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Suitability of drinking water quality in Chittagong Metropolitan City, Bangladesh: research on urban water bodies (UWBs) using multivariate analytic techniques

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ABSTRACT

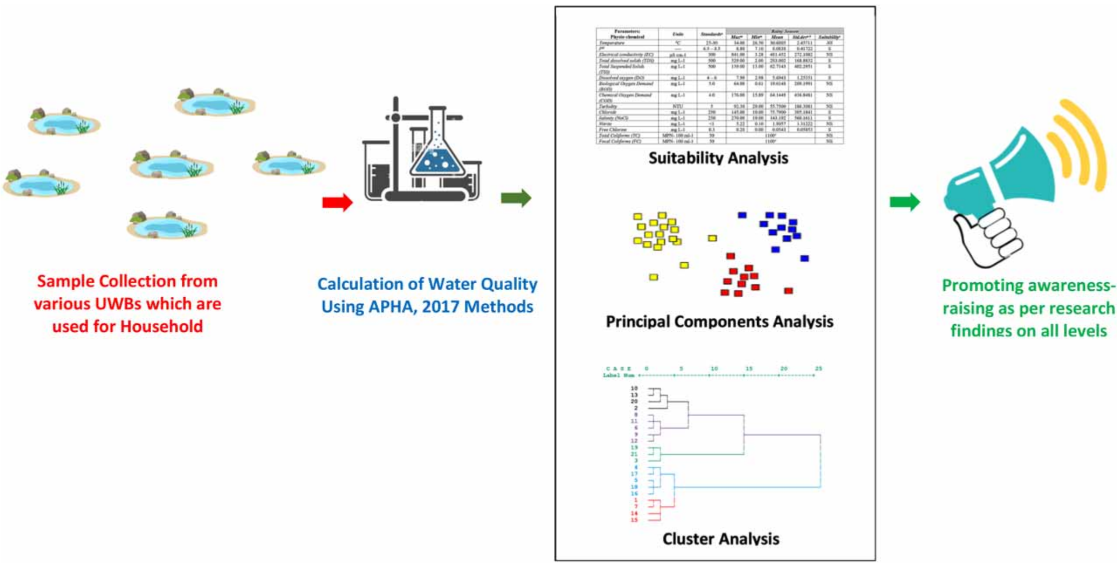
This is empirical research that focuses on the urban water ecosystems in the humid tropics of South Asia. The purpose of the study was to evaluate the quality of drinking water in the urban water bodies (UWBs) of Chittagong Metropolitan City (CMC), Bangladesh. The field data was centered on the analysis and depiction of twenty-three (23) water quality parameters, collected from twenty-one (21) spatial observation units. Analytic tools include suitability analysis, correlation matrix, principal component analysis (PCA), and cluster analysis (CA) as a means to an end. The data were analyzed using SPSS. The analysis reveals that drinking water quality in studied UWBs was inappropriate during the monsoon season. Parameters that crossed the extreme permissible concentration incorporate EC, BOD, COD, Turbidity, Nitrate, Total coliform, and Fecal coliform. The PCA extracted four factors (PC1–4) with an eigenvalue of 10.23, explaining 73.1% of the total variation in the dataset in cumulative terms. The CA recognized three (3) broad groups of the sampling stations. Group A represents nine cases, suffering the most from pollution concentration in CMC. Awareness building at all levels is advocated to improve clean water sources, increase service provision, and ensure public health safeguards.

Key words: Chittagong, cluster analysis, drinking water quality, PCA, urban water bodies

HIGHLIGHTS

- Urban water bodies are alternative sources of drinking water.
- A significant gap exists between the demand for and supply of municipal piped water supply.
- Anthropogenic activities have an impact on the quality of drinking water.
- Multivariate analytic techniques (MATs) have been used to determine the suitability of drinking water quality.
- Promoting awareness-raising on all levels is encouraged.

GRAPHICAL ABSTRACT



INTRODUCTION

Fresh water is an essential natural resource; it provides immense socioeconomic and ecological benefits for all forms of life on earth, and plays a vital role in maintaining the health and welfare of human beings (WHO & UNCF 2000; Agnew & Woodhouse 2011; Muhangane *et al.* 2017). However, this precious resource is scarce in nature, contains only 0.01% of the total hydrosphere, and water stored in small urban water bodies (UWBs)[1] is only a tiny fraction of it. Moreover, around 780 million people in the world do not have access to clean and safe water. As a consequence, around 6–8 million people die each year due to waterborne diseases and disasters. Furthermore, water pollution is one of the major environmental concerns of our time (Carr & Neary 2008). The UWBs are susceptible to various pollutants depending on physical processes and anthropogenic activities. The problem is serious for drinking water; public health is at high risk due to the presence of chemical contaminants. Prolonged exposure to contaminated water has been known to increase the risks of diarrheal diseases, cancer, and disorders in the kidney, liver, and reproductive organs (WHO 2002; Fawell & Nieuwenhuijsen 2003). The concern over the ensuing freshwater supply has compelled developing countries to search for alternative water sources. The UWBs can play a vital role in this regard as alternative sources of water for household consumption (United Nations 2010; Rahman *et al.* 2011). Ensuring the safety of drinking water is, therefore, a growing public concern. Drinking water is now recognized as a fundamental human right by the United Nations. Availability and sustainable management of good-quality water were set as one (Number 6) of the UN Sustainable Development Goals (SDGs) (United Nations 2015). An understanding of water quality[2] and its availability is vital because waterborne diseases are still a major cause of death in many parts of the developing world (WHO 2002, 2011). Therefore, monitoring and control of drinking water quality is a top-priority policy agenda in many parts of the world (UNESCO 2013).

Chittagong is one of the major developing metropolises, an important harbor and seaport city, and Bangladesh's manufacturing and commercial heart. There are a lot of large polluting industries in the city (DoE 2004). The city has recently seen the effects of increasing urbanization. Over the previous three decades, the overall quantity of UWBs in metropolitan has steadily decreased at a degree of 10% each year. In the previous 30 years, over 56% of the land cover had changed, owing mostly to the increase in developed areas and other anthropogenic activities (Molla *et al.* 2020). As a result, concerns about potable water quality and paucity apply to the water itself and the number of threats associated with harmful material diffusion into freshwater environments. In

[1] *Urban water bodies (UWBs)* have been defined as the collective name, given for 'lotic' and 'lentic' water environment in operational terms. In Bangladesh, small UWBs are classified into different categories such as *doba, pond, dighi, khal*, and *beel* (Huda & Alam 2006).

