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Assessing flooding extent and potential exposure to river pollution from urbanizing peripheral rivers within Greater Dhaka watershed

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Greater Dhaka area is home to large industrial clusters that are driving economic growth and the poverty reduction efforts of Bangladesh. These clusters are located around peripheral rivers- Turag, Buriganga, Dhaleswari, Balu, Shitalakhya, Bangshi, and Tongi-Khal, which are important for water transport, environment, and eco-systems where flooding of floodplains in monsoon is an integral part. The urban and industrial growth stressing natural resources has led to severe degradation of the rivers and floodplains, affecting the livelihoods, health, and well-being of the people. Monsoon-time exposure to polluted water is yet to be studied and addressed scientifically. This study looked into the water quality and flooding situation of Greater Dhaka for two successive monsoons through extensive river sampling coupled with the estimation of flooded area and exposed population using remote sensing tools. Sentinel 1's Synthetic Aperture Radar (SAR) images are used for flood mapping considering cost-effectiveness and its advantages for data-scarce regions. The estimated population exposed to flooding was over 668,000 in 2019, and this number increased by 1.53 times in 2020, totaling over one million. During the monsoon and post-monsoon periods of 2019 and 2020, Buriganga, Tongi Khal, and Balu were consistently in poor condition. The lowest water quality index (WQI) was observed in Balu during the monsoon of 2019 (32.28), post-monsoon of 2019 (35.71), and post-monsoon of 2020 (29.58). The lowest WQI during the monsoon of 2020 was recorded in Tongi Khal (35.75). Among the four districts, Dhaka and Gazipur were the most affected by floods in terms of inundation area and exposed population. Our study indicates that most rivers remain in poor condition during the monsoon when exposure is also high. This highlights the need for policymakers to take monsoon exposure seriously and design appropriate interventions.

Keywords Flood, Water pollution, Dhaka, Water Quality, Remote sensing, Sentinel 1, Water Quality Index

Floods stand out as the most destructive hazards globally, posing a constant threat to human lives and inflicting considerable economic hardships across the planet[1,2]. Between 1995 and 2015, floods accounted for approximately 47% of weather-related disasters, impacting 2.3 billion people and resulting in 157,000 fatalities[3]. Bangladesh, situated in one of the most flood-prone regions—the Ganges, Brahmaputra, and Meghna (GBM) basins—experiences frequent flooding[4,5]. With 80% of the country designated as floodplain, Bangladesh contends with annual inundation affecting around 20–25% of its land area, and in extreme years, this figure can soar to over 60% of the entire country[6,7]. According to the Bangladesh Bureau of Statistics, from 2009 to 2014, floods affected about 34% of households in the country, leading to an estimated total loss of approximately 42,807 million Taka (422 million USD)[8].

The monsoon season in Greater Dhaka brings about regular flooding. Over 30% of households in Dhaka, Gazipur, and Munshiganj are affected by floods, while in Narayanganj, the figure stands at approximately 18%[8]. The lowlands of Dhaka consistently face inundation, the severity of which depends on both rainfall and upstream

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flows, and along with the fluvial flooding, pluvial flooding is becoming a major concern for the residents of Dhaka[9–11].

Greater Dhaka has witnessed devastating floods in various years, including 1954, 1955, 1968, 1971, 1974, 1987, 1988, 1998, 2004, and 2007. The flood of 1988 submerged about 85% of Dhaka for several weeks and the 1998 flood submerged nearly 56% of Dhaka for approximately 10 weeks, causing extensive damage and suffering[12,13]. The major floods in 1988, 1998, 2004, and 2007 were primarily monsoon floods, driven by heavy seasonal rainfall[14]. The 2004 flood, although of shorter duration than the 1988 and 1998 events, took a longer time to drain from Dhaka city areas. During this flood, 40% of the city and its inhabitants directly suffered due to a combination of fluvial and pluvial flooding, and the ready-made garments sector incurred a loss of $10.3 billion (632 billion TK)[15,16]. The 2007 flood surpassed the duration of the 1988 and 2004 events, but peak water levels for all rivers surrounding Greater Dhaka were lower than those in 1988, 1998, and 2004[5].

Besides property damage and human fatalities, the secondary effect of flooding, such as the spread of water-borne diseases like diarrhea, dysentery, and typhoid, is severely affecting the health of Dhaka residents. Exposure to the contaminated floodwaters in Dhaka can increase the risk of diarrheal diseases, as the polluted water contaminates drinking water sources and spreads pathogens[17]. High levels of pollution in Dhaka's rivers suggest that the risk may be more significant in the urban setting[18]. During the 1988, 1998, and 2004 flood events, patient visits at the ICDDR, B almost doubled compared to non-flooded times[19]. In the 2007 flood, 43,250 diarrhea patients were admitted to the ICDDR, B hospital[20]. Prolonged exposure to persistent and toxic chemicals through the use of polluted floodwater for irrigation, washing, and bathing in the floodplain regions of Greater Dhaka that receive toxic contaminants from polluted rivers during monsoon flooding has led to reduced agricultural production and an increase in non-communicable diseases among both children and adults[21]. These studies underscore the rising health risks associated with the use of floodwater, posing serious implications for public health in Dhaka.

Effective response during flooding events requires real-time observation and monitoring of the affected areas[22–24]. In Bangladesh, the Flood Forecasting and Warning Centre (FFWC) relies on hydrological models for providing flooding information, using inputs like discharge, weather, and digital elevation model (DEM) data. However, accurate DEM and discharge data are often lacking. Remote sensing images, particularly Synthetic Aperture Radar (SAR) sensors, offer a solution by overcoming the limitations of hydrological models, especially in all weather conditions[25–28]. While optical images are effective during good weather conditions, they are limited by cloud interference[29]. SAR sensors, on the other hand, can penetrate clouds and operate day and night, offering a valuable tool for flood monitoring. The availability of free SAR data through the European Space Agency's (ESA) Sentinel-1 C-band SAR mission has opened up significant opportunities for flood extent monitoring.

In addition to flooding, surface water pollution is a major environmental concern, especially in developing countries like Bangladesh undergoing rapid industrialization and urbanization[30]. The rivers of Greater Dhaka, heavily impacted by domestic and industrial wastes from thousands of factories, exhibit high pollution levels. Industrial pollution alone contributes to 60% of the total pollution in the Dhaka watershed[31–34]. These industries primarily include textile, dyeing, printing, and washing, pharmaceuticals and are located along the banks of rivers, discharging untreated waste into these waterways[35,36]. The rivers in the Greater Dhaka Watershed show elevated levels of organic pollution, pathogens, ammonia, and heavy metals and exhibit high toxicity[37,38]. Water quality of the Tongi River was found to be in poor condition, with numerous indicators failing to meet Bangladesh's environmental conservation regulations[39]. Though exposure to polluted water occurs throughout the year for low-income communities living close to rivers, exposure is higher in monsoon through subsistence usage owing to the perceived low pollution in monsoon[40]. Industrial activities in Greater Dhaka also contribute to the contamination of river sediments with heavy metals and organic chemicals. These pollutants can be mobilized during floods, spreading contamination over a wider area. During flood events, sediments can transport and deposit industrial pollutants including heavy metals, leading to contamination of water bodies and agricultural lands. The accumulation of heavy metals and other pollutants in sediments poses serious health risks, particularly for vulnerable populations living in flood-prone areas[41]. The legacy effect of these pollutants become evident during monsoon season resuspension and through release due to chemical decay. However, these are expected to be evident downstream of major pollution hotspots through deterioration of the water quality during high flow season which otherwise would have low pollution.

Ensuring water quality is crucial for public health and safety, and to safeguard surface water resources, it is essential to establish a comprehensive water quality monitoring program[42]. However, analyzing a large number of samples and monitoring various parameters often makes it challenging to evaluate water quality as a single unit[43]. In such cases, a water quality index (WQI) serves as a convenient and useful tool to assess water quality status for different temporal and spatial resolutions. The first Water Quality Index (WQI) was developed by Horton[44], and after that many researchers developed many indexes, including the NSF index[45], the House index[46], the CCME Index[47], etc. Among them, the CCME-WQI has been applied widely to assess the quality of water in a variety of water bodies, including lakes, rivers, reservoirs[48], groundwater[49], etc. Because of its robustness in evaluating water quality, flexibility in selecting parameters, and global application, the Canadian Council of Ministers of Environment Water Quality Index is more recommended than other water quality indices[50–53]. The maximum number of variables or samples for CCME is not stated[54,55] so CCME can be calculated by using a wide range of parameters. Independent parameters and missing data can both be utilized with CCME-WQI[50]. It is a useful communication tool that can integrate several measuring units into a single metric. Even when the same objectives and variables are employed, the index can represent relative variations in water quality between sites[47]. The CCME WQI's adaptability to various hydrological and geological circumstances has been demonstrated by its effective application in several locations, including Greek rivers, the Rhine, Meuse, groundwater on Rhode Island, and Sulaimani City's water sources[56]. Numerous researchers examined and compared the benefits and drawbacks of CCME-WQI with alternative techniques for analyzing water quality[57]. assessed and compared the water quality of the Three Gorges Reservoir's tributaries using CCME-WQI and NPI. It was discovered that the CCME-WQI approach can accurately assess the overall water quality, but the NPI method overemphasized the most serious pollution issues. Furthermore, investigations evaluating the same water body have contrasted the Water Framework Directive (WFD) with CCME-WQI and discovered that the CCME-WQI evaluation is more trustworthy[58].

We understand that flooding adversely affects both living beings and floodplains, and if the floodwater is polluted, it can have even more harmful effects on the surrounding environment. While most studies examine flood exposure and water quality separately, this study integrates both aspects to provide a comprehensive analysis. Previous work has not adequately addressed the combined impact of monsoon and post-monsoon flood exposure and water quality degradation on the affected population. This study fills that gap by simultaneously assessing the extent of flood exposure and the deterioration of water quality, and by evaluating the implications for the population exposed during flooding events. This dual focus allows for a more detailed understanding of the public health risks associated with monsoon floods in Dhaka. Water samples were collected from the rivers of Greater Dhaka during the monsoon and post-monsoon seasons of 2019 and 2020. This study evaluates flooding and water quality in Greater Dhaka during the monsoon and post-monsoon seasons of 2019 and 2020 and also assesses the number of people exposed to floodwater.

Study area

Greater Dhaka is located within the coordinates of 90° E to 90.74° E longitude and 23.37° N to 24.34° N latitude, covering an area of approximately 4929.45 km². The majority of this area is utilized for cropland, accounting for 45.82%. Rural settlements and built-up areas follow with 27.17% and 13.67%, respectively (Fig. 1). Rivers and water bodies constitute 8.26%, while forestry covers 3.45%. Approximately 21% of the study area experiences flooding, primarily with depths ranging from 1.83 to 3.08 m. This region is situated in the southern part of the Madhupur Tract, characterized as a Pleistocene terrace elevated 1–10 m above the adjacent floodplains. According to the Köppen climate classification, the area exhibits a Tropical savanna climate with dry-winter characteristics. The monthly average temperature in the Dhaka area ranges from 16 °C to 33 °C (1953–2018). In January, temperatures average between 18 and 20 °C, while in April and July, they range from 28 to 29 °C. The yearly average rainfall is 2148 mm, with the highest monthly recorded rainfall being 856 mm. In the Dhaka city area, the annual average rainfall is approximately 2117 mm (1980–2012).

