Case Study

Effects of combined sewer overflow on water quality: a case study of Hatirjheel Lake in Dhaka

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Abstract

This paper presents a case study focusing on the impacts of combined sewer overflows on the water quality of the receiving water body, Hatirjheel. Hatirjheel, the largest surface water body in Dhaka City with an area of about 1.012 km^2, receives discharges from nine combined sewer overflow (CSO) structures. The water quality of Hatirjheel is poor throughout the year, but particularly during the wet season (June to October) near the CSO structures through which significant rainwater-sewage overflows. The water has been found to contain high concentrations of 5-day biochemical oxygen demand (BOD_5) and chemical oxygen demand; some of the BOD_5 values exceed the national discharge standards for treated effluents. Total ammonia concentration in Hatirjheel water increases during the wet season, often exceeding 20 mg/l; the concentration continues to increase after the end of the wet season, most likely due to the ammonification process. Nitrate concentration in Hatirjheel water increases at the end of the wet season, possibly due to nitrification; subsequent reduction in nitrate and ammonia concentration is possibly due to incorporation of nitrogen into algal mass. Excessive phosphorus in Hatirjheel promotes eutrophication, resulting in the visible greenish color of the water. This study highlights the significant adverse impact of combined sewer overflows, particularly for a densely populated city like Dhaka, where most of the rainfall occurs within a relatively short period during monsoon.

ArticleHighlights

- Combined sewer overflows could significantly deteriorate the water quality of the receiving water bodies.
- Sewer overflows create a significant spatiotemporal variation of water quality, with higher pollution close to the overflowing combined sewer overflow structures.
- Because of its significant adverse impact on water quality and ecology, combined sewer systems may not be viable for high-density urban areas.

Keywords Urban · Water pollution · Organic · Ammonia · Phosphate

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1 Introduction

In many cities, wastewater and stormwater are conveyed through combined sewer networks. During dry weather conditions, these systems carry wastewater (mainly sewage), while the sewers carry both wastewater and stormwater during the wet period. During heavy precipitation events, the capacity of combined sewer systems is often exceeded, and the mixture of wastewater and stormwater is discharged into receiving surface water bodies as combined sewer overflows. A combined sewer overflow (CSO) structure is designed to divert excess flows from the combined sewer networks directly into a receiving water body. CSOs are common in both developed and developing countries [1] and are a significant source of pollutants (including pathogens, oxygen demanding wastes, suspended solids, and nutrients) for water bodies [2–5]. The rationale supporting the technical acceptance of CSOs is that the pollutant concentration in the combined sewer decreases due to dilution during heavy rainfall, and the renewal (self-purification) time of the water body receiving overflows is short [6]. However, these conditions are often not met, resulting in a significant discharge of pollution load to water bodies from CSO structures and pollution of the receiving water bodies [7, 8]. In many urban areas, the storm runoff contains significant pollutants from diverse sources [9], and its mixing with sewage does not bring about the desired dilution.

In Dhaka, the capital of Bangladesh with a population of over 20 million, a sewerage system covers only about 20% of the city area; actual coverage, however, is significantly lower due to blockages in the sewer network and non-functional sewage lifting stations [10]. The remaining city areas are covered by an onsite sanitation system, mainly a septic tank system. But, due to high population density, the septic tank system (particularly the soakage wells) does not perform well. As a result, in most city areas, with and without sewerage networks, large-diameter storm sewer networks are illegally utilized for the discharge of domestic sewage. As a result, these sewer networks act as combined sewers and carry both domestic wastewater and stormwater. Hatirjheel, the largest lake in Dhaka City with an area of about 250 acres (1.012 km^2), used to receive discharges from 11 storm sewer outfalls covering a catchment area of over 23 km^2 [11, 12]. As shown in Fig. 1, two major lakes, Gulshan lake and Banani lake, also discharge into Hatirjheel. As a part of the restoration of Hatirjheel, 11 combined sewer overflow (CSO) structures were constructed at the 11 outfall locations surrounding Hatirjheel (see Fig. 1), and a flow control gate was constructed at its downstream end. Before the construction of the CSO structures, Hatirjheel received the entire discharge from the storm sewer outfalls that carry both sewage and stormwater throughout the year; this caused severe pollution of Hatirjheel and the downstream canal system [13]. The primary purposes of the CSO structures and the diversion sewers were to improve the water quality of Hatirjheel through the diversion of the entire dry weather flow (consisting of sewage) and a significant part of the combined sewage-stormwater flow during the wet season. However, the combined sewer overflows appear to be causing significant pollution of Hatirjheel. The water quality of Hatirjheel deteriorates significantly during the wet season every year due to huge overflows of mixed stormwater-sewage, which is evident from visual observation (dark color of water and obnoxious smell). There appears to be significant spatial variation in the water quality of Hatirjheel during the wet season, depending on the locations of the CSO structures. The water quality of Hatirjheel close to CSO-1, which receives the most significant sewage-stormwater flows, becomes very poor during the wet season.

Samad [14] reported the characteristics of flows (during both dry and wet seasons) that reach the CSO structures of Hatirjheel through the storm/combined sewers. The dry weather flows (which do not contribute to the combined sewer overflows) contain high concentrations of BOD_5 (68 to 240 mg/l), COD (257 to 622 mg/l), ammonia (22.6 to 41.9 mg/l, as total ammonia nitrogen), and phosphate (3.23 to 10.2 mg/l as PO_4) [14]. These characteristics are comparable to medium and high strength domestic sewage [15]. The characteristics of flows reaching the CSO structures improve to some extent during the wet season, due to dilution with rainwater, with BOD_5 varying from 42 to 250 mg/l; COD from 76 to 346 mg/l; and total ammonia nitrogen from 12.0 to 26.8 mg/l [14]. The characteristics of mixed stormwater-sewage coming into the CSO structures through the storm/combined sewers during the wet season (and which contribute to the combined sewer overflows during precipitation events) vary significantly depending on the precipitation. Nevertheless, these data suggest that the combined stormwater-wastewater carried through the sewer networks contains a high pollution load; this mixed stormwater-wastewater overflows into Hatirjheel during the wet season through the CSO structures.