[2] *Water quality* refers to the state of the water, including its chemical, physical, and biological characteristics, as well as its suitability for a specific purpose such as drinking or swimming. Poor water quality can also be harmful to ecosystems.

reality, access to clean water has become a critical concern for the city dwellers in Chittagong Metropolitan City (CMC). The Chittagong Water Supply and Sewerage Authority (CWASA) is the sole organization that supplies water to city dwellers through its limited distribution networks. However, the organization can only produce 450 core liters, or 4,500 MLD, of water each day; around 80% of the water is produced from surface water sources, and the remaining 20% is produced from underground water sources. Only 3.1 million individuals had access to piped water through their house connection, and about 2.03 million people were unable to access CWASA sources of drinking water last year (CWASA Annual Report 2020–2021). Many city residents still experience a severe water shortage and obtain their water from private sources or other sources, such as natural reservoirs like ponds, canals, and rainwater catchments. Due to ineffective management techniques, city people have been experiencing erratic, insufficient, and hazardous water delivery in these conditions (De 2020). Day by day, things are becoming worse, especially in CMC's low-income residential areas (Molla *et al.* 2014; Molla & Chowdhury 2021).

This paper was prepared as part of a recent comprehensive field inquiry entitled 'Management of Urban Water Bodies (UWBs) in Bangladesh: A Case Study of Chittagong Metropolitan City.' Table 1 shows the seasonal change of eleven (11) physiochemical parameters assessed throughout the rainy and winter seasons. The observed mean values of the examined parameters reveal a significant seasonal fluctuation between the two seasons: monsoon and winter. Except for nitrate, the mean values of 10 of the 11 parameters were found to be greater in the rainy season than in the winter (Table 1). This served as a foundation for deciding on a season for additional investigation, namely a multivariate study of water quality characteristics during the monsoon season.

Water quality concepts and measurement

Usually, drinking water quality refers to the characteristics of water, whether good or bad; it shows the suitability of water for human consumption; it is frequently used in a comparative sense, and its meaning is relative. In order to conduct an interpretive analysis, credible reference points known as 'standards' are required; they are considered authoritative assessments of risk exposure (WHO 1995; Kannan 1997). Some reputed recommending authorities have provided information on drinking water standards and unit weights in Table 2. If values surpass permissible limits, human health is jeopardized (Carr & Neary 2008). The World Health Organization (WHO), Bureau of Indian Standards (BIS 2012), Indian Council for Medical Research (ICMR), and Bangladesh Standard Testing Institute are among the recommending agencies used as references in this study (BSTI).

There is an abundance of literature on water quality monitoring and assessment. Of the multivariate methods, principal component analysis (PCA) and cluster analysis (CA) have been successfully used by many researchers as the more trustworthy technique for data reduction (Astel *et al.* 2007, 2008; Simeonova & Simeonov 2007). A number of academicians and researchers (especially Singh *et al.* 2004; Zhang *et al.* 2009; Prasanna *et al.* 2012; Bhuiyan *et al.* 2016; Howladar *et al.* 2017; Rahman *et al.* 2017; Ahmad *et al.* 2020; Akhtar *et al.* 2021) have conducted research on water quality applying multivariate techniques including PCA and CA at home and abroad.

Table 1 | Seasonal variations in physiochemical parameters in selected UWBs

Parameters	Rainy season (Mean of results; $N = 21$)	Winter season (Mean of results; $N = 21$)
1. Temperature	30.6805	25.3429
2. pH	8.0838	6.3143
3. Electrical conductivity (EC)	481.452	352.382
4. Total dissolved solids (TDS)	283.002	21.1712
5. Total suspended solids (TSS)	62.7143	16.0862
6. Dissolved oxygen (DO)	5.6943	3.6643
7. Biological oxygen demand (BOD)	19.6148	9.5500
8. Chemical oxygen demand (COD)	64.1448	37.8048
9. Turbidity	55.7500	25.1471
10. Chloride	30.6805	35.9048
11. Nitrite	1.8057	3.8295

Source: Measured and compiled by the Authors.

Table 2 | Drinking water standards endorsing agencies and unit weights (All values except temperature, pH, electrical conductivity, and turbidity were in mg L^{-1})

Parameters	Standard[a]	Recommended agencies[b]	Unit weight
1. Temperature	25–30	WHO	0.0866
2. pH	7–8.5	ICMR/BIS	0.2190
3. Electrical conductivity (EC)	300	ICMR	0.371
4. Total dissolved solids (TDS)	500	ICMR/BIS	0.0037
5. Total suspended solids (TSS)	500	WHO	0.0037
6. Dissolved oxygen (DO)	5.0	ICMR/BIS	0.3723
7. Biological oxygen demand (BOD)	5.0	ICMR	0.3723
8. Chemical oxygen demand (COD)	4.0	WHO	0.08266
9. Turbidity	5.0	WHO	0.16533
10. Chloride	250	ICMR	0.0074
11. Nitrite	<1	ICMR/BIS	0.0412

Source: Compiled by the Authors.

[a]Standard values have been selected by WHO (2017). *Guidelines for Drinking-Water Quality*. In: Health Criteria and Other Supporting Information, 4th edn. WHO, Geneva. ISBN 978 92 4 1548151 and Department of Environment, Bangladesh.

[b]ICMR – Indian Council for Medical Research / BIS – Bureau of Indian Standard and WHO – World Health Organization cited by Yogendra & Puttaiah (2008).

However, until recently, none of them has applied these methodologies to UWBs in CMC. Such an investigation is intended to aid in raising awareness at all levels (public and private), particularly among city inhabitants, about the importance of investigating alternative water sources for home consumption and public health protection. Based on the preceding concept, our objective for the study is three-fold as follows: (i) Collection of samples for drinking water from selected sample stations (UWBs: $N = 21$) in CMC, (ii) determination of drinking water quality by suitability analysis (SA) using a set of physiochemical and biological parameters including certain trace metals for the rainy season; and (iii) application of multivariate techniques for data reduction, i.e. PCA and CA.

MATERIALS AND METHODS

The study area: geographic description

Chittagong is one of the major port cities in the humid tropics of South Asia. It is the second-largest metropolis and the economic gateway of the country. It is located between 22°15 and 22°25 North latitudes and between 91°45 and 91°55 East longitudes on the right bank of the Karnaphuli river; occupying an area of about 168 km^2 in size; and inhabited by over 5.13 million people – a 2.25% increase from the 2020 level (United Nations 2021). The city's terrain is undulating and includes hills, coastal plains, lowlands, ponds, lakes, and other bodies of water. A major part of the city is subject to tidal inundation from the Bay of Bengal, twice a day. The three distinct seasons include (i) the Summer from March through May, (ii) the rainy season from June through October, and (iii) the cool dry Winter from November through February. The metropolis is significantly influenced by the monsoon season climate; the mean annual rainfall is 2,687 mm; and the mean annual temperature is 26.24 °C, respectively (Ahmed 2021; Ahmed & Mohanta 2021). Figure 1 illustrates where the sampling stations are located on the map of the Chittagong City Corporation.

