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Suitability of water quality index methods for assessing groundwater quality in the Ganges River basin area

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ABSTRACT

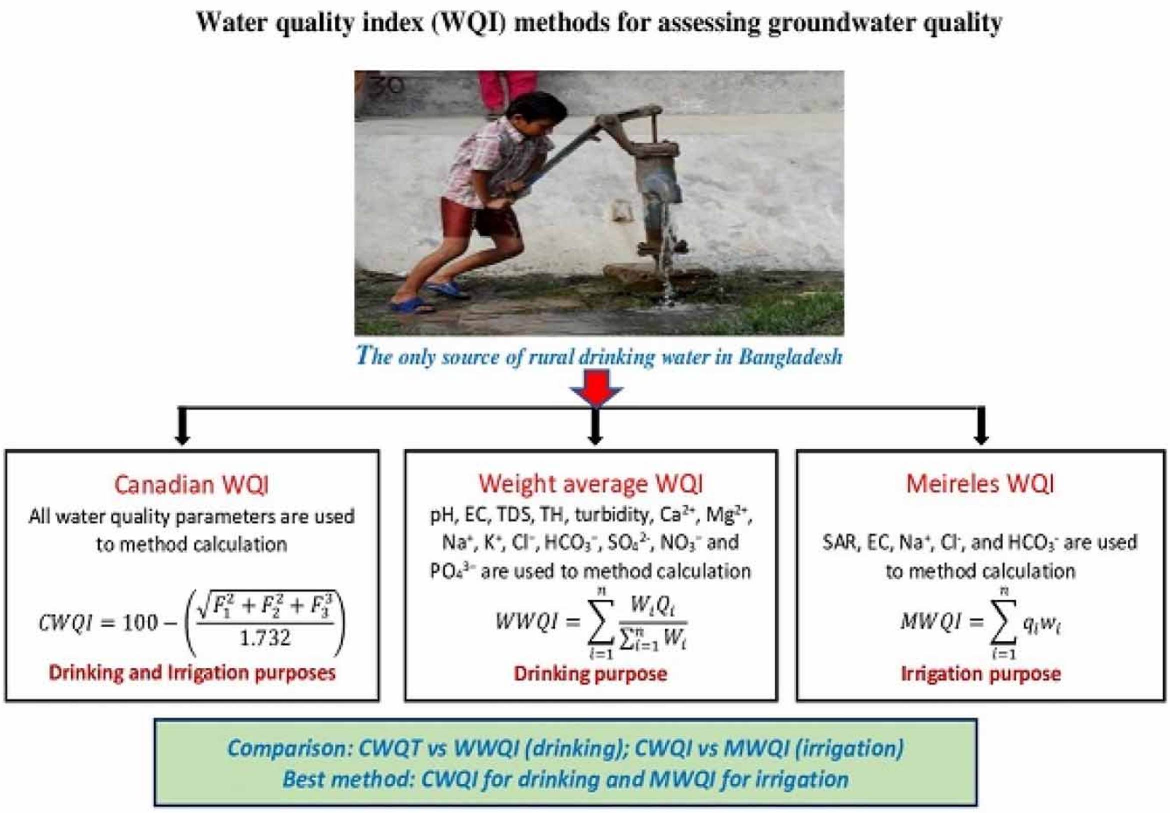
This study considered three different water quality indices (WQIs) for groundwater data collected from the middle-west part of Bangladesh, and the quantitative results were justified with the globally accepted water quality guidelines. It compared the results between the Canadian WQI with the Weighted Average WQI, and the Canadian WQI and Mierels WQI for drinking and irrigation purposes, respectively. The results revealed that the Canadian method categorized water as 'fair' quality while the Weighted WQI model results showed 'unsuitable' for drinking usage. Besides, the Meireles method showed that the water quality is classified as 'good' to 'excellent', while the categorization of the groundwater using the Canadian method was 'fair' to 'good' for the suitability of irrigation. When comparing the results of the Canadian method with the Weighted Average technique for drinking, the latter one gave the abnormal results; and pair difference statistics showed the significant negative correlation ($r = -0.91$) between them. Similarly, the analysis of the two methods (Canadian and Mierels) for irrigation use exhibited that there was no statistical variance between the two techniques at a significant correlation matrix ($r = +0.71$). The study concluded that the Canadian WQI for drinking and Mierels WQI for irrigation would deliver better results.

Key words: Canadian water quality index, groundwater chemistry, Meireles water quality index, *t*-test, weight average water quality index

HIGHLIGHTS

- The methods used in this study clearly illustrated the conditions for groundwater to be used for drinking and irrigation purposes.
- Three water quality indices (WQIs) were used and discussed the guidelines to improve the efficacy.
- The findings of this study can be used to develop and improve the quality of water that directly affects public health and crop production.

GRAPHICAL ABSTRACT



INTRODUCTION

These days, water quality issues in Bangladesh, a densely populated rural country, have become an extensive concern due to over-water mining, urban extension, agricultural diversity, industrial development, and weak water management. According to the World Health Organization (WHO), in developing countries, over 3 million people (90% are under 5) die every year owing to waterborne diseases (WHO 2004). Without any purification, over 12 crores of rural peoples of Bangladesh consume raw groundwater (MICS-B 2018). Not only that, 90% of the irrigation water of the country comes from this source (Zahid 2015). Huge agrochemical leaching, salinization, topsoil contamination, landfill, and vast flooding have influenced groundwater quality in the study area. In Bangladesh, 40,000 metric tons of pesticides were used in 2018, and a residual portion of this amount leached into the sublayer causes the contamination of groundwater (Islam & Mostafa 2021a). Every year, vast flooding is the common factor that pollutes the top soil and aquifer water in the country. In the coastal zone of the country, due to climate change and overexploitation of groundwater, sea water intrusion is a big concern regarding salinization (WB Group 2019). Moreover, the geogenic sources are also massively deteriorating the groundwater quality in some parts of the country during the last 30 years (MICS-B 2018; WB Group 2019).

The quality of natural surface water in the river, lack, and reservoirs is a key concern as it is used for drinking and domestic purpose, irrigation, and aquatic life and it can play a vital role in the social and economic structure of a developing country like Bangladesh. A number of studies (e.g., DE 2017; Hasan *et al.* 2019; Sarkar *et al.* 2019; Parvin *et al.* 2022) have been conducted to measure the surface water quality of the country. Those studies illustrated that the quality of this water resource is continuing to be contaminated through heavy industrialization, growing agrochemical-based cultivation, and municipal wastes. For groundwater quality, several investigations in Bangladesh have been conducted, especially in the coastal areas where water sodicity is a big issue (Rahman *et al.* 2011; Bhuiyan *et al.* 2016; Islam *et al.* 2016, 2017a, 2017b, 2017c; Ahmed *et al.* 2018; Islam & Majumder 2020). Nevertheless, in the upper deltaic plain, where heavy mineralization and water hardness are the main quality problems (Islam & Mostafa 2021d), there is no adequate information on which to base geochemical studies that have been carried out. Thus, constant observation is important to evaluate the suitability of water for various purposes and protect against the further deterioration of groundwater quality in the study zone.

The Himalayan and non-Himalayan rivers drain to the Bay of Bengal as a joint river, carry the major alluvial sediment load, and create the largest agrarian Bengal delta basin in the world. We considered the western upper part of this basin as a study area sited in the Kushtia District of Bangladesh. The previous study has confirmed the frequent variation of hydro-geologic and aquifers conditions of the study area (Dola *et al.* 2018; Akter *et al.* 2020; Nasher & Ahmed 2021). Due to the interference of the transboundary river flow of Bangladesh on the Indian side, the watercourse in Bangladesh territory was impeded significantly (DE 2017; Islam & Mostafa 2021b). Instead, during the dry period, those rivers become almost dead and this situation seriously impacted the neighboring groundwater composition. Therefore, the morphology of the river basin and river banks are always changing which is harmful to river ecosystem services in the river catchment area. Recently, the water flow of the transboundary rivers in the study zone decreasing significantly in the winter and pre-monsoon (PRM) season, creating a shortage of surface water (Islam & Mostafa 2021c). So, the inhabitants of the study area completely rely on the raw groundwater for drinking and other household purposes. Thus, the proper assessment of groundwater quality is imperative to ensure safe water for all purposes and justifies the widely used water quality indexing methods for the accurate assessment of water quality.

The water quality index (WQI) aims at evaluating through an arithmetical digit, computed based on one system, which adapts all the distinct parameters and their concentrations, present in a sample in a single number. This is an operative method that allows the quality of various water samples to be judged based on a single arithmetical value and not only the parameter values of each sample (UNEP-GEMS Water 2007; Dede *et al.* 2013; Paun *et al.* 2016). Even though there is no universally accepted composite index model of water quality, some countries and areas have used, or are using, combined water quality datasets in the development of WQIs. The maximum water quality indexing method depends on the normalizing dataset of water quality parameters. Parameters are often then weighted according to their apparent importance to complete water quality and the index is calculated as the weighted average of all observations of interest (Pesce & Wunderlin 2000; Liou *et al.* 2004). Frequent variations of WQIs were addressed in literature over the past five decades (Brown *et al.* 1970; Dunnette 1979; Bhargava 1985; Smith 1990; Horton 1995; Schultz 2001; Said *et al.* 2004; Tsegaye *et al.* 2006; UNEP-GEMS Water 2007; Nasirian 2007; Saeedi *et al.* 2010; Lumb *et al.* 2011a; Dede *et al.* 2013; Majeed 2018; Banda & Kumarasamy 2020a, 2020b; Islam & Mostafa 2021e). There is a crucial need to develop a commonly accepted WQI that is flexible enough to represent water that is suitable for drinking or other purposes for worldwide users. The use of the index to evaluate water quality was recently innovated by Sarkar & Abbasi (2006), Semiromi *et al.* (2011), Sutadian *et al.* (2016), Othman *et al.* (2020), Mukate *et al.* (2019), Tripathi & Singal (2019), and Zhang *et al.* (2020). Very recently, Najafzadeh *et al.* (2021, 2022) assess the reliability of groundwater quality index using remote sensing and data-driven models. In these two studies, four robust data-driven techniques – evolutionary polynomial regression (EPR), gene-expression programming (GEP), M5 model tree (MT), and multivariate adaptive regression spline (MARS) – based on the evolutionary algorithms and classification concepts have been applied to present formulations for the prediction of ground and surface WQI values.

Maximum WQIs were developed for surface water, especially for river water, and a limited number of indexing models are designed for groundwater. Horton (1995) was the first methodically proposed index to measure water quality by using the ten most regularly used water parameters, and this method was extensively applied and accepted in European, Asian, and African countries. One of the advantages of this method is that a lesser number of parameters are required to compare water quality for certain use (Tyagi *et al.* 2013). But then this model was subsequently modified by Brown *et al.* (1970). In the mid-1990s, a new WQI, the Canadian Council of Ministers of Environment Water Quality Index (CCEM-WQI), was offered which may be recognized as the Canadian Water Quality Index (CWQI) in 2001 (Khan *et al.* 2003; Lumb *et al.* 2011a). In this model, the WQI was evaluated based on the frequency of sampling variables, failed variables, and deviation from the standards values. Later, the CWQI model was accepted as an appropriate model for measuring the quality of drinking waters worldwide by the United Nations Environmental Program (Sarkar & Abbasi 2006; Bharti & Katyal 2011). In some cases, this indexing method was used for irrigation water quality evaluation (Majeed 2018). Later, the sensitivity test of the Canadian WQI was conducted by changing some input variables and the number of sampling stations with sampling periods (CCME 2001; UNEP-GEMS Water 2007). Except for the above two methods, the widely recommended Meireles water quality index (MWQI) model was also used for assessing irrigation water quality in the study area. Each WQI method has a different scale. Lumb *et al.* (2011a, 2011b), Banda and Kumarasamy (2020a, 2020b), and Tyagi *et al.* (2013) reviewed all the WQI models and presented water quality ratings for each of them. Good water quality, for example, ranges between 71 and 90 index scores according to NSF-WQI (National Sanitary Foundation WQI) model in the USA, while according to the model of the Canadian WQI the index scores ranged from 80 to 94. Besides, a particular model used some selected parameters which were significant for water suitability in a selected area but not for other areas. Dissolved oxygen (DO), biological oxygen demand (BOD), chemical oxygen demand (COD), or/and microbial parameters are not relevant to groundwater testing but are very important for indexing surface water.

