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Water quality patterns across seasons in major urban lakes of Dhaka Metropolitan City

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Abstract

Urban lakes in Dhaka are increasingly subjected to environmental degradation due to rapid urbanization and inadequate wastewater management. This study aims to assess and compare the water quality of three major urban lakes—Gulshan, Dhanmondi, and Hatirjheel—across four seasons—winter, pre-monsoon, monsoon, and post-monsoon—by analyzing key physicochemical parameters. In this study, data on various water quality parameters, including pH, dissolved oxygen (DO), biochemical oxygen demand (BOD), chemical oxygen demand (COD), total dissolved solids (TDS), turbidity, suspended solids, electrical conductivity (EC), chloride, and alkalinity, measured using standard methods, were referenced from the Bangladesh government's national report on water quality. The results revealed seasonal and spatial variations in water quality, with monsoon seasons showing dilution effects while pre-monsoon values indicate peak pollution. Among the three lakes, Dhanmondi Lake demonstrated the best water quality, with average BOD and COD levels remaining within environmental quality standards and DO concentrations that support aquatic life. Conversely, Gulshan Lake was found to be the most polluted, with BOD levels reaching up to 48 mg/L, COD up to 202 mg/L, turbidity as high as 208 NTU, and DO dropping to 0.12 mg/L. Hatirjheel Lake exhibited moderate pollution levels, with elevated TDS and EC values, particularly in the post-monsoon season. The study concludes that the urban lake system of Dhaka, particularly Gulshan and Hatirjheel, is subject to immense water quality degradation; therefore, compulsory lake management and pollution prevention actions should be adopted to enhance the ecological and recreational significance of the lakes.

Keywords: Dhaka Metropolitan City; Water quality; Seasonal variation; Gulshan Lake; Dhanmondi Lake; Hatirjheel Lake

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1. Introduction

Water is crucial for life and plays a foundational role in ecological sustainability, public health, and economic development.[1] In Bangladesh, although water is naturally abundant, rapid urbanization and inadequate waste management practices have severely impacted the quality of surface water bodies, particularly in metropolitan areas.[2,3] One of the most densely inhabited cities in the world, Dhaka is rapidly transforming into an urban hotspot,[4] resulting in the degradation of its natural water systems. Gulshan, Dhanmondi, and Hatirjheel Lakes are among them, which traditionally served as significant elements of the urban landscape, offering both drainage and recreational, as well as ecological services.[5,6] As Dhaka continues to expand, the burden on these lakes has intensified. Hatirjheel, covering around 302 acres, currently manages nearly one-third of the city's stormwater, linking various parts of the town and offering both infrastructural and recreational value.[7,8] However, like many urban water bodies, it now suffers from declining water quality due to the inflow of untreated wastewater, industrial discharges, and domestic sewage.[9] Similarly, Dhanmondi Lake, located in a highly residential area, and Gulshan Lake, situated in one of Dhaka's elite neighborhoods, are facing increasing environmental degradation due to human encroachment, solid waste dumping, and poor regulatory enforcement.[6,9,10]

In environmental assessments, physicochemical parameters serve as pivotal indicators of water quality.[11] These comprise pH, dissolved oxygen (DO), biochemical oxygen demand (BOD), chemical oxygen demand (COD), total dissolved solids (TDS), turbidity, chloride, suspended solids (SS), alkalinity, and electrical conductivity (EC). Each of these parameters offers insights into the chemical stability and ecological health of a water body.[12,13] The pH level reflects the water's acidity or alkalinity, which affects aquatic life and the solubility of nutrients and metals.[14] DO is vital for the survival of marine organisms, and levels below 5 mg/L often indicate ecological stress.[15,16] BOD represents the amount of oxygen required for microbial decomposition of organic matter, while COD measures the total oxygen needed to oxidize both organic and inorganic pollutants.[17,18] TDS accounts for the presence of dissolved salts and minerals, with the World Health Organization recommending values below 1000 mg/L for safe use.[19] Turbidity measures water clarity and impacts photosynthesis in aquatic plants.[20] Chloride concentration, often elevated due to domestic waste, can affect the taste and corrosiveness of water.[21] SS contributes to sedimentation and turbidity, degrading aquatic habitats.[22] Alkalinity reflects the water's ability to resist pH changes, maintaining chemical stability.[14] EC is an indicator of the water's ion concentration and is typically used to evaluate its mineral content. The World Health Organization recommends a maximum EC of 1200 µS/cm for drinking water, although lower values are usually found in ecologically healthy lakes.[23-25]

These parameters are essential not only for environmental control but also as indicators in making comparisons that will lead to compliance with international standards. The values are also influenced by seasons. In tropical climates such as Bangladesh, variations across winter, pre-monsoon, monsoon, and post-monsoon seasons can significantly impact water quality by altering temperature, runoff volume, and organic matter concentration.[26-28] Understanding these seasonal dynamics is essential for designing effective water resource management and pollution control strategies.

Although numerous studies have been conducted on the water quality of individual lakes in Dhaka,[15,16,28-30] there remains a lack of comparative research that analyzes seasonal variations in water quality across multiple lakes using a broad spectrum of standard parameters. Most previous assessments do not integrate both interlake and intraseasonal comparisons or consistently evaluate results against international environmental benchmarks. This gap limits the broader understanding of how urban pressures affect water bodies differently over time and space, emphasizing the need for global standards in environmental research.

A comprehensive comparative study involving physicochemical parameters across all major seasons is essential to evaluate the current state of Dhaka's urban lakes. By systematically analyzing and comparing Gulshan, Dhanmondi, and Hatirjheel Lakes with environmental standards, this research seeks to identify which lakes are under critical ecological threat and which seasonal periods show heightened vulnerability. These findings, once implemented, will have a significant impact on urban water management and restoration planning in one of the world's most water-stressed urban environments.

2. Methodology

This research employed a comparative study of water quality parameters of three urban lakes located in Dhaka Metropolitan City: Gulshan Lake, Dhanmondi Lake, and Hatirjheel Lake (Figure 1).