The Greater Dhaka area boasts some of the country's vital rivers, with the Padma flowing in the southwest direction and the Meghna in the southeast. Dhaka city is enveloped by four rivers: the Turag and Buriganga to the west, Tongi Khal to the north, and Balu to the east. To the northwest, the Bangshi and Kaliganga flow, while the Dhaleswari is situated to the south, and the Shitalakhya lies in the eastern part. All these rivers traverse Greater Dhaka, ultimately merging into the Meghna. Peripheral rivers refer to rivers that are located on the periphery or the outer boundaries of a city or urban area. Description of all the peripheral rivers in the study area can be found in Table 1. This region has developed into an economic hub due to its extensive river network, with Dhaka contributing 40% to Bangladesh's gross domestic product. Industries in Greater Dhaka predominantly include textiles, apparels, metals, FMCG (Fast-Moving Consumer Goods), electronics, and construction materials. Although agro-based industries, once common in areas like Narayanganj and Demra, are now lacking. Currently, 18 Export Processing Zones (EPZs) operate in Greater Dhaka, and an additional 8 EPZs are planned to launch in the coming years, foreseeably increasing production and impacting the surrounding environment. Many of these zones are located alongside rivers, with multiple outlets to the water bodies. Economic hubs are strategically formed around waterways, leading to various impacts on them, particularly due to inadequate waste management and drainage systems.

Materials and methods

Data used

This analysis utilized the Ground Range Detected (GRD) product of Sentinel-1 data for flood mapping. Sentinel-1 is a space mission funded by the European Union and conducted by the European Space Agency (ESA) under the Copernicus Programme. It captures C-band synthetic aperture radar (SAR) imagery at various polarizations and resolutions. The GRD products are amplitude images without phase information, and they are projected from the slant range to the ground range using an Earth ellipsoid. The resulting product features square pixels with reduced speckle. The acquisition employed the Interferometric Wide (IW) swath mode, covering a 250 km swath. Sentinel-1 data from specific dates were selected for this analysis and they are listed in Table 2.

For calculating permanent waterbody, seasonality data of JRC Global Surface Water Mapping Layers, v1.3 dataset from Earth Engine Data Catalog have been used. This data set is created by using three million Landsat satellite images over the past 32 years at a 30-meter resolution[59]. For the population exposure analysis, census data was unavailable for the flooding period in our study area, so we utilized 100 m resolution population data from WorldPop[60,61]. WorldPop data has been widely used in previous studies for population exposure analysis[62,63]. In this study, we used WorldPop data for 2019 and 2020, which is adjusted to align with the United Nations' national population estimates. The most recent census in Bangladesh was conducted in 2011. We compared the 2011 WorldPop data with the Bangladesh Bureau of Statistics (BBS) census data for 105 unions in Greater Dhaka. The two datasets demonstrated a strong correlation (supporting document: Population_data_validation.pdf). This data has been extracted from recent census-based population counts matched to their associated administrative units and disaggregated to ~100×100 m grid cells through machine learning approaches. For landcover analysis, Land Cover Map 2015 of Bangladesh has been used in this study[64]. Spatial resolution and sources of all the remote sensing data used in this study are mentioned in Table 3.

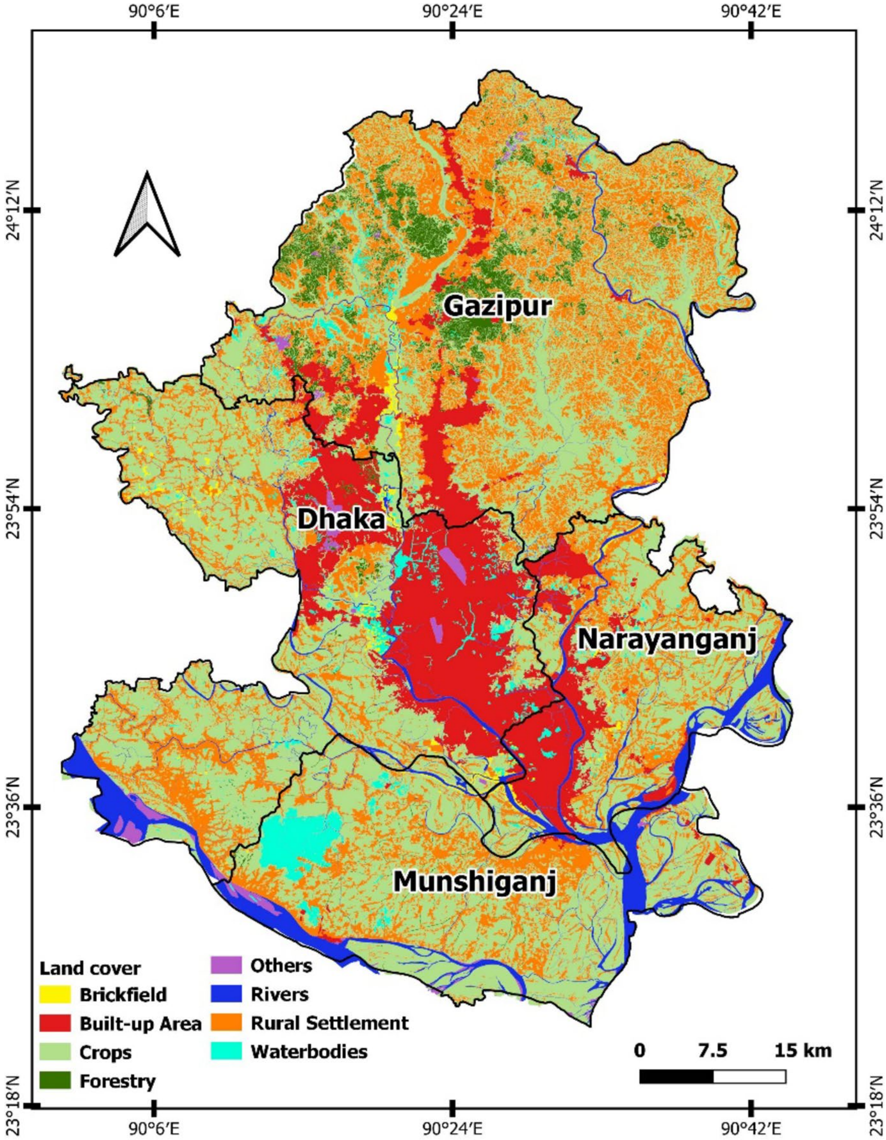

Fig. 1. Landcover of Greater Dhaka (Jalal et al., 2019).

River	Length (km)	Length in study area (km)	Average width (m)	Surrounding landcover/landuse
Balu	44	23	79	Mainly rural setup, Urbanization started
Bangshi	239	22	49	Semi-urban set up at upstream and downstream, rest rural setup
Bangshi Savar	13	13	73	Semi urban setup
Buriganga	29	29	302	Highly urbanized
Dhaleswari	292	60	144	Mainly rural setup with several industries at different locations
Shitalakhya	108	60	228	Upstream urban setup, downstream highly urbanized
Tongi Khal	15	15	55	Highly urbanized
Turag	62	50	82	Upstream urban setup, downstream highly urbanized

Table 1. River description.

Water samples have been collected from 64 locations of the Greater Dhaka River system which includes Balu, Bangshi, Bangshi Savar, Buriganga, Dhaleswari, Shitalakhya, Tongi Khal and Turag Rivers (Fig. 2). Field visits were conducted on the following dates: July 8, 14, 15, and August 18, 2019, for the monsoon season of 2019, and October 13, 14, and 15, 2019, for the post-monsoon season of 2019. For the 2020 monsoon season, visits took place on August 22, 23, and 24, and for the post-monsoon season, on October 11, 12, and 13, 2020. Due to the large area of Greater Dhaka, water sampling could not be completed in a single day, necessitating multiple

Data	Season	Date
Sentinel-1 GRD	Monsoon	07/07/2019, 09/07/2019, 19/07/2019, 21/07/2019, 25/07/2019
		03/08/2020, 06/08/2020, 08/08/2020, 15/08/2020, 18/08/2020, 20/08/2020, 27/08/2020, 30/08/2020
	Post-monsoon	01/10/2019, 08/10/2019, 11/10/2019, 13/10/2019, 20/10/2019, 23/10/2019, 25/10/2019
		02/10/2020, 05/10/2020, 07/10/2020, 14/10/2020, 17/10/2020, 19/10/2020, 26/10/2020, 29/10/2020

Table 2. Sentinel 1 data list.

Data	Type	Resolution	Time	Source
Sentinel 1	C band SAR	10 m	Specific dates are mentioned in Table 2	Earth Engine Data Catalog
WorldPop	Gridded population data	100 m	2019, 2020	www.worldpop.org
JRC Global Surface Water Mapping Layers, v1.3	Spatial and temporal distribution of surface water	30 m	1984 to 2021	Earth Engine Data Catalog

Table 3. Description of the remote sensing data used in this study.

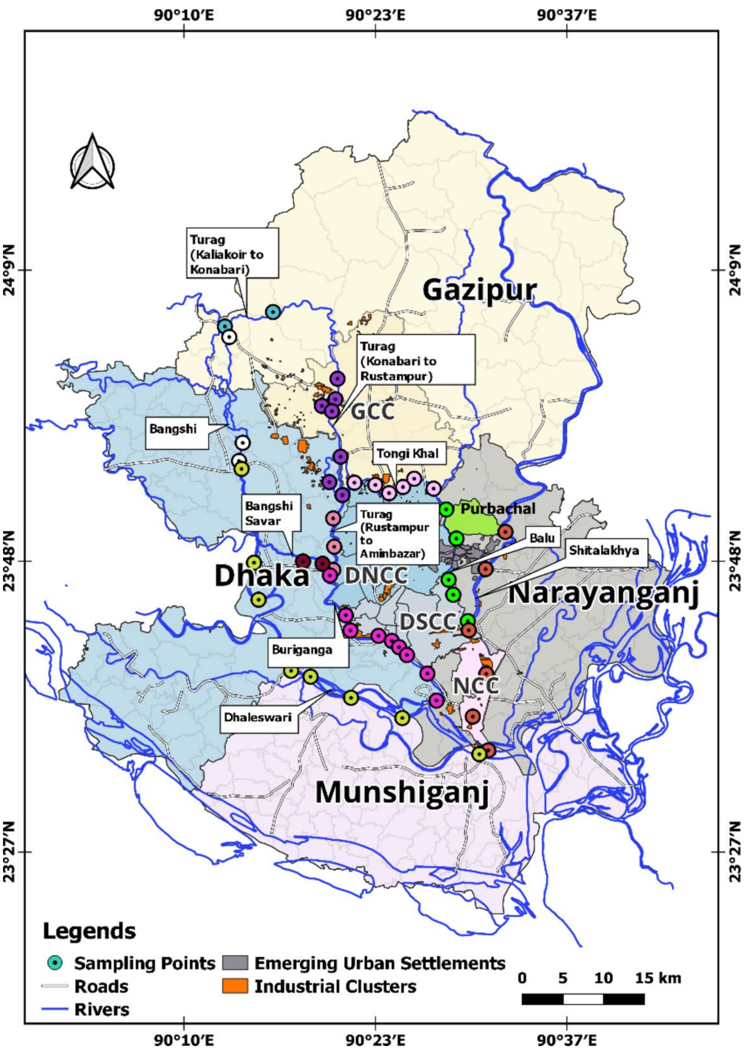

Fig. 2. Water sampling locations.