The study uses three different water quality indexing methods to assess the drinking and irrigation purposes and showed a comparison among the methods. For this purpose, annual spatiotemporal and seasonal variation of WQIs of the groundwater around the Ganges River basin area, Kushtia, Bangladesh is investigated using the CWQI (both drinking and irrigation), WWQI (drinking), and MWQI (irrigation) methods. Using some statistical methods (correlation and *t*-test), the study made a comparative study between them and selected an appropriate method to find out the suitability of water quality for drinking and irrigation purposes.

METHODS AND MATERIALS

Study area

Bangladesh, a South Asian country, is a densely populated and agrarian country. We considered the western upper part of this basin as a study area sited in the Kushtia District of Bangladesh. The main river, the Ganges (Padma), and the two braced rivers *Kaliganga* and *Gorai*, pass through the study area and carry the major alluvial sediment load, and create a big delta basin. The groundwater flows east–north to the west–south direction in this area. The upper basin area is mostly the recharge zone and the down basin area is the discharge zone. After the construction of the Farakka Barrage in 1975 on the Indian side, in the dry season, these rivers become almost dead and this situation highly influenced the river bank biodiversity and groundwater mineralogy. During the winter and PRM seasons, the aquifer discharging volume by river water was dramatically reduced. In this time, water residence time, percolation rate, groundwater flow direction, water–rock interaction, etc., were highly impacted. Along with those incidents, entire hydrogeochemical processes were changed and the groundwater quality deteriorated (Zahid 2015; MICS-B 2018). For that root cause, it is vital to assess the water quality for the suitability and sustainable management of groundwater with the help of appropriate indexing and other methods. So, the selection of the present study area to assess groundwater quality is appropriate and vitally needed.

The sampling stations in the study area are located between 23°42′ and 24°12′ north latitudes and 89°20′ east longitudes. The total area of sampling locations is 1,652 km^2 and is surrounded by the Ganges River (Padma River) and the other three branch rivers formed a big deltaic basin (Figure 1). The total population of the area is approximately 2 million. The groundwater is the single largest source of water for drinking and domestic. The study area is covered by a subtropical humid climate with a hot and rainy monsoon and a distinct dry season in the summer and winter periods. A total of 1,167 mm/y rainfall is received in the area (BBS 2020). Around 95% of the groundwater is used for irrigation, and the remaining was consumed for drinking purposes.

Sampling and analysis

A total of 40 sampling stations around the river basin areas in the middle-western part of Bangladesh (Figure 1) were selected for collecting the groundwater samples during the two sampling periods, namely April–May (premonsoon) and October–November (post-monsoon) of 2019–2020. Groundwater samples were collected from the first aquifer, which was up to 100 m below the surface, less than 100 years old, and continuously recharged by rainwater and river streams (DPHE-BGS 2000). It was collected randomly from the selected hand pump to cover the topographical extension of the study area and the key geologic sceneries. Groundwater samples were collected randomly from the selected hand pump, shallow, and semi-deep tube wells and their depths ranged from 22 to 125 m. Samples were collected in prewashed high-density polyethylene (HDPE) plastic bottles according to the standard procedure (US-APHA 2005). The samples were collected after pumping 3–5 min to get clean water or avoid any debris. For metal analysis, the samples were preserved with AR grade HNO_3 and kept at 4 °C for further analysis.

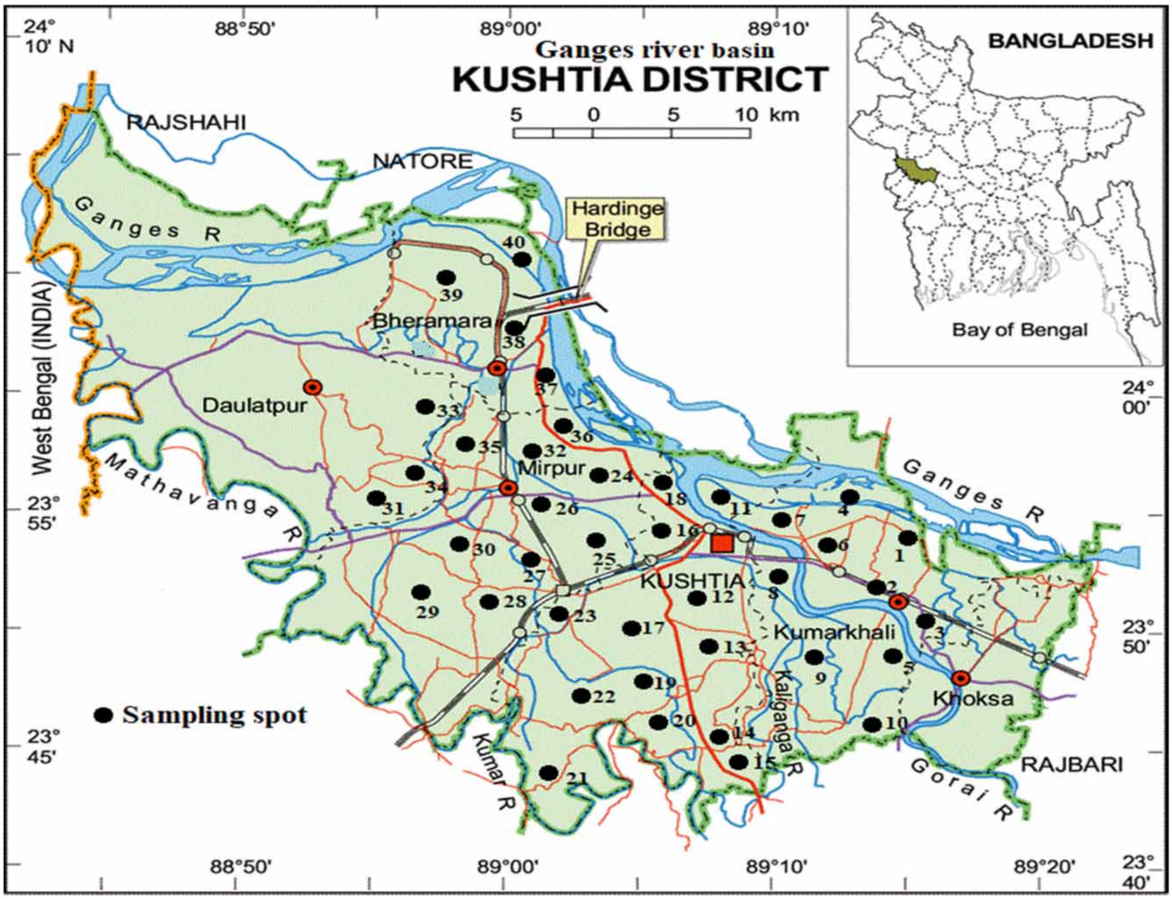


Figure 1 | Map of sampling stations in the Ganges River basin areas.

The study considered a total of 27 physical and chemical parameters, i.e., pH, electrical conductivity (EC), total dissolved solids (TDS), turbidity, total salinity, total alkalinity, total hardness (TH), DO, ammonia, Cl^-, NO_3^-, SO_4^{2-}, PO_4^{3-}, HCO_3^-, Na^+, K^+, Ca^{2+}, Mg^{2+}, B, Fe, Mn, Pb, Cr, Co, Cd, Cu, and Zn. The pH, DO, EC, and turbidity were measured by a pH meter (Adwa AD 110), DO meter (Lutron YK-22DO), EC meter (EC-210, HANNA, Italy), and turbidity meter (Lutron TU-2016), respectively, at the sampling sites just after collecting samples. Sulfate (SO_4^{2-}), nitrate (NO_3^-), and phosphate (PO_4^{3-}) were measured by a UV spectrophotometer using the respective standard solution at the $\gamma_{\max}$ of 500, 410, and 380 nm. Calcium (Ca), bicarbonate (HCO_3^-), chloride (Cl^-), and total hardness (TH) were determined by the titrimetric method using standard $KMnO_4$, H_2SO_4, $AgNO_3$, and EDTA solution. Total alkalinity was measured by $CaCO_3$ concentration of samples and magnesium (Mg) determined by the EDTA solution at pH 8–9. Sodium (Na^+) and potassium (K^+) were measured using a flame photometer. Trace elements, namely iron (Fe), manganese (Mn), boron (B), lead (Pb), chromium (Cr), cobalt (Co), copper (Cu), and zinc (Zn), were measured by the well-recognized method through the Perkin-Elmer Atomic Absorption Spectrophotometer (AAS: Model 3110). For sampling and analysis of all parameters, the US-APHA (2005) method was strongly followed.

Quality control was kept in all-metal analyses as stated by individual instruction manuals and method precision was more than 95% in confidence interval (*CI*) with the correlation coefficient, $r={\sim}1$ of respective calibration curves. Each method was recalibrated after running 10 samples and all quantitative analyses were executed in triplicate to ensure precision. Cation and anion charge balance was added proof of the precision of the data calculated by the following equation. Chemical and spectrometry analyses were carried out at the IES water laboratory; Central Science Laboratory, University of Rajshahi; and DPHE laboratory, Dhaka.

$$\text{Charge balance error, CBE} = \frac{\sum M_c|N_c| - \sum M_a|N_a|}{\sum M_c|N_c| + \sum M_a|N_a|} \times 100 \qquad (1)$$

where M_c and N_c are the molar concentration and charge of the cation; similarly, M_a and N_a are the same for the anion. All calculated ionic balance errors are within ±5%. Also, $TDS_{measured}$ and $TDS_{calculated}$ ratios were computed for quality control measures. The computed ratio varies from 1 to 1.3, which shows the accuracy of analytical data (US-APHA 2005).

Water quality indices

Based on the degree of contamination or hygiene, the records describing water quality levels started in 1848 in Germany (Lumb *et al.* 2011a). Since then, over 100 local and global-based water quality indexing models have been identified. Here, for easy interpretation of the datasets, three different WQI methods–the Canadian WQI, the weight average WQI, and Meireles WQI–were applied for the selected water quality parameters. Here, two published articles, namely Lumb *et al.* (2011a) and Banda & Kumarasamy (2020a, 2020b), were helpful in selecting the above-mentioned models. The suitability of the WQI models would be discussed concerning their pertinence in similar studies. Those indexing models are deliberated below:

Canadian water quality index (CWQI)

The CWQI was established by the Canadian Council of Ministers of the Environment (CCEM) based on the WQI equation [$WQI=(F_1^2+F_2^2+F_3^2)^{1/2}$] introduced by the British Columbia Ministry of Environment. The Canadian WQI does not specify any water quality parameters/variables or periods since the parameters change from place to place and depend on environmental situations. A minimum of four parameters and a minimum of four measurements of these variables are required for the computation of this index (CCME 2001; Lumb *et al.* 2011a).

The CWQI included three factors and each ranged from 0 to 100. The conceptual model for the index is shown in Figure 2. The values of three variants, namely *scope, frequency*, and *amplitude*, have generated a vector in an imaginary 'objective exceedance' space. The length of the vector is then scaled to range from 0 to 100 and deducted from 100 to yield an index value which is zero or close to zero for 'very poor' water quality, and close to 100 for 'excellent' water quality for any purposes (CCME 2001).

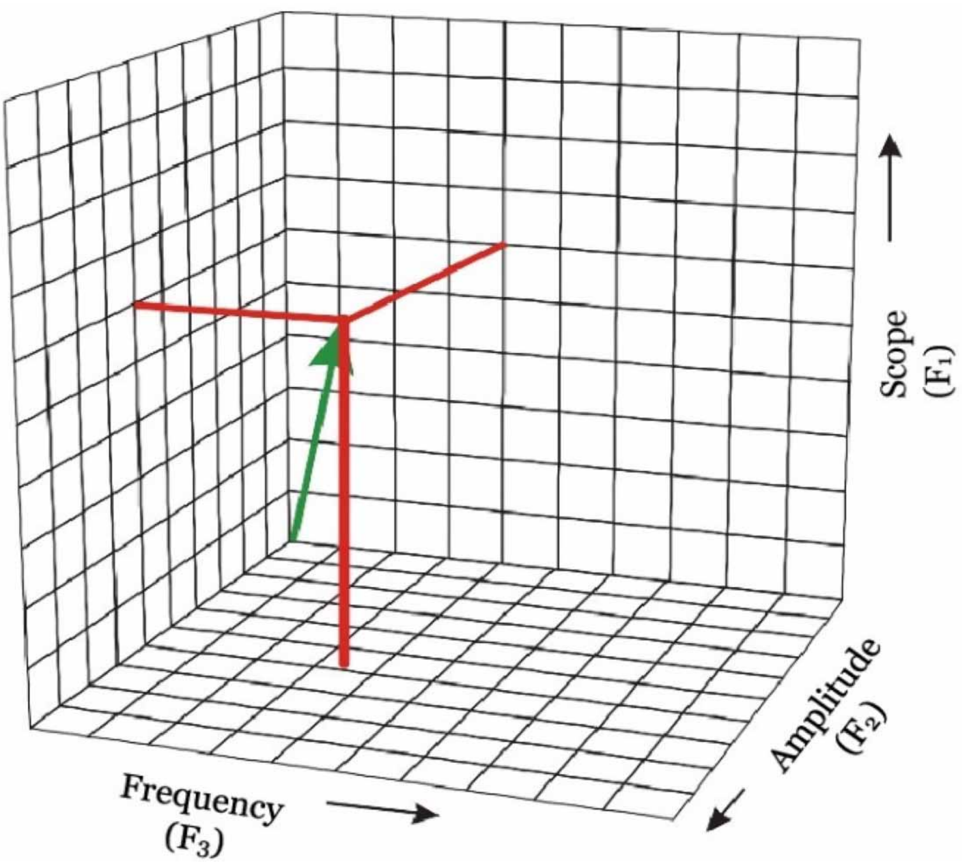


Figure 2 | Conceptual model of the Canadian WQI method.