Gulshan Lake is located in the northern part of Dhaka at approximately 23°48′ N and 90°25′ E. It is the northernmost lake in a chain of water bodies that include Hatirjheel and the Balu River. The lake stretches 3.8 km with an average depth of 2.5 m. It is long and narrow, resembling a natural channel. The lake is bordered by Baridhara in the north, Tejgaon-Hatirjheel in the south, Gulshan-Banani in the west, and Badda in the east.[9,16]

Dhanmondi Lake lies at the center of Dhaka, between 23°44′12″ to 23°45′22″ N and 90°22′ to 90°23′ E. It stretches from Jigatola to Road 27 and is surrounded by major residential zones. The lake is 3 km long and varies in width from 35 m to 100 m. It reaches a maximum depth of 4.77 m and spans a total surface area of 37.37 ha. Mohammadpur

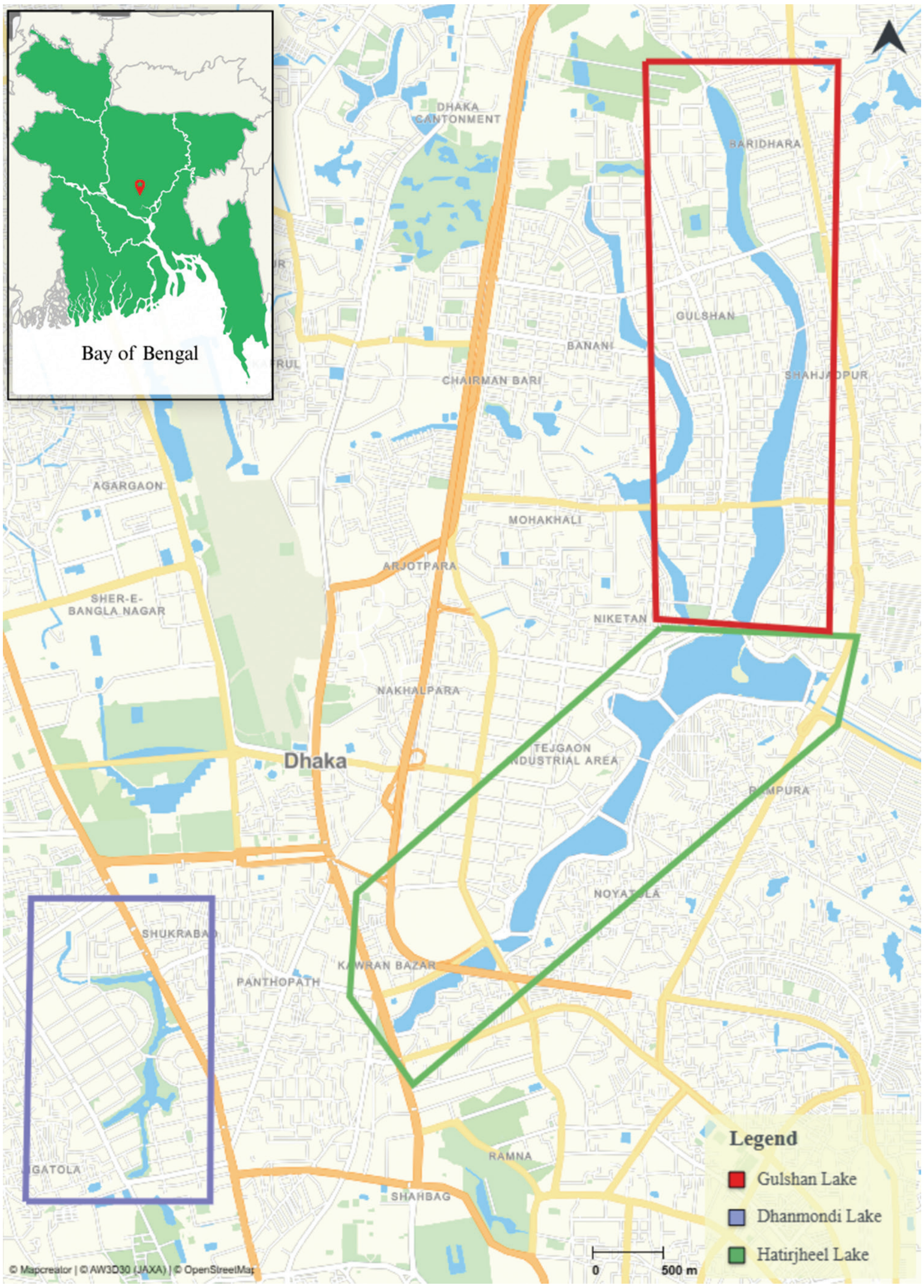

Figure 1. Study area map of Gulshan, Dhanmondi, and Hatirjheel Lake
Source: Open Street Map.

and Lalmatia bound the lake to the north, Satmasjid Road to the west, Border Guard Bangladesh Gate to the south, and Kalabagan to the east.[16,29]

Hatirjheel Lake, situated at 23°44′58.47″ N and 90°23′48.35″ E, is a centrally located urban water body that features recreational and transportation amenities. The lake extends 4.1 km in length with an average depth of 2.6 m and is up to 460 m wide at its broadest section. The surroundings include Gulshan-Banani to the north, Maghbazar and Banglamotor to the west, Rampura-Badda to the east, and Tejgaon industrial area to the south.[16,30-32]

2.1. Data source

The present study was conducted using secondary data sourced from the official publication titled "Surface and Ground Water Quality Report 2022," prepared and published by the Department of Environment, Ministry of Forest, Environment and Climate Change, Government of the People's Republic of Bangladesh.[10] This report presents credible, methodologically standardized data on surface water quality nationwide, making it suitable for academic and policy-level analyses. According to the original report, the water quality data were collected from the upper surface (within a depth of 1 m). Multiple sub-samples were collected from random places at midday (usually within a 5 m interval) within each sampling station, and the sub-sample data were averaged to form a compact data set for each sampling station. The data used in this study focused on surface water quality parameters of the three lakes. Out of many discrete sampling stations, three distinct locations within each of the selected lakes were chosen for this analysis (Table 1). This deliberate approach in determining specific geographic locations in each lake was strategic and designed to capture the spatial variability in the water quality of the lake systems.

Furthermore, the original data were gathered for four months in 2022 (February, May, August, and November). As these months represent the four climatic seasons in Bangladesh, February was categorized as winter, May as pre-monsoon, August as monsoon, and November as post-monsoon. This classification enabled the analysis of seasonal variation in water quality within each lake and among the three lakes. These data are accessible to the public and are reliable because they were gathered and recorded officially and scientifically.

2.2. Parameters and analytical methods

A total of 10 physicochemical water quality parameters were selected for the assessment. These parameters are widely accepted as indicators of surface water quality in both domestic and international standards.[33,34] The chosen parameters are pH, DO, BOD_5, COD, TDS, turbidity, SS, total alkalinity, and EC. These are critical for characterizing the properties of surface water. Although this research used secondary data, all the parameters listed above were analyzed in the original report using standardized laboratory methods approved by national and international agencies such as the American Public Health Association.[35] pH was estimated using a standard pH electrode, which indicates the degree of acidity or alkalinity of the water. DO was determined by the modified Winkler's method or the titrimetric method. This technique measures the oxygen concentration dissolved in water, which is crucial to the life of aquatic organisms. BOD_5 was measured using the dilution method after a 5-day incubation period at 20°C. This test estimates the oxygen required by microorganisms to decompose organic material in water. COD was determined using the closed reflux colorimetric method, which measures the oxygen equivalent of the organic matter that can be oxidized chemically. TDS was analyzed using the gravimetric method, where a water sample is filtered and the filtrate evaporated to measure the residue weight. Turbidity was measured using the nephelometric method, which uses light scattering to determine the cloudiness or haziness of water caused by SSs. Chloride was determined using the argentometric method, a titrimetric process where silver nitrate is used to quantify chloride ions in the sample. SS was measured using another gravimetric method, where solids retained on a filter are dried and weighed to determine the concentration. Total alkalinity was analyzed using standard titration methods, indicating the buffering capacity of the water against pH changes. EC was estimated with a standard EC meter, which allows detection of the water's conductivity of an electric current as a consequence of the presence of dissolved salts and minerals. These are widely used standard procedures for precise and dependable results and are routinely employed in water quality monitoring programs worldwide.