Selection of the sampling stations (UWBs)

To detect existing UWBs on the Chittagong City Corporation (CCC) Map, a time series of Landsat data (Landsat™ images 30 m spatial resolution) collected from Bangladesh's Space Research and Remote Sensing Organization (SPARRSO) was used. The actual number of UWBs had also been identified using the 'Ground Truthing Method' (1,249). In the research region, a total of 21 sample sites (UWBs) were chosen. The sampling stations, ward number, spatial location, area in square feet, and pollution status for each site are listed in Supplementary Appendix I. The locations of the surface water sample sites are shown in Figure 1 on the CCC map. The sampling stations were selected with the spot technique. Moreover, the absolute position of the sample location was determined using the geographical positioning system (GPS). Furthermore, the sample size was identified using a number of criteria, including the sample sites' (UWBs) connectedness with city

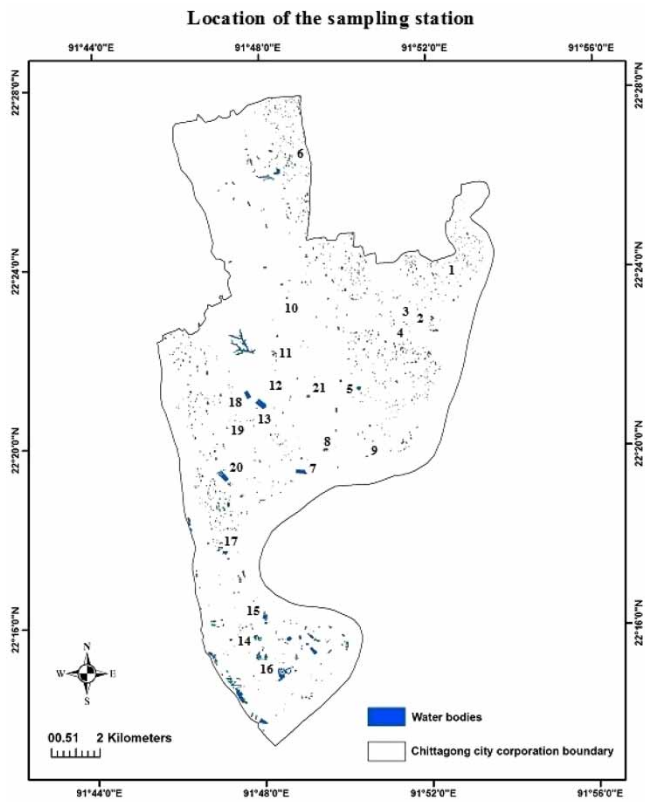


Figure 1 | Location of the sampling stations on the Chittagong City Corporation Map. 1. Master Colony Pond [Mohara, 05]. 2. Baitul Salat Jame Mosque Pond [Chandgaon, 04]. 3. Bahharhar Bari Pond [East Sholashahar, 06]. 4. Miar Baper Barir Pukur [Bakolia, 17]. 5. Munshi Pukur [Chawkbazar, 16]. 6. Fateabad Dighi [South Pahartali, 01]. 7. Asker Dighi [Jamalkhan, 21]. 8. Lal Dighi [Anderkilla, 32]. 9. Kola-Bagisa Pond [Patharghata, 34]. 10. Olima Dighi [Jalalabad, 02]. 11. Baizid Bostami Pond [Jalalabad, 02]. 12. Sheer-Shah Dighi [Sulakbahar, 08]. 13. Agrabad Deba Dighi [Agrabad, 28]. 14. Korno Mohon Sheal Bari Pond [South Patenga, 41]. 15. Hindu Para Pond (Durga Bari) [South Patenga, 40]. 16. Raja Pond, South Patenga [South Patenga, 41]. 17. Boro Pukur or Pond (Hadu Serang Bari) [South-Middle Halishar, 34]. 18. Kazir Dighi (Sharaipara) [North Kattali, 10]. 19. Voluar Dighi [Sharaipara, 19]. 20. Jora Dighi [Sharaipara, 19]. 21. Aladi Jumadar Wafkup State Mosque Pond [Dampara, 14].

residents, their proximity to recreational and other facilities, their potential to retain water permanently, their frequency of use (which includes ablutions, bathing, dressing, cleaning, dishwashing, somewhat drinking, and fishing), and their proximity to water bodies in lower-income residential areas. These are a few of the important factors that were taken into consideration when selecting sample stations from the entire UWB distribution map (Supplementary Appendix I).

Selection of the parameter

Water quality is determined by a number of factors, including physical, chemical, microbiological, and trace metals, all of which may be quantified in terms of their appropriateness for a certain function. The relative importance of one set of these factors over another would be determined mostly by the purpose for which they are to be used. The list of twenty-three (23) water quality metrics used to determine surface water quality in CMC is presented in Table 3. The table also provides the study's measuring units and analytical methodologies.

Sample collection and analytic procedures

In order to obtain samples from the sampling stations ($N = 21$ UWBs), 23 parameters were used (Table 3); each sample, which was collected in a 200 ml polyethylene bottle, was obtained at a depth below the water's surface. The bottles were cleansed with water to be examined before collecting the samples, and the collected samples were stored by acidifying pH 2 with HNO_3 and stored at 40 °C until analysis was done. The samples were subsequently tested at the Bangladesh Council of Scientific and Industrial Research (BCSIR Laboratory) in Chittagong's Chemistry Laboratory, Industrial Microbiological Research Division.

Table 3 | Water quality parameters, units, and analytical techniques

Parameters	Units	Analytical techniques
1. Temperature	°C	Thermometer
2. pH	–	pH meter (HANNA HI 8424 pH meter) (made in Romania)
3. Electrical conductivity (EC)	μS cm^{-1}	Combo meter, Model HI 98129 (HANNA Instruments, Inc., Woonsocket, RI)
4. Total dissolved solids (TDS)	mg L^{-1}	TDS meter (HANNA DiST 1 HI 98301, made in Mauritius)
5. Total suspended solids (TSS)	mg L^{-1}	**Reference 1**
6. Dissolved oxygen (DO)	mg L^{-1}	DO meter (HANNA HI 9146, made in Romania)
7. Biological oxygen demand (BOD)	mg L^{-1}	Manometric method: **Reference 1**
8. Chemical oxygen demand (COD)	mg L^{-1}	Titrimetric method (Dichromate reflux method: **Reference 1**)
9. Turbidity	NTU	Turbidity meter (HANNA HI 98703 Turbidity meter)
10. Chloride	mg L^{-1}	Titrimetric method (Mohr method): **Reference 1**
11. Salinity (NaCl)	mg L^{-1}	Chloride concentration and salinity
12. Ammonia (as nitrogen) (NH_3-N)	mg L^{-1}	Direct Nesslerization method, **Reference 1**
13. Free chlorine	mg L^{-1}	**Reference 1**
14. Copper (Cu)	μg L^{-1}	Heavy metal analysis was carried out on all samples by using atomic absorption spectrophotometer (AAS) after wet digestion. **Instrumentation:** Atomic absorption spectrophotometer (AAS) (Type: iCE 3300 AA system, Thermo Scientific, designed in the UK) was used to determine Cu, Cd, Cr, Fe, As, Pb, Hg, Mn in water samples. The analysis was carried out using respective hollow cathode lamps under standard instrumental conditions. *Reference Book for digestion technique*: **Reference 1**
15. Cadmium (Cd)	μg L^{-1}	
16. Chromium (Cr)	μg L^{-1}	
17. Iron (Fe)	μg L^{-1}	
18. Arsenic (As)	μg L^{-1}	
19. Lead (Pb)	μg L^{-1}	
20. Mercury (Hg)	μg L^{-1}	
21. Manganese (Mn)	μg L^{-1}	
22. Total coliform (TC)	MPN-100 ml^{-1}	MPN method
23. Fecal coliform (FC)	MPN-100 ml^{-1}	MPN method