The index consists of three factors (CCME 2001; UNEP-GEMS/Water 2007):

Factor 1: F_1 is factor 1 and is denoted as *scope* (Figure 2). It gives the %variables that exceed the objective or standard value in the recognized guidelines relative to the total number of variables. Thus, F_1 is calculated from the following equation.

$$F_1 = \left(\frac{\text{Number of failed variables}}{\text{Total number of variables}}\right) \times 100 \tag{2}$$

Factor 2: F_2 is factor 2 and is denoted as *frequency* (Figure 2). It gives the %failed tests relative to the total number of tests carried out during the monitoring process and calculated by the following equation.

$$F_2 = \left(\frac{\text{Number of failed test}}{\text{Total number of tests}}\right) \times 100 \tag{3}$$

Factor 3: F_3 is factor 3 and is named *amplitude*. F_3 gives the amounts of failed test values that exceed the objective value in the guidelines. F_3 can be computed in three steps with the help of Equations (4i)–(4v).

Step a. The number of times that the value of the variable/parameter does not meet the objective is denoted as '*excursion*' and can be calculated as follows:

i. For the situation in which the value of the parameter should not be greater than the objective/guideline value:

$$excursion_i = \left(\frac{\text{Failed test value}_i}{\text{Objective}_i}\right) - 1 \tag{4(i)}$$

ii. For the situation in which the value of the variable should not be less than the objective/guideline value:

$$excursion_i = \left(\frac{\text{Objective}_i}{\text{Failed test value}_i}\right) - 1 \tag{4(ii)}$$

iii. For the case in which the value of the objective is zero:

$$excursion_i = \text{Failed test value}_i \tag{4(iii)}$$

Step b. The next step is estimating the ratio of the sum of *excursions* obtained in step 1 to the total number of tests. This ratio denotes the normalized sum of *excursions (nse)*.

$$nse = \frac{\sum_{i=1}^{n} excursion_i}{\text{Total number of tests}} \tag{4(iv)}$$

Step c. The finishing step is the calculation of F_3 with the scaling of the '*nse*' value from the objectives to the range between 0 and 100. Hence,

$$F_3 = \left(\frac{nse}{0.01nse + 0.01}\right) \tag{4(v)}$$

Lastly, the Canadian WQI is then denoted as Equation (5) through the aggregation method:

$$\text{CWQI} = 100 - \left(\frac{\sqrt{F_1^2 + F_2^2 + F_3^3}}{1.732}\right) \tag{5}$$

The figure of 1.732 rises because each of three individual index factors can range as high as 100. It means that the vector length can reach $\sqrt{100^2 + 100^2 + 100^2}$=1.732 as a maximum. Dividing by 1.732 brings the vector length down to 100 as a maximum value.

The calculation method of CWQI or CCME is a somewhat complicated and lengthy process. It was performed using the MS-Excel program. Like other WQI, it transforms the data by (a) summarizing and simplifying the raw analytical data, (b) single value (e.g., CCME-WQI=44.6, or 87), and (c) water quality category (i.e., excellent/good/poor, etc.). For this index calculation, we chronologically calculated the three main elements of this method namely, F_1 (scope), F_2 (frequency), and F_3 (amplitude) by three separate steps and finally sum of those three to get the final index value. F_1 (Equation (2)), F_2 (Equation (3)), and $F3$ [Equations (4i)–(4v)] were calculated for 27 water variables (Table 2), two sampling seasons, and 40 sampling stations; and used the WHO standard value of each variable. At first, we identified which value exceeded the permissible limit (objectives) and selected the number of fail variables, the total number of variables (27), and the total number of the test (27×2 sampling seasons). Using the calculated value of three components of each sample, the final index value was computed by Equation (5).

Weighted average water quality index (WWQI)

The index value of the weighted average WQI method was calculated from Equation (3). The WWQI was computed using the weighted arithmetic/average WQI method which was projected by Horton (1995). It was then developed by Brown *et al.* (1970) and Cude (2007) in which water quality parameters are multiplied by a weighting factor and are then combined using simple sums mean by the following three equations (Equations (6)–(8)):

$$W_i = \frac{K}{S_i} = \frac{1}{\sum (1/S_i)} \div S_i \tag{6}$$

$$Q_i = \frac{(V_n - V_0)}{(S_n - V_0)} \times 100 \tag{7}$$

$$\text{WWQI} = \sum_{i=1}^{n} \frac{W_i Q_i}{\sum\limits_{i=1}^{n} W_i} \tag{8}$$

where W_i is the unit weightage of the ith parameter, Q_i is the sub-index of the ith parameter, n is the number of parameters included, V_n is the experiential value of the parameter, V_0 is the ideal value of clean water, and S_i is the standard value of the ith parameter.

The ideal value for pH=7, DO=14.6 mg/L, and for other parameters, is generally equal to zero for most parameters except pH (Tripaty & Sahu 2005; Chowdhury *et al.* 2012).

That is,

$$Q_{\text{pH}} = \frac{(V_{\text{pH}} - 7)}{8.5 - 6.5} \times 100$$

The weightage unit (W_i) of each parameter has calculated a value in reverse proportional to the standard of the World Health Organization (S_i) (WHO 2011).

Using a simple Excel program, the calculation of this index value was performed. The average observed value (V_n) is included in Table 2 and the standard value (S_n) of all detected parameters is shown in Table 3. The quality index (Q_n) for all measured parameters was calculated first. For example, in the case of pH (POM, DO=6.6): 7.83−7=0.83 and 7.5−7=0.5, then (0.83/0.5)×100=166; and for TH (POM): (404.65/300)×100=134.88. The unit weight (W_n) of Ca (PRM), for example, is (1/95.64)=0.0105. The ideal values (V_i/V_0) of pH and DO are 7 and 14.6 mg/L, respectively, and this value of other parameters is zero. Then, the final index (WWQI) is calculated by Equation (8).

Meireles water quality index (MWQI)

Meireles proposed a new classification for irrigation water and determined the WQI for irrigation purposes (Meireles *et al.* 2010). The parameters which cause more variability in irrigation water quality were selected. In this method, five parameters such as sodium adsorption ratio (SAR), EC, Na^+, Cl^-, and HCO_3^- were specified. These take the major factorial weight, which means defining the best water quality.

The classification of water quality measurement limits (q_i) and accumulated weights (w_i) was recognized. The values of q_i were found based on each parameter value, considering the criteria established by Ayers & Westcot (1985) and irrigation water quality parameters proposed by the UCCC (1974) which are itemized in Table 1. The

Table 1 | Parameter limiting values for quality measurement (q_i) calculation

Q_i	SAR $(mEq/L)^{1/2}$	EC (μS/cm)	Na^+ (mEq/L)	Cl^- (mEq/L)	HCO_3^- (mEq/L)
$85 \leq 100$	$2 \leq SAR < 3$	$200 \leq EC < 750$	$2 \leq Na < 3$	$1 \leq Cl < 4$	$1 \leq HCO_3 < 1.5$
$608 \leq 5$	$3 \leq SAR < 6$	$750 \leq EC < 1{,}500$	$3 \leq Na < 6$	$4 \leq Cl < 7$	$1.5 \leq HCO_3 < 4.5$
$35 \leq 60$	$6 \leq SAR < 12$	$1{,}500 \leq EC < 3{,}000$	$6 \leq Na < 9$	$7 \leq Cl < 10$	$4.5 \leq HCO_3 < 8.5$
$0 \leq 35$	$SAR \geq 12$ or $SAR < 2$	$EC < 200$ or $EC \geq 3{,}000$	$Na < 2$ or $Na \geq 9$	$Cl \geq 10$ or $Cl < 1$	$HCO_3 < 1$ or $HCO_3 \geq 8.5$
Weight value (w_i)	**0.189**	**0.211**	**0.204**	**0.194**	**0.202**

Table 2 | Destructive statistics of chemical composition in groundwater during the PRM and POM

	Pre-monsoon, PRM (n=40)				Post-monsoon, POM (n=40)				
Parameter[a]	Mean	Min.	Max.	±SD	Mean	Min.	Max.	±SD	Applied method[b]
pH	7.02	6.65	7.80	0.218	7.83	7.0	8.91	0.404	1,2,
EC	669.95	366	1,035	172.5	956.8	662	1,708	206.1	1,2,3,4
TDS	413.15	219	675	113.21	601.5	450.5	1,109	156.2	1,2
Turbidity	7.09	0.89	19.22	11.6	8.93	1.32	28.5	9.76	1,2
T. Salinity	77.13	45.8	104.2	13.73	71.22	46.81	87.07	12.7	1
T. Alkalinity	179.45	79.0	230.2	38.05	187.43	76.90	257.0	46.54	1
DO	6.5	2.7	7.1	1.23	6.6	3.3	7.0	1.44	1,2
TH	362.61	122	562	93.52	404.65	225	625	94.03	1,2
Ca	95.64	56.6	151.4	22.46	114.4	67.2	187.8	26.87	1,2
Mg	32.62	13.0	63.8	12.31	28.96	14.0	52.6	9.438	1,2
Na	14.12	5.10	71.6	11.68	11.56	3.90	51.6	8.7303	1,2,3,4
K	1.27	0.30	2.90	0.717	1.013	0.20	2.90	0.682	1
B	0.202	0.001	1.20	0.314	0.223	0.001	1.25	0.343	1
NH_3	2.56	1.89	3.39	0.76	2.44	1.95	3.09	0.71	1
Cl^-	31.19	12.0	562	9.292	27.09	12.9	41.8	7.604	1,2,3,4
HCO_3^-	418.6	271.5	703	110.81	448.78	248.5	817	124.45	1,2,3,4
SO_4^{2-}	16.46	2.91	45.7	9.292	15.14	2.95	41.7	9.246	1,2
NO_3^-	4.14	0.80	14.3	3.805	3.695	0.80	18.3	3.641	1,2
PO_4^{3-}	0.99	0.21	2.90	0.604	0.908	0.20	2.10	0.512	1,2
Fe	7.18	0.60	14.71	2.57	8.11	0.50	17.34	3.12	1
Mn	2.66	0.86	6.08	0.59	3.11	1.56	5.43	0.61	1
Cr	0.05	BDL	0.12	0.09	0.05	BDL	0.17	0.08	1
Pb	0.08	BDL	0.13	0.03	0.07	BDL	0.12	0.04	1
Co	0.05	BDL	0.09	0.05	0.06	BDL	0.12	0.07	1
Cu	0.91	0.03	3.11	0.99	0.88	BDL	4.44	1.11	1
Zn	1.44	0.99	6.44	1.87	2.01	1.17	7.65	2.43	1
Cd	0.01	BDL	0.8	0.02	0.012	0.001	0.8	0.019	1

[a] All parameters unit are in mg/L except EC in μS/cm, turbidity in NTU, and pH.

[b] Parameters used for the index models [1. CWQI(drinking); 2. WWQI; 3. MWQI; and 4. CWQI(irrigation)].