field visits. Most samples were collected between 8:00 AM and 5:00 PM local time. Samples were collected from a boat at 2 m depth. Temperature, pH, dissolved oxygen, redox potential, and electrical conductivity of the samples were measured in the field using HACH HQ40d multiparameter device and turbidity was measured with VELP Scientifica TB-1 portable Turbidimeter. Laboratory analysis of Color, Alkalinity, Iron, Ammonia-Nitrogen, Nitrate, Phosphate, Sulfide, Sulfate, and Chloride were conducted by spectrophotometric method and measuring range of the parameters are 15–500 mg/L Pt-Co, 0.02 to 3.0 mg/L, 0.02 to 2.50 mg/L, 0.3 to 30 mg/L, 0.3 to 45.0 mg/L, 5 to 800 µg/L and 2 to 70 mg/L, respectively. Analysis of Alkalinity and chloride was performed by titrimetric method where the method ranges were 10- 4000 mg/L (as CaCO3) and 10 to 10,000 mg/L, respectively. Arsenic, Zinc, Lead, Cobalt, Cadmium, Nickel, Iron, Chromium, and Copper were measured in ICP (Inductively coupled plasma) machine. We included a list of accuracies for the water quality parameters measured during field observations and lab tests (supporting document: accuracy_level_of_wq_data.pdf). All the laboratory analyses were conducted at The Soil and Water Analysis Laboratory at the Institute of Water and Flood Management (IWFM), Bangladesh University of Engineering and Technology (BUET).

Flood detection process

The detection of floods in the study area using Sentinel-1 data was carried out on the Google Earth Engine platform[65]. The Sentinel-1 Ground Range Detected (GRD) imagery available in the Google Earth Engine data catalog has undergone several preprocessing steps, including the application of an orbit file, removal of border noise, thermal noise removal, radiometric calibration, and terrain correction. The resulting backscatter coefficient values, adjusted for terrain, are converted to decibels through log scaling. To mitigate the inherent speckle effect in radar imagery, a smoothing filter with a radius of 25 m was applied. For this study, backscattering values in the VV polarization were utilized for extracting flood-affected areas. This choice was based on the fact that the co-polarized VV band exhibits stronger backscattering intensities compared to the cross-polarization VH band[66,67].

Figure 3 illustrates the methodology for inundation mapping for this study. For this analysis to distinguish water and non-water areas in the image, the thresholding method was used, where the image is segmented into water and non-water classes based on the threshold value (Fig. 4). We plotted histograms of Sentinel-1 data, which reveal a bimodal distribution during flooding events. One peak corresponds to flooded pixels, while the other represents non-flooded pixels. By analyzing the histograms, we determine the threshold value that separates flooded from non-flooded pixels. This process was repeated for histograms from all four flooding events to identify the respective thresholds.

To refine the flooded areas the JRC Global Surface Water dataset is used to mask out all areas covered by water for more than 10 months per year. Furthermore, to reduce the noise of the flood extent product the connectivity of the flood pixels is assessed to eliminate those connected to eight or fewer neighbors. Flood areas are calculated by counting the flooded pixels in Google Earth Engine. For population exposure analysis UN adjusted population data of Bangladesh had been used. Then the population count for the inundated areas was calculated by using QGIS's zonal statistics tool. QGIS 3.16.8 version was used for processing the geospatial task.

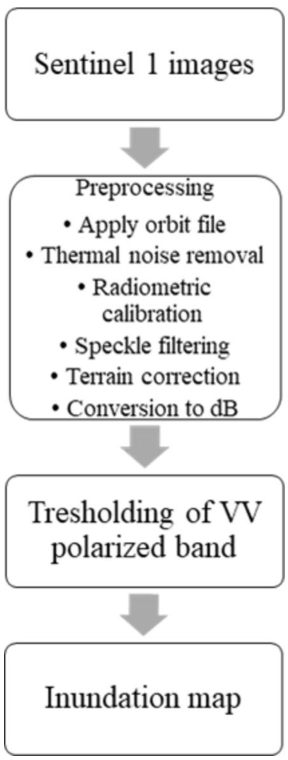

Fig. 3. Flow chart of flood mapping methodology.

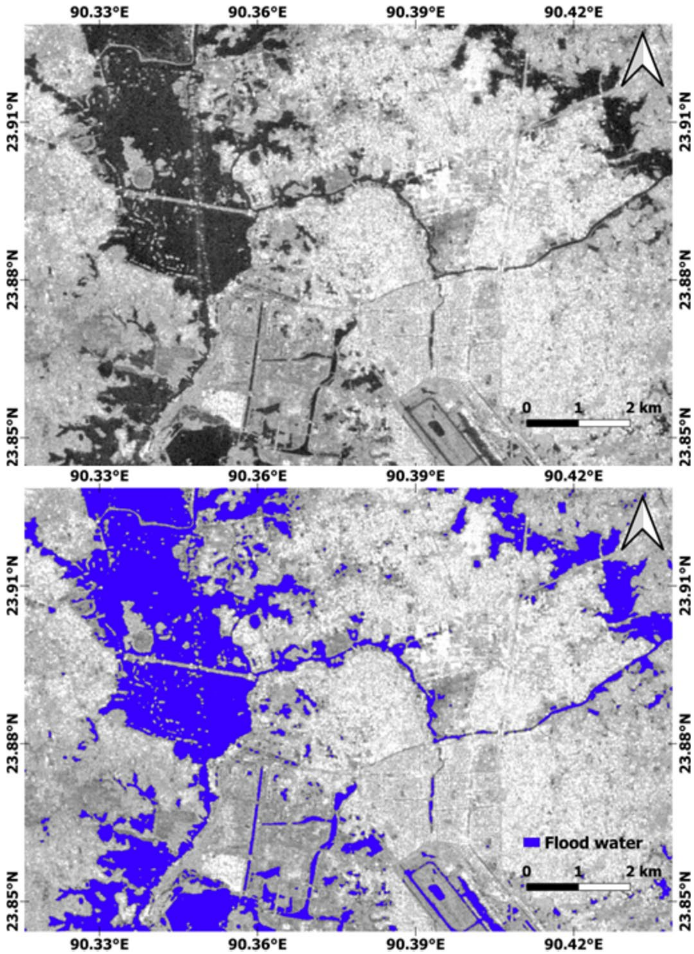

Fig. 4. Waterbody extraction after thresholding.

During the processing of flood maps, Landsat satellite data (30 m) and the JRC Global Surface Water dataset (30 m) were resampled to align with the finest spatial resolution available, which was the 10 m resolution of Sentinel-1, as demonstrated by[62], to maintain spatial heterogeneity and a consistent spatial domain. Likewise, for flood exposure analysis, both population data and flood datasets were resampled to match the 10 m resolution.

Flood accuracy assessment

To assess the accuracy of the flood maps, a validation process was necessary for the classification results[68,69]. Conducting fieldwork during floods poses challenges; hence, for validation purposes, the flood map generated from Sentinel-1 data was compared both qualitatively and quantitatively with Landsat 8 data (Fig. 5). A subset of the Landsat-8 image acquired on October 8, 2020 (with 18% cloud cover) was classified for flood mapping, serving as a reference to compare with the flood map derived from Sentinel-1 on October 7, 2020. The subset area is quite small, covering only about 0.75% of the total study area. This limitation arises because most Landsat images over our study area during the monsoon and post-monsoon flooding events were cloud-covered. Although some cloud-free portions exist, they are not flood-affected. Consequently, we identified flood-affected areas from the cloud-free parts of the Landsat images, resulting in a very small subset area. The Modified Normalized Difference Water Index (MNDWI) was calculated for the Landsat image to generate a flood map[70]. Subsequently, a threshold value was applied to MNDWI values to distinguish water bodies from non-water areas. A comparison was conducted between Landsat-8 and Sentinel-1-derived inundation areas, revealing 894 hectares and 877 hectares, respectively, for the same region. Figure 5 illustrates the comparison between Sentinel-1 and Landsat 8 flood inundation maps.

Water Quality Index (WQI)

Water Quality Index (WQI) was calculated for the river reaches using the method adopted by the Canadian Council of Ministers of the Environment (CCME)[47]. Ambiguity and eclipsing are common issues in WQI models[46]. So, we examined different water quality indices and chose CCME WQI as it has several advantages over other methods. The index provides flexibility in choosing variables and objectives according to the study area and has tolerance for missing data. It can be used both for tracking changes at one site over time and for comparisons among sites. CCME is calculated by using spatiotemporal averages of water quality, most of

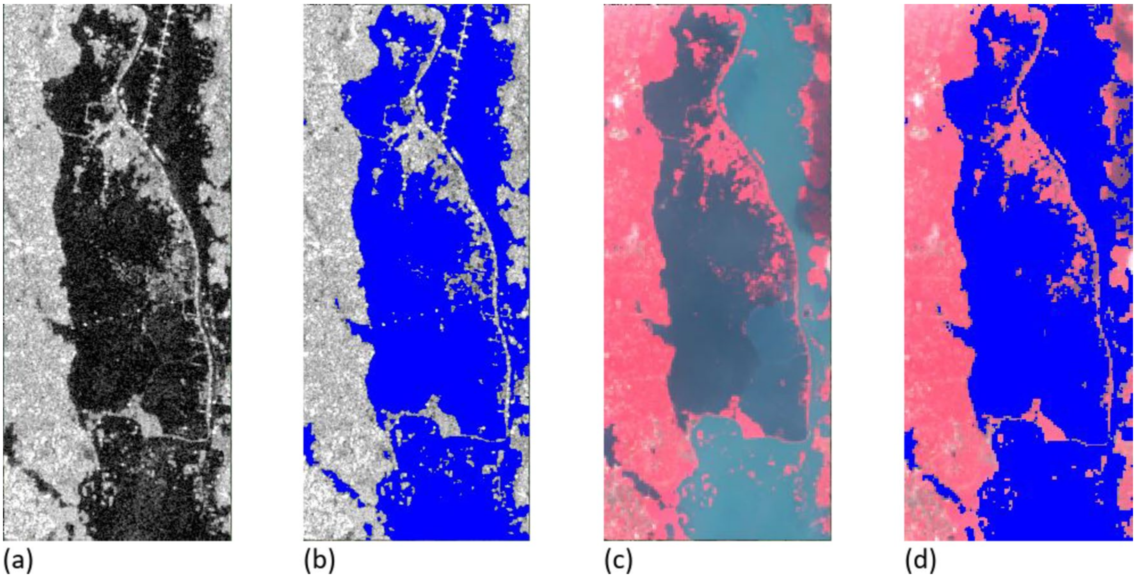

Fig. 5. (a) Sentinel 1 image of 07-10-2020, (b) Water extraction from Sentinel 1, (c) False colour composite of Landsat 8 image of 08-10-2020, (d) Water extraction from Landsat 8- (a typical example for Turag).

the WQI cannot calculate spatiotemporal averages. In evaluating the water quality for population exposure along rivers, spatiotemporal averages are essential. CCME WQI is a semi-parametric method while other WQI are parametric methods. In CCME factors F1 and F2 are non-parametric and only F3 is parametric. It is a comprehensive tool for evaluating water quality and purity requirements because of its capacity to consider a wide variety of characteristics, compare pollutant concentrations to norms, and consider the robustness of treatment procedures. The CCME WQI is a useful option for water quality assessments worldwide because of its reliable performance in various environments and sensitivity to variations in source water quality.