The restoration works of Hatirjheel included construction of CSOs, laying of diversion sewers along the lake periphery, plantations and seating arrangements surrounding the lake, and construction of walkways and a foot overbridge across the lake. These developments have made Hatirjheel an important recreational place for city dwellers. There are boat services that take people from

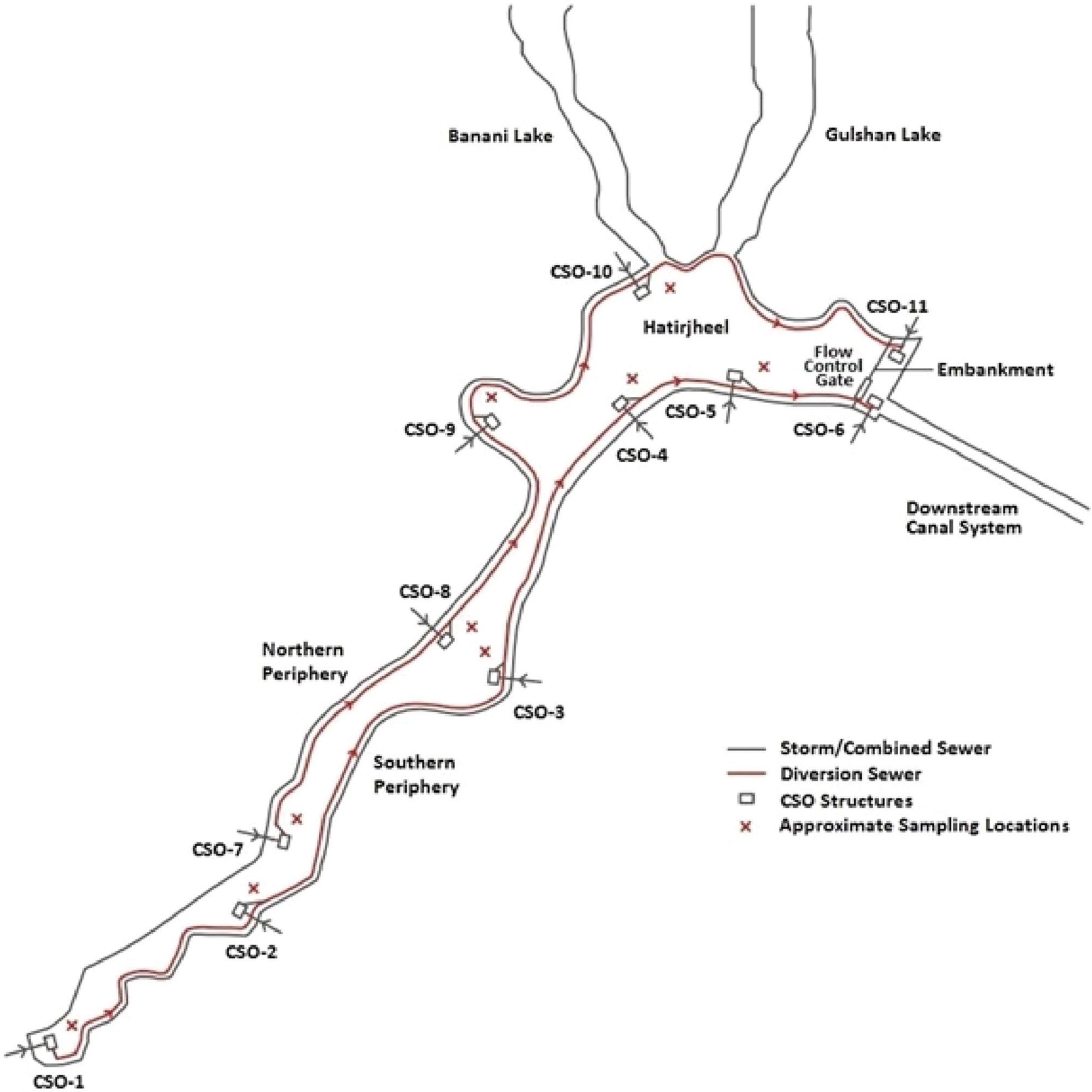


Fig. 1 Schematic representation of Hatirjheel Lake showing the CSO structures, diversion sewers, and the approximate sampling locations

one end of the lake to the other along two routes; people also use this service for recreation. During the peak wet season, water in some lake areas turns dark and emits an obnoxious smell; during this period, boat service often has to be suspended because of the intense pollution. Efforts by the project implementing agency to introduce recreational fishing in Hatirjheel are reported to have failed due to water pollution. The continued pollution of Hatirjheel by sewer overflows, particularly during the wet season, is a significant concern and a public nuisance. However, no system is in place to monitor the water quality of Hatirjheel, and there is no systematic data on temporal or spatial variation of water quality. The primary purpose of this case study was to assess the impact of combined sewer overflows on the water quality of Hatirjheel through year-long monitoring of important water quality parameters including pH, EC, turbidity, color, suspended solids, ammonia, nitrate, phosphate, sulfate, chloride, BOD_5, and COD.

In the next section (Sect. 2), we describe the layout and operation of the CSO structures in Hatirjheel. This section also presents the methodology followed for water quality monitoring of Hatirjheel. Section 3 describes the variation of the water quality of Hatirjheel based the monitoring results. The major conclusions from the present study are summarized in Sect. 4.

2 Materials and methods

2.1 Hatirjheel system description

The Hatirjheel provides detention storage and drainage passage to over 23 km^2 of western Dhaka City [11, 12]. Storm runoff from this large area, primarily comprising high-density residential and commercial establishments, is currently drained into Hatirjheel through 11 storm sewer outfalls and also through Gulshan and Banani lakes (see Fig. 1). The restoration works of Hatirjheel involved excavation of the lowlands to remove the accumulated sludge, the construction of 11 CSO structures (at 11 storm sewer outfall locations; identified here as CSO-1 through CSO-11), and diversion sewers along the periphery of Hatirjheel (connected to the CSO structures), and a flow control system at the downstream end of Hatirjheel. The average bottom level of Hatirjheel is 0.0 m [Public Works Department (PWD) datum]. The flow control gate at the downstream end (eastern side) of Hatirjheel allows it to serve the function of a storm retention pond. The water level of Hatirjheel could be maintained at any level between + 2.5 m to + 5.00 m by raising or lowering the flow control gates. The water level of Hatirjheel is usually maintained at around + 3.5 m (PWD). The canal system downstream of Hatirjheel is connected to the peripheral river system of Dhaka City, and the water level in this canal-river system often rises (in response to higher upstream flows and precipitation) during monsoon. If the water level at the canal system downstream of Hatirjheel rises during the wet season/floods, the flow control gates are raised to prevent the backflow of water into Hatirjheel. During this period, Hatirjheel serves the purpose of a retention pond and stores the overflows from CSO structures and surface runoff. Depending on weather conditions, the flow control gates remain raised for a period varying from weeks to a few months (e.g., during prolonged flooding conditions) during the monsoon period each year.

