bangladesh. A distributary of Ganges River named Pashur in the upper area becomes Rupsha in the lower area. Nitrate concentrations was above FAO recommended safe limit for irrigation (Table 1). From Table 2, metals concentration was high in several points in the river. Based on the research data, higher concentrations of Fe, Pb, Cr, Mn and Ni were found in several sampling points, which were higher than WHO recommended standards for drinking water and even higher than the FAO recommended standards for irrigation water. The main pollution source is wastes from Khulna city and anthropogenic activity in that area. Higher

Table 4. Common health problems caused by toxic metals from drinking water and foodstuffs intake.

Metals	Associated health problem
As	Hypertension, psychological effects, decreased mental performance, diabetes mellitus, Arsenicosis, carotid atherosclerosis, cardiovascular disease risk, lung cancer and carcinogenesis.
Cd	Diabetes, bone demineralization, prostate cancer, breast cancer, kidney damage, end stage renal disease, neurodegenerative disorders.
Pb	Bladder cancer, lung cancer, reproductive toxicity, hemolytic anemia, decreased memory, neurotoxic effects of intelligence, cardiovascular system diseases.
Cr	Hemolysis, gastrointestinal hemorrhage, kidney/renal dysfunction/failure, collapse/dysfunction of respiratory system through lung cancer and pulmonary fibrosis.
Hg	Allergy, nephrotic syndrome, hypersensitivity (pink disease), proteinuria, kidney damage, lung damage and amalgam disease, perturbs central nervous system coordination and health of plants, neuropsychological symptoms and historical Minamata disease.
Ni	Carcinogenesis, reproductive toxicity, bronchitis, asthma, lung cancer, skin cancer, oral cancer, oral hypersensitivity and risk of gingival hypersensitivity, allergic contact dermatitis.
Mn	Dopamine oxidation, glial toxicity particularly astrocytes, mitochondrial dysfunction, oxidative stress, alteration in the expression of Parkinson's disease related gene.
Cu	Affect in renal and metabolic functions.
Fe	Cancer risk, aging, heart disease, Parkinson's disease, Alzheimer's disease, growth element for diseases causing microorganism as well as in tumors, placental malaria parasite in pregnant women, gastrointestinal stress and increased oxidative damage to biological membranes, proteins or DNA.
Zn	Respiratory problems, significant decrease in erythrocyte superoxide dismutase concentration in adult female.
Co	Co ions in tissues and blood circulation causes neurological, cardiovascular and endocrine deficits.

Source: [245, 246, 247, 248].

amount of natural arsenic was in ground water from Khulna region. Therefore, villagers depend largely on surface water for drinking, household activity and irrigation purpose. So they might be suffering from surface water pollution. Cd, Ni, As, Pb and Cr in water from Rupsha River were higher than permissible value and 85% of the samples posed moderate ecological risk [180]. Shrimp cultivation is popular in Khulna region, which may act as another pollution source in that area. The concentrations of Zn, Cu, Pb, Cd, As, Cr and Ni in sediments (Table 3) of Rupsha River exceed US EPA recommended thresh hold level, which indicates higher rate of pollution in that river.

6. River pollution and data availability during last 40 years

We have tried to collect river pollution data from published research paper, books, thesis papers, conference papers and reports from government organization like Department of Environment. The data presented in this paper in form of tables and figures have been drawn from those surveyed original data. Some observations on data which affect pollution trend analysis are:

- Data collected from different source.
- Sampling location was different.
- Time and season of sample collection.
- Number of samples to represent whole river pollution.
- Sample collection and analysis process.
- Selection of parameters for analysis.

All these reasons remain behind to attain clear figure of pollution. Data in figures are not continuous because of these reasons. However, the peak points in data indicate that river pollution is in very critical condition now. Data in some years were too low peak, which might be ascribed to these reasons or to some positive results of government and nongovernment activities on river water management. Therefore, considering these situations extensive research is very much needed to investigate the river pollution clearly.