Source: Compiled by the Authors.
Reference 1: APHA 2017. *Standard Methods for the Examination of Water, Sewage and Industrial Wastes*, 23rd edn. American Public Health Association Inc., New York, 2012.

Suitability analysis (SA) of water quality

The acceptability of drinking water in CMC UWBs was tested using a set of fifteen (15) physiochemical and microbiological parameters. With the help of SPSS, these parameters were tested and evaluated using certain common scientific and statistical procedures. For the rainy season, descriptive statistics such as observed mean value, units of measurement, standard deviation, range-maximum and minimum, suitability measures, and many more are included in the analyzed data.

Correlation matrix (CM)

A correlation analysis was performed for fourteen (14) water quality parameters, obtained from 21 spatial observation units/sample stations – UWBs in CMC, as a piece of necessary background information for multivariate analysis. The Pearson's correlation coefficient matrix ($14 \times 21 = 294$) for the analyzed parameters is presented in Table 6. The matrix was utilized to recognize the relationship between sample parameters. The correlation coefficient matrix, which serves as a context and rationale for multivariate analysis, quantifies how well each parameter's variance explains.

Multivariate statistical methods

As a way to unravel the primary structure in the data matrix two contrasting, but complementary multivariate analytical techniques – namely trend seeking ordination, i.e. PCA and recognition of group structure, i.e. CA were employed in the dataset. The data were analyzed using the IBM Statistical Package for the Social Sciences (SPSS), Statistics Version 25 for Windows, and CAP version: 5.0.0.465. A detailed treatment of multivariate methods such as PCA and CA may be found in Orlóci (1978), Howladar *et al.* (2017), and Costa *et al.* (2020). Prior to subjecting the data to the aforementioned analytical methods, the raw data was centered and standardized using standard score transformation to have 0 mean and unit variance.

PCA technique

The PCA is an extremely effective approach used to reduce the dimensionality of a dataset made up of many interconnected variables. PCA makes an effort to explain the correlations between the observations in terms of factors that are not immediately evident (Yu *et al.* 2003). In order to reduce the amount of data, the original dataset is converted into a new set of variables known as the principal components (PCs). These components, which are ranked in decreasing order of significance, are weighted linear combinations of the original variables that are orthogonal (non-correlated) to one another (Wunderlin *et al.* 2001). Typically, the first three PCs often explain a significant amount of the total variance. The Varimax rotated PCA matrix solution was sought using the SPSS package. The r-mode technique was performed using covariance as the resemblance function, which minimized the number of variables (parameters in this study) with high loading on each component, thus facilitating the interpretation of PCA results (Gotelli & Ellison 2004). Details of the technique may be found in a number of publications including Orlóci (1978), Fewster & Orloci (1978), Gotelli & Ellison (2004), Howitt & Cramer (2005), Dragović *et al.* (2008), Franco-Uría *et al.* (2009), Bhuiyan *et al.* (2016), Billa *et al.* (2016), Vega *et al.* (1998), and Helena *et al.* (2000).

CA technique

The next step of the data reduction technique is CA. The fundamental goal of clustering is to arrange a collection of items (such as sample stations or UWBs, the spatial observation units) so that objects in the same group, or cluster, are more similar to one another than units in other categories (clusters). To put it another way, the generated object clusters should have strong external heterogeneity (across groups) and high internal heterogeneity (within the group) (McGarial *et al.* 2000). In this way alone, the CA is a powerful data-mining tool for researchers to identify discrete groups. Hierarchical agglomerative clustering is the method that is used the most frequently in cluster analysis. The outcomes of the CA assist with interpreting the data and point out patterns (Vega *et al.* 1998).

Using the Ward-algorithmic approach of clustering, the dataset's built-in group structure was revealed. This is an algorithm – a polythetic agglomerative method of clustering, which hierarchically groups the cases so that those with greater similarity (lesser distance) cluster together earlier in the numeric manipulation of the data. For calculating the distance between clusters of similar characteristics, the Euclidean rescaled linkage distance was used as the resemblance function (a measure of similarity; Singh *et al.* 2004; Howladar *et al.* 2017; Costa *et al.* 2020). We used a fantastic idea called a Dendrogram, which is a graphical representation of the cluster solution, to determine the number of clusters for hierarchical clustering. More specifically, a Dendrogram is a tree-like diagram that illustrates the distance between groups when they are linked and records the sequences of merges and splits. The stages of hierarchical clustering are easily recognizable just from the Dendrogram. However, determining the number of clusters by looking at the classification tree is a subjective process. Generally, one begins by looking for 'gaps' between joining along the horizontal axis. A Dendrogram can be understood by concentrating on the height at which any two things are connected to one another.

RESULTS AND DISCUSSION

Results of the SA: physiochemical and biological parameters

The results of the suitability research are presented and summarized in Table 4 for fifteen (15) physiochemical and microbiological criteria.