Figure 1 shows the locations of 11 CSO structures along the periphery of Hatirjheel. There are six CSO structures (CSO-1 through CSO-6) along the southern periphery of Hatirjheel and five CSO structures (CSO-7 through CSO-11) along its northern periphery. Among these, CSO-6 and CSO-11 are located outside the boundary of Hatirjheel and overflows from these two CSO structures discharge into the canal system downstream of Hatirjheel. Along the southern periphery of Hatirjheel, the 4.47 km "diversion sewer" system consists of two 1830 mm diameter concrete sewers. The 3.39 km "diversion sewer" along the northern periphery consists of 1200 mm diameter concrete sewers from CSO-7 to CSO-8; 1524 mm diameter concrete sewers from CSO-8 to CSO-10; and two 1830 mm diameter sewers from CSO-10 to CSO-11 [16]. The estimated full-flow conveyance capacity of the twin 1830 mm diversion sewers is about 4.66 cumec (cubic meter per second), while those of the 1200 mm and 1524 mm sewers are 0.76 cumec and 1.43 cumec, respectively. Although a yearly sewer cleaning program is in place, the actual conveyance capacities of these diversion sewers are likely to be lower than these estimated values due to the deposition of sludge.

Each CSO structure receives sewage/stormwater through a storm/combined sewer and diverts/directs it to the diversion sewer, which carries it downstream to the canal system (outside the boundary of Hatirjheel; see Fig. 1). This continues as long as the "diversion sewer" systems along the southern and northern periphery of Hatirjheel can accommodate the sewage/stormwater flows diverted to it. Estimated dry weather flows through the storm/combined sewers connected to the CSO structures varied from a low of 0.057 cumec (for CSO-7) to 1.926 cumec (for CSO-1) [16]. The estimated conveyance capacities of the diversion sewer systems are much higher than these dry weather flows, and the diversion sewers along both the southern and northern periphery of Hatirjheel carry the entire dry season flow received at the CSO structures.

During high precipitation events in the wet season, the flows reaching the CSO structures (through the respective storm/combined sewers) increase significantly, and the flows diverted to the diversion sewers exceed the conveyance capacity of the diversion sewer system. Thus, only a part of the combined sewage/storm flows (roughly equivalent to the conveyance capacities of the diversion sewer systems) is carried downstream through the diversion sewers, while the remaining part overflows into Hatirjheel through the CSO structures. Each CSO structure has gates at the overflow weir that could be raised to control the water level at which overflow would occur. Apart from these overflows, Hatirjheel receives relatively small quantities of storm runoff from the peripheral roads during precipitation events.

The flows received at a particular CSO structure (through the associated storm/combined sewer) during the wet season are related to the catchment it serves. The catchment areas of all 11 CSO structures were estimated based on an analysis of GIS-based map of Dhaka Water Supply and Sewerage Authority (DWASA) sewer network. The total catchment area of Hatirjheel is around 23.2 km^2; the total catchment area of the 11 CSO structures is about

Table 1 Catchment areas of different CSO structures of Hatirjheel

CSO Structure ID	Catchment areas (km^2)
CSO-1	6.10
CSO-2	1.90
CSO-3	1.30
CSO-4	0.20
CSO-5	0.30
CSO-6	0.79
CSO-7	1.60
CSO-8	0.40
CSO-9	0.40
CSO-10	4.87
CSO-11	0.64

17.97 km^2, while the Gulshan and Banani lakes account for the remaining 5.23 km^2 of the catchment [12]. Table 1 shows catchment areas of different CSO structures of Hatirjheel.

Among the five CSO structures along the southern periphery of Hatirjheel, CSO-1 has the largest catchment area (6.1 km^2), followed by CSO-2 (1.9 km^2). These two CSO structures receive significant stormwater-sewage flows during precipitation, and CSO events are common for these two CSO structures during moderate to heavy precipitation. There are usually no overflow events through the CSO-3, 4, and 5. This is possibly because these CSO structures receive relatively low stormwater-sewage flows (because of their lower catchment areas) and also because the gates at the overflow weirs of these CSO structures are raised (by the managing authority) to prevent overflows from these structures. Among the four CSO structures along the northern periphery of Hatirjheel, overflow usually takes place through CSO-7. The lower conveyance capacity of the 1200 mm diversion sewer associated with CSO-7 is possibly responsible for the overflows through this CSO structure. Some overflows have also been reported through CSO-9 during heavy precipitation events. Despite serving a significant catchment of 4.87 km^2, no overflows usually take place through CSO-10. This is possibly because of the higher conveyance capacity of the twin 1830 mm diversion sewer connected to it; this diversion sewer could carry/divert significant flows without causing overflow at the CSO structure.

2.2 Water quality monitoring

To assess spatial and temporal variation of water quality, water samples were collected from Hatirjheel lake close to the locations of nine CSO structures and analyzed for a range of water quality parameters. At each CSO structure, water samples were collected from a location within about 50–100 m from the overflow discharge location of that particular CSO structure. Table 2 shows the sampling dates. As discussed earlier, Hatirjheel receives overflows from the CSO structures during the wet season every year, particularly during heavy precipitation events, and its water quality visibly deteriorates. For this study, water samples were collected from Hatirjheel during the period June 2014 to May 2015. A total of 10 samplings were carried out during this period (roughly one sampling per month), four during the wet season (June to October), four during the following dry season (December to March), and two during Summer (April to May).

During each sampling campaign, samples were collected in the morning (between 8:30 a.m. to 1:00 p.m.). Two liters of samples were collected from each sampling point in pre-washed plastic bottles with polypropylene caps; the bottles were rinsed with Hatirjheel water at the sampling location three times before collecting water samples from that particular point. The samples were kept in ice boxes and were transported to the laboratory within a couple of hours of sample collection.

The water samples collected from Hatirjheel were analyzed for a range of parameters, including pH, electrical conductivity (EC), turbidity, color, NO_3^-, NO_2^-, NH_3, PO_4^{3-}, SO_4^{2-}, S^{2-}, Cl^-, COD, BOD_5, TS, TDS, and TSS. pH was measured by a pH meter (Geotech) attached with a pH electrode (WTW, Sen Tix 41), electrical conductivity (EC) was measured by a conductivity meter (HACH HQ14D), and Turbidity by a Turbidimeter (HACH 2100P). Ammonia, nitrate, nitrite, phosphate, sulfate, and sulfide concentrations were measured with a Spectrophotometer (HACH DR4000U). Ammonia was measured by the Nessler method, nitrate by the Cadmium Reduction Method, nitrite by the Diazotization method, and phosphate by the Molybdenum Blue method. Other parameters (e.g., TDS, TSS) were measured following Standard Methods [17].