Table 1. Sampling stations and their surroundings in the selected urban lakes

Study area	Sampling station	Spatial distribution		Surroundings
Gulshan Lake	S_1	23°48′16″N	90°25′00″E	United Hospital Limited
	S_2	23°47′27″N	90°25′19″E	Manarat International School
	S_3	23°46′28″N	90°25′05″E	Shooting complex
Dhanmondi Lake	S_1	23°44′45″N	90°22′39″E	8 no. bridge
	S_2	23°44′19″N	90°22′35″E	Jigatola bus stand
	S_3	23°45′03″N	90°22′33″E	32 no. bridge
Hatirjheel Lake	S_1	23°46′10″N	90°25′16″E	Rampura bridge
	S_2	23°45′41″N	90°24′33″E	Kuni para
	S_3	23°45′16″N	90°24′10″E	FDC Mor Bridge

2.3. Data processing and analysis

The raw data collected from the Surface and Ground Water Quality Report 2022 were systematically structured in Microsoft Excel. Data on each water parameter were tabulated for each lake and by season. In this study, statistical analyses such as Pearson's correlation, type III analysis of variance, coefficient of variance (%), and principal component analysis were applied to the water quality data to understand the correlation among water quality parameters, as well as season-wise and lake-wise variations. These data were then compared across the three lakes to identify lake-seasonal interactions and trends in water quality. The collected data were further evaluated against national Environmental Quality Standards (EQS) and World Health Organization guidelines to assess their suitability for ecological functions and public health. Using a comparative and seasonal approach, this study aimed to evaluate the degree of pollution, identify the most critical seasons, and determine which types of lakes most urgently require protective measures.

3. Results

The findings on the water quality parameters of three urban lakes in Dhaka—Gulshan Lake, Dhanmondi Lake, and Hatirjheel Lake—focused on the seasonal variations of key water quality parameters within each lake and provided a comparative overview across the three lakes. The average values, along with their minimum, maximum, and standard deviations, are discussed for each parameter across different seasons. Furthermore, the observed water quality parameters were compared with relevant EQS to assess the overall health of these urban aquatic ecosystems.

3.1. Seasonal water quality of Gulshan Lake

The seasonal dynamics of water quality at Gulshan Lake exhibited contrasting patterns of influence, both natural and anthropogenic. As revealed in Table 2, during the winter season, Gulshan Lake had an average pH of 7.46, indicating a slight alkalinity, and a moderate DO value of 5.32 mg/L. The BOD and COD were recorded at 33.33 mg/L and 124 mg/L, respectively, suggesting the presence of organic pollutants. The average TDS stood at 296 mg/L, while turbidity reached 43.6 NTU. EC was relatively high at 498 µmhos/cm. Among all sampling stations, Station S_3 recorded the highest DO value at 6.68 mg/L, reflecting localized variations in water quality.

In the pre-monsoon season, the lake experienced a sharp rise in pollution indicators. BOD increased substantially to an average of 48 mg/L, and COD peaked at 202 mg/L. Turbidity rose drastically to 108.6 NTU, while SS reached its highest average of 214.7 mg/L. Interestingly, DO also peaked during this season, averaging 6.97 mg/L, possibly due to algal growth or increased surface aeration. Station S_3 exhibited high levels of BOD (64 mg/L) and COD (343 mg/L), indicating local contamination (Table 2).

During the monsoon, the variation of water quality was significantly different, implying the dilution impact of precipitation. The DO of the lake decreased drastically, reaching a mean value of 1.41 mg/L, the minimum among all the seasons, thus registering severe oxygen stress. BOD and COD levels declined to 22 mg/L and 82.67 mg/L, respectively. TDS also fell to its lowest seasonal average of 41.33 mg/L, and turbidity was reduced due to water flushing. An extremely low DO value of 0.12 mg/L was recorded at Station S_1, indicating critical conditions for aquatic life (Table 2).

Table 2. Water quality parameters of Gulshan Lake during different seasons

Season	Sampling station	pH	DO (mg/L)	BOD (mg/L)	COD (mg/L)	TDS (mg/L)	Turbidity (NTU)	Chloride (mg/L)	SS (mg/L)	Alkalinity (mg/L)	EC (µmhos/cm)
Winter	S_1	7.34	3.82	40	130	293	43.6	42	136	204	484
	S_2	7.32	5.47	32	122	280	61.4	42	159	189	486
	S_3	7.73	6.68	28	120	315	25.8	42	52	183	524
	Avg.	7.46	5.32	33.33	124	296	43.6	42	115.7	192	498
Pre-monsoon	S_1	7.19	5.7	45	134	204	63.2	39	192	195	388
	S_2	7.41	9.4	35	129	201	54.5	33	199	198	394
	S_3	7.42	5.8	64	343	254	208	48	253	184	440
	Avg.	7.34	6.97	48	202	219.7	108.6	40	214.7	192.3	407.3
Monsoon	S_1	7.01	0.12	22	83	41	47.1	41	92	161	415
	S_2	7.12	2.1	22	75	41	37.1	41	77	162	443
	S_3	7.42	2	22	90	42	38.7	42	81	170	430
	Avg.	7.18	1.41	22	82.67	41.33	40.97	41.33	83.33	164.3	429.3
Post-monsoon	S_1	7.27	5.4	42	76	267	67	40	136	160	360
	S_2	7.32	5	38	78	269	61.4	44	159	158	356
	S_3	7.49	6	32	85	288	50.7	40	52	164	365
	Avg.	7.36	5.47	37.33	79.67	274.7	59.7	41.33	115.7	160.7	360.3

Abbreviations: Avg.: Average; BOD: Biochemical oxygen demand; COD: Chemical oxygen demand; DO: Dissolved oxygen; EC: Electrical conductivity; SS: Suspended solids; TDS: Total dissolved solids.