The observed mean value of the parameters of interest was compared to their assigned standard value to assess the water quality. The mean value indicates that the maximum sample size has exceeded the allowable limit. As shown in Table 4, 8 of the 15 water quality criteria were determined to be unfit for drinking during the rainy

Table 4 | Analysis of the biological, physiochemical, and suitability of the CMC's UWBs

			Rainy season				
Parameters: Physiochemical	**Units**	**Standards[a]**	**Maximum**	**Minimum**	**Mean**	**Std. deviation[b]**	**Suitability[c]**
Temperature	°C	25–30	34.00	26.50	30.6805	2.45711	NS
pH	–	6.5–8.5	8.80	7.10	8.0838	0.41722	S
Electrical conductivity (EC)	$\mu S\ cm^{-1}$	300	841.00	3.28	481.452	272.1082	NS
Total dissolved solids (TDS)	$mg\ L^{-1}$	500	529.00	2.00	283.002	168.8832	S
Total suspended solids (TSS)	$mg\ L^{-1}$	500	139.00	13.00	62.7143	402.2951	S
Dissolved oxygen (DO)	$mg\ L^{-1}$	4–6	7.90	2.98	5.6943	1.25351	S
Biological oxygen demand (BOD)	$mg\ L^{-1}$	5.0	64.00	0.61	19.6148	209.1991	NS
Chemical oxygen demand (COD)	$mg\ L^{-1}$	4.0	176.00	15.89	64.1448	436.8481	NS
Turbidity	NTU	5	92.30	29.00	55.7500	186.3081	NS
Chloride	$mg\ L^{-1}$	250	145.00	10.00	75.7900	305.1841	S
Salinity (NaCl)	$mg\ L^{-1}$	250	270.00	19.00	143.192	560.1611	S
Nitrite	$mg\ L^{-1}$	<1	5.22	0.10	1.8057	1.31222	NS
Free chlorine	$mg\ L^{-1}$	0.3	0.20	0.00	0.0543	0.05853	S
Total coliforms (TC)	$MPN\text{-}100\ ml^{-1}$	50	1,100 +				NS
Fecal coliforms (FC)	$MPN\text{-}100\ ml^{-1}$	50	1,100 +				NS

Source: Compiled by the Authors.
[a]The WHO recommended guidelines for water quality (WHO 2004).
[b]The values are calculated by averaging at least three successive measurements. Standard deviation (SD).
[c]Suitability for drinking as compared with the WHO suggested water quality standards, 'S', suitable; 'NS', not-suitable.

season. The following parameters are all above the permitted limit: temperature, EC, BOD, COD, Turbidity, Nitrate, and two biological metrics, Total and Fecal coliform.

Findings of the SA: trace metals

Table 5 sums up and illustrates the findings of the suitability study for detecting trace metals in CMC's ample stations (UWBs). For the rainy season, a total of eight (8) factors were used. Except for one parameter, lead (Pb), which has levels over the permitted limit, the other trace element content of UWBs is not concerning for drinking purposes. The examined water bodies had no copper (Cu) or cadmium (Cd), however, arsenic (As) levels were found to be below detected levels (BDLs). The samples also contained chromium (Cr), iron (Fe), mercury (Hg), and manganese (Mn). However, it has been demonstrated that drinking is safe during the rainy season.

Results of the CM analysis

Table 6 displays Pearson's correlation matrix. The observed parameters have a substantial relationship. For instance, EC has a significant correlation with TDS ($r = 0.964$), TSS ($r = 0.572$), BOD ($r = 0.661$), Chloride

Table 5 | Suitability analysis of trace metals in UWBs of CMC

			Rainy season				
Parameters: Trace metals	**Units**	**Standards**	**Maximum**	**Minimum**	**Mean**	**Std. deviation**	**Suitability**
Copper (Cu)	$\mu g\ L^{-1}$	2	Nil				
Cadmium (Cd)		0.003	Nil				
Chromium (Cr)		0.05	0.04	00.00	0.0062	0.01244	S
Iron (Fe)		0.3	1.20	00.00	0.2176	0.35417	S
Arsenic (As)		0.01	BLD (Below detected level)				
Lead (Pb)		0.01	0.09	0.01	0.0481	0.01861	NS
Mercury (Hg)		0.006	BLD (Below detected level)				
Manganese (Mn)		0.4	0.27	0.00	0.0348	0.07229	S

Source: Compiled by the Authors.

Table 6 | Correlation matrix between water quality parameters

	Temperature	pH	EC	TDS	TSS	DO	BOD	COD	Turbidity	Chloride	Salinity	Nitrite	Free chlorine	Pb
Temperature	1	0.303	0.184	0.287	0.227	0.172	0.127	−0.134	0.104	−0.329	−0.334	0.067	−0.149	−0.298
pH	0.303	1	0.170	0.126	−0.076	0.449*	0.058	−0.300	0.151	0.160	0.166	0.100	−0.232	0.082
EC	0.184	0.170	1	0.964**	0.572**	0.053	0.661**	0.428	0.225	0.565**	0.580**	0.306	0.079	0.079
TDS	0.287	0.126	0.964**	1	0.601**	0.038	0.681**	0.487*	0.205	0.422	0.435*	0.339	0.094	0.056
TSS	0.227	−0.076	0.572**	0.601**	1	−0.321	0.489*	0.476*	0.104	0.086	0.087	0.038	0.307	−0.311
DO	0.172	0.449*	0.053	0.038	−0.321	1	−0.225	−0.220	0.150	−0.102	−0.087	−0.175	−0.268	−0.008
BOD	0.127	0.058	0.661**	0.681**	0.489*	−0.225	1	0.636**	0.191	0.336	0.338	0.595**	0.300	0.384
COD	−0.134	−0.300	0.428	0.487*	0.476*	−0.220	0.636**	1	0.076	0.165	0.170	0.067	0.232	0.087
Turbidity	0.104	0.151	0.225	0.205	0.104	0.150	0.191	0.076	1	0.298	0.286	0.102	−0.197	0.223
Chloride	−0.329	0.160	0.565**	0.422	0.086	−0.102	0.336	0.165	0.298	1	0.998**	0.268	−0.005	0.473*
Salinity	−0.334	0.166	0.580**	0.435*	0.087	−0.087	0.338	0.170	0.286	0.998**	1	0.256	0.018	0.465*
Nitrite	0.067	0.100	0.306	0.339	0.038	−0.175	0.595**	0.067	0.102	0.268	0.256	1	0.165	0.449*
Free chlorine	−0.149	−0.232	0.079	0.094	0.307	−0.268	0.300	0.232	−0.197	−0.005	0.018	0.165	1	0.274
Pb	−0.298	0.082	0.079	0.056	−0.311	−0.008	0.384	0.087	0.223	0.473*	0.465*	0.449*	0.274	1

*Correlation is significant at the 0.05 level (two-tailed).

**Correlation is significant at the 0.01 level (two-tailed).

Note: Few parameters did not detect during the rainy season, for example, Copper (Cu), Cadmium (Cd), Arsenic (As), and Mercury (Hg).