7. Changes of heavy metals concentration in soil

Bangladesh is a riverine country and most of the soils belong to Inceptisol category of soil classification. This means that the soils are newly developed. The soils close to river area receive sediments during the rainy season. This soils are used extensively for vegetable cultivation. River water is cheaper and easily available for irrigation. At present, most of the river contaminated with higher concentrations of heavy metals and these metals are transferred to soil and crop through irrigation. According to Uddin *et al.*, [2012], the background concentrations of Zn, Cu, Pb and Cd in soil from Sitalakhya river area were 86, 36.24, 17.75 and 0.12 mg/kg. A vegetable (Kalmi: *Ipomoea aquatic*) was grown in that soil and adjacent Sitalakhya river water was used as irrigation water (Pot experiment). After harvest (growing time: 35 days), the concentration of Zn, Cu, Pb and Cd were 113.16, 36.69, 14.07 and 0.08 mg/kg [200]. Soils contain higher concentrations of metals due to sediment deposition and irrigation with contaminated river water [201, 202]. Several researchers analyzed soil from area adjacent to river and compared with uncontaminated soil and found that these soils contain higher concentrations of heavy metals [12, 182]. Crop grown in contaminated soil having irrigated with contaminated water accumulate higher concentrations of metals compared to uncontaminated soil and water [203, 204, 205]. Most of the researchers collected soil, water and crops from the agricultural land close to contaminated river and showed the toxicity level of contamination.

Excluding these a few researches, very limited data on metal concentration in background soil are available. Therefore, in-depth surveys are needed to find out the heavy metals concentration of background soil as well. These kinds of works can act as bases for further researches for the transfer of heavy metals from river to agricultural soil and soil to crop.

8. Bioaccumulation of toxic metals into foodstuff and human health

Concentrations of Pb, Cd and Cr in water, fish and sediment are shown in Figure 8. The figure for Buriganga, Turag, Sitalakhya and Meghna showed almost similar pattern. In all the figure, the trend of metal concentrations like water<fish<sediment. Buriganga River showed higher metal concentrations comparatively. The concentration of Pb and Cr in fish were higher in Buriganga and Sitalakhya but for Cd the trend was Turag<Buriganga<Sitalakhya <Meghna. The ratio of metals accumulated in organism body to the metals in water is called bioaccumulation factor (BAF). Based on the data, BAF of all the metals followed the trend like Turag<Buriganga<Sitalakhya <Meghna except the BAF for Cr in Buriganga River which is higher than others for Cr. In Turag, Buriganga, Sitalakhya and Meghna River, the bioaccumulation orders are Cd<Pb<Cr, Cd<Pb<Cr, Cd<Cr<Pb and Cr<Pb<Cd respectively. Sarah et al., 2019 found that the order of accumulation of metals in fish liver was Fe > As > Cd > Zn > Pb and in kidney Zn > Fe > As > Cd > Pb [206]. We have taken the available data through random selection (always targeted to take data of water, sediment and fish from similar research year but sometime it was difficult due to lake of research data). While water contained small amount of metals their concentrations increased in fish. It might be due to bioaccumulations of metals into fish body [207, 208]. Additionally, pollutant outlets may be discharging huge amount of toxic metals with water but it is settled down to the sediment and continuous deposition increased the concentrations beyond the toxic level.

There are approximately 90 types of vegetable and 60 types of fruits growing in Bangladesh and most of them are growing in winter season. In this season research data showed that water have higher concentrations of pollutants. Usually vegetables are grown easily in river bank area in Bangladesh where river water can be used easily for irrigation. Continuous irrigation of toxic metals polluted water from the river elevated the concentrations of metals in foodstuff grown in the vicinity of the river [65, 89, 203, 209]. Several researchers found higher levels of heavy metals in agricultural crops grown in polluted area which were irrigated with polluted water [90, 204]. Khan et al., 2014 found higher concentrations of certain metals in foodstuffs grown in Buriganga River vicinity [162]. Higher concentrations of heavy metals were found in vegetables collected from several markets and bazars in Dhaka cities [65]. Research data found that vegetables grown in industrial area have higher concentration of metal accumulation than village area. Road side vegetables have higher concentration of metals (especially Pb) accumulation [13, 210]. The soils from Dhaka city area were found highly polluted based on the geoaccumulation index value (I_{geo}) and it also showed that agricultural soils from the city areas in Bangladesh are polluted with Zn, Cr, Ni, Pb, Cu, As, Hg and cd. Use of agrochemicals and irrigation with polluted water are the main source of metal pollution [10, 201].