Fifteen parameters are considered for calculating the CCME index, including temperature, pH, EC, DO, ORP, turbidity, color, alkalinity, iron, ammonia-nitrogen, nitrate, phosphate, sulfide, sulfate, and chloride. The river water is mostly used for irrigation purposes, and people do not drink this water. Therefore, irrigation standards from ECR, 2023 have been used primarily. In some cases where the ECR, 2023 standard is missing, the FAO irrigation standard has been used. In cases where both ECR, 2023 and FAO standards are missing, standards have been collected from other sources. The standards of the water quality parameters used in this study are listed in Table 4.

Calculation from CCME water quality gives a value to a range between 0 and 100, where a value of 100 is the best possible index score and a value of 0 is the worst possible. Once the CCME WQI value has been determined, water quality is ranked by relating it to one of the following categories: Excellent, Good, fair, marginal, and poor (Table 5).

Table 6 provides the numbering of the rivers for maps and graphs.

Results and discussion

Flood

Inundation maps of Greater Dhaka have been prepared for the monsoon and post-monsoon periods for both 2019 and 2020 (Figs. 8 and 9). The monsoon floods of 2020 have had an overall impact on the northern, northeastern, and southeastern regions of Bangladesh. The flood has impacted 30 districts of Bangladesh, with moderate to severe impact on 15 districts. A total of 1022 unions from 158 upazilas have been inundated by floodwater, affecting 5.4 million people and leaving 100,000 families waterlogged[71]. Due to heavy rainfall and rising water levels in the rivers, Greater Dhaka experienced extensive flooding in 2020. The annual rainfall of 2020 was around 2500 mm, whereas the annual average rainfall is about 2117 mm (1980–2012). This study reveals that about 65,700 ha area were inundated during the monsoon, which is about 13% of the total study area. 70% of the inundated areas are croplands, and the built-up area covers 3%. Among the four districts, the inundated areas mostly fell in Dhaka, which accounted for about 41% of the total inundation. Inundation in Gazipur, Munshiganj, and Narayanganj was 28%, 19%, and 10%, respectively, with respect to the total inundation (Table 7).

Considering the inundation with respect to the total district area, it is also found that inundation was higher in Dhaka district. 18% of Dhaka was inundated, followed by Munshiganj (17%), Gazipur (10%), and then Narayanganj (7%) (Table 7; Figure 7). The lowlands of Dhamrai under Dhaka were mostly flooded, which is attributed to the overflow of the Dhaleswari River. Furthermore, inundation was higher in Savar, Kaliakoir, and Gazipur Sadar due to the overflow of the Turag and Bangshi rivers, and in Kaliganj, Uttar Khan, Badda, Khilgaon, Demra, and Rupganj due to the overflow of the Balu River. About 1 million people were exposed to flooding during the monsoon of 2020 in Greater Dhaka, which is about 4% of the total population of the study

Parameters	Standard
Temperature	20–30 [b]
pH	6.5–8.5 [a]
EC (μS/cm)	700 [c]
DO (mg/L)	5 [a]
ORP (mV)	100 [e]
Turbidity (NTU)	5 [b]
Color (Pt-Co)	15 [b]
Alkalinity (Total) (mg/L as CaCO3)	250 [e]
Ammonia-Nitrogen (NH3-N) (mg/L)	1.5 [b]
Nitrate (mg/L)	22 [a]
Phosphate (mg/L)	6 [a]
Sulfide (μg/L)	2 [f]
Sulfate (mg/L)	250 [b]
Chloride (mg/L)	355 [c]
TC (count/100 ml)	50 [g]

Table 4. Water quality parameter standards. *[a] Irrigation water quality standard of ECR, 2023 (MoEFCC 2023) [b] Drinking water standard of ECR, 2023 (MoEFCC 2023) [c] FAO irrigation standard (FAO, 1972, 1985), [d] USEPA surface water quality standard (USEPA, 2003), [e] From Environmental literature, [f] USEPA aquatic life standard (USEPA, 2018) [g] Surface water Quality Standard of ECR, 2023 (MoEFCC 2023).*

Category	Range	Remark
Excellent	95–100	The water quality is not under any threat, and it is not degraded and close to natural levels.
Good	80–94	Water quality is protected with only a minor degree of threat or impairment; conditions rarely depart from natural or desirable levels.
Fair	65–79	The overall water quality is protected; however, it is under threat in some cases and sometimes not in the desired conditions
Marginal	45–64	The water quality is frequently under threat and degradation and often not in the desired conditions.
Poor	0–44	Water quality departs from its desirable level

Table 5. Category of Water Quality Indices using CCME. *Source: CCME index*[47].

River Name	River/River Reach Number
Turag (Kaliakoir to Konabari)	1
Turag (Konabari to Rustampur)	2
Turag (Rustampur to Aminbazar)	3
Tongi Khal	4
Balu	5
Bangshi	6
Buriganga	7
Bangshi Savar	8
Dhaleswari	9
Shitalakhya	10

Table 6. River numbering for maps and graphs.

area. As water started to drain out during the post-monsoon period, inundation was much less than during the monsoon but still covered about 9% of the study area, with about 700,000 people exposed to inundation. The inundation pattern observed was almost the same as during the monsoon, while Dhamrai (Dhaka) and Sreenagar (Munshiganj) showed some exceptions. Dhamrai showed less inundation than during the monsoon, while flooding was higher in Sreenagar.

The flood of 2019 was less severe than that of 2020 in terms of inundation (Tables 8 and 7). Approximately 42,200 hectares were inundated, and around 668,000 people were exposed to the flood during the 2019 monsoon season. In the post-monsoon, the inundated area reduces to 31,300 hectares, affecting 517,000 people. The inundation pattern in 2019 was almost similar to that of the 2020 flood, both during the monsoon and the post-monsoon periods. Dhamrai experienced less flooding during the 2019 monsoon compared to 2020. Observing the floods of these two years, it can be said that Dhaka and Gazipur are more affected by floods, while Munshiganj and Narayanganj are less affected (Figs. 6 and 7). During both the monsoon and post-monsoon

District	Total area (ha)	Total population	Monsoon 2020						Post-monsoon 2020					
			Inundated area (ha)	Percentage with respect to total inundation (%)	Percentage with respect to total district area (%)	Exposed population	Percentage with respect to total exposed population (%)	Percentage with respect to total district population (%)	Inundated area (ha)	Percentage with respect to total inundation (%)	Percentage with respect to total district area (%)	Exposed population	Percentage with respect to total exposed population (%)	Percentage with respect to total district population (%)
Gazipur	181,753	5,783,164	18,897	28.77	10.4	289,058	28.28	5	15,598	34.22	8.58	231,702	32.59	4.01
Dhaka	147,640	15,505,383	27,534	41.92	18.65	509,326	49.83	3.28	15,397	33.78	10.43	320,693	45.11	2.07
Narayanganj	93,288	3,614,222	6699	10.2	7.18	124,248	12.15	3.44	4685	10.28	5.02	87,230	12.27	2.41
Munshiganj	70,370	1,516,072	12,559	19.12	17.85	99,566	9.74	6.57	9897	21.71	14.06	71,352	10.04	4.71
Total	**493,051**	**26,418,841**	**65,689**	**100**		**1,022,198**	**100**		**45,577**	**100**		**710,978**	**100**	

Table 7. Flooded areas and exposed population during 2020 flood.

District	Total area (ha)	Total population	Monsoon 2019						Post-monsoon 2019					
			Inundated area (ha)	Percentage with respect to total inundation (%)	Percentage with respect to total district area (%)	Exposed population	Percentage with respect to total exposed population (%)	Percentage with respect to total district population (%)	Inundated area (ha)	Percentage with respect to total inundation (%)	Percentage with respect to total district area (%)	Exposed population	Percentage with respect to total exposed population (%)	Percentage with respect to total district population (%)
Gazipur	181,753	5,783,164	16,985	40.25	9.35	238,237	35.64	4.12	12,059	38.53	6.63	168,113	32.51	2.91
Dhaka	147,640	15,505,383	12,633	29.93	8.56	273,058	40.85	1.76	10,600	33.87	7.18	246,565	47.68	1.59
Narayanganj	93,288	3,614,222	5278	12.51	5.66	97,567	14.60	2.70	3591	11.48	3.85	68,129	13.17	1.89
Munshiganj	70,370	1,516,072	7308	17.32	10.39	59,502	8.90	3.92	5044	16.12	7.17	34,332	6.64	2.26
Total	**493,051**	**26,418,841**	**42,204**	**100**		**668,365**	**100**		**31,294**	**100**		**517,140**	**100**	

Table 8. Flooded areas and exposed population during 2019 flood.

periods, the exposed population was mainly from Dhaka district, which is the most populous among the four districts. Approximately 30% of Dhaka falls in the least to less flood-prone zones, while 35% are in high to very high flood-prone zones[72].

Although the exposed population in Dhaka was higher, it constitutes only 3% of the district's population, whereas this percentage is higher for Gazipur (5%) and Munshiganj (7%). The western part of Dhaka is protected by embankments on the Buriganga River. People exposed to floods in Dhaka are mainly slum dwellers who have no alternative but to live near riverbanks. The poorer inhabitants of Dhaka city are among the most vulnerable to floods, as they live in densely populated slums located in areas of unplanned and unregulated development. It is also observed that people living in low-lying agrarian lands are more exposed to flooding than those in built-up areas. These results are consistent with a previous study by[73], where they observed that agricultural fields covered the areas most affected by floods. Poor economic conditions, lower adaptive capacity, and higher exposure to the flood make certain areas more vulnerable than others[74]. Satellite observations show that population density is higher near rivers. The population density of Greater Dhaka is 5,400 per square kilometer, but within 1 km of river buffers, it is 6,600 as of 2020. Although population density is higher near rivers, the growth rate is lower compared to Greater Dhaka. The growth rate of Greater Dhaka was 36% for the period of 2010–2020, while it was 28% near the rivers.

Observing the water quality of the Greater Dhaka rivers, it is found that Tongi Khal, Balu, and Buriganga are severely polluted (Table 9). Buriganga and Tongi Khal receive a huge amount of industrial waste from the BSCIC industrial estate, textile dyeing, chemical, pharmaceutical, printing, packaging, glass, ceramic factories, food processing, and other miscellaneous industries, along with municipal waste. During dry periods and relatively low flow situations, pollution becomes more intense[75]. Even during high flow periods, these rivers remain in marginal conditions. Industrial effluents, domestic sewage, and urban runoff from the Tongi area contribute to pollution in the Balu River. Due to the relocation of the tannery industry from Hazaribag to Harindhara, Savar, pollution of the Dhaleswari River has significantly increased in recent years[76]. However, in this study, we found that Dhaleswari water quality was marginal only during the post-monsoon period of 2019, whereas it was poor at all other times (Figs. 10 and 11). High concentrations of Ammonia/Nitrogen, Total Organic Carbon, and Sulfate were found downstream of the new tannery near Harindhara (Location 35 in Fig. 12).