SAR value of the water sample calculates the relative proportion of Na^+ to Ca^{2+} and Mg^{2+} (Alrajhi *et al.* 2017), and according to Richards (1968), SAR was calculated by the following equation:

$$SAR = \frac{Na^+}{\sqrt{(Ca^{2+} + Mg^{2+})/2}} \tag{9}$$

Table 3 | Drinking and irrigational water quality standards

	Drinking water quality standard				Irrigational water quality standard		
Parameters	**BDWS**[a]	**WHO**[b]	**US-EPA**[c]	**INDIA**[d]	**BIWS**[e]	**FAO**[f]	**US-EPA**[g]
pH	6.5–8.5	7.5–8.5	6.5–8.5	7–8.5	7.5–8.5	6.5–8.4	7.5–8.0
EC (μS/cm)	<1,000	–	–	–	750	350–500	–
TDS (mg/L)	1,000	600	500	500	–	450–2,000	500–1,000
T. Hardness (mg/L)	200–500	300	–	300	–	300–400	–
Na (mEq/L)	8.7	8.6	1.3–2.6	8.0	–	0–40	–
K (mEq/L)	0.3	–	–	–	–	0–0.05	–
Ca (mEq/L)	3.75	5.0	–	3.75	–	0–20.0	–
Mg (mEq/L)	2.5	12.5	–	2.5	–	0–5.0	–
Cl^- (mEq/L)	4.2–17	7.0	7.0	7.0	17.0	0–30	–
NO_3^- (mg/L)	10	50 (as N)	10 (as N)	45	–	0–10 (as N)	–
SO_4^{2-} (mg/L)	400	500	250	200	–	0–800	–
PO_4^{3-} (mg/L)	6.0	–	–	–	0.2	0–2(as P)	–
B (mg/L)	1.0	–	–	0.01	< 1.0	0–2.0	0.75
Mn (mg/L)	0.1	0.5	–	0.1	–	0.2	0.2
Fe (mg/L)	0.3–1.0	0.3	0.3	0.3	–	5.0	5.0
Co (mg/L)	0.05	–	–	–	–	0.05	0.05
Ni (mg/L)	0.1	0.02	–	–	0.5	0.2	0.2
Cu (mg/L)	1.0	2.0	1.3	0.05	0.2	0.2	0.2
Zn (mg/L)	5.0	3.0	–	–	–	2.0	2.0
Cr(6) (mg/L)	0.05	0.05	0.1	0.05	0.01	0.1	0.1
Cd (mg/L)	0.005	0.03	0.005	0.01	0.01	0.01	0.01
Pb (mg/L)	0.05	0.01	0.015	0.05	0.1	5.0	5.0
As (mg/L)	0.05	0.01	0.01	0.05	1.0	0.1	0.1

[a] Department of Public Health and Engineering, Bangladesh (2019).
[b] WHO-Drinking water standard, 4th edn. (2011).
[c] US-EPA-Drinking water standard (2018).
[d] Drinking water standard for India (IS10500, 2012).
[e] Bangladesh irrigation water standard (2009).
[f] FAO-Water quality for agriculture (1985).
[g] US-EPA-Guidelines for water reuse (2004).

The values of q_i were obtained by applying the following equation:

$$Q_i = Q_{i\,\max} - \frac{\{(x_{ij} - x_{\mathrm{inf}})Q_{i\mathrm{amp}}\}}{x_{\mathrm{amp}}} \tag{10}$$

where $Q_{i\max}$ is the greatest value of Q_i for the corresponding class; x_{ij} is the measured value of the parameter; x_{inf} is the lower value of the parameter to which the class belongs; $Q_{i\mathrm{amp}}$ is class capacity; x_{amp} is the class capacity to which the parameter belongs.

To determine x_{amp} in the case of the last class of each parameter, the highest value obtained from the physicochemical analysis of the water samples was considered to be the upper limit. The weight of each parameter applied in calculating *MWQI* was normalized such that the sum of them equals one. Table 1 illustrates the weights of the WQI parameters. Finally, MWQI was calculated using Equation (11) as follows:

$$\mathrm{MWQI} = \sum_{i=1}^{n} q_i w_i \tag{11}$$

where q_i represents the quantity of the ith parameter, which is a function of its measurement or concentration and ranges between 0 and 100, and w_i represents the normalized weight of the ith parameter, which is important in the variability of water quality. Values of Q_i were computed using Equation (11), based on the laboratory result of water quality analysis (Table 2) and the tolerance limits shown in Table 1. Also, the weight of each parameter used in the MWQI is shown in the same table.

RESULTS AND DISCUSSION

Water chemistry

The basic statistics of groundwater chemistry of both the PRM and post-monsoon (POM) seasons and the standard value of the physicochemical data concerning the WHO (2011) and DPHE (2009) for suitability of drinking water are presented in Table 2. The BDWS and the WHO have recommended a maximum acceptable limit of pH for drinking from 7.5 to 8.5; and according to FAO, the standard value of this parameter is 6.5–8.4 for irrigation water (Table 3). The results showed that the pH of groundwater in the study area was slightly acidic to alkaline in nature (PRM: 6.65–7.8; POM: 7.0–8.91) and both ranges are within the acceptable limit for drinking and irrigation purposes. Table 2 illustrates that the average values of EC were 669.95($\pm$172.5) in the PRM and 956.8($\pm$206.1) μS/cm in the POM sampling period, indicating moderate to high mineralization in the samples of study area aquifers. On the other hand, as with EC, the TDS value in the POM (mean values 601.5 mg/L) was greater than the PRM season (mean values 413.15 mg/L). These indicated that with regards to the EC and TDS values, the groundwater was safe for drinking but unsuitable for irrigation purposes (Table 3). The higher values of turbidity in groundwater, mostly during POM, might be caused by boosted erosion of host minerals or rocks and leaching from lateritic soil. Salinity and alkalinity values were observed within the permissible limit. Like coastal zones of Bangladesh, the sodicity problem was not observed in this study zone.

The result shows that major cations and anions in the water samples are Ca^{2+}, Mg^{2+}, and HCO_3^-. The sequential order of the main ions of groundwater samples are $Ca^{2+}>Mg^{2+}>Na^+>K^+$, and $HCO_3^- \gg Cl^- > SO_4^{2-} > NO_3^- > PO_4^{3-}$. Table 2 shows that the Ca concentration in groundwater of shallow aquifers contained 95.64 and 114.4 mg/L in the PRM and POM seasons, respectively, which are above the WHO and FAO standards for drinking and irrigation purposes (Table 3). Calcium plays an important role in human cell functioning, hormones, cancer, heart disease, fluid balance in the body, muscle contraction, neurodegenerative disease, etc., as well as the descent of the testes (Heaney *et al.* 1982). Even though Ca is good for bones and it prevents osteoporosis, it is bad for the brain and excessive consumption leads to hypercalciuria, kidney and arterial disease, urinary tract concretion, and compression of bone restoration (Nerbrand *et al.* 2003). The Ca loaded along with Mg is mainly responsible for the hardness of water which brought about the main threat to the domestic and industrial water (Pravina *et al.* 2012). Tables 2 and 3 show that both the values of Ca and total hardness (TH) in the samples of two sampling periods are not suitable for drinking and irrigation uses. But other essential metals concentrations, Mg, Na, and K, are within the safe limit for both purposes. The Ca^{2+} and Mg^{2+} ions usually originate from the dissolution/weathering of carbonate minerals like calcite and dolomite and Na^+ and K^+ generated from the feldspar and granite rocks in groundwater.

Iron (Fe) is the burning issue of rural drinking water in Bangladesh (Islam & Mostafa 2021f). It is a big threat in the study area with a mean concentration of 7.18 and 8.11 mg/L in PRM and POM seasons, respectively, which is dangerously higher than the WHO and FAO guidelines for drinking and irrigation (Tables 2 and 3). Although a low level of iron is essential in the human diet and for plant metabolism and cannot do much harm, it encourages objectionable bacterial growth ('iron bacteria') inside a waterworks and supply system, resulting in the deposition of a slushy coating on the piping (CanDNHW 1990). Besides, high iron content (over 0.3 mg/L) leads to an excess which can cause stomach problems, vomiting, diabetes, nausea, and hemochromatosis (Toyokuni 2009). Except for Mn and Pb in some cases, other measured trace metals are almost within the safe limit. Mn is an element vital to the proper working of humans, animals, and plant metabolism, as it is obligatory for the operation of several cellular enzymes and can aid in the activation of hydrolases, kinases, transferases and decarboxylases (IPCS 2002). The concentration of this element (PRM: 2.66 mg/L; POM: 3.11 mg/L) was found to be very much higher than the WHO and FAO guideline value of 0.1 and 0.2 mg/L (primary contamination level) for drinking and irrigation, respectively (Table 3). Excessive consumption (over 0.5 mg/L) of Mn-rich water then showed neural symptoms that are alike to Parkinson's disease (ATSDR 2000). Memory damage, hallucinations, disorientation, and impulsive instability are also concerns related to manganese overdose (Dorman 2000). However, a secondary extreme contaminant level of 0.5 mg/L for Mn creates offensive taste, odor, color, staining, and corrosion (WHO 2011). Lead (Pb) is another omnipresent toxic trace metal and substantial public health concern

(Flora *et al.* 2012). It can cause different biochemical effects when exposed to it for a relatively short time duration. These effects may comprise interfering with red blood cell chemistry, delays in usual physical and mental growth in an infant, hearing and learning capacities of children, poor attention span, kidney disease, stroke, cancer, and rise in the blood pressure of adults (Moore 1988; WHO 2011). The mean concentration of this metal was observed to be higher than the drinking guideline value (0.01 mg/L) during both seasons in 50% of samples (Table 3). Among the anionic constituents, HCO_3^- load in all samples and both seasons are very high, and the high concentration of Ca^{2+} and Mg^{2+} makes the water very hard. The drinking and irrigation standard will assist in understanding the suitability of the three water quality indexes (WQIs) mentioned. The value or concentration of measured water parameters can significantly impact the WQI values.

In the study region, the primary aquifer consists of unconsolidated fluvial sediments which are overlain by the impervious silt and clay. Based on subsurface geological information, it appears that most of the good aquifers of this region occur between 20 and 150 m depth. The groundwater flow direction in the study area is usually from north to south. The recharge of groundwater occurs from rainfall and floodwaters during the monsoon season, resulting in groundwater level rise. After the monsoon season, part of the water recharges from the river, stream, pond, and low-lying areas. But during the PRM season, the flow rate of these three rivers in the study area highly decreased and the recharging from the river has been stooped. Besides, the piezometric level of groundwater drops during the dry period due to overexploitation for irrigation with low specific yield and is replenished completely during the monsoon season.

A strong seasonal variation of the values of detected water variables was observed. Table 2 shows that the values of maximum parameters in the POM season were found to be higher than the dry period (pre-monsoon). This may be due to the weathering processes during surface run-off and percolation in the rainy season (Helal *et al.* 2011). During the rainy season, the surface run-off of rainwater enters the soil through percolation and infiltration and finally reaches the aquifer with a higher mineral concentration. The analysis results showed that the higher EC and TDS values were found in the POM (just after the rainy season) season compared to the PRM period due to the cause of mineralization of the aquifer (Xiao *et al.* 2016). The results showed that EC and TDS values are relatively lower at the recharge zone and higher at the discharge zone. When the water moved through the recharge to discharge zone it dissolved extra ingredients along its flow path. For this reason, more ions or electrolytes in the groundwater were added and led to a higher EC and TDS value. On the other hand, in the rainy season, CO_2 in rainwater can facilitate carbonate mineral dissolution. For this reason, the concentration of Ca^{2+}, Mg^{2+}, and HCO_3^- in the POM was relatively higher than in the PRM period.

Application of WQI methods

Globally, over a hundred indexing methods for assessing water quality are available. The majority of those are used for the assessment of surface water quality but they are very limited for groundwater quality assessment. The parameters such as DO, BOD, COD, and Coliform are very much more relevant for the measurement of surface water quality but not for groundwater at all. So, the maximum indexing models are not fit for groundwater. Here, the study followed two commonly used WQI methods, which were subsequently modified by various investigators or water programmers. Firstly, there is the weighted average method, whereby sub-indices are generated and further combined into an overall WQI value. Sub-indices are value functions used to convert the different units of water quality parameters to a mutual scale (Boyacioglu 2007; Banda & Kumarasamy 2020a, 2020b). The second method is the amplitude technique (objective-based), where the overall WQI value is originated through quantifying the extent to which water quality variables/parameters deviate from the objectives or standard values (CCME 2001; Khan *et al.* 2003; Radwn 2005; Mostafaei 2014). The calculation procedures of these three methods are mentioned in the methodology section. In this study, the weighted arithmetic index model (WWQI) and MWQI model as the first category and the CWQI as second category methods were utilized for investigating the groundwater quality of the study area. Here, the WWQI and MWQI methods are used only for the judgment of drinking and irrigation water quality, respectively, but the CWQI method is used for the examination of both drinking and irrigation water quality. Using the various statistical techniques, the results compared those methods with each other and tried to select one to find the groundwater quality for both purposes properly.