Naturally, Bangladesh is suffering from arsenic problem in water, soil and food. Crops accumulated higher amount of arsenic in areas where irrigation water contained higher amount of arsenic [211]. Arsenic contaminated rice, vegetables and other food stuffs are continuously consumed in many parts of Bangladesh [65]. Metals enter into food chain through the accumulation into foodstuffs and finally come to human. Continuous consumption of the contaminated foods will build up higher concentrations gradient of the toxic metals into human body which will causes non carcinogenic and carcinogenic health hazards [205].

9. Accumulation of metals into the ground water

Ground water is the important water source to meet about 86% of drinking water demand in Dhaka city and approximately 96% people in Bangladesh depends on ground water. The main ground water reserver in Dhaka city is Dupi Tilla sand aquifer which is underlying below the Modhupur clay layer have 10 m thickness. The aquifer thickness varies from 100 to 200 m. This aquifer is exposed to the surrounding rivers and these rivers facilitates the ground water recharge in aquifer [212, 213, 214]. Due to over extraction and pollution ground water is not safe without treatment. Ground water table decreased almost 20 m in last decade [215] and decreased 70 mitre since 1990 [216]. Dhaka water supply and sewerage authority (DWASA) installed ground water tube wells in Dhaka city need to be relocated because of river pollution. There is higher possibility of ground water contamination by pollutant flowing in the ground water flow from surrounding polluted rivers [120, 214, 217, 218]. Khan et al., 2020 showed that the toxic metals in river water and soil go down with infiltration water and mix with ground water, which may causes serious health injuries [219]. Over extraction of ground water may increase the concentration of metals in the ground water [220]. Higher concentration of metals deposited in riverbed sediment might be mixed with groundwater flow, which can enhance the concentrations in the aquifer [221]. Approximately 1% tube wells in Dhaka city contain higher concentrations of Pb which is higher than WHO recommended drinking water standard [222]. Extensive use of inorganic fertilizer, pesticides and insecticides affect ground water all over the country. Higher concentrations of nitrate, ammonia, dichlorodiphenyltrichloroethane (DDT), Fe, Mn, Ni, Co, B and Arsenic were found in ground water from several parts of the country [196]. Natural processes and anthropogenic activities are polluting river and ground water continuously. As ground water recharge occurs between river and aquifers, pollutants move to aquifer which is the prime source of drinking water in Bangladesh [222].

10. Toxicity for human health and ecology

Peoples from developing countries are suffering serious health issues due to water pollution. The most important thing is most of them don't know the reason of their suffering. Among the five continent (Europe, South America, North America, Africa and Asia), the highest dissolved heavy metal concentrations found in Asia and the lowest in Europe. The risk of cancer due to Cr pollution decreased in the order Asia˃Africa˃North America in 1970–2017 time period [223, 224]. Research data showed that the situation for Cr pollution in Bangladesh is critical. From a long time ago Bangladesh is suffering from As induced severe health diseases which is mainly coming from surface and ground water [58, 225, 226]. Bioaccumulations of toxic metals in edible portion of fish collected from rivers was found by several researchers [206, 227, 228, 229]. Food stuffs growing on the vicinity of contaminated river or growing with contaminated water irrigation have higher concentrations of different toxic metals. These metals comes into human body through the consumption of these foods and causes toxic effects (Table 4) [202, 226, 230]. Besides that, presence of harmful microorganisms in surface water causes serious health hazards [231, 232]. Cholera, typhoid, diarrhoea, fever, dengue, viral hepatitis, gastroenteritis etc. are common diseases caused by surface water pollution [233]. People in Bangladesh suffer from waterborne diseases severely due to surface and groundwater pollution [234].