A sudden drop in dissolved oxygen was also observed at this location, indicating that untreated organic wastes were discharged at that point. A recent study found that heavy metal concentrations increase from upstream to downstream sites from the tanneries' discharge points, expected to reach serious levels during the upcoming dry season, particularly for Cr, Cd, and As[38]. The observed metal values for the rivers of Greater Dhaka during 2019 and 2020 are shown in Figs. 13 and 14.

Flooding and pollution near riverbanks (within 1 km from the banks):

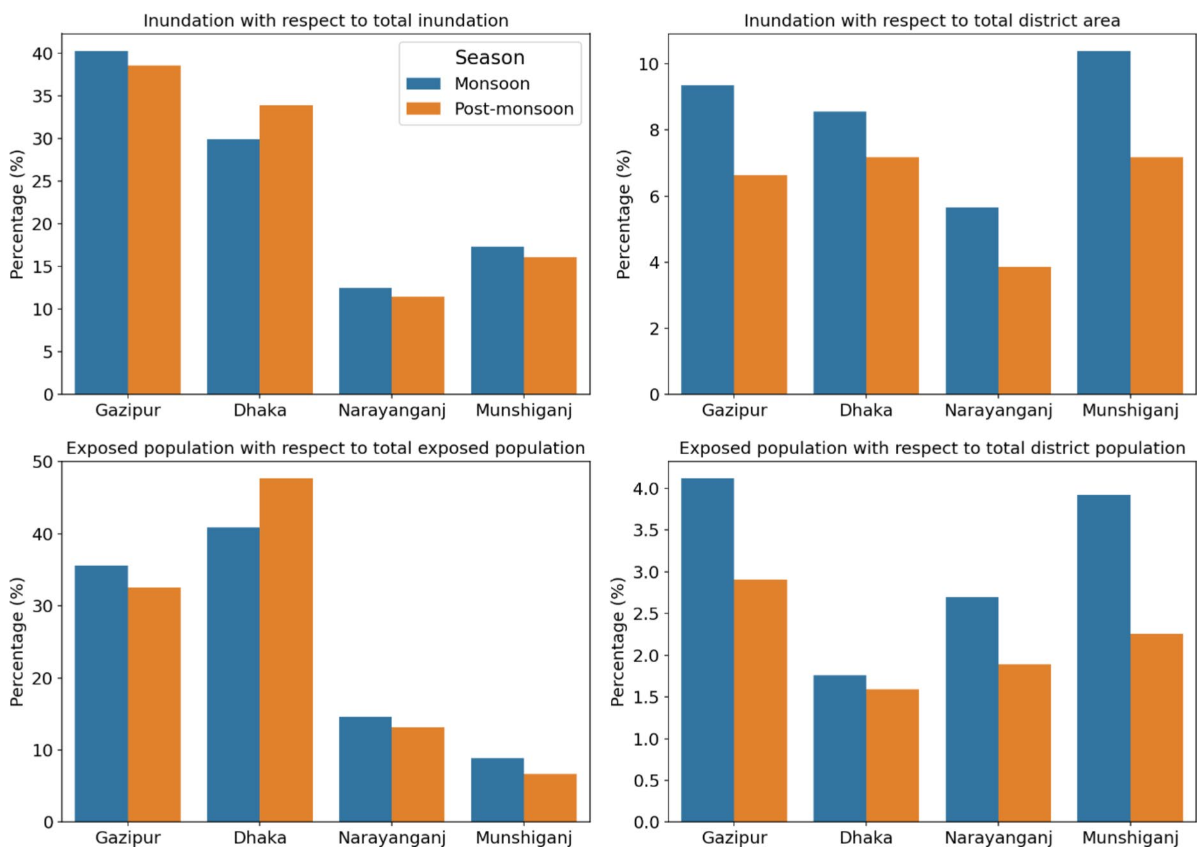

Fig. 6. Flooded areas and exposed population during 2019 flood.

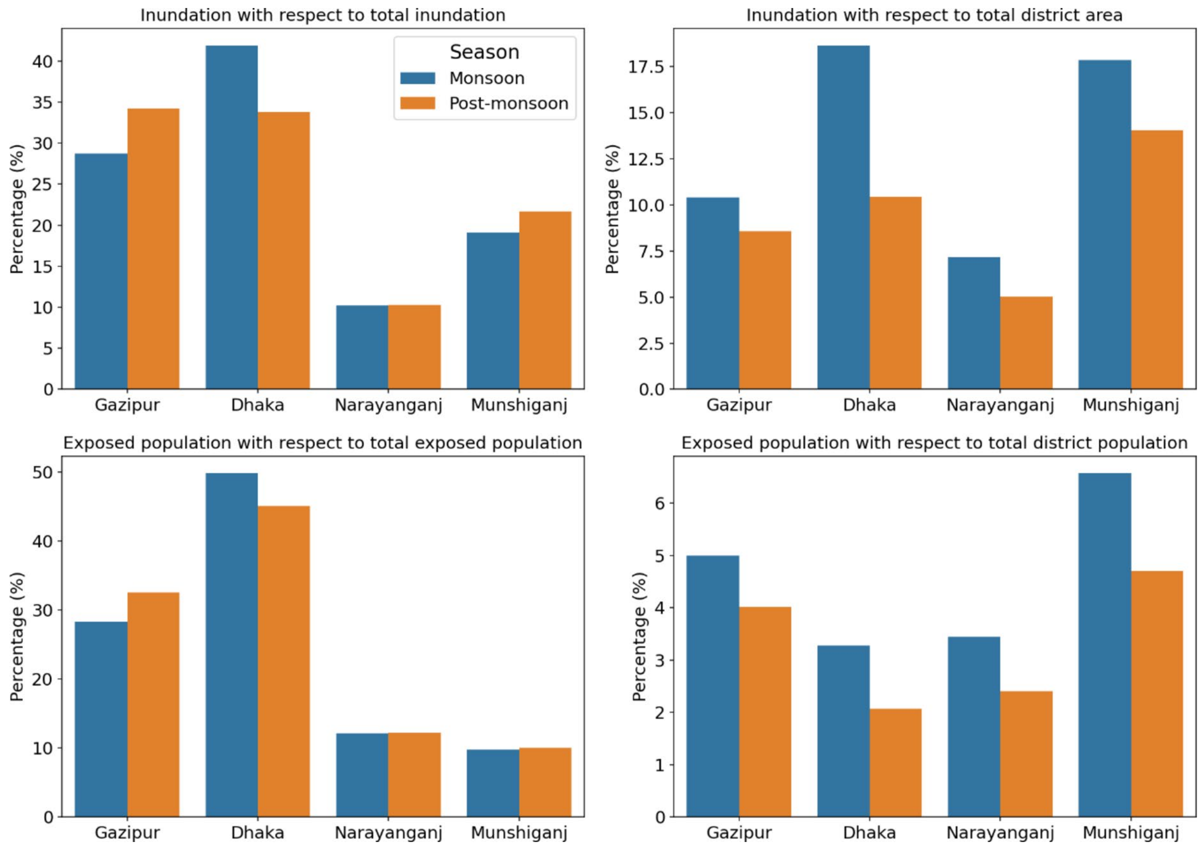

Fig. 7. Flooded areas and exposed population during 2020 flood.

The study also observes flooding condition within 1 km of the rivers as most of the industries, economic zones and growth centers are located around the rivers and people reside near the river are more vulnerable to various type of waterborne diseases. Floodwaters in Dhaka are often contaminated with pollutants from various sources, including industrial effluents, agricultural runoff, and domestic waste. This contamination can lead to the spread of waterborne diseases[36,77]. In terms of inundation, Gazipur is the highest affected district among the four districts. Also, the number of exposed populations in Gazipur is higher than in the other districts. It is mainly because of Upper Turag and the upstream part of Balu flowing through Gazipur being more susceptible to flooding than other rivers of Greater Dhaka. After Gazipur, inundation was higher at Dhaka followed by Munshiganj and Narayanganj. Narayanganj is the lowest affected district among the four. In Narayanganj, flooding due to overflow of Shitalakhya is less. Overflow of Balu River inundates some parts of Rupganj Upazila (Narayanganj). About 20.29% of people of Greater Dhaka live within 1 km of the selected rivers area whereas this area covers 17% of the total study area. About 40% of the area within 1 km of rivers are cropland. Built-up area comprises of about 22% and rural settlement is about 20%. Brickfields occupy about 3.47%, which is higher than the brickfields percentage within the whole greater Dhaka.

Out of the 26 economic zones in Greater Dhaka, 6 are within 1 km of rivers. Among the 18 industrial parks, 8 are also within this proximity, along with 38 out of 92 metal industries. There are 817 rural markets in the Greater Dhaka area, with 300 of these located within 1 km of rivers, and 165 of them situated within 1 km of the study area's rivers. Most of these markets lack planned waste management or drainage systems. Alongside wastewater, people dispose of garbage wherever they find space, often into nearby rivers or canals. Out of the 95 growth centers (GCs) in Greater Dhaka, 62 are within 1 km of rivers, and 35 are near the major rivers of the study area. Based on these criteria and the location of GCs and rural markets in Greater Dhaka, rivers and canals appear to be important factors in selecting GCs, playing a vital role in the rural economy. Economic hubs tend to develop around waterways, which impacts them in various ways, especially due to inadequate waste management and drainage systems throughout the country. Polluted floodwater is commonly used for bathing, washing, and irrigation purposes. Reduced agricultural production, decreased fish catches, and increased incidence of diseases among children have been reported by a significant number of households near Tongi Khal[21]. Pollution exposure through domestic activities is prevalent among women, while swimming peaks among men and children during the monsoon, increasing the risk of exposure to pathogenic pollution[40]. This study found that approximately 36,000 people were exposed to floodwater within 1 km of the Tongi Khal and Balu rivers when water quality was marginal (Table 10). During the post-monsoon period, this number increases to 60,000 as the water quality of the Buriganga was also found to be marginal. During disasters, the percentage of households affected by waterborne diseases increases up to 94.20%, and post-disasters, the percentage of households affected by waterborne diseases is 91.65%[8]. Flooding occurrences combined with polluted water