Table 2 Sampling schedule for characterization of Hatirjheel water

Sampling Cycle	Date of Sample Collection	Season
1	29 June 2014	Rainy/monsoon
2	09 August 2014	Rainy/monsoon
3	07 September 2014	Rainy/monsoon
4	18 October 2014	Onset of dry season
5	06 December 2014	Dry/winter
6	17 January 2015	Dry/winter
7	28 February 2015	Dry/winter
8	28 March 2015	Dry
9	25 April 2015	Summer
10	30 May 2015	Summer

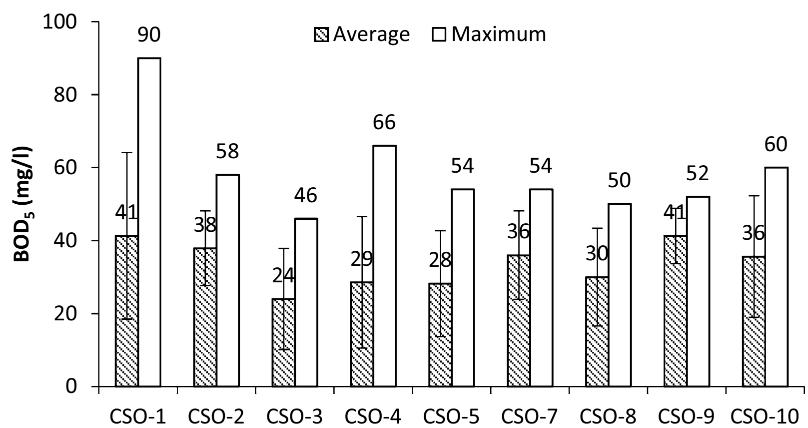
3 Results and discussion

In this study, water quality monitoring was carried out from June 2014 to May 2015. During June to October, significant CSO events took place regularly at CSO-1 and 2 in response to moderate/heavy rainfall during this period [please see "Supplementary materials" for rainfall data during the sampling period]. Some overflow/spilling occurred at CSO-7, and occasional overflows occurred at CSO-9 (only during heavy rainfall) from June to October. Virtually no overflow events took place during mid-October 2015 to mid-Mar 2015 from any of the CSO structures, while some occasional overflows (mainly through CSO-1 and 2) took place during mid-March to May 2015. The sampling dates reported in Table 2, however, are not associated with specific overflow events. During the sampling period, there were no overflows through the CSO-3, 4, 5, 8, and 10. The water quality of Hatirjheel during the monitoring period is discussed below.

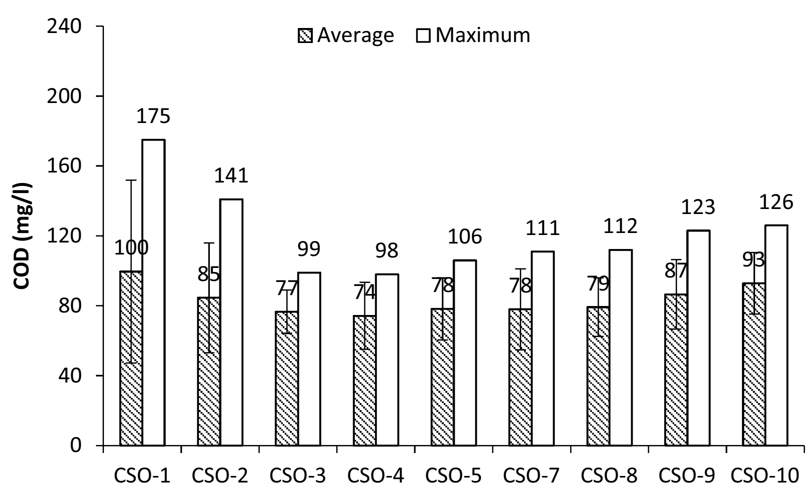
3.1 Organic pollution

The average (over the sampling period) and maximum BOD_5 and COD (in mg/l) concentrations of water samples at the nine sampling locations located close to the 9 CSO structures are shown in Fig. 2a and b, respectively. These figures show high levels of organic pollution throughout Hatirjheel. However, the average BOD_5 and COD values (over the one-year sampling period) are relatively higher at locations close to CSO-1 and CSO-2, which experienced significant overflows during the wet season. The maximum BOD_5 (90 mg/l) and COD (175 mg/l) values were recorded at the sampling location close to CSO-1. The average BOD_5 values at the sampling locations close to CSO-1, 2, 7, and 9 (varying from 36 to 41 mg/l) are close to or exceed the national standard for discharge of treated domestic

Fig. 2 Average (over the sampling period) and maximum concentrations of **a** BOD_5 (mg/l), and **b** COD (mg/l), at the 9 sampling locations located close to the 9 CSO structures



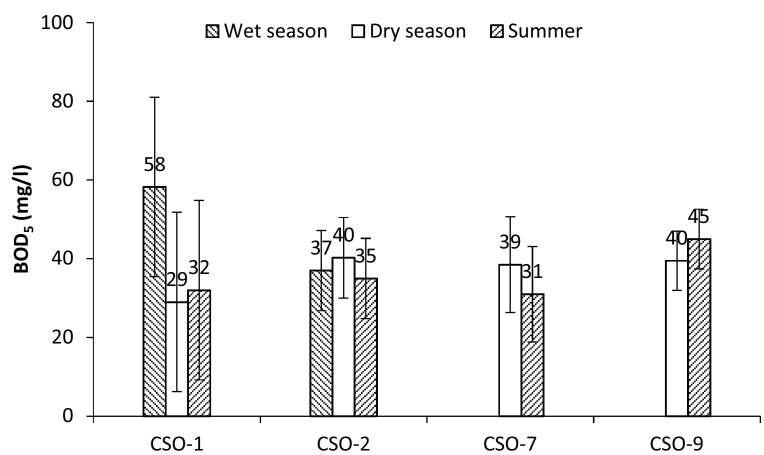
(a) Average (over the sampling period) and maximum concentrations of BOD_5 (mg/l)