($r = 0.565$), and Salinity ($r = 0.580$). Then, BOD has a strong correlation with EC ($r = 0.661$), TDS ($r = 0.681$), TSS ($r = 0.489$), COD ($r = 0.636$), and Nitrite ($r = 0.595$). After that TDS ($r = 0.487$), TSS ($r = 0.476$), and BOD ($r = 636$) all have a moderate correlation with CODs. Similarly, Nitrite has a strong correlation with BOD ($r = 0.595$) and Pb ($r = 0.449$). In addition, Chloride has a strong relationship with EC ($r = 0.565$), Salinity ($r = 0.998$), and Pb ($r = 0.473$). Also, EC ($r = 0.580$), TDS ($r = 0.435$), Chloride ($r = 0.998$), and Pd ($r = 0.465$) all have a moderate correlation with salinity. Besides, TDS is also linked to EC ($r = 0.964$), TSS ($r = 0.601$), BOD ($r = 0.681$), COD ($r = 0.487$), and salinity ($r = 0.435$). Moreover, TSS also has a strong association with EC ($r = 0.572$), TDS ($r = 0.601$), BOD ($r = 0.489$), and COD ($r = 0.476$). Additionally, DO has a strong correlation with pH ($r = 0.449$). Furthermore, pH has a modest correlation with DO ($r = 0.449$). As well, Pb, like Chloride ($r = 0.473$), Salinity ($r = 0.465$), and Nitrite ($r = 0.449$), has a modest correlation. The results of this discovery served as a foundation for multivariate analysis, such as PCA and CA.

Results of the PCA

The PCA approach was used to detect potential pollutants sources in the sample locations. By identifying a new collection of variables known as principal components, the PCA allows for an objective summary of the water quality metrics (Factors). The consecutive components are orthogonal to one another, and each component is a linear grouping of the initial variables (parameters). Table 7 summarizes the findings of Varimax rotated PCA during the rainy season. As shown in the table, the analysis included fourteen (14) physiochemical water quality indicators collected from CMC's 21 sample stations (UBS). The raw data were normalized with standard score transformations to have a 0 mean and unit variance before being subjected to PCA. The table also includes the eigenvalue, percentage of variation, and cumulative percentage of all the variables (14 parameters) loaded on the first four (4) main components (i.e. component loadings).

The correlation matrix suggests that the original dataset may have some key underlying dimensions, referred to as Factors. By extracting new variables termed Factors-dimensions from the implicit factors in samples (extracted by PCA), the original dataset was reduced. The eigenvalues of four factors were retrieved from UWB's dataset. Table 7 shows the calculated factor loadings, as well as the percentages of variation explicated by each component and the cumulative percentage. Factor I (PC1), Factor II (PC2), Factor III (PC3), and Factor IV (PC4), respectively, explain roughly 25, 19, 15, and 14% of the overall variation. In cumulative terms, the first four

Table 7 | Results of varimax rotated PCA for the rainy season

Parameters	PC1	PC2	PC3	PC4
Temperature	0.373	−0.583	**0.527**	0.061
pH	0.017	0.057	**0.779**	0.167
EC	**0.849**	0.366	0.193	0.132
TDS	**0.889**	0.212	0.176	0.172
TSS	**0.848**	−0.113	−0.226	−0.114
DO	−0.138	−0.021	**0.706**	−0.110
BOD	**0.692**	0.129	−0.104	**0.604**
COD	**0.624**	0.136	−0.439	0.054
Turbidity	0.189	0.344	0.363	0.042
Chloride	0.231	**0.921**	0.064	0.163
Salinity (NaCl)	0.240	**0.920**	0.063	0.159
Nitrite	0.180	0.072	0.057	**0.831**
Free chlorine	0.149	−0.114	−0.546	0.441
Pb	−0.207	0.488	−0.034	**0.734**
Eigenvalue	4.454	2.321	2.131	1.332
% of variance	25.011	18.860	15.337	13.992
Cumulative variance	25.011	43.872	59.208	73.130

Note that remark numbers indicate moderate and strong loadings [Liu *et al.* (2003) categorized factor loadings as 'strong', 'moderate', and 'weak,' respectively, corresponding to absolute loading values of 40.75, 0.75–0.50, and 0.50–0.30].

(4) principal components (PC1–4), which may also be utilized as Factors (I–IV), explain 73.1% of the overall variation in the dataset (Hanssen *et al.* 1980; Steinnes & Henriksen 1993; Prasanna *et al.* 2010).

Explanation

PC1 (Factor I)

With an eigenvalue of 4.45, it accounts for 25% of the overall variance in the dataset; it is predominantly a consequence of five parameters: TDS (0.89), TSS (0.85), EC (0.85), BOD (0.69), and COD (0.62), all of which have strong positive component loadings (coefficient of association). The presence of (TDS) inorganic salts and tiny quantities of organic matter in the solution is described by this factor, whereas TSS refers to particles bigger than 2 microns present in the water column. The EC is a metric for determining what is dissolved in water. Because the existence of dissolved salts like nitrate, sulfate, and other inorganic compounds affects water, electrical conductivity rises as salinity rises. TDS and TSS have large loadings on PC1, but they do not exceed the maximum permissible concentration, hence they are safe. EC, BOD, and COD, on the other hand, were found to be unfit for consumption. When biological organisms degrade organic substances in water, they use a certain amount of dissolved oxygen (DO). A higher BOD means that more oxygen is required, which results in less oxygen being available for organisms to consume and worsen water quality. When a water sample is chemically oxidized, COD is the quantity of oxygen consumed. Higher COD values indicate that the sample contains more oxidized organic material.

PC2 (Factor II)

With an eigenvalue of 2.32, it explains around 19% of overall variance and is dominated by two parameters: chloride (0.92) and salinity (0.92), as seen by their significant positive component loadings on PC2. Dissolved solids contain a lot of chlorides. Chloride concentrations in UWBs that are too high can be hazardous to aquatic life. Drinking water quality and ecosystem health can be harmed by high levels of dissolved salt in water.

PC 3 (Factor III)

With an eigenvalue of 2.13, it accounts for around 15% of the overall variance in the dataset and is highly impacted by two parameters: pH (0.74) and DO (0.71). DO is required for fish and other aquatic species to survive. In the appropriateness study, however, these characteristics were deemed to be within the safe limit.

PC 4 (Factor IV)

With an eigenvalue of 1.33, it explains around 14% of the overall variance in the dataset. Nitrate (0.83), Pb (0.73), and BOD (0.73) are the most influential factors in this component (0.60). BOD, on the other hand, was found to be similarly loaded on PC1 (0.60) and PC4 (0.60). These exceeded the maximum permitted level during the rainy season and were thus deemed unfit for consumption. Especially for infants and pregnant women, nitrate levels in drinking water can be harmful to one's health. If the element lead in the water reaches the bloodstream, it generates a high blood lead level and hence excessive amounts of lead in UWBs might cause health problems. In addition to causing damage to the kidneys and brain, it can also prevent the production of red blood cells, which carry oxygen throughout the body.

Results of the CA

The CA was carried out using the same parameters (14) and sample stations (21) as the PCA. The outcome is a Dendrogram (Figure 2). The Dendrogram clearly shows the horizontal succession of the sample stations (21: see legend in Figure 1 for reference numbers and names allocated to the sampling stations – UWBs) as they have fused and aggregated. Three (3) major groupings (clusters) may be easily identified at the rescaled distance cluster level 10 (Figure 2). Cluster I consist of the following sample locations in the following order (from bottom to top): 15, 14, 7, 1, 16, 5, 18, 17, 4; Cluster II: 3, 21, 19; and Cluster III: 12, 9, 6, 11, 8, 2, 20, 13, 10.