Canadian water quality index (CWQI)

In this method, all measured parameters of groundwater for two seasons, the PRM and POM, were considered. The total number of variables (parameters) and sampling sites were 27 and 40, respectively, for each season. The higher CWQI index numbers denote sophisticated water quality, while the lower number indicated lower water quality. Using Equations (2)–(5) mentioned in the methodology section, indexes were computed very carefully, and results were revealed systematically. The result of CWQI calculation for drinking and irrigation uses is presented in Table 4 and CWQI designations are included in Table 5. The results showed that the average value of CWQI was 54.17 (38.3–70.5) with a standard deviation of ± 11.51 and a variance of 132.56. The water quality categorization for sampling stations was found to be 'fair (C category)' for 37.5%; 'marginal (D category)' for 22.5%, and 'poor (E category)' for 40% (Table 5). The values of EC, turbidity, total hardness, Ca^{2+}, HCO_3^-, Fe, and Mn were very high concerning national and WHO standards that influenced lowering of the CWQI values. The groundwater in the coastal area of the country contained high salinity (Na^+ and Cl^-) with high ranges of EC relative to the present study area. But the total hardness (Ca^{2+}, Mg^{2+}, and HCO_3^-) is very low in the groundwater of the same area (Rahman & Majumder 2012; Dider-Ul *et al.* 2017; Islam *et al.* 2017c). So, the study expected that the CWQI value of this area's water showed the same results as the present study. Besides, the values of the maximum parameters of groundwater in the northwest part of Bangladesh were much less than the coastal areas as well the present study area. Some literature confirmed that the WQIs value of the northern part of the country was very good in the position (Howladar *et al.* 2017).

The CWQI method indicated that three factors, namely the selection of inputs, the number of sampling events, and the choice of the water quality objectives contrary to which the index is being computed affected the result of the indexing method. The Canadian Council of Ministers of the Environment examined the sensitivity of this model to changing some of the inputs on a large set of water quality data (UNEP-GEMS Water 2007). One of the results of these tests is: 'the performance of CWQI model was reasonable when at least 10 or more parameters were included and at least 30 observations over at least 3 years were used in the index calculation'. In this regard, the study expected that the present dataset provided good enough information about the water quality because the number of inputs (parameter and station) was sufficient and the study followed the WHO and native guidelines (which one is appropriate) for water quality standards. In this model, the selection of input parameters and objectives is flexible and it tolerates the missing data. But the CWQI model has some limitations, such as (a) the same importance was given to all variables; (b) missing guidelines about the objectives definite to each location and specific water use; (c) only fractional diagnostic of the water quality; (d) easy to manipulate; and (e) F_1 not working properly when too few variables were measured or when excessive covariance exists among them. Besides, a maximum number of parameters is not specified in this model and this model did not utilize the sub-index technique; and scoring, rating, and weight of water parameters to establish the final index equation (Equation (5)). Thus, keeping in mind those above-mentioned limitations and suggestions, it should be modified again to get better outcomes.

Weight average water quality index (WWQI)

The WWQI is another well-recognized model to justify the drinking water quality. This index is a single value expression that summarizes several parameters and delivers a measure of water quality. The WWQI value and water type of the individual samples are presented in Table 4 and the categorization of that model is presented in Table 5. According to Equations (6)–(8) mentioned in the methods section, this index was calculated for the samples using the concentration/value of 14 parameters such as pH, EC, TDS, TH, turbidity, Ca^{2+}, Mg^{2+}, Na^+, K^+, Cl^-, HCO_3^-, SO_4^{2-}, NO_3^-, and PO_4^{3-}. The WWQI ranges from 88.8–551.6 and 95.5–543.3 for PRM and POM seasons, respectively. The result revealed that the mean index value of the samples ranged from 92.3 to 524.7. The mean value was 287.6 with a standard deviation and variance of 128.95 and 16,627.40 (Table 4). These figures are an average of two seasons, namely the PRM and POM. According to the calculated value, 95% of the experimented samples show 'undesirable (E category)', and 5% of the samples fall under 'very poor (D category)' quality type for drinking purposes (Table 5). Howladar *et al.* (2017) used the same parameters of groundwater to calculate the WWQI of Dinajpur District, the northern part of Bangladesh. They found 70.97, 22.5, and 6.45% of water samples fell into excellent, good, and poor ranges. This is the big difference between both results. The high EC value of the present samples provided the higher WWQI value indicating unsuitability for potable uses. Besides, if we considered the concentration of Fe and Mn, then these index values exceeded over 500 in the case of all samples. High values of EC, TDS, turbidity, and TH (Ca, Mg, and HCO_3^-) also contributed to high index values, typically during the POM rather than the PRM period. The study areas are situated in the upper Ganges flood plain and rivers delta basin areas, which create rich aquifers with excess mineralization by the mineral/rock weathering process which is the main feature of geochemical

Table 4 | Statistical summary of WQIs value of collected water samples in different sampling periods

	CWQI (Drinking and Irrigation)		WWQI (Drinking)			MWQI (Irrigation)		
S. ID	**Drinking**	**Irrigation**	**PRM**	**POM**	**Average**	**PRM**	**POM**	**Average**
S1	43.3	62.7	322.7	407.6	365.15	81.8	79.3	80.55
S2	39.9	64.0	342.1	456.8	399.45	82.9	83.2	83.05
S3	41.0	70.6	298.3	372.0	335.15	85.3	81.0	83.15
S4	43.3	68.9	311.6	391.0	351.30	86.0	83.1	84.55
S5	51.7	71.3	302.2	427.9	365.05	84.1	86.9	85.50
S6	41.8	67.3	433.5	478.4	455.95	78.9	80.2	79.55
S7	42.4	70.6	377.7	470.1	423.90	85.4	77.0	81.20
S8	51.1	66.4	276.6	405.9	341.25	86.3	80.6	83.45
S9	44.0	61.7	266.6	371.5	319.05	78.0	76.4	77.20
S10	55.3	75.4	304.6	400.6	352.60	86.1	84.8	85.45
S11	43.5	68.5	276.6	346.6	311.60	79.0	77.4	78.20
S12	38.3	70.0	423.1	479.0	451.05	81.0	79.9	80.45
S13	66.5	78.4	176.5	166.8	171.65	89.0	90.8	89.90
S14	65.1	74.1	123.6	193.7	158.65	85.9	86.1	86.0
S15	68.0	74.0	94.8	141.8	118.30	88.8	91.2	90.0
S16	59.7	76.6	233.5	198.9	216.20	85.1	84.0	84.55
S17	65.3	75.7	89.1	95.5	92.30	89.0	86.3	87.65
S18	43.6	71.9	377.6	379.9	378.75	83.5	77.9	80.70
S19	42.1	78.9	411.6	407.0	409.30	85.7	83.0	84.35
S20	64.0	73.2	177.2	267.8	222.50	86.0	85.5	85.75
S21	63.8	76.4	99.1	142.8	120.95	90.3	87.3	88.80
S22	68.4	75.0	88.9	98.6	93.75	91.8	90.0	90.90
S23	67.0	76.2	88.8	129.0	108.90	86.3	84.5	85.40
S24	43.0	75.3	302.4	376.8	339.60	88.9	81.3	85.10
S25	65.8	78.2	123.6	233.7	178.65	85.1	82.5	83.80
S26	69.1	71.8	92.6	123.1	107.85	87.5	88.0	87.75
S27	70.5	72.0	94.2	159.8	127.01	90.4	89.1	89.75
S28	42.3	67.8	354.7	372.0	363.35	81.4	79.9	80.65
S29	39.9	70.5	551.6	497.8	524.70	83.6	81.1	82.35
S30	40.4	69.0	412.0	397.0	404.50	81.1	82.0	81.55
S31	66.1	71.6	149.7	182.7	166.20	89.5	86.5	88.0
S32	69.3	79.0	95.6	179.1	137.35	91.8	89.1	90.45
S33	67.8	72.6	111.5	156.5	134.02	89.4	87.3	88.35
S34	64.0	70.9	188.6	232.8	210.70	87.3	86.8	87.05
S35	45.5	69.0	408.7	516.5	462.60	82.6	83.5	83.05
S36	65.4	75.0	319.7	313.7	316.70	87.3	84.0	85.65
S37	66.6	73.8	175.6	208.1	191.85	91.0	87.9	89.45
S38	49.9	66.9	400.5	386.0	393.25	81.8	79.1	80.45
S39	41.5	63.9	488.6	543.3	515.95	76.1	75.4	75.75
S40	49.1	65.0	311.6	422.0	366.80	72.5	70.0	71.25
Mean	**54.17**	**71.52**	**262.51**	**313.25**	**287.6**	**85.09**	**83.25**	**84.17**
Range	**38.3–70.5**	**61.7–79.0**	**88.8–551.6**	**95.5–543.3**	**92.3–524.7**	**72.5–91.8**	**70–91.2**	**71.25–90.9**
Variance	**132.56**	**20.30**	**–**	**–**	**16,627.40**	**–**	**–**	**18.58**

(*Continued.*)

Table 4 | Continued

	CWQI (Drinking and Irrigation)		WWQI (Drinking)			MWQI (Irrigation)		
S. ID	Drinking	Irrigation	PRM	POM	Average	PRM	POM	Average
±SD	11.51	4.56	129.16	132.79	128.95	4.33	4.61	4.31
Std. error	1.847	0.722	–	–	20.648	–	–	0.690

processes in this area (Bodrud-Doza *et al.* 2016; Islam & Mostafa 2021c). For this reason, the groundwater became highly mineralized and contained huge mineral ions that could enhance the WWQI values. About 100% of people in the study area consumed groundwater without any treatment, causing harm to public health.

This WWQI method has some limitations and uncertainty. It may not convey sufficient information about the real water quality. Many important water quality parameters (like trace metals) are not used in the calculation of this index. The hiding or over-emphasizing of a single bad parameter value can affect this model. A single figure cannot express the whole story of water quality, and many other water quality parameters that were missing in the index. But this method is simple, easy to compute, and some very vital water quality parameters are used to assess the drinking water quality.

Meireles water quality index (MWQI)

This method is used only for the determination of irrigation water quality for better crop production. Using Equations (9)–(11), this index was calculated accordingly and the sample-by-sample index value was mentioned in Table 4 with some basic statistics. The average value of the MWQI of both PRM and POM season in the groundwater of the study area was 85.09 and 83.25 indicating a 'no' and 'low' restriction, respectively, in use for irrigation purposes (Table 4). But in the case of the PRM period, out of 40 samples, 62.5% fall in 'no' restriction, whereas 37.5% of samples of the POM season were in the same category. On an average of both seasons, the MWQI value is 84.17, of which 47.5 and 52.5% of samples fell into 'no restriction' and 'low restriction', respectively (Tables 4 and 5). The results seemed to be associated with seasonal effects, as waters showed a higher concentration of HCO_3^- during the POM season (after heavy rain) and Na and Cl enrichment in the PRM season (dry period) due to intense evaporation. The water with 'no restriction' (MWQI: $85 \leq 100$) class may be used for most soils with a low possibility of causing salinity and sodicity problems and leaching is suggested within irrigation practices, excluding soils with extremely low permeability (Semiromi *et al.* 2011). These water sources have no toxicity risk for most plants. Besides, the water with 'low restriction' (MWQI: $70 \leq 85$) class is recommended for use in irrigated soils with light texture or moderate permeability, with salt leaching recommended. Soil sodicity in heavy texture soils is recommended to avoid its use in soils with high clay levels of 2:1 (Schultz 2001; Semiromi *et al.* 2011). In this case, it should avoid salt-sensitive plants. Some researchers in Bangladesh assessed the irrigation water quality through other indices like IWQ_{index}, SAR, soluble sodium percentage (SSP), residual sodium carbonate (RSC), magnesium adsorption ratio (MAR), salinity hazard (SH), Kelly's ratio (KR), permeability index (PI), etc., in and neighboring areas of the present study (Bhuiyan *et al.* 2015, 2016; Ahmed *et al.* 2018; Islam *et al.* 2018; Islam & Mostafa 2021e). The overall results of their investigations were almost similar to this study.

Canadian water quality index (CWQI) for irrigation water

The CWQI is used for the evolution of drinking water, but some water managers and researchers used this index model for the evaluation of irrigation water quality. Like the MWQI, there are five parameters, SAR, EC, Na^+, Cl^-, and HCO_3^- considered in this model for irrigation water quality assessment, the results are shown in Table 3. It revealed that about 65% of samples range from 70 to 84 index value and fell into a 'good' category, and about 35% of samples were found within the 'fair' category (Table 5). The average value of this model was 71.52 with a standard deviation of ±4.56.