Heavy metals toxicity are usually measured by calculating target carcinogenic risk (TR), hazard index (HI) and target hazard quotients (THQs) values and comparing them to standard values. THQ˃1 indicates potential health hazards and TR $> 10^{-6}$ indicates carcinogenic effects for human health. Islam et al., 2014 found high THQ (THQ˃1) for Pb in vegetables and As in cereals, which can cause serious health problems. In addition, they found TR $> 10^{-6}$ for dietary ingestion of Pb and As from foods which indicates severe cancer risk in Karatoya River bank area, Bogura city [235]. Samples from Sitalakhya, Meghna, Rupsa, Pashur, Teesta and Karatoya River water was analysed for As, Pb and Cr status and potential risk to human health. The HI value showed that drinking of water from these rivers would cause detrimental health impacts especially for adults and children's. TR value of Cr exceeded the US EPA recommended value, which may cause serious health hazards in this region [37]. Ali et al., 2020 analysed heavy metals concentration in six fish species collected from coastal area of Karnaphuli River. Based on calculated THQs and TR values, those who eating these fishes are exposed to non-carcinogenic and carcinogenic health consequences [236]. Based on calculated HQ and HI values for Fe and Mn in ground water collected from Dhaka city, the south-western (Turag-Buriganga-Dhaleshwari) part is vulnerable to public health issue [7]. Total cancer risk (TCR) value for Pb, Ni and Cr in vegetables grown on the Buriganga River bank area were higher than US EPA threshold value (1×10^{-6}), which indicated that the people eating those vegetables may be exposed to cancer problem [205]. Fish samples were collected from Dhaleshwari River and analysed 10 different heavy metals by Hasan et al., 2020. They found that fish samples contain higher concentrations of Ni and Cr. Therefore, eating those contaminated fish can causes carcinogenic (TR˃10^{-4}) health problems [237].

The estimated daily intakes (EDIs) of Pb, Cd, As, Ni and Cr were higher than the maximum tolerable daily intake (MTDI), which meant that dietary intake was the potential source of these metals. For fishes, vegetables, fruits and rice, the calculated value PHQ˃1 (combined hazard quotient) indicated that the inhabitants may suffer severe health problems [84]. Palash et al., 2020 analysed Cd, Pb, As, Zn, Cu and Cr in 9 fish species from Meghna River. Fishes may not cause any toxicity to human health based on EDI value. In addition, THQ were found to be <1 for all metals except As which remained in organic state in fish body. They concluded that Cd can cause carcinogenic risk for both adults and children's [238]. Economically important giant freshwater prawn *Macrobrachium rosenbergii* were collected from different farm, Meghna and Karnaphuli River and analysed to determine heavy metal concentrations. Higher concentrations of Mn, Cu, Fe, Cr and Pb were found in water and fish body. The calculated EDI value for Pb and Cr found more than permissible limit. In addition, THQ values for Zn, Cu, Cd and Pb were ˃1 and TR values for Ni and Pb were higher than standards value (10^{-6}). The researchers concluded that prawn species contained higher concentrations of toxic metals which could cause severe health problem [229]. In 2012, Saha and Zaman collected vegetable, fruit and fish samples from central market of Rajshahi city and analysed As, Cr, Pb, Cd and Mn. THQ and HI values were calculated for individual and combined heavy metals. Based on data consumption of fruit, vegetable and fish can cause serious health injury [239].

Toxic metals and harmful microorganisms can cause' serious toxicity for aquatic lives such as tissue damage, DNA damage, restlessness, hyperactivity, neurotoxicity, cellular damage, genotoxicity etc. [18, 27, 79, 230, 240, 241]. Cr in fish in Buriganga River was found to cause genotoxic and other serious toxic effects [242]. Some fish species suffer from severe toxicity of Cr in polluted rivers [87]. Hilsa fish is one of the most delicious and popular fish in the world. Almost 50–60% of world's hilsa was produced in rivers and Bay of Bengal in Bangladesh. From last several years, production of hilsa reduced and genotypic changes occurred due to river water pollution and climate change [243]. World's largest natural breeding ground for carp fishes like *Cirrhinus cirrhosis*, *Gibelion catla* and *Labeo rohita* is in Halda River. Heavy metals in edible tissue of 7 economically important shellfish and fish species were analysed and it was found that Zn, Ni and Pb concentrations in some species were above the dietary limit value. Bioaccumulation factor (BAF) showed that toxic metals were naturally bioaccumulated in the studied species. Fulton's condition factor data revealed that some fish species were in poor health condition. Estimated weekly intake (EWI), THQ and CR values are within safe limit. However, Monte Carlo simulation data showed that children in that area were more vulnerable to carcinogenic and non-carcinogenic health hazards caused by Pb toxicity [244].