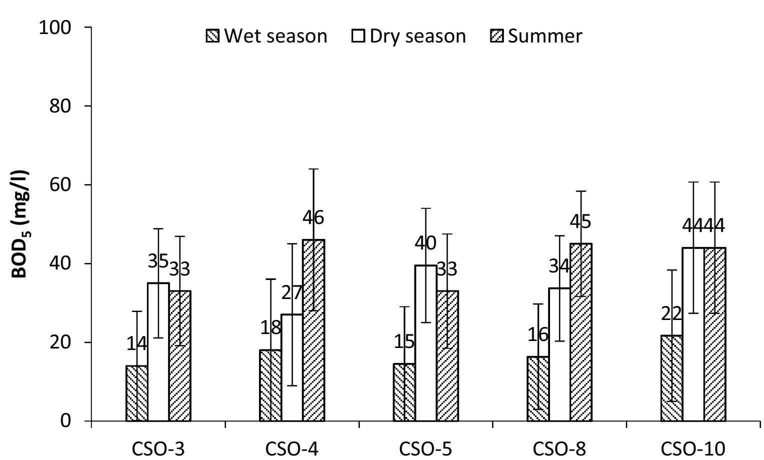
(b) Average (over the sampling period) and maximum concentrations of COD (mg/l) sewage into inland water bodies (40 mg/l). It should be noted that the discharge of polluted water from Banani Lake (see Fig. 1) might have contributed to the relatively high values of BOD_5 and COD at the sampling location close to CSO-10. The Department of Environment of the Bangladesh Government has set standards of BOD_5 of surface water bodies for different uses (varying from ≤ 2 mg/l for use as a source of drinking water supply to ≤ 10 mg/l for use in irrigation) [18]; thus, based on BOD_5 values, Hatirjheel is unsuitable for any productive use such as recreation, fisheries or irrigation. The high average levels of organic pollution throughout Hatirjheel possibly suggest that pollutants that enter Hatirjheel mainly through a few overflow structures (CSO-1, 2, 7, and 9) become well-mixed over time. An analysis of the seasonal variation of water quality at the sampling locations, presented below, explains the effect of overflow events on the water quality of Hatirjheel.

Figure 3 shows the seasonal (wet season, dry season, and Summer) average values of BOD_5 at all the sampling locations. Figure 3a shows the average BOD_5 values at the sampling locations close to CSO-1, 2, 7, and 9, which overflowed during the wet season; Fig. 3b shows the average BOD_5 values at the remaining five sampling locations. Similarly, Fig. 4 shows seasonal averages of COD values at the nine sampling locations. These figures (Fig. 4a, b) show that during the wet season (June to October), average BOD_5 and COD values are significantly higher at the sampling locations close to CSO-1, 2, 7, and 9. For example, the average wet weather (June to October) BOD_5 and COD values at the sampling location close to CSO-1 (the CSO structure that contributed the most significant overflows to Hatirjheel) are 58 mg/l and 155 mg/l, respectively. On the other hand, average wet weather BOD_5 for the remaining sampling locations varied from 14 to 22 mg/l (see Fig. 3b). Similarly, average wet season COD values at the sampling locations close to CSO-1, 2, 7, and 9 varied from 95 to 155 mg/l, while it varied from 66 to 92 mg/l at the remaining five sampling locations. A general trend (with few exceptions) could

Fig. 3 Average concentrations of BOD_5 (mg/l) during (i) wet season (June to October, 4 samples), (ii) dry season (December to March, 4 samples), and (iii) summer (April to May, 2 samples) at the 9 sampling locations located close to the 9 CSO structures [Note: wet season data for BOD_5 at locations close to CSO-7 and 9 are not available]

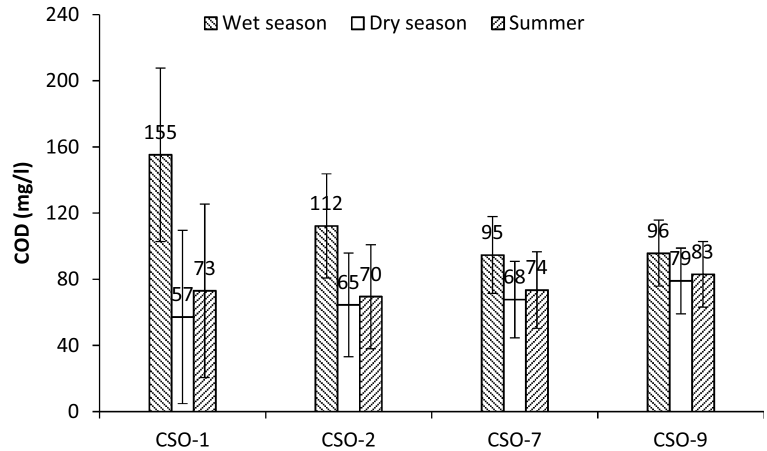


(a) Average BOD₅ close to the CSO structures that overflowed during the wet season

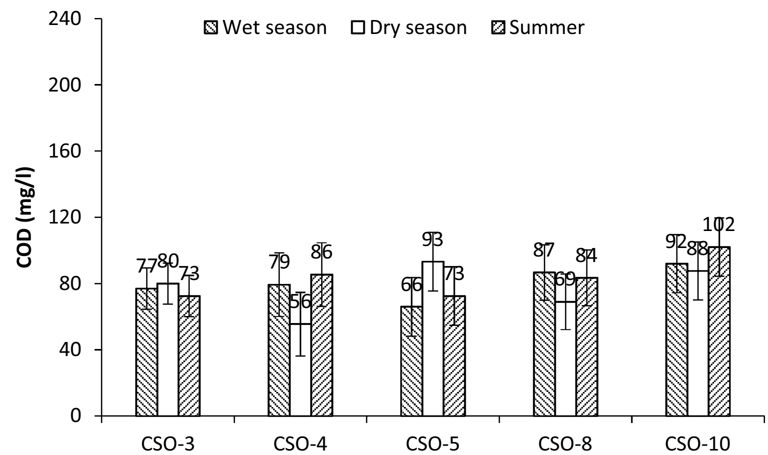


(b) Average BOD₅ close to the CSO structures that did not overflow during the wet season

Fig. 4 Average concentrations of COD (mg/l) during (i) wet season (June to October, 4 samples), (ii) dry season (December to March, 4 samples), and (iii) summer (April to May, 2 samples) at the 9 sampling locations located close to the 9 CSO structures



(a) Average COD close to the CSO structures that overflowed during the wet season



(b) Average COD close to the CSO structures that did not overflow during the wet season

be observed in Figs. 3 and 4. The BOD_5 and COD were higher during the wet season at locations close to the CSO structures that overflowed (CSO-1, 2, 7, and 9). During the following dry season (December to March), with no overflow events, the BOD_5 and COD values decreased at these locations due to bio-degradation and mixing/transport within Hatirjheel. On the other hand, during the dry season (December to March), BOD_5 and COD values at locations that did not receive overflows (CSO-3, 4, 5, 8, and 10) increased (compared to the wet season). This is most likely due to mixing/transport within Hatirjheel. During Summer (April to May), there were some increases in BOD_5/COD at locations close to most of the overflowing CSOs. Thus, during the wet season, the water quality of Hatirjheel becomes particularly poor near the overflowing CSO structures. During the subsequent periods with no or limited overflows, the organic pollution is dispersed within Hatirjheel.