Table 8 summarizes and presents the cluster diagnostic of the three easily recognizable groups. A group ID, sample ID, cluster ID, the proportion of samples in the cluster, group means, and standard deviation are all provided. Cluster I (Group A) accounts for 43% of the sample stations, according to Table 8, with a group mean of 25.2. Cluster II (Group B) is responsible for 14% of the spatial observation units, with a group mean of 21.5. Cluster III (Group C) accounts for 43% of the samples and has a low group mean of 16.04.

In terms of similarity, Group A and Group C are equally loaded in terms of similarity (representing $43 + 43 = 86\%$ of the sample stations). The difference between the two groups, however, is striking, as seen by the mean

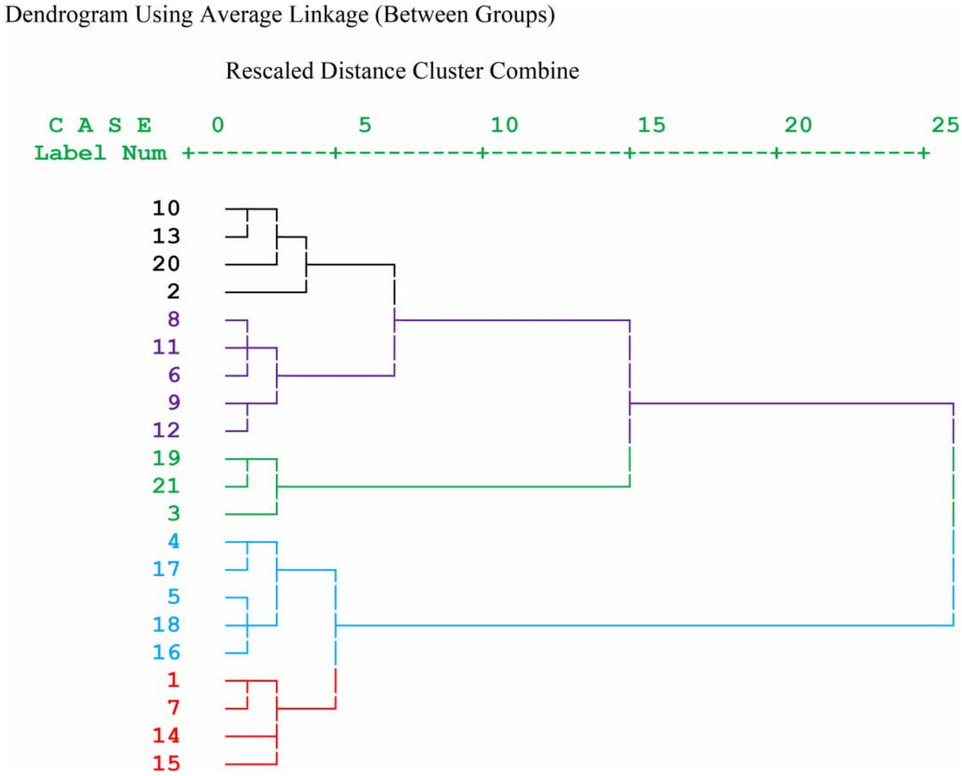


Figure 2 | Results of CA and the sample-wise Dendrogram for the rainy season.

Table 8 | Cluster diagnosis of the water samples in the rainy season

Group name	Sample ID/Number	Cluster ID	Sample percentage	Group mean	Group std. deviation
A	S-15, S-14, S-7, S-1, S-16, S-5, S-18, S-17, and S-4; **Total = 9 samples**	Cluster I	43%	25.1601	±26.22859
B	S-3, S-21, and S-19; **Total = 3 samples**	Cluster II	14%	21.5133	±19.48524
C	S-12, S-9, S-6, S-11, S-8, S-2, S-20, S-13, and S-10; **Total = 9 samples**	Cluster III	43%	16.0461	±34.42239

values, even if variance within Group A is lower (S.D. 26.22859) than Group C (S.D. 34.42239), showing greater disparity within the group. Cluster II (Group B) is unusual in that it has only three examples and represents only 14% of the sample stations. Due to the limited number of objects, it has a medium mean value (21.5) and a lower SD (19.48524), indicating more homogeneity (less distance) within the group.

Table 9 displays the descriptive statistics (means and standard deviations) for the selected clusters (1–3). In comparison to Groups B and C, Group A appears to be the most affected by pollutant concentration. COD (91.6), Chloride (87.5), TSS (86.9), and BOD (37.2) are important contributing variables to Cluster 1 (Group A), as seen by their high mean values in the table. Cluster 2 (Group B) is substantially influenced by salinity (89.7), turbidity (65.0), EC (24.5), and TDS (18.3). Except for Chloride, which is significantly high, characteristics in Group C were shown to be modestly linked with Cluster 3 (73.5).

Explanation

Cluster 1 (Group A): The mean value indicates that factors (COD 91.63), Chloride (87.55), and TSS (86.89) have a considerable impact on this group (Table 9). This collection of samples is found in CMC's western and eastern regions, mainly near the Bay of Bengal's coastal area and the Karnafulli River. Because tidal creeks and streams are connected, members of this group are affected by urban floods, tidal floods, and storm surges. The area suffers from high pollution concentrations because of the synchronization of surface runoff in the higher catchment areas,

Table 9 | Group mean and std. deviation among the clusters and samples

	Cluster I: $N = 9$		Cluster II: $N = 3$		Cluster III: $N = 9$	
Parameters	**Mean**	**Std. deviation**	**Mean**	**Std. deviation**	**Mean**	**Std. deviation**
Temperature	**31.2322**	1.32319	**30.4667**	3.51615	30.2000	3.10363
pH	8.1100	0.35937	8.1900	.31512	8.0222	.52148
EC	7.32332	88.49576	**24.4767**	28.59510	3.82892	130.47073
TDS	4.50782	55.48373	**18.3333**	20.98412	2.03442	55.30396
TSS	**86.8889**	31.80976	24.3333	10.01665	**51.3333**	40.66325
DO	5.7911	1.29021	6.0333	.63509	5.4844	1.43512
BOD	**37.2111**	18.08870	3.1000	1.64621	7.5233	12.29358
COD	**91.6333**	53.52025	47.2967	31.55605	**42.2722**	12.75997
Turbidity	**62.6511**	20.67913	**65.0000**	12.76715	**45.7656**	14.19770
Chloride	**87.5556**	23.40999	47.3333	37.00450	**73.5100**	31.19016
Salinity	1.65422	39.61831	**89.7533**	70.52116	1.38762	58.16111
Ammonia	2.5300	1.69982	1.2833	0.48563	1.2556	0.56873
Free chlorine	0.0678	0.06960	0.0333	0.05774	0.0478	0.04969
Cr	0.0044	0.01014	0.0000	0.00000	0.0100	0.01581
Fe	0.4367	0.45834	0.0500	0.08660	0.0544	0.08472
Pb	0.0511	0.02369	0.0433	0.01528	0.0467	0.01500
Mn	0.0733	0.09937	0.0000	0.00000	0.0078	0.01563
Group	**25.1601**	**26.22859**	**21.5133**	**19.48524**	**16.0461**	**34.42239**