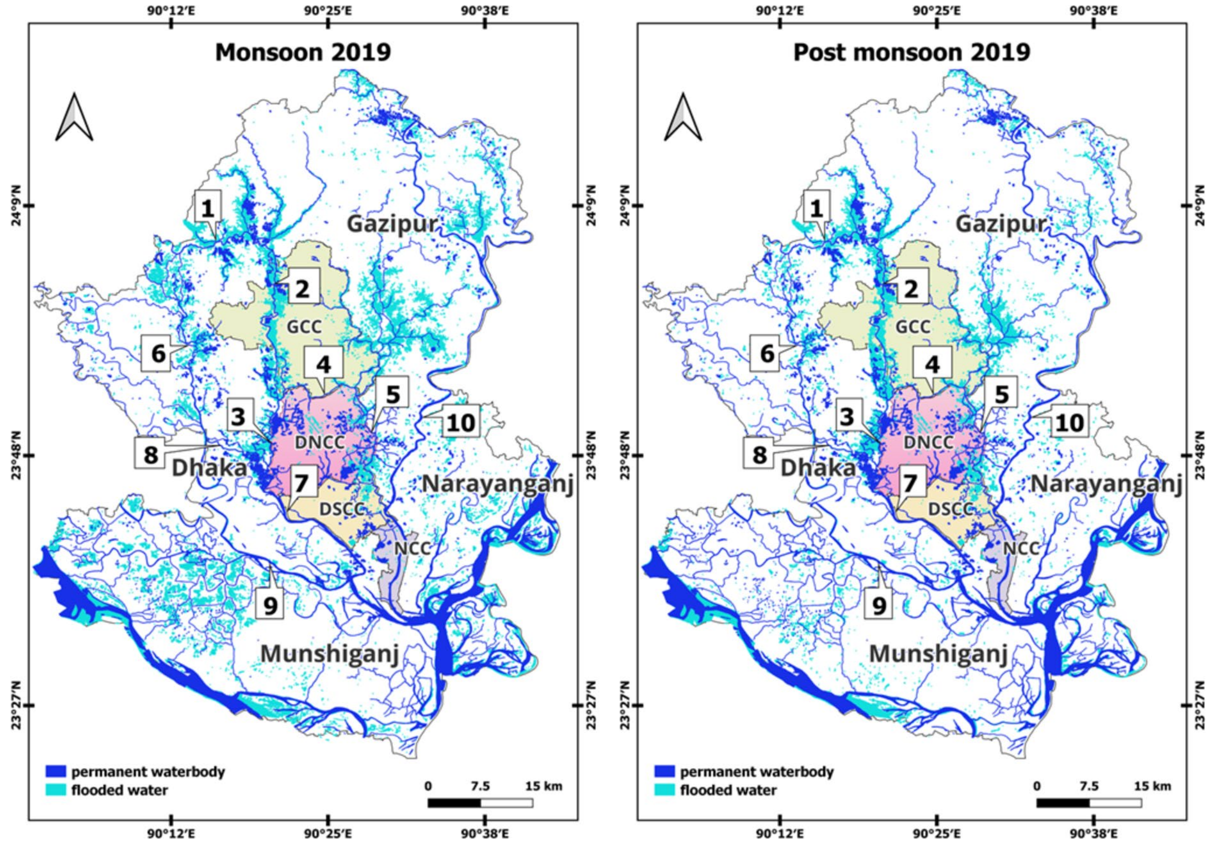

Fig. 8. Inundation maps of flood 2019.

sources increase the risk of waterborne illnesses, especially cholera, which is common in Greater Dhaka[16]. It has been established that consuming contaminated water and food can cause major health problems, including cancer[78]. Over 90,000 people in Dhaka alone experienced diarrhea during the 2007 floods[79]. Urban flooding episodes have a detrimental effect on women's health because they do not obtain enough food, medical attention, or physical protection. This leads to a rise in illnesses, health problems, and even fatalities among women[80,81].

From field visits to Islampur, Hazratpur, and Mausaid, which are located downstream of heavy industrial zones, it was found that during the monsoon and post-monsoon periods, most of these areas are flooded with polluted water. More than 50% of the flooded areas are croplands. The livelihood of most residents depends on farming and fishing in these areas, and people use this polluted water for irrigation. This has not only affected crops but also the health and wellbeing of the people. Although embankments alter the natural river system, in situations like this, embankments may not be a bad choice.

Rising temperatures and rainfall, particularly during the monsoon season, are expected to cause more frequent and severe flooding, with extreme rainfall events projected to increase by 16% by 2050[79,82]. The Dhaka River System, already heavily polluted, faces worsening water quality due to climate change, which affects dissolved oxygen levels and is further strained by industrial discharges, particularly during extreme weather[83]. While climate projections indicate increased dry season flow and more frequent floods, concerns also arise over how rising temperatures could alter pollutant release mechanisms in the river system.

Flooding and poor water quality in Greater Dhaka disproportionately impact vulnerable populations, particularly low-income and marginalized groups living in poorly constructed, flood-prone housing[84]. These communities face higher exposure to polluted floodwaters containing industrial waste and untreated sewage, which increases the risk of waterborne diseases, especially for children and the elderly[85,86]. The combined effects of flooding and poor water quality place significant economic strain on these populations, as they must spend more on healthcare and clean water, deepening poverty[40]. Structural vulnerability, such as the lack of adequate water access and flood awareness, further exacerbates their risk. Dhaka's rapid, unplanned urban expansion has worsened these challenges, with a large portion of informal settlements in areas highly susceptible to flooding and waterlogging. The economic burden of floods falls heavily on low-income communities, often resulting in displacement, loss of livelihoods, and increased health expenses, reinforcing existing social inequalities and hindering sustainable development efforts[87].

Addressing these challenges requires strengthening infrastructure and incorporating resilience principles into urban planning[88]. Structural measures such as new pipelines, control structures, and pumps can reduce the impact of floods, but these solutions are expensive for densely populated cities like Dhaka. However, early warning systems offer a low-cost way to minimize damage[89]. Utilizing existing water bodies as retention ponds could also significantly mitigate Dhaka's flooding problems[79]. Building resilience necessitates involvement of

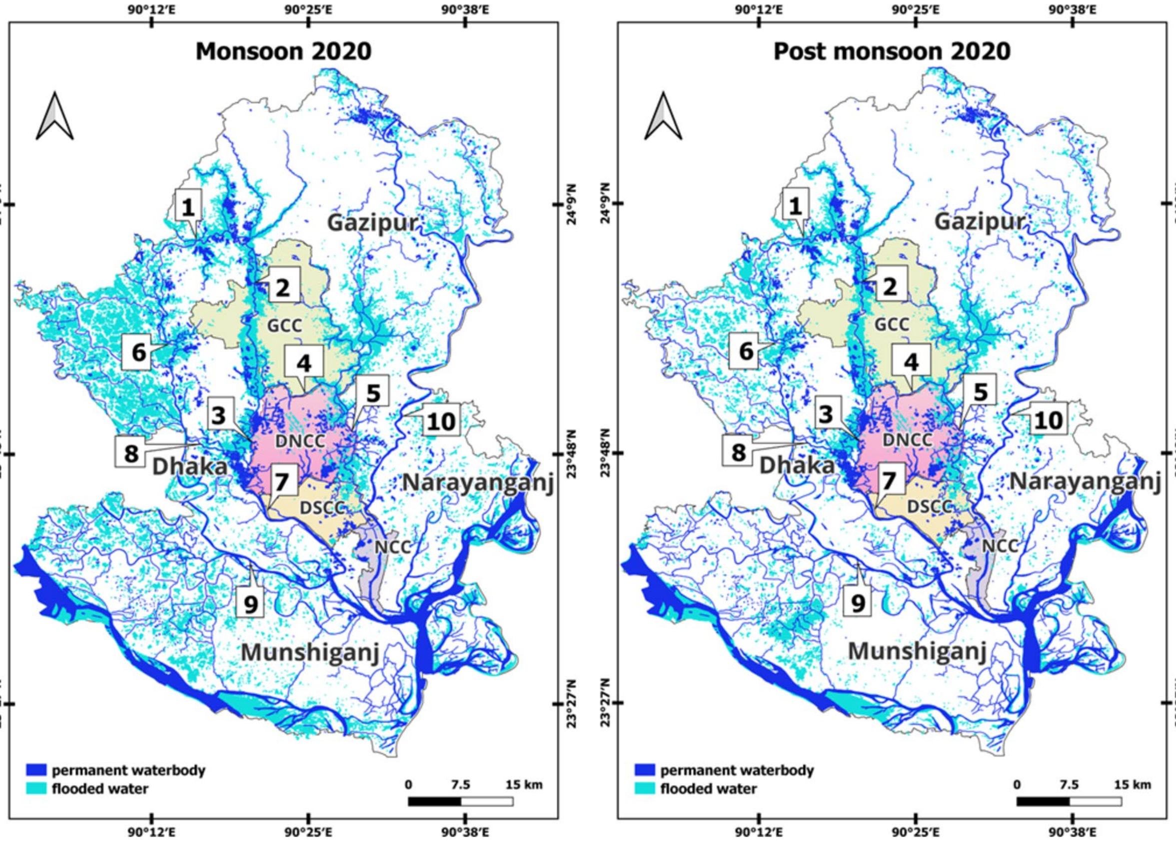

Fig. 9. Inundation maps of flood 2020.

River Name	Monsoon 2019 (July)		Post-monsoon 2019 (October)		Monsoon 2020 (August)		Post-monsoon 2020 (October)	
	WQI	Category	WQI	Category	WQI	Category	WQI	Category
Balu	32.28	Poor	35.71	Poor	36.77	Poor	29.58	Poor
Bangshi	44.63	Poor	57.62	Marginal	36.43	Poor	39.56	Poor
Bangshi Savar	42.56	Poor	44.37	Poor	39.21	Poor	34.40	Poor
Buriganga	40.95	Poor	39.99	Poor	37.90	Poor	32.94	Poor
Dhaleswari	38.22	Poor	53.01	Marginal	35.86	Poor	37.13	Poor
Shitalakhya	37.36	Poor	45.69	Marginal	37.31	Poor	38.77	Poor
Tongi Khal	33.09	Poor	35.95	Poor	35.75	Poor	31.01	Poor
Turag (Kaliakoir to Konabari)	46.75	Marginal	59.54	Marginal	52.58	Marginal	49.99	Marginal
Turag (Konabari to Rustampur)	39.42	Poor	50.24	Marginal	41.59	Poor	43.33	Poor
Turag (Rustampur to Aminbazar)	41.08	Poor	52.49	Marginal	43.50	Poor	47.47	Marginal

Table 9. River wise water quality index at different times.

communities in identifying risks and developing tailored mitigation strategies. Effective non-structural initiatives can be implemented by leveraging strong social networks and capital[88]. There has been some broad suggestions in contemporary literature to improve the social, economic, institutional, and physical components, which can be implemented through community awareness and disaster preparedness programs, to assist communities in strengthening resilience and coping with floods[90]. There has been also argument that though the rising land costs have made traditional methods such as wetlands seem unfeasible for floodwater pollution mitigation, planning should account for implementing these solutions, particularly in areas like Narayanganj and Eastern Dhaka[91]. Improving floodwater quality also requires designing and implementing a comprehensive solid waste and industrial effluent disposal system, as well as an efficient human-waste management system[79].