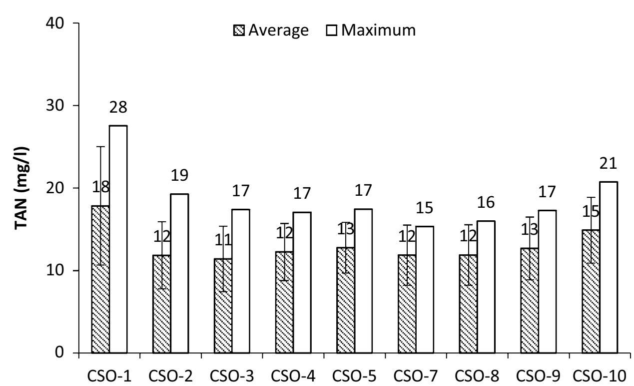


Fig. 5 Average (over the sampling period) and maximum concentrations of total ammonia nitrogen (TAN, mg/l), at the 9 sampling locations located close to the 9 CSO structures

3.2 Ammonia and other nutrients

3.2.1 Ammonia

Figure 5 shows the average (over the sampling period) and maximum total ammonia nitrogen (TAN) concentrations of water samples at the nine sampling locations, while Fig. 6 shows the seasonal variation of TAN at these locations. Figure 5 shows that average ammonia concentrations are high throughout Hatirjheel, but relatively more elevated at the sampling locations close to CSO-1 and 2, which receive significant overflows during the wet season. The highest-average (18 mg/l) and maximum (28 mg/l) TAN concentrations were recorded at the sampling location close to CSO-1. As noted earlier, it is possible that the polluted discharges from Banani Lake (see Fig. 1) contributed to the relatively high values of TAN at the sampling location close to CSO-10.

We could see the seasonal variation of TAN from Fig. 6a and b. During the wet season, the average TAN values are higher (varying from 10 to 20 mg/l) at the sampling locations close to the overflowing CSO structures compared to average TAN values (varying from 8 to 12 mg/l) at the remaining sampling locations. Figure 6 also shows a general trend of seasonal variation of TAN concentration. Ammonia concentration increased (in December and January) immediately after the end of the wet season in mid-October at almost all sampling locations. This is most likely due to the release of ammonia into the water column from the ammonification process (i.e., the decomposition of nitrogenous organic matter). The subsequent reduction in TAN concentration at almost all sampling locations during the following Summer (March–April) is most likely due to nitrification (conversion of ammonia into nitrate) and incorporation of nitrogen into algal mass.

Ammonia is one of the most important parameters for fish species. Water with concentrations of less than

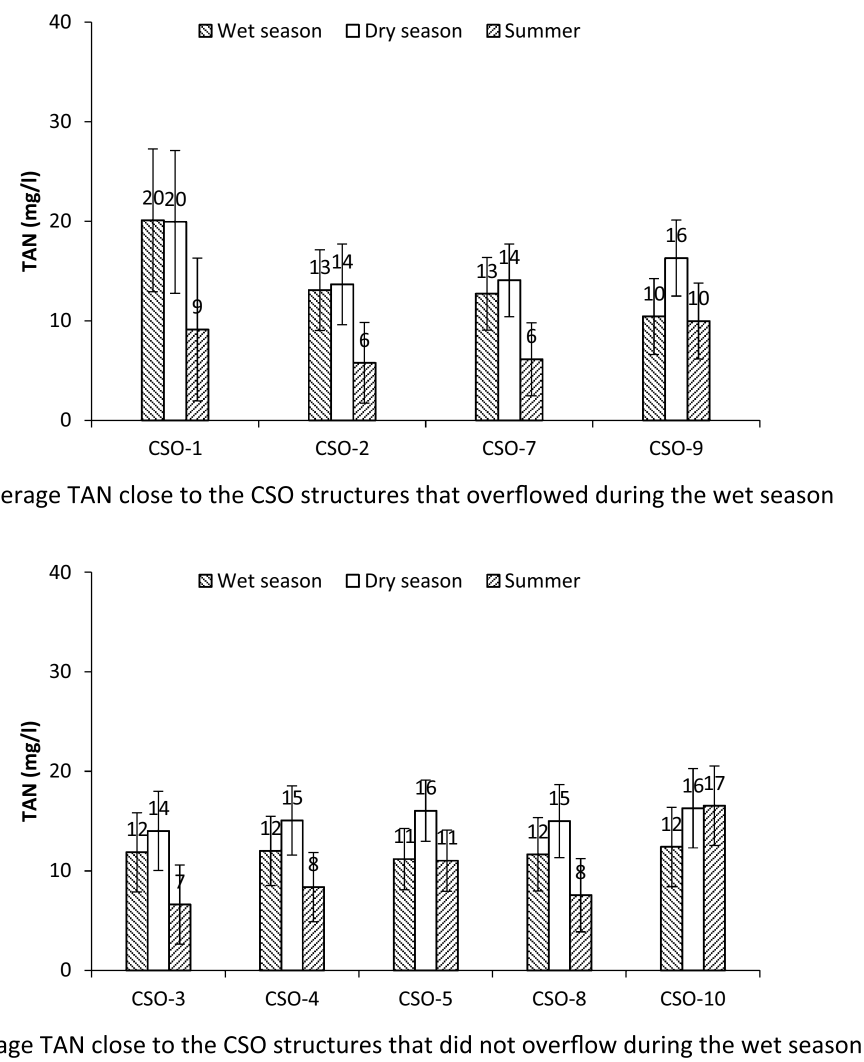


Fig. 6 Average concentrations of total ammonia nitrogen (TAN, mg/l) during (i) wet season (June to October, 4 samples), (ii) dry season (December to March, 4 samples), and (iii) summer (April to May, 2 samples) at the 9 sampling locations located close to the 9 CSO structures

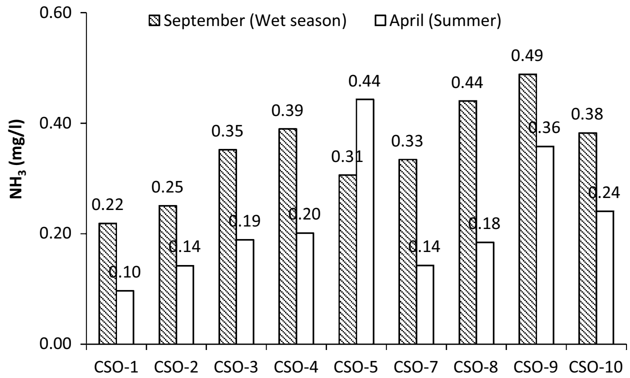


Fig. 7 Calculated free ammonia concentration (as NH_3-N, mg/l) at the 9 sampling locations close to the CSO structures in September (Wet season) and April (Summer)