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Table 2 also showed that the post-monsoon measurements reflected some recovery in water quality. DO improved to 5.47 mg/L, and BOD and COD increased moderately to 37.33 mg/L and 79.67 mg/L, respectively. Turbidity remained high at 59.7 NTU, and SS averaged 115.7 mg/L. Despite partial improvements, Gulshan Lake consistently showed higher levels of organic pollution, including BOD, COD, turbidity, and SS, compared to the other lakes in all seasons.

3.2. Seasonal water quality of Dhanmondi Lake

Dhanmondi Lake showed relatively stable and superior water quality across all seasons. In winter, the lake had an average pH of 7.57 and recorded the highest average DO among all lakes at 6.04 mg/L. BOD and COD were low, averaging 6.67 mg/L and 39.67 mg/L, respectively, indicating minimal organic pollution. TDS levels were also low at 144.3 mg/L, and turbidity was measured at 5.6 NTU. SS concentration was only 10 mg/L, confirming the lake's relatively clean status. Station S_3 reported the highest DO value at 7.14 mg/L (Table 3).

According to Table 3, during the pre-monsoon period, DO declined to 4.2 mg/L, yet BOD and COD remained low at 4.67 mg/L and 33 mg/L, respectively. Chloride levels peaked at 51.33 mg/L, while SS increased to 52 mg/L, possibly due to surface runoff. The overall water quality remained within acceptable limits.

In the monsoon season, Dhanmondi Lake showed improved conditions. DO rose to 5.29 mg/L, and turbidity reached its lowest at 1.67 NTU, indicating excellent water clarity. BOD remained low at 6.67 mg/L, although COD increased to 61 mg/L (Table 3), likely due to accumulated organic matter from stormwater discharge.

Table 3 shows that the post-monsoon data reported a decrease in DO to 3.23 mg/L, the lowest for the lake. However, BOD and COD levels declined further to 2.5 mg/L and 27 mg/L, respectively. Turbidity increased to 44.33 NTU, possibly influenced by sediment disturbance. Despite seasonal fluctuations, Dhanmondi Lake consistently exhibited better water quality than Gulshan and Hatirjheel Lakes, with lower values of BOD, COD, turbidity, and TDS throughout the year.

3.3. Seasonal water quality of Hatirjheel Lake

Hatirjheel Lake exhibited a range of conditions from moderately polluted to stressed throughout the seasons. In winter, the lake showed a slightly alkaline average pH of 7.7. DO was relatively low at 3.06 mg/L, and BOD and COD were 29 mg/L and 103 mg/L, respectively, indicating moderate pollution. TDS levels were highest among the three lakes at 313 mg/L, while EC peaked at 556.7 µmhos/cm. Station S_1 recorded the maximum EC value of 597 µmhos/cm (Table 4).

Table 3. Water quality parameters of Dhanmondi Lake during different seasons

Season	Sampling station	pH	DO (mg/L)	BOD (mg/L)	COD (mg/L)	TDS (mg/L)	Turbidity (NTU)	Chloride (mg/L)	SS (mg/L)	Alkalinity (mg/L)	EC (µmhos/cm)
Winter	S_1	7.49	5.27	6	27	138	5.6	29	9	86	251
	S_2	7.54	5.71	8	58	134	4.5	26	8	95	242
	S_3	7.68	7.14	6	34	161	6.7	28	13	89	290
	Avg.	7.57	6.04	6.67	39.67	144.3	5.6	27.67	10	90	261
Pre-monsoon	S_1	7.35	4.5	4	26	142	5.33	51	42	101	277
	S_2	7.19	3.2	6	32	146	18.4	47	67	114	281
	S_3	7.39	4.9	4	41	160	6.22	56	47	102	311
	Avg.	7.31	4.2	4.67	33	149.3	9.98	51.33	52	105.7	289.7
Monsoon	S_1	7.46	5.86	8	34	132	1.6	33	12	89	302
	S_2	7.39	5	6	73	136	1.9	29	14	92	268
	S_3	7.52	5	6	76	150	1.5	35	15	90	294
	Avg.	7.46	5.29	6.67	61	139.3	1.67	32.33	13.67	90.33	288
Post-monsoon	S_1	7.62	4.3	2.8	30	121.7	56	29	48	89	222
	S_2	7.49	2.1	1.4	10	127.2	7	31	5	91	233
	S_3	7.65	3.3	3.3	41	148.9	70	35	62	105	274
	Avg.	7.59	3.23	2.5	27	132.6	44.33	31.67	38.33	95	243

Abbreviations: Avg.: Average; BOD: Biochemical oxygen demand; COD: Chemical oxygen demand; DO: Dissolved oxygen; EC: Electrical conductivity; SS: Suspended solids; TDS: Total dissolved solids.

Table 4. Water quality parameters of Hatirjheel Lake during different seasons

Season	Sampling station	pH	DO (mg/L)	BOD (mg/L)	COD (mg/L)	TDS (mg/L)	Turbidity (NTU)	Chloride (mg/L)	SS (mg/L)	Alkalinity (mg/L)	EC (μmhos/cm)
Winter	S_1	7.53	2.43	32	112	335	40.2	44	103	226	597
	S_2	7.92	4	25	117	315	26.1	47	58	226	559
	S_3	7.65	2.75	30	80	289	8.3	44	11	186	514
	Avg.	7.7	3.06	29	103	313	24.87	45	57.33	212.7	556.7
Pre-monsoon	S_1	7.25	1.8	25	90	272	82.7	51	133	214	521
	S_2	7.34	1.5	23	95	273	67.8	46	121	175	517
	S_3	7.34	3.9	32	80	261	58.5	61	87	151	496
	Avg.	7.31	2.4	26.67	88.33	268.7	69.67	52.67	113.7	180	511.3
Monsoon	S_1	7.49	4.5	24	161	251	40	50	86	151	493
	S_2	7.3	3.65	22	63	162	67.6	44	110	162	497
	S_3	7.4	8	22	58	150	72.2	48	116	150	474
	Avg.	7.4	5.38	22.67	94	187.7	59.93	47.33	104	154.33	488
Post-monsoon	S_1	7.92	4.3	28	96	280	165	63	158	202	508
	S_2	7.92	5.5	21	39	235	35	45	29	189	426
	S_3	7.72	2.1	26	115	284	123	66	116	218	555
	Avg.	7.85	3.97	25	83.33	266.3	107.7	58	101	203	496.3

Abbreviations: Avg.: Average; BOD: Biochemical oxygen demand; COD: Chemical oxygen demand; DO: Dissolved oxygen; EC: Electrical conductivity; SS: Suspended solids; TDS: Total dissolved solids.

Pre-monsoon observations reflected a further decline in water quality. DO dropped to 2.4 mg/L, representing the lowest seasonal value for Hatirjheel. BOD and COD were measured at 26.67 mg/L and 88.33 mg/L, respectively. Turbidity increased to 69.67 NTU, and SS peaked at 113.7 mg/L. Chloride levels also reached a high of 52.67 mg/L (Table 4), pointing to increased domestic and industrial inflow.