Judgment of WQIs and their use in practice

Regarding water quality parameters, in practice, there have some differences between surface and groundwater. Maximum indexing methods were calculated using surface water parameters such as microbial contents and biochemical loads which are insignificant for groundwater quality measurement. Because of the insufficient index

Table 5 | WQI designations and summarized results of samples

WQI	Parameter uses	Scale	Index value	Category	Description	Av. result (%sample)
CWQI(Drinking)	All parameters	0–100	95–100	A	All measurements are within objectives virtually all the time: Excellent	–
			80–94	B	Conditions rarely depart from natural or desirable levels: Good	–
			65–79	C	Conditions sometimes depart from natural or desirable levels: Fair	37.5
			45–64	D	Conditions often depart from natural or desirable levels: Marginal	22.5
			0–44	E	Conditions usually depart from natural or desirable levels: Poor	40
CWQI(Irrigation)	EC, Na^+, HCO_3^-, Cl^-, SAR	0–100	85–100	A	Excellent	–
			70–84	B	Good	65
			55 –69	C	Fair	35
			40–54	D	Poor	–
			0–39	E	Restrict	–
WWQI(Drinking)	pH, EC, TDS, Total Hardness, Turbidity, Ca^{2+}, Mg^{2+}, Na^+, Cl^-, HCO_3^-, SO_4^{2-}, NO_3^-, PO_4^{3-}	0–100	0–25	A	Excellent	–
			26–50	B	Good	–
			51–75	C	Poor	–
			76–100	D	Very poor	5
			>100	E	Undesirable	95
MWQI(Irrigation)	EC, Na^+, HCO_3^-, Cl^-, SAR	0–100	$85\leq100$	A	No restriction	47.5
			$70\leq85$	B	Low restriction	52.5
			$55\leq70$	C	Moderate restriction	–
			$40\leq55$	D	High restriction	–
			$0\leq40$	E	Severe restriction	–

model, it is very difficult to assess properly the quality of groundwater for potable, industrial, and agricultural use. The study used two models in each drinking and irrigation water quality assessment. It made a comparison between the CWQI(drinking) vs WWQI, and CWQI(irrigation) vs MWQI to find out which one is better than the other for the present study.

Comparison between CWQI(drinking) and WWQI

There is a significant difference between the results of the two methods; at a certain significant limit the paired *t*-test was adopted which is a statistical procedure to determine whether the mean difference between the two sets of observations is zero. The results of running paired *t*-test by the SPSS program are tabulated in Table 6.

Table 6 shows a big difference in the mean score between the Canadian WQI (54.17) and the weighted average WQI (287.6). Also, the standard deviation, variance, and standard error of both the models are numerically dissimilar to each other, which gave a statistically nonsignificant sign. Table 6 illustrates that a very high negative correlation ($r=-0.91$)), and zero population correlation coefficient ($p=0$) were obtained, so a zero correlation could exist (significant=0.000). Besides, the mean difference was equal to −233.463, and the standard deviation and standard error mean of difference were 141.299 and 22.341, respectively, that are statistically abnormal figures. Furthermore, about 95% CI for the mean difference was −278.652 to −188.273. The calculated *t*-value (T) was −10.450, the degree of freedom (*df*) was 39, and the *p*-value denoted by 'Significant (two-tailed)' was 0.000. That statistical information indicated the absence of any statistical significance between both indexes for drinking water quality evaluation.

Among these three index models, the Canadian WQI is the only method that permits the utilization of all the available variables in the calculation of the overall index value. In this method, the water quality data for all sampling sites were characterized as fair to poor (Table 4). The EC, TH (Ca^{2+}, Mg^{2+}, and HCO_3^-), turbidity, NH_3, Fe, and Mn were the main parameters that lower the overall CWQI value in all sampling stations. In the sub-index models (such as WWQI), the number of parameters was restricted and the sub-index equations were intended for each parameter. The WWQI model included the 14 vital parameters for the assessment of water quality data: pH, EC, TDS, total hardness, turbidity, Ca^{2+}, Mg^{2+}, Na^+, K^+, Cl^-, HCO_3^-, SO_4^{2-}, NO_3^-, and PO_4^{3-}. The index values obtained for all stations were categorized as 'undesirable'. In this method, the combination of the sub-index values removed the eclipsing problem and provided rational results by using weighting factors for each parameter. The result shows a big difference between the index value of the CWQI and WWQI for the drinking purposes of all stations (Figure 3). In the case of CWQI, the samples were three categories, fair, marginal, poor; but most of the samples were 'undesirable' for potable use in the WWQI model (Table 4). The maximum samples (mainly S13 to S40) showed completely inverse results of these two methods, i.e., one sample with a lower index value but the same one gives a higher number of another index value (Figure 3). The CWQI included all the estimated parameters (with trace metals) but the WWQI included some common physical and chemical parameters. However, if only one parameter crossed the objective or standard value, then the sub-index value of the WWQI was highly increased. Besides, the study result of the sensitive test of the CWQI model (UNEP-GEMS Water 2007) showed that the variation of input factors could impact very slowly the total index value. For example, if the study were considered the Fe concentration of samples in the WWQI method, then the index values increased by over 100 points but in the case of CWQI, minor changes

Table 6 | Paired samples test (CWQI-WWQI) for comparable study

	Paired differences									
				Paired samples correlations		**95% confidence interval (*CI*) of the difference**				
Indices comparison	**Mean**	**Std. deviation**	**Std. error mean**	**Correlation**	**Sig.**	**Lower**	**Upper**	***T***	***df***	**Significant (two-tailed)**
Pair CWQI-WWQI (drinking)	−233.463	141.299	22.341	−0.910	0.000	−278.652	−188.273	−10.450	39	0.000
Pair CWQI-MWQI (irrigation)	−12.67	3.384	0.535	+0.714	0.000	−13.747	−11.582	−23.67	39	0.000

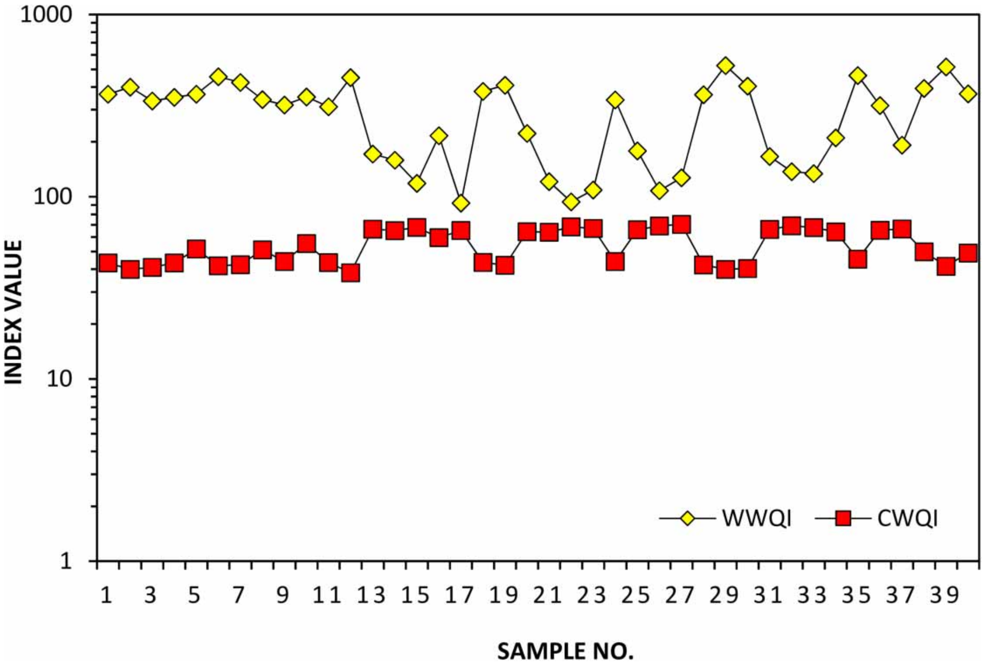


Figure 3 | The pair difference statistics between CWQI(drinking) vs WWQI values for all water samples.

occurred in the total index value. So, the study assumed that the output of the results of the CWQI was better than the WWQI method.

Comparison between CWQI(irrigation) and MWQI

The Canadian WQI model was not only used to index the water quality for drinking purposes but also provides suitable information about the irrigation water quality. Here, the study compares the CWQI with another irrigation water quality sub-index method, Meireles WQI. The dataset of the WQI for irrigation purposes in two methods was tested by the SPSS statistical procedure. There is a significant difference between the two methods at a certain significant limit of the paired *t*-test. It is a statistical technique to determine the zero of the mean difference between the two sets. The results of the running paired *t*-test are presented in Table 6.

In Table 4, the CWQI has a lower mean score (71.52) than Mieriles WQI (84.17). The standard deviation, variance, and standard error of both models were numerically very similar to each other (Table 4). Table 6 illustrates that there is a strong positive correlation (r=0.714) where the population correlation coefficient is zero (p=0). So, a zero correlation could exist (sig.=0.000). This significant correlation shows the importance of the *t*-test. Besides, the mean difference was equal to −12.665 and the standard deviation and standard error mean of difference were 3.384 and 0.535, respectively. Furthermore, about 95% CI for the mean difference was −13.747 to −11.582. The calculated *t*-value (T) and df were −23.671 and 39, respectively. The *p*-value denoted by 'Significant (two-tailed)' was 0.000. So, the outputs of the comparative study results indicated that the irrigation water quality of both indexing methods was statistically significant.

Same as the MWQI method, only five parameters were used for the CWQI calculation but the procedures were completely different. The result of the CWQI calculation revealed that irrigation water of the study area was good (65%) to fair (35%), whereas 47.50–52.5% of the samples fell within no restriction to low restriction categories for the MWQI model (Table 5). Figure 4 and Table 4 show that the difference of the sample-by-sample index value and trend line of both methods was almost the same and the CWQI values were regularly 10–15 points less than the MWQI values. Also, the variance and standard deviation of both models were almost the same (Table 4). There were two ways to adjust both the results such as increasing the input parameters or/and increasing the test volume. If the study considers pH, TDS, and boron in the CWQI model, then the values of this index increase to 10–15 points from the previous values, and the result will be similar to the MWQI. Further study is needed to improve the indexing methods.

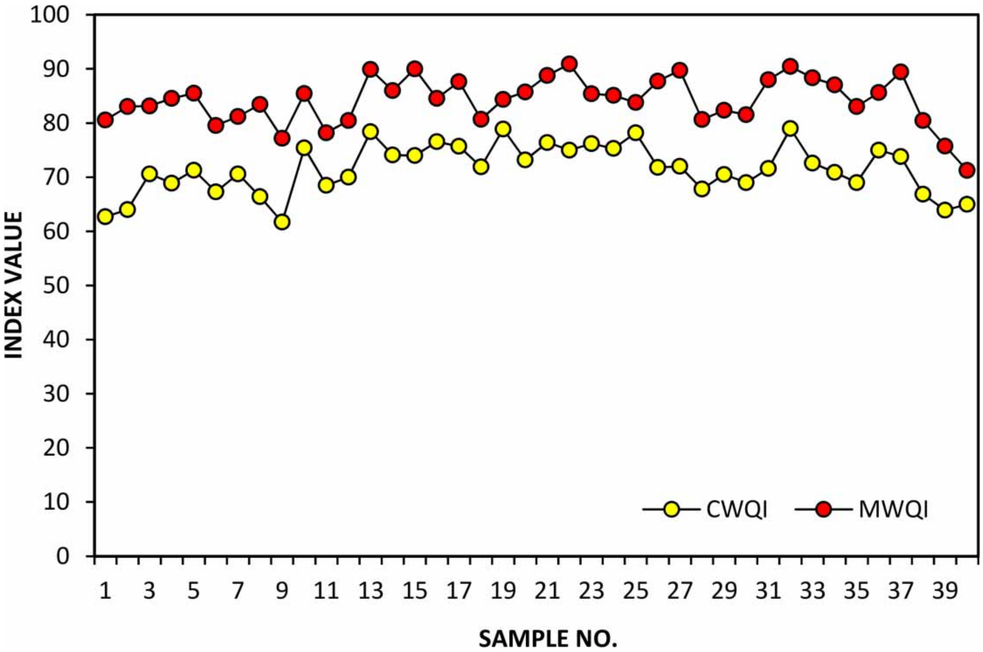


Figure 4 | The pair difference statistics between CWQI(irrigation) vs MWQI values for all water samples.