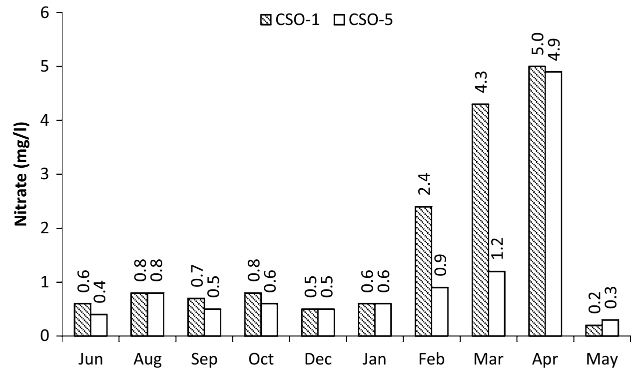


Fig. 8 Variation of nitrate (exprssed as NO_3-N, mg/l) at different sampling times at the sampling locations close to CSO-1 and CSO-5. Overflows took place through CSO-1 during wet season (June to October), while there were no overflows through CSO-5

0.020 mg/l unionized ammonia is considered safe for fish reproduction [19]. Anytime free ammonia (NH_3) exceeds 0.05 mg/l, it begins to affect fish species. At 2.0 mg/l and above, most fish species would not survive. In this study, we calculated concentrations of free ammonia (NH_3) and ammonium (NH_4^+) from the measured pH and total concentration of ammonia, using the mass balance equation for ammonia [Total Ammonia = $(NH_3) + (NH_4^+)$] and the mass law expression for the dissociation of ammonium $[(H^+)(NH_3)/(NH_4^+) = 10^{-9.26}]$. Figure 7 shows calculated free ammonia (NH_3) concentration at all sampling locations in September (wet season) and April (Summer). It shows high free ammonia concentration throughout Hatirjheel. During the entire sampling period in this study, the free ammonia (NH_3) concentration throughout Hatirjheel was higher than 0.05 mg/l. Thus, it can be concluded that ammonia concentration in Hatirjheel is so high that fish species are unlikely to survive in this environment.

The USEPA has set ambient water quality criteria for ammonia for the protection of aquatic life, with specific associated duration and frequency, in surface waters that are protective of aquatic life designated uses [20]. For example, USEPA recommends a chronic criterion magnitude of 1.9 mg TAN/l at pH 7 and 20 °C for a 30-day average duration, not to be exceeded more than once every three years on average. The concentration of TAN (total ammonia nitrogen) throughout Hatirjheel was much higher than the USEPA chronic ammonia criteria throughout the year. This indicates that the water of Hatirjheel is unsuitable for the survival of fish species. Therefore, it is not surprising that, according to local people, the largest water body in Dhaka is devoid of any fish species.

3.2.2 Nitrate

The variations of nitrate with time at the sampling locations close to CSO-1 and CSO-5 are shown in Fig. 8. As noted earlier, CSO-1 experienced significant overflows during the wet season, while no overflow occurred through CSO-5. The concentration of nitrate in front of both CSO structures was relatively low during the wet season; it increased in the subsequent dry season during December to April. Thus, nitrate concentration did not increase during the overflow of the rainwater-sewage mixture into Hatirjheel but began to increase later on. This is most likely due to nitrification, i.e., conversion of ammonia to nitrate; nitrate concentration began to increase after the commencement of the dry season in February (Fig. 8). Finally, nitrate (and also ammonia) concentration reduced significantly in May, possibly due to incorporation into algal mass.

3.2.3 Sulfate and sulfide

Sulfate concentration in Hatirjheel water was found to be relatively high throughout the year. During the wet season (i.e., from June to October), average sulfate concentrations at the sampling locations close to CSO-1, 2, 3, 4, 5, 7, 8, 9, and 10 were 26, 21, 28, 30, 28, 27, 29, 29, and 25 mg/l, respectively. The sulfate concentration decreased slightly during the dry season.

Unlike sulfate, sulfide appears to have a strong seasonal variation, with higher concentration during the wet season and lower concentration during the dry season. During the wet season (i.e., from June to October), average sulfide concentrations close to CSO-1, 2, 3, 4, 5, 7, 8, 9 and 10 were 64, 33, 27, 20, 23, 29, 24, 23 and 25 µg/l, respectively. Sulfide concentration reduced significantly during the dry season. Figure 9 shows the variation of sulfide

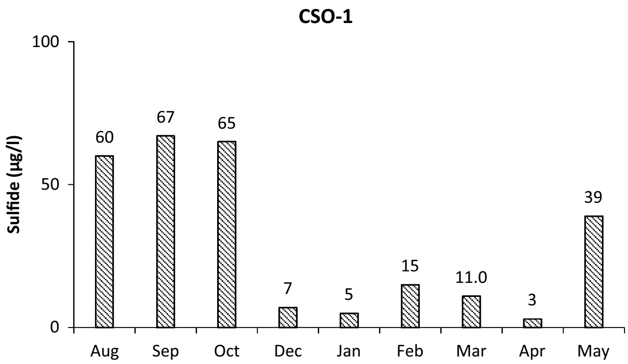


Fig. 9 Variation of sulfide (as S^{2-}, µg/l) concentration at the sampling location close to CSO-1

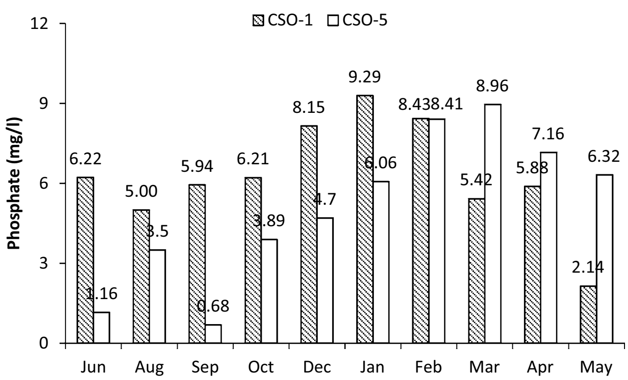


Fig. 10 Variation of phosphate (as PO_4^{3-}, mg/l) at different sampling times at the sampling locations close to CSO-1 and CSO-5. Overflows took place through CSO-1 during wet season (June to October), while there were no overflows through CSO-5

concentration at the sampling location close to CSO-1. At this sampling location, the average sulfide concentration was 64 µg/l during the wet season (June to October), which decreased to about 9.5 µg/l during the dry season (December to March). These data suggest that sulfide enters into Hatirjheel with overflows of the rainwater-sewage mixture during the wet season.

3.2.4 Phosphate

The variation of phosphate with time at the sampling locations close to CSO-1 and CSO-5 is shown in Fig. 10. During the wet season (June to October), the average phosphate concentration at the sampling locations close to CSO-1 (at which overflows took place) and CSO-5 (at which no overflow took place) were 5.85 mg/l and 2.31 mg/l, respectively. Phosphate concentration appears to increase after the end of the wet season. This is possibly due to the release of phosphate from the decomposition process. Mixing and transport (from upstream locations within Hatirjheel) could contribute to the observed gradual increase of phosphate concentration close to CSO-5 at the end of the wet season.