Following Table 4, with the onset of the monsoon, Hatirjheel showed signs of improvement in DO. DO increased to a seasonal high of 5.38 mg/L. BOD and COD slightly decreased to 22.67 mg/L and 94 mg/L, respectively. TDS also declined to 187.7 mg/L due to dilution from rainwater inflow.

In the post-monsoon season, Hatirjheel recorded its highest average pH of 7.85. DO slightly improved to 3.97 mg/L, while BOD and COD were measured at 25 mg/L and 83.33 mg/L, respectively. Turbidity reached its highest level for this lake at 107.7 NTU, and chloride peaked at 58 mg/L (Table 4). Overall, Hatirjheel consistently showed higher TDS and EC values compared to Dhanmondi Lake and had lower DO concentrations, reflecting ongoing environmental stress.

3.4. Comparative analysis of water qualities

The correlation between key physicochemical parameters was evaluated using Pearson's correlation analysis and presented as a heatmap in Figure 2. In this analysis, BOD indicated strong positive correlations with COD ($r = 0.8$), SS ($r = 0.81$), alkalinity ($r = 0.77$), and turbidity ($r = 0.65$), signifying that the organic load was closely related to SSs and buffering capacity. COD was also highly correlated with SS ($r = 0.71$) and turbidity ($r = 0.67$). EC exhibited a strong correlation with alkalinity ($r = 0.89$). On the other hand, DO showed a negative correlation with chloride ($r = -0.28$), alkalinity ($r = -0.16$), and EC ($r = -0.24$), emphasizing the lakes' insufficiency under stressed conditions.

3.5. Comparative analysis across lakes and seasons

The seasonal and spatial comparison of key water quality parameters across Gulshan, Dhanmondi, and Hatirjheel Lakes revealed distinct differences in environmental conditions and pollutant loads. These differences are illustrated in Figure 3, which shows trends for each parameter across the four seasons: winter, pre-monsoon, monsoon, and post-monsoon. Table 5 shows the statistical significance (type III analysis of variance) of lake-season effects and the coefficient of variance (%).

pH levels in the lakes remained stable, ranging from 7.18 to 7.85 (Figure 3A) with significant lake effects ($F = 18.32$, $p<0.001$) and moderate seasonal variation ($F = 3.89$, $p=0.023$) (Table 5). Hatirjheel Lake showed the highest average pH (7.85) in the post-monsoon season,

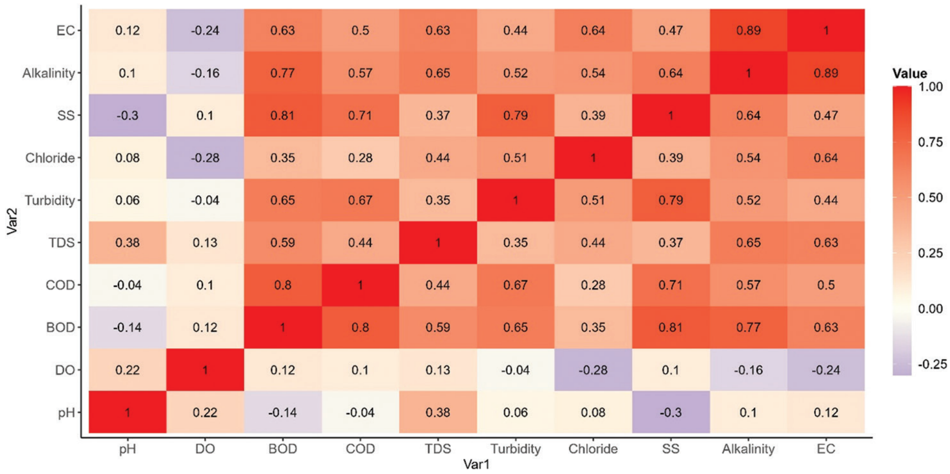

Figure 2. A heatmap showing the correlation among water quality parameters
Abbreviations: BOD: Biochemical oxygen demand; COD: Chemical oxygen demand; DO: Dissolved oxygen; EC: Electrical conductivity; SS: Suspended solids; TDS: Total dissolved solids; Var: Variable.

Table 5. Statistical significance of lake-season effects

Water quality parameter	Lake (*p*-value)	Season (*p*-value)	Lake×Season (*p*-value)
pH	<0.001	0.023	0.215
DO	<0.001	<0.01	0.132
BOD	<0.001	<0.05	0.087
COD	<0.001	0.061	0.243
TDS	<0.001	<0.001	0.054
Turbidity	<0.001	<0.01	<0.01
Chloride	<0.001	<0.05	0.178
SS	<0.001	0.037	<0.05
Alkalinity	<0.001	<0.05	0.096
EC	<0.001	<0.01	0.067

Abbreviations: BOD: Biochemical oxygen demand; COD: Chemical oxygen demand; DO: Dissolved oxygen; EC: Electrical conductivity; SS: Suspended solids; TDS: Total dissolved solids.

Table 6. Coefficient of variation (%) by season

Parameter	Coefficient of variation (%)			
	Winter	Pre-monsoon	Monsoon	Post-monsoon
pH	2.25	1.5	2.59	3.04
DO	33.67	69.97	58.97	35.08
BOD	58.36	79.52	49.02	75.2
COD	50.96	93.24	50.37	43.47
TDS	32.35	24.89	94.47	29.64
Turbidity	77.36	105.1	71.88	64.01
Chloride	18.79	20.34	13.46	27.61
SS	81.65	63.11	56.91	60.3
Alkalinity	29.87	26.82	24.82	28.05
EC	26.63	22.13	23.73	28.88

Abbreviations: BOD: Biochemical oxygen demand; COD: Chemical oxygen demand; DO: Dissolved oxygen; EC: Electrical conductivity; SS: Suspended solids; TDS: Total dissolved solids.

and Gulshan Lake recorded the lowest pH (7.18) value in the monsoon season. The coefficient of variation for pH remained low across all seasons (1.50–3.04%) (Table 6).

DO displayed substantial fluctuation (Figure 3B), with highly significant lake (F = 15.67, $p<0.001$) and seasonal effects (F = 5.61, $p<0.01$) (Table 5). Dhanmondi Lake consistently maintained higher DO values, with seasonal averages ranging from 3.23 mg/L in the post-monsoon to 6.04 mg/L in winter. In contrast, Gulshan Lake recorded critically low DO during the monsoon season (1.41 mg/L), with one sampling station recording an extreme value of 0.12 mg/L. Hatirjheel Lake also showed signs of oxygen depletion, particularly during the pre-monsoon season, when the average DO dropped to 2.4 mg/L. The coefficient of variation for DO reached 69.97% during pre-monsoon (Table 6), reflecting high variability in oxygen availability.