and river flows in the low-lying areas with that of periodic tidal inundation. There are other reasons as well; these locations are home to the Chittagong Export Processing Zone (EPZ), which houses medium and heavy businesses. As a result, contaminants make their way into UWBs and pollute them. Salinity (89.75), Turbidity (65.00), EC (24.48), and TDS all have a strong impact on Cluster 2 (Group B) (18.33). This group's members were discovered around CMC. Due to excessive surface runoff during the rainy season, the water bodies are impacted by urban floods. Furthermore, the urban slum dwellers near surrounding water bodies are negatively impacted by their unhealthy lives. Cluster 3 (Group C): This group discovered a significant link to Chloride (73.51). This group's members may be found in the east and south of CMC, although there are no apparent distribution trends. Since the samples were found at the Karnafully River's edge, they are thought to be linked to tidal creeks and streams. Some sampling sites are also strewn around the residential and business regions. Residential and commercial wastes are more likely to be the point sources of pollution in the water bodies included in this category.

DISCUSSION

Bangladesh is a tropical country with hot, humid summers and heavy rainfall during the rainy season, which causes floods in Chittagong. As a result of the increased activity of algae and microorganisms during the monsoon, surface runoff suffers from excess water, and turbidity rises. Other contaminants include sawdust, wood flames, plant residues, clay/mud, sand, silt, and chemicals in the water. Salinity rises when dissolved solids and salts accumulate in UWBs, increasing electrical conductivity; nitrate and turbidity concentrations have already exceeded the city's maximum allowable limit. Similarly, the maximum permissible concentrations of BOD and COD have been exceeded. BOD is produced in cities from a variety of sources, including leaves and woody debris, dead animals and plants, livestock manure, effluents from pulp and paper mills, wastewater treatment plants, feedlots, and food-processing enterprises, malfunctioning septic systems, and urban storm stormwater. COD-rich water includes high quantities of decomposing plant debris, human waste, or industrial effluent, all of which are harmful to aquatic life. Concisely, environmental deterioration in UWBs is manifested by the presence of dissolved solids (e.g. chloride); excessive concentrations of dissolved salts (e.g. nitrate), greater BOD and COD, and increased turbidity. The problem has a microbiological component as well; UWBs are heavily contaminated with TC and FC bacteria. The observed TC value during the rainy season was 1,100, compared to the normal value of 50 MPN-100 ml^{-1}, which is worrying. Disease-causing organisms (pathogens) may be present in the water system if they are found in the pathogens (disease-causing organisms) in drinking water. The inability to maintain a 'closed' system is the most common cause of TC bacteria in a water system. The majority of germs that might pollute surface water come from human or animal excrement. The primary sources of TC and FC bacteria in freshwater are failing septic systems, animal waste, and wastewater treatment plant discharges. However, extreme river flow, i.e. synchronization of tidal oscillations and heavy rains; inflow of water caused by the monsoon season, and flash floods are primarily responsible for the periodic inundation, particularly during the rainy season. Besides, flooding increases the rate of urban discharge via surface runoff, which permits dirty water (urban wastes and industrial fluids) to combine with standing water bodies. Furthermore, improper municipal waste management, unidentified blockage of municipal drains by urban solid wastes, illicit drain connection to water bodies, encroachment of tidal creeks, channels, and streams, low-lying topography of certain parts of the city, and saline intrusion from the Bay of Bengal are the main causes of urban floods in Chittagong. As a result, the water quality in UWBs quickly deteriorated.

SUMMARY AND CONCLUSIONS

The current research reveals that almost all water bodies in CMC are polluted with various contaminants and are unsafe for human consumption unless properly treated. Due to pollution levels, the drinking water quality of UWBs in CMC is found to be unfit for family consumption during the rainy season. Fresh water shortages also exist in the urban water supply system. However, the application of MATs is a suitable and advanced technique for the analysis of the quality of water, displaying sample patterns, and making clear assessments of the unabridged research. The SA analysis found that the mean value of the maximum sample has exceeded the allowable limit and they have a substantial relationship. The bulk of the characteristics employed in the SA were determined to be inappropriate for drinking during the rainy seasons. EC, BOD, COD, Turbidity, Nitrate, Lead, TC, and FC are the eight metrics that have exceeded the maximum allowed level. Besides, the PCA extracted four factors (PC1–4). These factors [Factor I (PC1), Factor II (PC2), Factor III (PC3), and Factors IV (PC4)] explain roughly 25, 19, 15, and 14% of the overall variation. With an eigenvalue of 10.23, the PCA indicates that the first four components (PC1–4) account for 73.1% of the total variation in the dataset. Moreover, the CA recognized three different groups or clusters (A, B, C – Clusters I–3) of the entire sample. In these clusters, 43% loaded in Group A, 14% loaded in Group B, and 43% loaded in Group C of the entire sample, respectively. These loading or mean values denoted greater disparity with Group A and less disparity with Group C. However, Group A (comprising nine members) is the most affected by pollution levels in CMC. The cause of this unacceptably bad situation is a combination of environmental, socioeconomic, and managerial issues. Because of the consumption of contaminated water, the health of city inhabitants, particularly the poorer parts of the population, is in danger; public and private sector awareness development on water contaminants is essential to enhance public healthcare delivery. Regular monitoring and assessment of a large number of water quality indicators are critical for efficient water quality maintenance through suitable control methods.

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AUTHORS CONTRIBUTION

M.H.M. – conceptualization, methodology, software, formal analysis, investigation, resources, data curation, writing – original draft, visualization. M.A.T.C., Md.M., and K.Md.B.A. – methodology, critical review, editing, formal analysis, and supervision. Md.H.R.B. – methodology, data curation, formal analysis, and supervision. S.D. A.J.M.M., and J.D. – methodology, data curation, and formal analysis. S.I. – methodology, formal analysis, resources, and editing. All authors read and approved the final manuscript.

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ETHICS APPROVAL AND CONSENT TO PARTICIPATE

Participation in this survey was voluntary, and respondents had the right to withdraw from the survey at any time during the interview. Before participating in the survey, potential respondents had to answer a yes/no question to confirm their consent to participate voluntarily. After receiving their verbal consent, respondents were requested to participate in the questionnaire survey.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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