A relatively high concentration of phosphate has been found at all nine sampling locations in Hatirjheel. During the wet season (i.e., from June to October), average phosphate concentration close to CSO-1, 2, 3, 4, 5, 7, 8, 9, and 10 were 6, 4, 3, 3, 2, 3, 3, 3, and 3 mg/l, respectively. These phosphate levels are almost two orders of magnitude higher than the USEPA standard of 0.033 mg/l [21]. Excessive phosphorus promotes eutrophication (algal bloom) in freshwater systems, which subsequently results in oxygen depletion and water quality degradation. Algal bloom in Hatirjheel was visible through the greenish color of the water.

3.3 Conductivity and TDS

During the wet season (i.e., from June to October), the average electrical conductivity close to CSO-1, 2, 3, 4, 5, 7, 8, 9 and 10 were 671, 587, 567, 553, 529, 589, 571, 543 and 537 µS/cm, respectively and average TDS were 347, 308, 298, 278, 287, 300, 295, 284 and 272 mg/l, respectively. At the end of the wet season, EC and TDS continued to increase at some of the sampling locations, possibly due to the release of dissolved decomposition products.

3.4 Turbidity and TSS

During the wet season (i.e., from June to October), the average turbidity close to CSO-1, 2, 7, 8, 9, and 10 were 60, 70, 71, 51, 54, and 60 NTU, respectively; and average TSS close to CSO-7, 8, 9, and 10 were 34, 47, 42, and 47 mg/l, respectively. Maximum turbidity of 107 NTU was recorded in October close to CSO-2, and maximum TSS of 110 mg/l was recorded in August close to CSO-10. High turbidity and TSS values were recorded at the sampling locations even during the dry season when there was no overflow of the rainfall-sewage mixture into Hatirjheel.

3.5 Color

A relatively high level of color was detected throughout Hatirjheel during the entire sampling period. During the wet season, water close to CSO-1 and CSO-2 was dark due to the overflow of the dark-colored rainfall-sewage mixture through these two CSO structures. The color of the water in front of other CSO structures was greenish due to the high algal bloom. The high level of color recorded throughout Hatirjheel during the dry season (when there was no overflow) was primarily due to algal bloom. The greenish color of the water was visible to the naked eye. Figure 11 shows

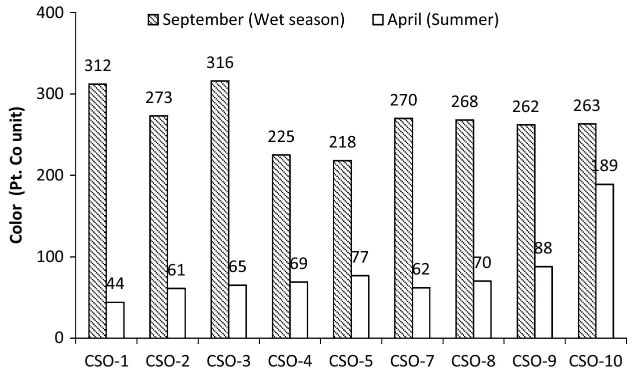


Fig. 11 Variation of color (Pt. Co unit) at all 9 sampling locations close to the CSO structures in September (Wet season) and April (Summer)

Table 3 Variation of pH at the sampling locations during the sampling period

CSO Structure near the sampling location	Variation of pH during sampling period
CSO-1	6.93–8.19
CSO-2	7.42–8.63
CSO-3	7.50–8.54
CSO-4	7.66–8.40
CSO-5	7.59–8.61
CSO-7	7.39–8.50
CSO-8	7.49–8.45
CSO-9	7.44–8.62
CSO-10	7.34–8.52

the variation of color (Pt. Co unit) for all sampling locations in September (wet season) and April (Summer).

3.6 pH

The pH of the water samples collected from Hatirjheel varied from 6.93 to 8.63. In most cases, the water samples were slightly alkaline. The maximum pH of 8.63 was recorded at the sampling location close to CSO-2 in December. The minimum pH of 6.93 was recorded at the sampling location close to CSO-1 in October. Table 3 shows the variation of pH at the sampling locations during the sampling period. The higher pH values (exceeding 8) could be due to the formation of algae, which is often accompanied by a rise in pH.

4 Conclusions

This research analyzed the impacts of combined sewer overflows on the water quality of Hatirjheel, the largest water body in Dhaka city. Analysis of spatial variation of water quality suggests that the water quality is poor throughout Hatirjheel. However, water quality is particularly poor (with high concentrations of organic matter, ammonia) near the CSO structures through which significant sewage-stormwater overflows during the wet season. There appears to be significant spatiotemporal variation of the water quality in Hatirjheel. We found high levels of organic pollution (BOD_5 and COD) during the wet season, particularly at locations close to the overflowing CSO structures. During the subsequent dry season, organic pollution appears to disperse through mixing/transport. The water of Hatirjheel contains high concentrations of BOD_5 and COD; some even exceeding the discharge standards of treated effluents. Total ammonia (and free ammonia) nitrogen concentration in Hatirjheel water increased during the wet season, particularly close to the overflowing CSO structures, due to the overflow of sewage-stormwater mixture; ammonia concentration continued to increase after the end of the wet season, most likely due to the release of ammonia into the water column from the ammonification process. Ammonia concentration in Hatirjheel water is so high that fish species are unlikely to survive in this environment. Nitrate concentration in Hatirjheel water increased at the end of the wet season, possibly due to oxidation of ammonia to nitrate; subsequent reduction in nitrate (and also ammonia) concentration in Summer is possibly due to its incorporation into algal mass. Sulfide concentration was high during the wet season, indicating anoxic condition, but reduced significantly during the subsequent dry season. Hatirjheel water appears to be unsuitable for any useful purpose, including fisheries, recreation, and irrigation.

With the rapid growth of the population in Dhaka, wastewater/sewage flow is likely to increase. This may result in an increasing overflow of sewage-stormwater mixture into Hatirjheel during the wet season in the future. This is likely to cause an even higher level of pollution of Hatirjheel. This paper presents strong evidence on the adverse impacts of combined sewer overflows on receiving water bodies in Dhaka city, and questions the viability of using a combined sewer system for conveying sewage and stormwater in high-density urban areas with similar climatic features.

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Data availability The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

Code availability Not applicable.

Declarations

Conflict of interest The authors declare that they have no conflict of interest.

Ethical approval: Not applicable.

Consent to participate Not applicable.

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