BOD and COD levels, which indicate organic pollution, depict the differences with significant lake effects (BOD: F = 142.33, $p<0.001$; COD: F = 38.45, $p<0.001$) (Table 5). Dhanmondi Lake showed the lowest BOD (2.5–6.67 mg/L) and COD (27–61 mg/L) across all seasons, signifying minimal organic contamination (Figure 3C and D). In contrast, Gulshan Lake displayed the highest levels, with BOD reaching 48 mg/L and COD peaking at 202 mg/L during the pre-monsoon. A maximum COD value of 343 mg/L was obtained at Gulshan Station S_3, indicating severe localized pollution. Hatirjheel Lake exhibited moderate organic pollution, with BOD ranging from

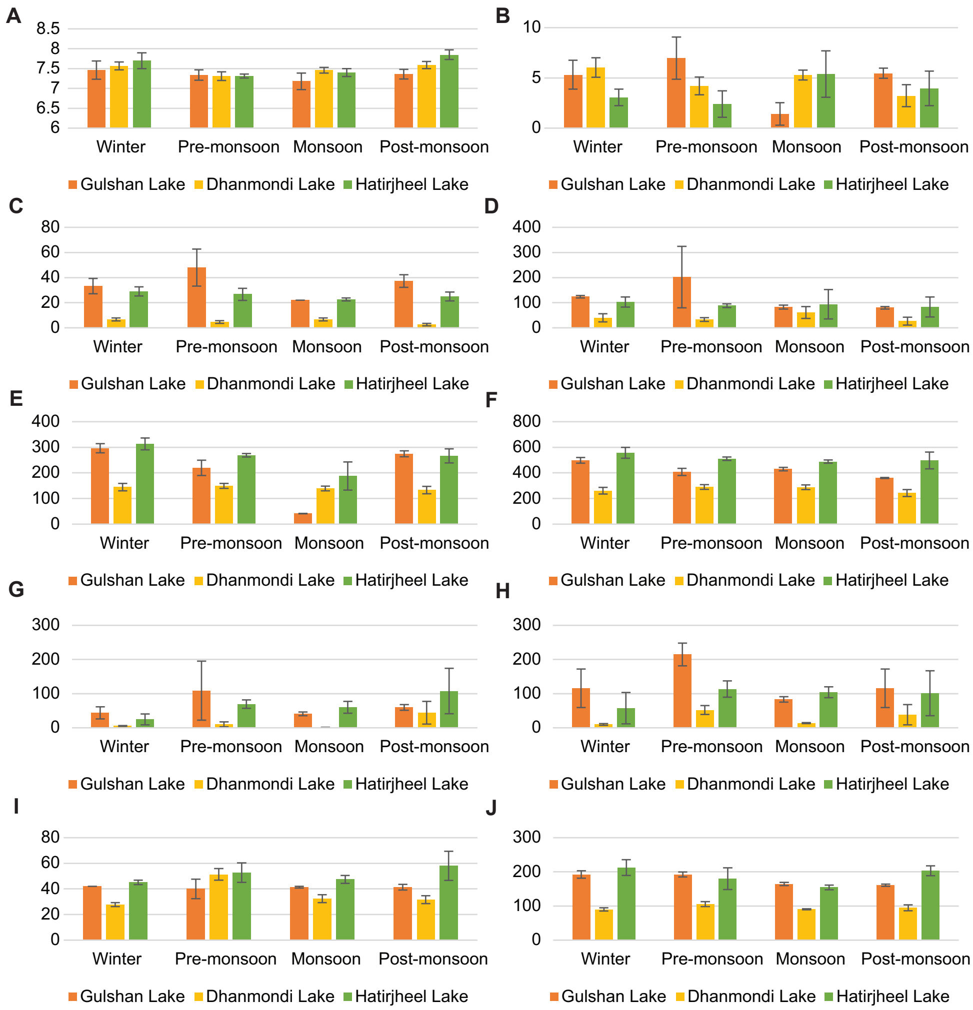

Figure 3. Water quality parameters across seasons in Gulshan, Dhanmondi, and Hatirjheel Lakes. (A) pH, (B) DO, (C) BOD, (D) COD, (E) TDS, (F) EC, (G) Turbidity, (H) SS, (I) chloride, and (J) alkalinity.
Abbreviations: BOD: Biochemical oxygen demand; COD: Chemical oxygen demand; DO: Dissolved oxygen; EC: Electrical conductivity; SS: Suspended solids; TDS: Total dissolved solids.

22.67 to 29 mg/L and COD from 83.33 to 103 mg/L. The coefficients of variation for BOD and COD were significantly high during pre-monsoon (79.52% and 93.24% respectively), as shown in Table 6, reflecting substantial temporal variability in organic loading.

TDSs and EC showed significant lake effects (F = 27.51, $p<0.001$ and F = 64.28, $p<0.001$, respectively) and seasonal variation (F = 45.23, $p<0.001$ and F = 6.45, $p<0.01$, respectively) (Table 5). Hatirjheel Lake recorded the highest TDS and EC levels (Figure 3E and F), with TDS peaking at 313 mg/L and EC at 556.7 µmhos/cm during monsoon dilution. Gulshan Lake also exhibited elevated values, particularly during the monsoon season. The coefficient of variation for TDS during monsoon reached 94.47% (Table 6), indicating substantial dilution-driven variability. Dhanmondi Lake consistently reported the lowest TDS (132.6–149.3 mg/L) and EC (243–289.7 µmhos/cm), suggesting less ionic load.

Turbidity and SS demonstrated significant lake-season interactions (turbidity: F = 3.42, $p<0.01$; SS: F = 2.76, $p<0.05$) (Table 5), indicating that seasonal patterns varied among lakes. Dhanmondi Lake maintained relatively clear water, with turbidity ranging from 1.67 to 44.33 NTU and SS between 10 and 52 mg/L. In comparison, Gulshan and Hatirjheel Lakes showed higher and more variable values. Gulshan's turbidity peaked at 108.6 NTU in the pre-monsoon season, while Hatirjheel's highest turbidity (107.7 NTU) was recorded in the post-monsoon season. Extreme values were observed at Gulshan Station S_3, where turbidity reached 208 NTU, and SS hit 253 mg/L during the pre-monsoon period (Figure 3G and H). The coefficient of variation for turbidity reached 105.1% during pre-monsoon (Table 6), the highest variability observed among all parameters.