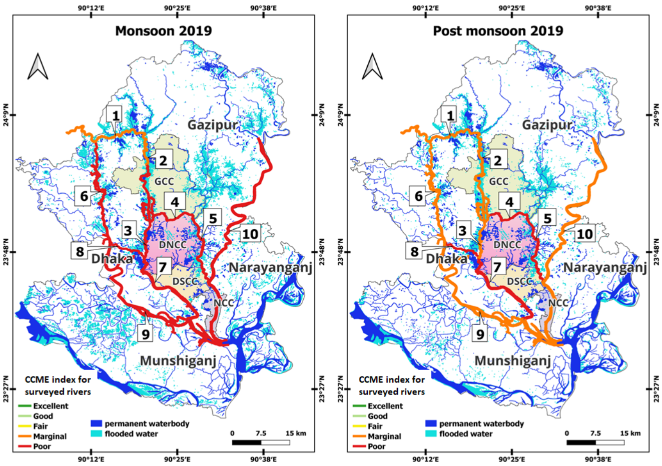

Fig. 10. Water quality index during flood 2019.

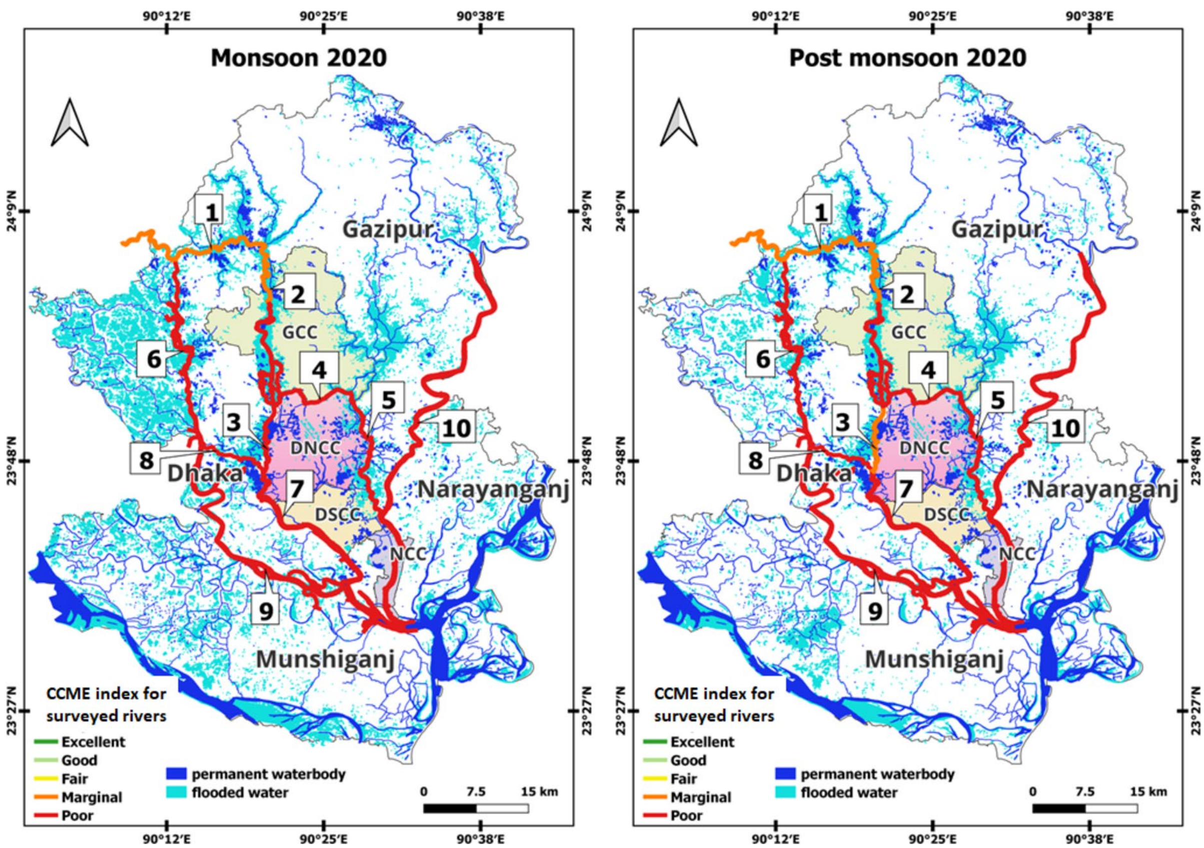

Fig. 11. Water quality index during flood 2020.

Conclusions

This study conducted estimation of flooded areas and preparation of flood maps for Greater Dhaka during both the monsoon and post-monsoon periods for the years 2019 and 2020. Simultaneously, water quality was assessed through field observations and laboratory analysis, and the exposed population was calculated using remote sensing data during flooding events. This study presents a comprehensive picture of flooding and water quality in the rivers of Greater Dhaka, which had not been systematically targeted in earlier studies.

Remote sensing-based flood mapping was used in this study instead of hydrodynamic-based flood mapping. Flood mapping using hydrodynamic models offers several advantages, such as producing flood maps at higher temporal and spatial resolutions and providing detailed information about flood characteristics like depth, duration, and flow velocity. However, developing a hydrodynamic model is complex and requires both

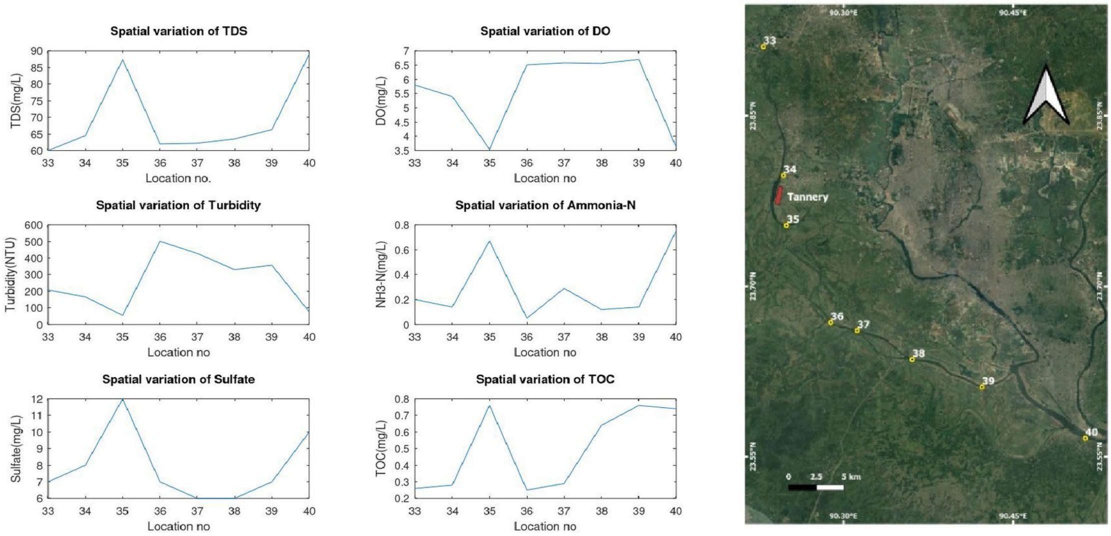

Fig. 12. Spatial variation of water quality parameters in Dhaleswari (from u/s to d/s) (July 2019).

hydrological and bathymetric data for the study area. In developing countries like Bangladesh, acquiring these data can be challenging, particularly for a large study area covering 8 rivers and approximately 500 km of waterways where such data are lacking. Given these challenges, flood mapping using Sentinel-1 is advantageous for our study area. This method utilizes microwave remote sensing, which can monitor the Earth even under cloudy conditions, unlike optical remote sensing. Moreover, Sentinel-1 SAR data are freely available online with high spatial resolution and a revisit time of six days. Since our focus was on observing flood extent rather than flood depth, remote sensing-based flood mapping proved effective for our study area and could potentially replace hydrodynamic-based methods solely for assessing flood extent. Google Earth Engine's cloud-based computation environment was found effective for flood monitoring in this study because it could accurately differentiate between active flood zones and perennial water bodies, thereby attributing flood exposure directly to the respective rivers involved. This approach could assist disaster management authorities in initiating emergency responses during flood events.

Scholarly contributions with regard to risk reduction concentrated their effort on pollution of rivers only with little or no regard to their floodplain regime functions. This is true for the Greater Dhaka area as well. It is often ignored that this polluted water stays at the floodplain for a long period of time during monsoon and post-monsoon. This may have a long-time adverse effect on the soil quality of these areas and also on the crops that are cultivated in these floodplains with effect on agricultural growth and human health from consuming such agricultural produce which was raised in a number of literatures at recent times, albeit with different scale or focus. So, it is recommended that while implementing any projects on the rivers of Greater Dhaka, the governing authority should consider both the rivers and the floodplains.

It is a common belief in the country that water quality remains poor only during dry periods and that the monsoon is a blessing for riverine communities. This belief is based on the assumption of the rivers' natural, unpolluted or less polluted state, where sediment regime and inundation play critical roles in ecosystem sustenance and functions. It also assumes that monsoon flows and associated dilution can mitigate pollution, making pollution primarily a phenomenon of the dry season. This often results from assessing too few parameters to evaluate water quality or disregarding its intended use. This belief is integral to the planning and policy-making processes within the country, evident in restoration efforts for the Greater Dhaka Watershed. This study challenges these myths by demonstrating that despite high flows during the monsoon and post-monsoon periods, many rivers in Greater Dhaka, especially the Buriganga, Tongi Khal, and Balu, still remain in marginal to poor condition. During this time, hundreds of thousands of people living in floodplains or active flood zones are exposed to polluted water for prolonged periods. This is particularly true for river stretches housing large municipalities and industries, such as Tongi Khal, Buriganga, and parts of Turag. For these areas, the monsoon is not necessarily a blessing but rather a period of strife and suffering, either in the short or long term. Therefore, a change in narrative is imperative, which, alongside raising awareness about potential risks of exposure, can reduce risks to people. The lack of awareness is evident in the water usage during the monsoon and post-monsoon periods by affected communities, even in the presence of alternative sources[40].