CONCLUSION

The study was conducted to evaluate the drinking and irrigation water quality using indexing methods in the Ganges basin (Kushtia District) of Bangladesh using different hydrogeochemical parameters of groundwater for both the PRM and POM seasons. Almost neutral pH and higher EC, TDS, total hardness, Fe, and Mn of groundwater samples were the main geochemical characteristics in the study area. The study introduces an interpretation of water quality data based on 40 monitoring sites by using three different water quality index methods (CWQI, WWQI, and MWQI). Among these models, the CWQI and WWQI were considered for the assessment of drinking water quality, and the CWQI and MWQI were used for irrigation purposes. The results of the CWQI and WWQI models showed that the groundwater was classified into C, D, and E with 'fair' to 'very poor' or 'unsuitable' water quality for drinking purposes. Statistically, the output of the results of both the models shows a big difference with a highly negative correlation matrix ($r=-0.91$), and all pair difference values were found to be abnormal. The Canadian WQI allows all parameters in the same index formulation to be detected and can be applied easily to water quality data without assigning any weighting factors. But in the case of WWQI, limited fixed parameters are used and the same importance is given to all variables. The study assumed that the CWQI was better than the WWQI method. The Meireles WQI model showed that the water quality of the study area was classified as a 'low/no' restriction (A/B class) in water use, while the Canadian model classified the water into B/C with 'good' to 'fair' water quality. Statistically, the pair difference is very low and the correlation matrix ($r=+0.71$) is strongly positive between the CWQI and MWQI. The results revealed that the mean pair difference was -12.665 from the MWQI to CWQI. The study found that there was no significant difference between the models. Finally, it may be concluded that the CWQI model was found to be more reasonable in comparison to the WWQI model for drinking purposes and the MWQI model was better than the CWQI for assessing the irrigation water quality. While there is no universally accepted integrated index model or any single model for water quality assessment, some countries and areas have used, or are using, combined water quality datasets in the development of WQIs. Every method partially fulfilled the requirements of a well-fitted and complete indexing equation. So, the ambiguity of water quality indexing encourages future studies to develop an integrated model considering maximum water parameters and hazard classes for getting the best solution for drinking and irrigation practices.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

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

REFERENCES

Ahmed, N., Bodrud-Doza, M., Didar-Ul, S. M., Choudhry, M. A., Muhib, M. I., Zahid, A., Hossain, S., Moniruzzaman, M., Deb, N. & Bhuiyan, M. A. Q. 2018 Hydrogeochemical evaluation and statistical analysis of groundwater of Sylhet, north-eastern Bangladesh. *Acta Geochimica* **38**, 440–455. doi:10.1007/s11631-018-0303-6.

Akter, S., Ahmed, K. R., Marandi, A. & Schüth, C. 2020 Possible factors for increasing water salinity in an embanked coastal island in the southwest Bengal Delta of Bangladesh. *Science of The Total Environment* **713**, 136668. doi:10.1016/j.scitotenv.2020.136668.

Alrajhi, A., Beecham, S. & Ali, H. 2017 Effects of partial root-zone drying irrigation and water quality on soil physical and chemical properties. *Agricultural Water Management* **182**, 117–125. doi:10.1016/j.agwat.2016.12.011.

ATSDR 2000 *Toxicological Profile for Manganese*. United States Department of Health and Human Services, Public Health Service, Atlanta, GA. Agency for Toxic Substances and Disease Registry.

Ayers, R. S. & Westcot, D. W. 1985 *Water Quality for Agriculture, Irrigation and Drainage, Paper No. 29*. FAO, Rome. Available from: www.fao.org/docrep/003/T0234E/T0234E01.htm

Banda, T. & Kumarasamy, M. 2020a Development of water quality indices (WQIs): a review. *Polish Journal of Environmental Studies* **29** (3), 1–11. doi:10.15244/pjoes/110526.

Banda, T. & Kumarasamy, M. 2020b A review of the existing water quality indices (WQIs). *Pollution Research* **39**, 489–514.

BBS 2020 *Statistical Annual Report 2019*. Bangladesh Burrow of Statistics, Ministry of Planning, Bangladesh.

Bhargava, D. S. 1985 Expression for drinking water supply standards. *Journal of the Environmental Engineering Division* **111** (3), 304–316.

Bharti, N. & Katyal, D. 2011 Water quality indices used for surface water vulnerability assessment. *International Journal of Environmental Sciences* **2**, 154–173.

Bhuiyan, M. A. H., Ganyaglo, S. & Suzuki, S. 2015 Reconnaissance on the suitability of the available water resources for irrigation in Thakurgaon District of northwestern Bangladesh. *Applied Water Science* **5**, 229–239. doi:10.1007/s13201-014-0184-8.

Bhuiyan, M. A. H., Bodrud-Doza, M., Islam, A. R. M. T., Rakib, M. A., Rahman, M. S. & Ramanathan, A. L. 2016 Assessment of groundwater quality of Lakshmipur district of Bangladesh using water quality indices, geostatistical methods, and multivariate analysis. *Environmental Earth Sciences* **75** (1020), 1–23. doi:10.1007/s12665-016-5823-y.

Bodrud-Doza, M., Islam, A. R. M. T., Ahmed, F., Das, S., Saha, N. & Rahman, M. S. 2016 Characterization of groundwater quality using water evaluation indices, multivariate statistics and geostatistics in central Bangladesh. *Water Science* **30**, 19–40. doi:10.1016/j.wsj.2016.05.001.

Boyacioglu, H. 2007 Development of a water quality index based on a European classification scheme. *Water SA* **33** (1), 100–106. doi:10.4314/wsa.v33i1.47882.

Brown, R. M., McClelland, N. I., Deininger, R. A. & Tozer, R. G. 1970 A water quality index - Do we dare? *Water and Sewage Works* **117** (10), 339–343.

CanDNHW 1990 *Nutrition Recommendations. The Report of the Scientific Review Committee, Department of National Health and Welfare (Canada), DSS Cat. no. H49-42/1990E*. Ottawa. Available from: https://catalogue.nla.gov.au/Record/1785247

CCME 2001 *Canadian Water Quality Guidelines for the Protection of Aquatic Life. Canadian Environmental Quality Guidelines CCME WATER QUALITY INDEX 1.0 Technical Report*. Ottawa.

Chowdhury, R. M., Muntasir, S. Y. & Monowar, H. M. 2012 Water quality index of water bodies along Faridpur-Barisal road in Bangladesh. *Global Engineering Technologies Reviews* **2** (3), 1–8.

Cude, C. G. 2007 Oregon water quality index: a tool for evaluating water quality management effectiveness. *Journal of the American Water Resources Association* **37** (1). doi:10.1111/j.1752-1688.2001.tb05480.x.

DE 2017 *Surface and Groundwater Quality Report 2016*. Department of Environment, Ministry of Forest and Environment, Bangladesh.

Dede, O., Telci, I. & Aral, M. 2013 The Use of water quality index models for the evaluation of surface water quality: a case study for Kirmir Basin, Ankara, Turkey. *Water Quality Exposure and Health* **5**, 41–56. doi:10.1007/s12403-013-0085-3.

Dider-Ul, S. M. I., Bhuiyan, M. A. H. & Rume, T. 2017 Hydrogeochemical investigation of groundwater in shallow coastal aquifer of Khulna District, Bangladesh. *Applied Water Science* **7**, 4219–4236. doi:10.1007/s13201-017-0533-5.

Dola, S. S., Bahsar, K., Islam, M. & Sarker, M. M. R. 2018 Hydrogeological classification and the correlation of groundwater chemistry with basin flow in the South-Western part of Bangladesh. *Journal of Bangladesh Academy of Sciences* **42** (1), 41–54. doi:10.3329/jbas.v42i1.37831.

Dorman, D. C. 2000 Neurotoxicity of manganese chloride in neonatal and adult CD rats following sub chronic (21-day) high-dose oral exposure. *Journal of Applied Toxicology* **20**, 179–187. doi:10.1002/(sici)1099-1263(200005/06)20:3%3C179::aid-jat631%3E3.0.co;2-c.

DPHE 2009 *Bangladesh National Drinking Water Quality Survey*. Department of Public Health and Engineering, Govt. of Bangladesh, Dhaka.

DPHE-BGS 2000 *Groundwater Studies of Arsenic Contamination in Bangladesh*. Department of Public Health & Engineering and British Geological Survey, Final Report, Dhaka.

Dunnette, D. A. 1979 A geographically variable water quality index used in Oregon. *Journal of the Water Pollution Control Federation* **51** (1), 53–61.

Flora, G., Gupta, D. & Tiwari, A. 2012 Toxicity of lead: a review with recent updates. *Interdisciplinary Toxicology* **5** (2), 47–58. doi:10.2478%2Fv10102-012-0009-2.

Hasan, M. K., Shahriar, A. & Jim, K. U. 2019 Water pollution in Bangladesh and its impact on public health. *Heliyon* **5** (8), e02145. doi:10.1016/j.heliyon.2019.e02145.

Heaney, R. P., Gallagher, J. C., Johnston, C. C., Neer, R., Parfitt, A. M. & Whedon, G. D. 1982 Calcium nutrition and bone health in the elderly. *The American Journal of Clinical Nutrition* **36**, 986–1013. doi:10.1093/ajcn/36.5.986.

Helal, U. S. M., Mostafa, M. G. & Haque, A. B. M. H. 2011 Evaluation of groundwater quality and its suitability for drinking purpose in Rajshahi City, Bangladesh. *Water Science and Technology: Water Supply* **11** (5), 545–559. doi:10.2166/ws.2011.079.

Horton, R. K. 1995 An index number system for rating water quality. *Journal of the Water Pollution Control Federation* **37** (3), 300–306.

Howladar, M. F., Al Numanbakth, M. A. & Faruque, M. O. 2017 An application of Water Quality Index (WQI) and multivariate statistics to evaluate the water quality around Maddhapara Granite Mining Industrial Area, Dinajpur, Bangladesh. *Environmental Systems Research* **6**, 1–13. doi:10.1186/s40068-017-0090-9.

IPCS 2002 *Principles and Methods for the Assessment of Risk From Essential Trace Elements*. World Health Organization, Geneva. International Programme on Chemical Safety (Environmental Health Criteria 228). Available from: www.inchem.org/documents/ehc/ehc/ehc228.htm

Islam, M. S. & Majumder, S. M. M. H. 2020 Alkalinity and hardness of natural waters in Chittagong City of Bangladesh. *International Journal of Science and Business* **4** (1), 137–150. doi:10.5281/zenodo.3606945.

Islam, M. S. & Mostafa, M. G. 2021a Trends of chemical pesticide consumption and its contamination feature of natural waters in especial reference to Bangladesh: a review. *American-Eurasian Journal of Agricultural & Environmental Sciences* **21** (3), 151–167. doi:10.5829/idosi.aejaes.2021.151.167.

Islam, M. S. & Mostafa, M. G. 2021b Groundwater status and challenges in Bangladesh. In: *Sustainable Agriculture Reviews*, Chapter 4, Vol. 52 (Lichtfouse, E., ed.). Springer Nature, Switzerland AG, pp. 79–146. doi:10.1007/978-3-030-73245-5_4.

Islam, M. S. & Mostafa, M. G. 2021c Hydro-geochemical evaluation of groundwater for irrigation in the Ganges river basin areas of Bangladesh. *Research Square* (Preprint), 1–33. doi:10.21203/rs.3.rs-161359/v1.

Islam, M. S. & Mostafa, M. G. 2021d Groundwater suitability for irrigated agriculture in Alluvial Bengal delta plain: a review. *International Journal of Advances in Applied Sciences* **10** (2), 156–170. doi:10.11591/ijaas.v10.i2.pp156-170.

Islam, M. S. & Mostafa, M. G. 2021e Development of an integrated irrigation water quality index ($IIWQ_{Index}$) model. *Journal of Water Supply* **22** (2), 2322–2337. doi:10.2166/ws.2021.378.

Islam, M. S. & Mostafa, M. G. 2021f Groundwater quality and risk assessment of heavy metal pollution in Middle-West part of Bangladesh. *Journal of Earth and Environmental Science Research* **3** (2), 1–15. doi.org/10.47363/JEESR/2021(3)143.

Islam, K., Rahman, M. S., Ali, M. H. & Hossain, A. F. M. A. 2016 Evolution of the aquifers system and groundwater quality of the North-west District of Bangladesh for development potential. *BRAG University Journal* **XI** (2), 85–100.