Chloride and alkalinity levels further showed significant lake effects (F = 19.87, p<0.001 and F = 87.34, p<0.001, respectively) with moderate seasonal variations (Table 5). Hatirjheel recorded the highest average chloride concentration at 58 mg/L during the post-monsoon, followed by Gulshan, which maintained average values between 40 and 42 mg/L. Dhanmondi Lake exhibited lower chloride levels, ranging from 27.67 to 51.33 mg/L. In terms of alkalinity, both Gulshan and Hatirjheel Lakes displayed higher values (160.7–212.7 mg/L), while Dhanmondi ranged from 90 to 105.7 mg/L (Figure 3I and J), indicating different buffering capacities among the lakes. The coefficients of variation for chloride and alkalinity remained moderate (13.46–27.61% and 24.82–29.87%, respectively) as shown in Table 6, suggesting relatively stable chemical characteristics across seasons.

Principal component analysis explained 65.8% of total variance, with Dimension 1 (50.6%) primarily loaded by BOD (0.87), COD (0.91), and SS (0.78), representing organic matter dynamics. In comparison, Dimension 2 (15.2%) showed strong loadings from TDS (0.92), EC (0.94), and chloride (0.76), indicating ionic composition variations (Figure 4A). The clear separation of lakes along Dimension 1 positioned Gulshan and Hatirjheel Lakes with positive scores (high organic matter indicators), while Dhanmondi Lake clustered with negative scores, indicating better water quality conditions (Figure 4B).

4. Discussion

This study reveals essential seasonal and spatial variations in water quality across Gulshan, Dhanmondi, and Hatirjheel Lakes. A comprehensive comparison of the observed parameters with EQS (Table 7) and findings from previous studies clarifies the current pollution status and potential causes of degradation in these vital urban water bodies.

The pH values across all three lakes consistently ranged between 6.6 and 7.7 (Tables 2-4), falling well within the EQS for fisheries (6.0–9.0) and industrial standards (6.5–8.5) (Table 7). This pH is stable to an extent, as observed in previous studies,[10,17,28,36] which suggests that despite changes in other parameters, the acid-base status of these lakes has remained stable, probably due to their natural buffering capacity.

DO concentrations, however, showed significant seasonal and spatial variations, highlighting critical differences in lake health (Figure 3B). Dhanmondi Lake maintained consistently healthy DO levels, averaging above 5 mg/L in all seasons except post-monsoon (3.23 mg/L) (Table 3), thereby generally meeting the EQS for fisheries (Table 7). In contrast, the Gulshan and Hatirjheel Lakes frequently recorded critically low DO values, particularly during the monsoon and winter seasons. For instance, Gulshan Lake's average monsoon DO plummeted to 1.41 mg/L, with an alarming low of 0.12 mg/L at station S_1 (Table 2), far below the 5 mg/L fisheries standards (Table 7). Similarly, Hatirjheel Lake's DO averaged only 3.06 mg/L in winter and 2.4 mg/L in pre-monsoon (Table 4), indicating

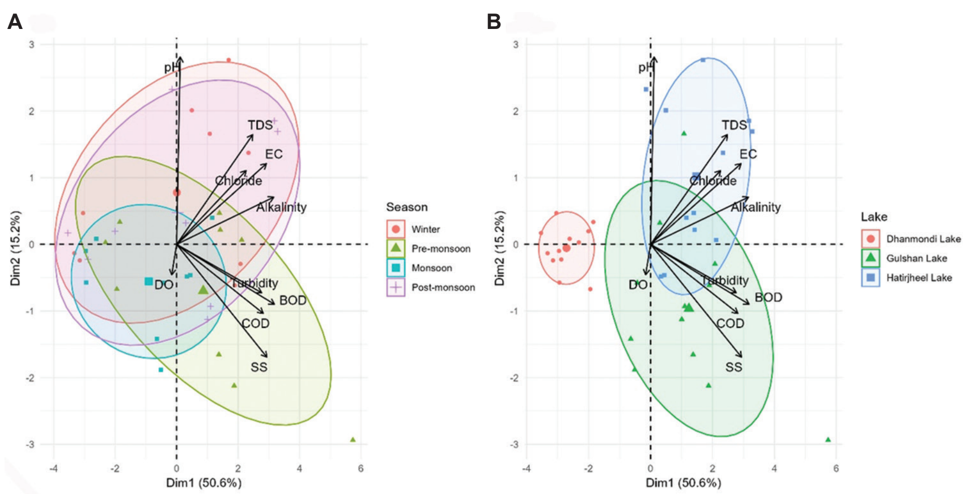

Figure 4. Principal component analysis of water quality parameters. (A) Variable loadings showing parameter contributions and (B) sample scores showing lake separation.

Abbreviations: BOD: Biochemical oxygen demand; COD: Chemical oxygen demand; DO: Dissolved oxygen; EC: Electrical conductivity; SS: Suspended solids; TDS: Total dissolved solids.

Table 7. Environmental Quality Standard for water quality parameters

Parameter	Fisheries	Industrial use	Treated wastewater
pH	6.0–9.0	6.5–8.5	-
Dissolved oxygen	≥5 mg/L	-	-
Biochemical oxygen demand	≤6 mg/L	≤30 mg/L	-
Chemical oxygen demand	≤50 mg/L	≤200 mg/L	-
Total dissolved solids	≤1000 mg/L	-	-
Turbidity	-	-	≤10 NTU
Chloride	-	-	150–600 mg/L
Suspended solids	-	-	≤100 mg/L
Alkalinity	-	-	≤150 mg/L
Electrical conductivity	-	-	≤1200 µmhos/cm

Source: Surface and Ground Water Quality Report 2022.[10]

severe oxygen depletion. These findings align with Uddin *et al.*,[37] who reported severe DO depletion in Gulshan Lake due to untreated sewage discharge. Previous studies[9,38] observed DO levels below 2 mg/L in Hatirjheel during dry seasons. Such low DO values are primarily attributed to high organic loading, limited aeration, and potential stratification effects during specific seasons.

The BOD values further underscore the varying pollution loads. Gulshan Lake consistently exhibited excessive BOD, with averages ranging from 33.33 mg/L in winter to 48 mg/L in pre-monsoon (Table 2), significantly exceeding both the EQS for fisheries (≤6 mg/L) and industrial effluent standards (≤30 mg/L) (Table 7). Hatirjheel Lake also showed elevated BOD, averaging between 22.67 mg/L and 29 mg/L, thus exceeding the fisheries standard but generally remaining below the industrial threshold (Table 7). In sharp contrast, Dhanmondi Lake's BOD was consistently low, averaging between 2.5 mg/L and 6.67 mg/L, consistently meeting the fisheries standard across all seasons. This clear distinction suggests more effective management and fewer direct pollution sources in Dhanmondi Lake.[6] Uddin *et al.*[37] reported similar high BOD trends in Gulshan, while Peeters and Shannon[31] noted that Hatirjheel's proximity to stormwater drains increased organic matter accumulation, explaining its moderate pollution.