One of the limitations of this study is the accuracy assessment of flood mapping. Due to extensive cloud cover in Landsat images during the monsoon, we had to use smaller subset areas for validation. Future studies could explore the use of satellites with more frequent revisit times, such as PlanetScope (daily revisit), to improve the likelihood of acquiring cloud-free imagery during flood events. This study employs manual thresholding for flood mapping; however, future research could explore automated thresholding techniques such as Otsu's method. The resolution mismatch between datasets can introduce uncertainties and inaccuracies in analyzing population exposure to flooding. Since the population data has a coarser resolution than the flood data, there is a risk of overestimating or underestimating the number of people exposed to floods. To reduce these discrepancies,

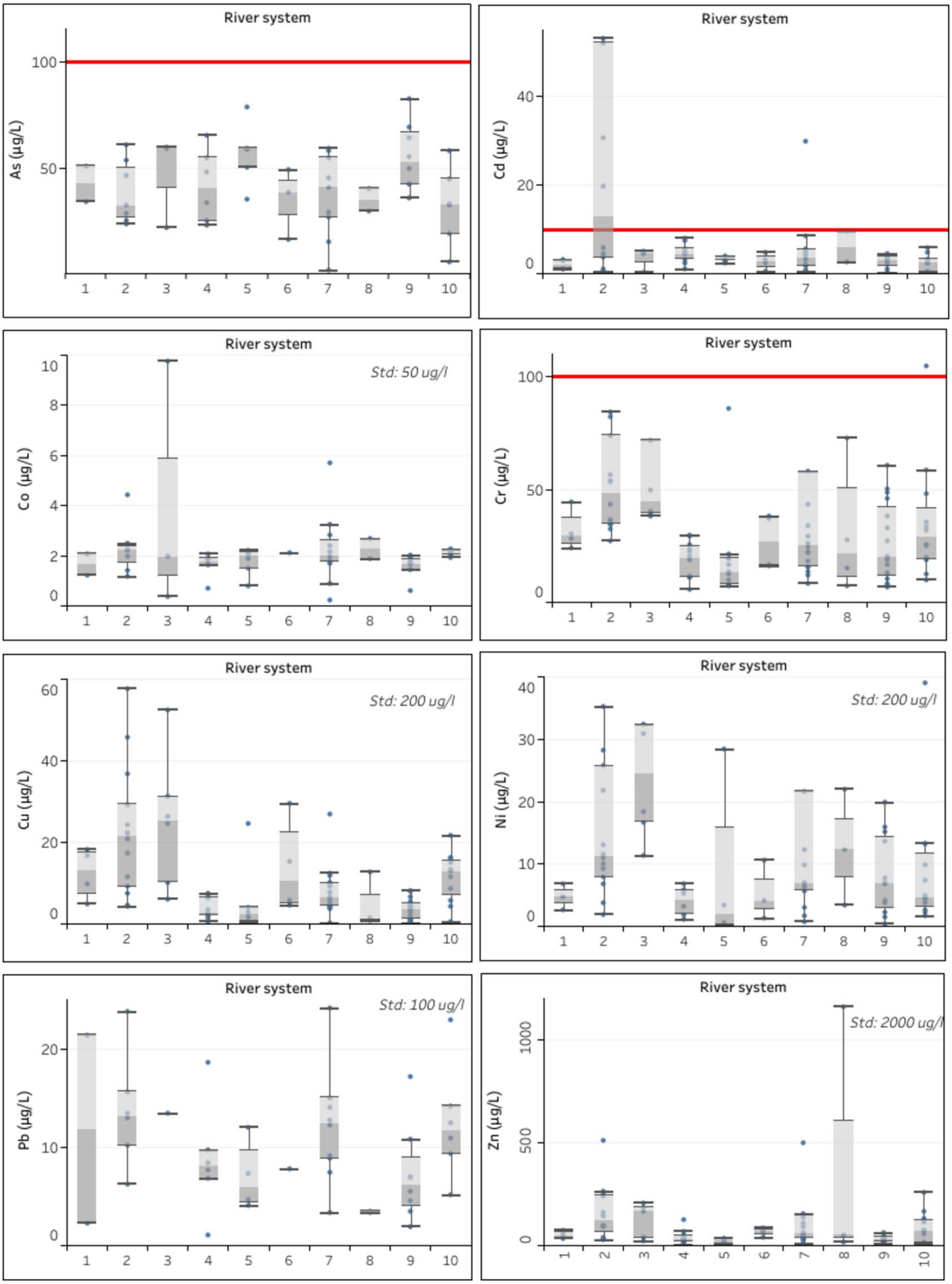

Fig. 13. Observed heavy metals concentration ranges for the rivers during 2019.

future researchers are advised to use datasets with matching resolutions. This study did not consider sediment pollution assessment. In-depth study to understand the multi-cascade (Water-Sediment-Soil-Plant) pollution accumulation and their impact needs to be undertaken to do a proper health risk assessment from exposure of agricultural lands and people to polluted floodwaters.

Our findings indicate that most rivers in Greater Dhaka were in 'marginal' to 'poor' condition during both the monsoon and post-monsoon periods of 2019 and 2020. Buriganga, Tongi Khal, and Balu were consistently in poor condition throughout the study period. Preventing waste dumping into these rivers could help improve their water quality. Among the four districts, Dhaka and Gazipur were the most affected by floods in terms of inundation area and exposed population. The index-based water quality as done here for river reaches can serve

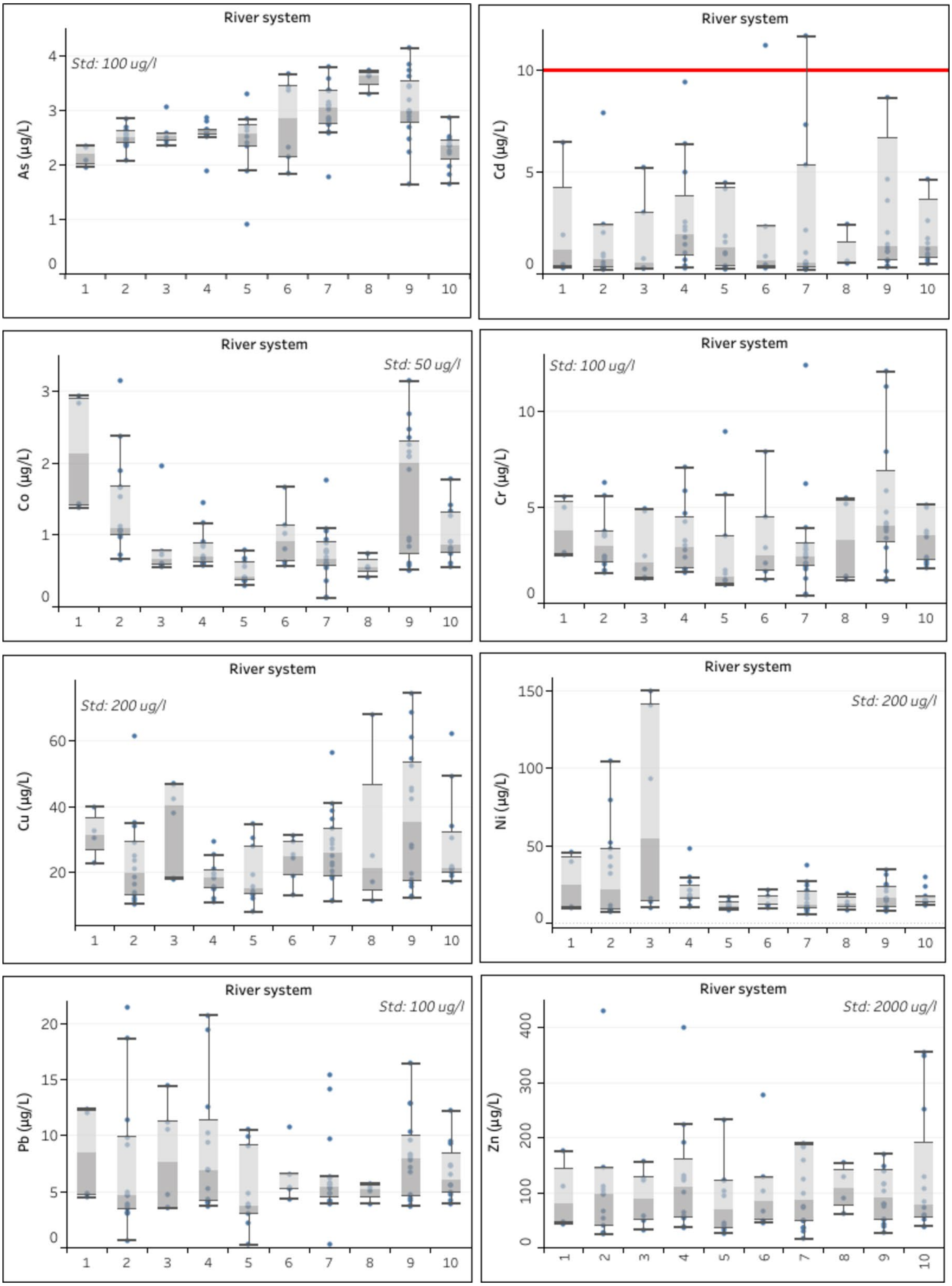

Fig. 14. Observed heavy metals concentration ranges for the rivers during 2020.

as a guideline. The parameters considered for this study to assess water quality largely derive from irrigation standards and ambient surface water quality standards which implies poor water quality would be detrimental to agriculture and human health. The River Masterplan has included embankments and dredging of polluted rivers for restoration efforts whereas recent recommendations from donor agencies have emphasized flood protection for exposed areas of the study area. The findings of this study and the methodologies employed may serve as

River Name	Monsoon 2019 (July)		Post-monsoon 2019 (October)		Pre-monsoon 2020 (February)		Monsoon 2020 (August)	
	WQI Category	Exposed Pop.	WQI Category	Exposed Pop.	WQI Category	Exposed Pop.	WQI Category	Exposed Pop.
Balu	Poor	20,413	Poor	20,964	Poor	31,492	Poor	10,920
Bangshi	Poor	19,041	Marginal	14,607	Poor	32,657	Poor	8323
Bangshi Savar	Poor	15,088	Poor	14,585	Poor	24,565	Poor	12,218
Buriganga	Poor	18,031	Poor	19,215	Poor	25,240	Poor	19,313
Dhaleswari	Poor	36,654	Marginal	33,083	Poor	63,231	Poor	20,617
Shitalakhya	Poor	32,687	Marginal	29,939	Poor	36,864	Poor	33,716
Tongi Khal	Poor	6717	Poor	7943	Poor	14,474	Poor	38,788
Turag (Kaliakoir to Konabari)	Marginal	43,308	Marginal	39,841	Marginal	53,798	Marginal	48,767
Turag (Konabari to Rustampur)	Poor	35,568	Marginal	35,477	Poor	52,825	Poor	48,813
Turag (Rustampur to Aminbazar)	Poor	17,495	Marginal	19,377	Poor	21,319	Marginal	26,335

Table 10. River wise water quality index and exposed population within 1 km of the rivers.

guidelines to decide on priority locations and interventions including soft interventions like communication and awareness building. Further studies coupled with economic and social benefits assessment of interventions would be essential to guide a targeted restoration effort for the Greater Dhaka watershed. Collaboration between science and practitioners including international partners have yielded good result in shaping proper implementation strategies with evidence based findings leading to alternation of plans, setting priorities and adoption programmes tailored to meet the needs as has been observed in[92].

This study makes several significant contributions to the existing literature on flood pollution and its impacts on urbanizing regions. While previous studies have primarily focused on flood inundation or water quality separately, this research integrates these two critical aspects by using remote sensing to assess flood extent and primary data to analyze water quality during the same period. This comprehensive approach provides a more holistic understanding of the environmental challenges faced by Greater Dhaka. By incorporating primary water quality data, the study adds a new dimension to the understanding of how industrial pollutants and untreated sewage exacerbate the health risks associated with flooding, as discussed in previous literature. It also negates the myth regarding monsoon time good water quality and shows that monsoon poses more risks than post-monsoon in most cases in terms of pollution severity. The river health consideration with regard to water quality should be a determining factor while addressing flood related issues and devising mitigation or adaptations measures and a separate kind of interventions tailored to fit the need of people living in rural settings and in downstream riparian areas. The findings are particularly relevant for policymakers focused on developing comprehensive strategies to mitigate the adverse effects of flooding and improve the resilience of vulnerable communities living close to the rivers through targeted adaptation options, e.g., flood protection in areas downstream to urban centers in conjunction with interventions targeting reduction of pollution at source, removing polluted sediments from narrow rivers like Tongi Khal reducing pollution from resuspension of sediments during monsoon, etc. be actively under consideration.

Data availability

Data can be requested by emailing the corresponding author.

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Competing interests
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