Based on the sediment pollution data, Islam et al., 2020 suggested that the flora and fauna in upstream, midstream and downstream rivers in Bangladesh were faced alarming condition [189]. In Feni River, enrichment factor (EF), *Igeo* and contamination factor were calculated based on metal concentrations in river sediment and were found to be moderate to high pollution level for Hg, Co and Ag. Probable effect concentration (PEC) and threshold effect concentration (TEC) values revealed that only Cr and Ni concentrations exhibited toxic effects on ecosystem occasionally. Research data also found that Hg, Ni, Co and Ag were coming from anthropogenic sources [186].

11. Environmental pollution control in Bangladesh

At present, there are different ordinance, laws, rules, acts and policies have been made to control environmental pollution in Bangladesh. These are: Environment Pollution control Ordinance 1977, The Bangladesh Environment Policy 1992, The Environmental Conservation Act 1995 (amended 2000, 2002, 2010), Environmental Conservation Rules 1997 (amended 2002, 2005, 2010, 2017), National Policy for Safe Water Supply & Sanitation 1998, National Water Policy 1999, Bangladesh Environment Court Act 2000, National policy for As mitigation 2004, The Environment Court Act 2010, The Climate Change Trust Act 2010 and Bangladesh Water Act 2013 [249]. The Government, for carrying out the purposes of The Environmental Conservation Act 1995, established the Department of Environment and headed by a Director General [81]. Environmental pollution related all activities are taken care of by this department. The Centre for Environmental and Geographic Information Services (CEGIS) was organized to aim at achieving green environment, blue water and balanced development for better well-being of the nation. Ministry of water resources, Ministry of environment, forest and climate change are responsible ministry of Government of Bangladesh controlling the protection and development of all environment pollution related decisions. Water supply and sewerage authority (WASA) are signed authority to control surface water pollution in cities. They have office in major cities to manage water supply and management.

In 2009, a well-known TV channel named Channel-i and a popular English daily newspaper started a joint campaign called ‘To the Prime Minister: Save Rivers, Save Dhaka’. They introduced the critical condition due to pollution in four rivers surrounding Dhaka city. Based on this, authorities responded immediately and took some steps to control pollution. However, abrupt news with simple data was not enough to make huge impact against present rate of pollution [250]. Realizing the fact and considering the urgency, High Court declared that rivers are “legal entity” and have similar rights as living thing and a river protection commission was appointed to control and manage the river pollution in February 3, 2019. Following its actions, High Court observed that DWASA controlling 68 underground drainage and sewerage line which were continuously polluting the river water. In December 9, 2019, High Court ordered DWASA to stop all the sewerage line. In addition, High Court also ordered Department of Environment to take necessary steps against pollution [251]. At present, Department of Environment is trying to control and manage river pollution. However, research data showed that present water quality in major urban rivers were not good for human health and ecology.

12. Future challenges and measures for smart water management in Bangladesh

High dependence in ground water and careless behaviour toward surface water is not a sustainable way to save world from water scarcity. According to UN (2012), water demand in 2030 will be 40% more than the available [252, 253]. Specific (S), measurable (M), assignable (A), realistic (R) and time (T) based, that is SMART, water management is urgently needed in Bangladesh considering the river pollution status [254]. Based on research data, the most polluted rivers are Buriganga, Turag, Balu, Sitalakhya and Karnaphuli. Water quality data also suggest that other rivers especially Rupsha, Teesta, Korotoa, Karnaphuli and Meghna is deteriorated by pollution. Ground water level was already depleted and contaminated in several parts of the country. Geological and anthropogenic contaminant play jointly for river water pollution.