COD values mirrored the BOD trends, indicating the extent of chemical contamination (Figure 3C and D). Gulshan Lake's COD values were alarmingly high, peaking at an average of 202 mg/L in pre-monsoon (Table 6), with an individual reading of 343 mg/L at station S_3 (Table 2), far exceeding both the EQS for fisheries (≤50 mg/L) and industrial discharge (≤200 mg/L). Hatirjheel Lake's COD ranged from 82.67 mg/L to 103 mg/L, crossing the fisheries threshold but generally remaining within industrial limits (Table 7). Dhanmondi Lake consistently showed the lowest COD levels, averaging between 27 mg/L and 61 mg/L, thereby meeting both standards across all seasons. These findings align with previous studies[9,38,39] that identified industrial effluents and residential wastewater as primary contributors to COD in Gulshan and Hatirjheel. Dhanmondi's lower values likely result from fewer direct inflow sources and better containment measures.

Regarding TDS and EC, levels across all lakes were generally below the EQS for fisheries (≤1000 mg/L for TDS and ≤1200 µmhos/cm for EC) (Table 7). However, Hatirjheel and Gulshan Lakes occasionally showed elevated TDS values, exceeding 300 mg/L (Hatirjheel's average was 313 mg/L in winter, and Gulshan's average was 296 mg/L in winter), suggesting moderate pollution from urban runoff. EC values, while within acceptable limits, were highest in Hatirjheel (average 556.7 µmhos/cm in winter) and Gulshan (average 498 µmhos/cm in winter), consistent with higher dissolved solids (Figure 3E and F). Previous studies[10,40] also found similar EC ranges, supporting these findings.

Turbidity and SS were significant concerns for Gulshan and Hatirjheel lakes (Figure 3G and H). Turbidity values in Gulshan (average up to 108.6 NTU in pre-monsoon, with an individual high of 208 NTU at S_3) and Hatirjheel (average up to 107.7 NTU in post-monsoon) substantially exceeded the EQS for treated wastewater (10 NTU). In contrast, Dhanmondi Lake consistently maintained low turbidity, generally within or just above this limit (average 1.67–44.33 NTU). Similarly, SS concentrations in Gulshan and Hatirjheel frequently surpassed the EQS limit of 100 mg/L, with values reaching an average of 214.7 mg/L in Gulshan during pre-monsoon (Table 7) and an individual high of 253 mg/L at Gulshan's sampling station S_3 (Table 2). Dhanmondi Lake's SS values were consistently below the standard (average 10–52 mg/L) (Table 3). These elevated values correspond with the study of Uddin *et al.*,[37] who reported on solid waste dumping and construction runoff near Gulshan Lake. Rain-induced sediment resuspension during the monsoon likely explains the turbidity peaks observed in these lakes.

Chloride concentrations in all lakes remained below the EQS limit for treated wastewater (150–600 mg/L) (Figure 3I), though Hatirjheel showed slightly higher average values (up to 58 mg/L in post-monsoon). Alkalinity levels, however, exceeded the 150 mg/L standard in some stations of Gulshan (average 192–192.3 mg/L, with a maximum of 212.7 mg/L in winter) and Hatirjheel (average 180–212.7 mg/L), suggesting influence from detergents, cleaning agents, or leachates. This aligns with previous studies,[9,29,41] which attributed the high alkalinity observed in Gulshan to the input of household wastewater.

The overall comparison of the water quality parameters from Gulshan, Dhanmondi, and Hatirjheel Lakes with the EQS reveals that Gulshan and Hatirjheel Lakes are generally under significant environmental stress and are not ecologically healthy. DO levels in these two lakes frequently fall below the minimum fisheries standard of 5 mg/L, especially during the monsoon season, indicating poor oxygen availability that severely threatens aquatic life. BOD and COD values in Gulshan Lake often exceed both fisheries and industrial limits, signaling substantial organic and chemical pollution. Turbidity and SSs in Gulshan and Hatirjheel frequently exceed the EQS for treated industrial wastewater, significantly reducing water clarity and impacting habitat quality. Although the overall water quality of Dhanmondi Lake was found to be slightly better, specific parameters, such as turbidity and BOD, tend to reach or exceed permissible limits at certain times, which reflects the necessity of continuous monitoring. The elevated pollution levels, particularly in Gulshan and Hatirjheel Lakes, suggest that these water bodies are not safe for recreational use or sustainable fisheries without immediate intervention. Therefore, immediate and integrated actions, such as controlling wastewater discharge, upgrading sewage treatment facilities, and conducting regular surveillance, are necessary to recover their ecological balance and maintain public health.

5. Conclusion

This study provides a comprehensive assessment of the seasonal variations in water quality across Gulshan, Dhanmondi, and Hatirjheel Lakes, three vital urban water bodies within Dhaka city. The findings reveal significant spatial and temporal differences driven by both natural seasonal cycles and anthropogenic influences. Using standard physicochemical parameters, the study adopted a comparative and seasonal analytical approach to identify spatial and temporal trends in pollution levels. Principal component analysis indicated that 65.8% of the total variance was explained by two major dimensions: organic pollution load (BOD, COD, and SS) and ionic composition (TDS, EC, and chloride). Statistical analysis confirmed highly significant lake effects for all parameters ($p<0.001$), with notable seasonal variations and significant lake-season interactions for turbidity and SSs ($p<0.01$). Dhanmondi Lake maintained relatively stable and healthier conditions across most parameters, with low BOD (2.5–6.67 mg/L) and COD (27–61 mg/L) levels. Gulshan Lake exhibited significant organic pollution, particularly during the pre-monsoon period, accompanied by severe oxygen depletion during the monsoon (DO 1.41 mg/L). Hatirjheel Lake revealed elevated ionic content, with TDS peaking at 313 mg/L and high turbidity levels (>100 NTU), particularly during the post-monsoon period. Comparison with EQS and similar studies indicated that some parameters remained within acceptable limits, but organic pollution indicators and turbidity frequently exceeded safe thresholds, indicating environmental stress and potential public health risks. The study underscores the need for targeted lake-specific management strategies, prioritizing Gulshan Lake for organic pollution control and Hatirjheel for ionic and turbidity management. These findings provide a scientific basis for policymakers to identify pollution hotspots, allocate resources efficiently, and implement seasonally adaptive conservation measures. Biological indices, long-term and continuous monitoring accuracy, and remote sensing techniques can be combined in future research to better understand and predict water quality. As a whole, the study contributes to a developing knowledge base that is needed to better protect and manage urban aquatic ecosystems in cities, such as Dhaka.

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Conflict of interest

The authors declare that they have no competing interests.

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Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Availability of data

The data used in this study were obtained from the "Surface and Ground Water Quality Report 2022" published by the Department of Environment, Ministry of Forest, Environment and Climate Change, Government of the People's Republic of Bangladesh. This report is publicly available through official government channels. Any further details or access to the dataset can be obtained from the Department of Environment upon request.

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