Islam, A. R. M., Shuanghe, S., Bodrud-Doza, M., Atiqur, M. R. & Samiran, D. 2017a Assessment of trace elements of groundwater and their spatial distribution in Rangpur district, Bangladesh. *Arabian Journal of Geosciences* **10** (4). doi:10.1007/s12517-017-2886-3.

Islam, A. R. M., Nasir, A., Bodrud-Doza, M. & Ronghao, C. 2017b Characterizing groundwater quality ranks for drinking purposes in Sylhet district, Bangladesh, using entropy method, spatial autocorrelation index, and geostatistics. *Environmental Science and Pollution Research* **24**, 26350–26374. doi:10.1007/s11356-017-0254-1.

Islam, S. M.-U., Majumder, R. K., Uddin, M. J., Khalil, M. I. & Alam, M. F. 2017c Hydrochemical characteristics and quality assessment of groundwater in Patuakhali district, southern coastal region of Bangladesh. *Exposure Health* **9** (1), 43–60. doi:10.1007/s12403-016-0221-y.

Islam, A. R. M., Shen, S., Haque, M., Bodrud-Doza, M., Maw, K. & Habib, M. 2018 Assessing groundwater quality and its sustainability in Joypurhat district of Bangladesh using GIS and multivariate statistical approaches. *Environment Development and Sustainability* **20**, 1935–1959. doi:10.1007/s10668-017-9971-3.

Khan, A. A., Paterson, R. & Khan, H. 2003 Modification and application of the CCME WQI for the communication of drinking water quality data in Newfoundland and Labrador. Presented at *38th, Central Symposium on Water Quality Research, Canadian Association on Water Quality*, 10–11 February 2003, Burlington, Canada.

Liou, S. M., Lo, S. L. & Wang, S. H. 2004 A generalized water quality index for Taiwan. *Environmental Monitoring and Assessment* **96**, 35–52. doi:10.1023/B:EMAS.0000031715.83752.a1.

Lumb, A., Sharma, T. C. & Bibeault, J.-F. 2011a A review of genesis and evolution of water quality index (WQI) and some future directions. *Water Quality, Exposure and Health* **3** (1), 11–24. doi:10.1007/s12403-011-0040-0.

Lumb, A., Sharma, T. C., Bibeault, J.-F. & Klawunn, P. 2011b A comparative study of USA and Canadian water quality index models. *Water Quality, Exposure and Health* **3** (3-4), 203–216. doi:10.1007/s12403-011-0056-5.

Majeed, S. A. 2018 Comparison of water quality indices (Bani-Hassan river as a case study). *Journal of Kerbala University* **14** (1), 53–65.

Meireles, A., Andrade, E. M., Chaves, L., Frischkorn, H. & Crisostomo, L. A. 2010 A new proposal of the classification of irrigation water. *Revista Ciencia Agronomica* **41** (3), 349–357.

MICS-B 2018 *Water Quality Thematic Report: 2012–2013*. Multiple Indicator Cluster Survey, UNICEF and BBS, Bangladesh. Available from: www.unicef.org/bangladesh/en/reports/multiple-indicator-cluster-survey-2012-2013

Moore, M. R. 1988 Hematological effects of lead. *Science of the Total Environment* **71**, 419–431. doi:10.1016/0048-9697(88)90214-8.

Mostafaei, A. 2014 Application of multivariate statistical methods and water-quality index to evaluation of water quality in the Kashkan River. *Environmental Management* **53**, 865–881. doi:10.1007/s00267-014-0238-6.

Mukate, S., Wagh, V. & Panaskar, D. 2019 Development of new integrated water quality index (IWQI) model to evaluate the drinking suitability of water. *Ecological Indicators* **101**, 348–354. doi:10.1016/j.ecolind.2019.01.034.

Najafzadeh, M., Homaei, F. & Farhadi, H. 2021 Reliability assessment of water quality index based on guidelines of national sanitation foundation in natural streams: integration of remote sensing and data-driven models. *Artificial Intelligence Review* **54**, 4619–4651. doi:10.1007/S10462-021-10007-1.

Najafzadeh, M., Homaei, F. & Mohamadi, S. 2022 Reliability evaluation of groundwater quality index using data-driven models. *Environmental Science & Pollution Research* **29**, 8174–8190. doi.org/10.1007/s11356-021-16158-6.

Nasher, N. M. R. & Ahmed, M. H. 2021 Groundwater geochemistry and hydrogeochemical processes in the Lower Ganges-Brahmaputra-Meghna River Basin areas, Bangladesh. *Journal of Asian Earth Sciences X* **6** (1). doi:10.1016/j.jaesx.2021.100062.

Nasirian, M. 2007 A new water quality index for environmental contamination contributed by mineral processing: a case study of Amang (tin tailing) processing activity. *Journal of Applied Sciences* **7**, 2977–2987. doi:10.3923/jas.2007.2977.2987.

Nerbrand, C., Agréus, L., Lenner, R. A., Nyberg, P. & Svärdsudd, K. 2003 The influence of calcium and magnesium in drinking water and diet on cardiovascular risk factors in individuals living in hard and soft water areas with differences in cardiovascular mortality. *BMC Public Health* **18** (3), 1–21. doi:10.1186/1471-2458-3-21.

Othman, F. M. E., Seyam, A. H., Ahmed, A. N., Teo, F. Y., Fai, C. M., Afan, H. A., Sherif, M., Sefelnasr, A. & El-Shafie, A. 2020 Efficient river water quality index prediction considering minimal number of inputs variables. *Engineering Applications of Computational Fluid Mechanics* **14** (1), 751–763. doi:10.1080/19942060.2020.1760942.

Parvin, F., Haque, M. M. & Tareq, S. M. 2022 Recent status of water quality in Bangladesh: a systematic review, meta-analysis and health risk assessment. *Environmental Challenges* **6** (100416), 1–13. doi:10.1016/j.envc.2021.100416.

Paun, I., Cruceru, L., Chiriac, F. L., Niculescu, M., Vasile, G. & Marin, N. 2016 Water quality indices –methods for evaluating the quality drinking water. In *INCD ECOIND–INTERNATIONAL SYMPOSIUM–SIMI 2016 'THE ENVIRONMENT AND INDUSTRY,' PROCEEDINGS BOOK*. pp. 395–402. doi:10.21698/simi.2016.0055.

Pesce, S. F. & Wunderlin, D. A. 2000 Use of water quality indices to verify the impact of Cordoba city (Argentina) on Suquia River. *Water Resource* **34** (11), 2915–2926. doi:10.1016/S0043-1354(00)00036-1.

Pravina, P., Sayaji, D. & Avinash, M. 2012 Calcium and its role in human body. *International Journal of Research in Pharmaceutical and Biomedical Science* **58**, 144.

Radwn, N. 2005 Evaluation of different water quality parameters for the Nile River and the different drains. In *Ninth International Water Technology Conference, IWTC9*, Sharm El-Sheikh, Egypt, pp. 1293–1303.

Rahman, S. H. & Majumder, R. K. 2012 Groundwater quality of irrigation of deep aquifer in southwestern zone of Bangladesh. *Songklanakarin Journal of Science and Technology* **34** (3), 345–352.

Rahman, M., Majumder, R., Rahman, S. & Halim, M. 2011 Sources of deep groundwater salinity in the southwestern zone of Bangladesh. *Environmental Earth Sciences* **63**, 363–373. http://doi:10.1007/s12665-010-0707-z.

Richards, L. A. 1968 *Soil and Water Conservation Research Branch. Agricultural Research Service. Agricultural Handbook no. 60*. U.S. Department of Agriculture (USDA), Bushland, TX.

Saeedi, M., Abessi, O., Sharifi, F. & Meraji, H. 2010 Development of ground water quality index. *Environmental Monitoring Assessment* **163**, 327–335. doi:10.1007/s10661-009-0837-5.

Said, A., Stevens, D. K. & Sehlke, G. 2004 An innovative index for evaluating water quality in streams. *Environmental Management* **34** (3), 406–414.

Sarkar, C. & Abbasi, S. A. 2006 Qualidex - a new software for generating water quality indices. *Environmental Monitoring Assessment* **119** (1–3), 201–231. doi:10.1007/s10661-005-9023-6.

Sarkar, A. M., Lutfor Rahman, A. K. M., Samad, A., Bhowmick, A. C. & Islam, J. B. 2019 Surface and ground water pollution in Bangladesh: a review. *Asian Review of Environmental and Earth Sciences* **6** (1), 47–69. doi:10.20448/journal.506.2019.61.47.69.

Schultz, M. T. 2001 A critique of EPA's index of watershed indicators. *Journal of Environmental Management* **62** (4), 429–442. doi:10.1006/jema.2001.0451.

Semiromi, F., Hassani, A., Torabian, A., Karbassi, A. R. & Lotfi, F. 2011 Evolution of a new surface water quality index for Karoon catchment in Iran. *Water Science and Technology* **64**, 2483–2491. doi:10.2166/wst.2011.780.

Smith, D. G. 1990 A better water quality indexing system for rivers and streams. *Water Resource* **24** (10), 1237–1244. doi:10.1016/0043-1354(90)90047-A.

Sutadian, A. D., Muttil, N., Yilmaz, A. G. & Perera, B. 2016 Development of river water quality indices-a review. *Environmental Monitoring and Assessment* **188**, 58–90. doi:10.1007/s10661-015-5050-0.

Toyokuni, S. 2009 Role of iron in carcinogenesis: cancer as a ferro toxic disease. *Cancer Science* **100** (1), 9–16. doi:10.1111/j.1349-7006.2008.01001.x.

Tripathi, M. & Singal, S. K. 2019 Use of principal component analysis for parameter selection for development of a novel water quality index: a case study of river Ganga India. *Ecological Indicators* **96**, 430–436.

Tripaty, J. K. & Sahu, K. C. 2005 Seasonal hydrochemistry of groundwater in the barrier spit system of the Chilika Lagoon, India. *Journal of Environmental Hydrology* **13** (7), 1–9.

Tsegaye, T., Sheppard, D., Islam, K. R., Johnson, A., Tadess, W., Atalay, A. & Marzen, L. 2006 Development of chemical index as a measure of in stream water quality in response to land-use and land-cover changes. *Water, Air, & Soil Pollution* **174** (1), 61–79. doi:10.1007/s11270-006-9090-5.

Tyagi, S., Sharma, B. & Singh, P. 2013 Water quality assessment in terms of water quality index. *American Journal of Water Resources* **1**, 34–38. doi:10.12691/ajwr-1-3-3.

UCCC 1974 *Guidelines for Interpretations of Water Quality for Irrigation*. University of California Committee of Consultants (UCCC), USA National Field Manual, US – Geological Survey, California.

UNEP-GEMS Water 2007 *Global Drinking Water Quality Index. Development and Sensitivity Analysis Report*. United Nations Environment Programme Global Environment Monitoring System (GEMS)/Water Programme, Burlington, Ontario L7R 4A6, Canada.

US-APHA 2005 *Standard Methods for the Examination of the Water and Wastewater*, 21st edn. American Public Health Association, AWWA, WPCF, Washington, DC, p. 1134.

WB Group 2019 *Multi-Hazard Groundwater Risks to the Drinking Water Supply in Bangladesh*. Water Global Practice 8922. doi:10.1007/s12403-019-00325-9.

WHO 2004 *Guidelines for Drinking-Water Quality*, Vol. 1, 3rd edn. Water, Sanitation and Health Team, World Health Organization, Geneva. Available from: http://www.who.int/iris/handle/10665/42852

WHO 2011 *Guidelines for Drinking-Water Quality*, 4th edn. World Health Organization, Geneva. Available from: https://www.who.int/water_sanitation_health/

Xiao, T., McPherson, B., Pan, F., Esser, F., Jia, W., Bordelon, A. & Bacon, D. 2016 Potential chemical impacts of CO_2 leakage on underground source of drinking water assessed by quantitative risk analysis. *International Journal of Greenhouse Gas Control* **50** (C), 305–316. doi:10.1016/j.ijggc.2016.04.009.

Zahid, A. 2015 *Groundwater Management Aspects in Bangladesh*. Technical Report 2015, Center for Water and Environment, Bangladesh Water Development Board, Dhaka, pp. 1–83. Available from: www.researchgate.net/publication/320556522

Zhang, Q., Xu, P. & Qian, H. 2020 Groundwater quality assessment using improved water quality index (WQI) and human health risk (HHR) evaluation in a semi-arid region of Northwest China. *Exposure and Health* **12**, 487–500. doi:10.1007/s12403-020-00345-w.

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