About 76.2 million populations in 1974 turned 149.77 million in 2011 in Bangladesh. The projected population in 2030 and 2050 will be 186 and 202 million [255]. Present water demand for drinking, irrigation and industrial purpose mostly depends on ground water which is already depleted and contaminated. Therefore, river water is the most important source to meet huge water demand but research data showed that present condition of river water is not safe for human health either drinking and irrigation. Toxicity analysis data on foodstuffs grown under river water irrigation and fishes from rivers suggested that people can suffer carcinogenic and non-carcinogenic disease by eating these foods. Obesity, Fever, pain, itching, coughing, hypertension, mental disorder, heart failure, brain stroke, tumour, diabetes, cancer etc. are most common diseases in Bangladesh [36, 256]. Considering the present ground and surface water condition based on research data, Bangladesh will face safe water scarcity severely in near future which already started [257]. Natural hazard events are common and frequently occur in Bangladesh [67]. Salinity intrusion in river and ground water changes the chemistry of chemical components in water adversely. Data showed that about 20 million people in southern part of Bangladesh were suffering from shortage of safe water. Climate change data suggested the situation for safe water in coastal area of Bangladesh would be worse in future [258, 259].

Bangladesh is riverine country with fertile lands. SMART management of river water is the only way to solve future water demand. Most of the area in Bangladesh is covered by different rivers which are natural reservoir to store rainfall water and recharge ground water. Shifting the dependency on ground water to river water is the sustainable way to manage water demand and save human health and ecology. Therefore, strict regulations and monitoring is very much needed in priority basis focusing the present situation. Contaminant specific research is needed to evaluate the accumulation pathway and fate of element and compounds in human health and ecology. Government should try to build awareness on people about surface water use and earn public trust on water safety. Unmanned automatic river water quality measuring stations can be setup along the river flowing path and central monitoring system of different rivers can control the river water from pollution. Different software and programming models (SCADA-Supervisory control and data acquisition) can be used for river water quality monitoring and measurement. Sharing of public and private research data can show more efficient and realistic figure on safe water quality management.

13. Conclusion

This manuscript first time collected and gathered last 40 years research data on river pollution in Bangladesh and tried to express tabular and graphical representation to show pollution trends and present situations. Trends of physicochemical and toxic metals data showed that extreme pollution events occurred but not frequently. From 2008 to 2012, most of the parameters in Turag, Buriganga River water showed similar peak and from 2011 to 2015 similar peak was found in Sitalakhya

River. It might be due to extreme pollution in Turag and Buriganga River which ultimately comes to Sitalakhya River after some time. In Karnaphuli River, higher pollution events occurred from 2012 to 2015 time periods. The data showed that Turag, Buriganga, Balu, Sitalakhya and Dhaleshwari River water and sediment is contaminated with toxic metals and in some sampling points it was above the drinking, irrigation and surface water standards. Lower Basin Rivers receive this huge pollutant loads continuously. Besides that anthropogenic pollution events also occurring on the lower basin river bank area. Heavy metals concentrations were above the drinking water quality standards in Karnaphuli River. Cd, Ni, Mn and Cr were above the irrigation water quality standards. Higher concentrations of Fe and Mn in Teesta, Cd and Cr in Korotoa and Fe, Mn, Zn and Cr in Rupsha River water which are above irrigation standards. River sediments contain higher amount of metals. The metal concentrations in Old Brahmaputra River were below US EPA recommended threshold value.

Most of the river sediment are polluted with Fe, Zn, Cu, Pb, Cd, Ni, Mn and Cr which is above threshold value. There is higher possibility of groundwater contamination by accumulation of these metals in ground water flow in aquifers. In Dhaka city, ground water from several area was already contaminated with metals, which should be treated prior to use. Bioaccumulation of heavy metals in fish body occurred in the polluted river, which causes toxic effects in fish body. Consumption of this contaminated fish might cause severe toxic effects in human body. Food crops grown on the vicinity of polluted river contain higher amount of metals. Daily intake (EDI), target hazard quotient (THQ), target carcinogenic risk (TR), health index (HI) and total cancer risk (TCR) analysis data by several researchers showed that continuous consumption of metal contaminated food may cause severe carcinogenic and non-carcinogenic health impacts on human body.

Based on research data, it is confirmed that river pollution is occurring in all the major urban rivers and some are facing extreme situation. In addition, till date, all the available data only based on physicochemical and metals analysis. Research on organics, antibiotics, micro plastics, personal care products and other toxic pollutants in river water are overlooked. Therefore, extensive research, continuous monitoring and strict rules and regulations are needed urgently to control river pollution in Bangladesh.

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Author contribution statement

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