J. Bangladesh Acad. Sci. 49(1); 87-102: June 2025 DOI: https://doi.org/10.3329/jbas.v49i1.79738

Journal of Bangladesh Academy of Sciences

Journal homepage: http://www.bas.org.bd/publications/jbas.html

Research Article

Assessing corrosion and scaling potential of drinking water samples: A case study of Chattogram water distribution network, Chattogram, Bangladesh

Ummeh Sadia[1], Md. Akter Hosen Rifat[1], Md. Abid Hasan[1], Nobonita Sarker[2], Shahidul Islam[2], Mohammad Fahimul Hoque[1], Md Abdus Sabur[3], Amitava Bandyopadhyay[4*] and Sumon Ganguli[1*]

Department of Applied Chemistry and Chemical Engineering, University of Chittagong, Chattogram, Bangladesh.

ARTICLE INFO

Article History

Received: 09 February 2025
Revised: 10 April 2025
Accepted: 21 April 2025

Keywords: Corrosion, Scaling potential, Drinking water, Water quality.

ABSTRACT

The consequences of corrosion and scaling potential in drinking water resources are susceptible to public health. In Chattogram, Bangladesh, the Chattogram Water Supply and Sewerage Authority (CWASA) is principally responsible for providing water and sanitation services. Here, 100 samples were collected to forecast the corrosive-scaling behaviors using five indices: Aggressiveness (AI), Puckorius (PSI), Larson-Skold (LS), Langlier (LSI), and Ryznar (RSI). The findings revealed that 100% of the samples had corrosive tendencies established on the values for LSI, RSI, and PSI; in contrast, the LS index indicated scaling tendency in 83% of the samples, and the remaining samples either showed corrosion or a high corrosion rate. A range of artificial and natural sources of potential contamination were indicated by statistical correlations and principal component analysis (PCA). To prevent problems with finances and health, water supply networks should take corrective action to remove corrosion and its by-products.

Introduction

The most significant factor that can affect the general public's health, the acceptability of the water source, and the price of supplying clean water is corrosion. The kind and extent of scaling and corrosive compounds, the location of the water source about the surface or ground, and the physico-chemical and biological quality of the water are all significant factors in determining the stability of water for general and industrial uses. Corrosion-induced material degradation can result in substantial annual resource expenditures for replacement, repairs, and system upkeep. Many metals are more concentrated in tap water due to corrosion. Pipes in the water distribution lines are constructed of a variety of materials, and corrosion allows different substances to enter the water body (Asghari et al., 2018). Corrosion characteristics of water can lead to pitting in pipes, shortened facility life spans, and water loss. Furthermore, the most significant health issues associated with corrosion are caused by heavy metals found in drinking water, such as lead, copper, zinc, and arsenic (Mirzabeygi et al., 2017).

Dissolution and carbonate reactions often raise pH levels, harming disinfectants, water aesthetics, and asbestos fiber release. This raises regulatory concerns. Although plastic plumbing materials have higher corrosion resistance, they can also deteriorate due to their particular appliances and cause other obstacles such as odor, taste, brittleness, support for biofilms, and both organic and inorganic leachates.

*Corresponding author:<sumonganguli@cu.ac.bd, amitava.bandy1@gmail.com>
[1]*Biomaterials Research Laboratory, Dept. of Applied Chemistry and Chemical Engineering, University of Chittagong, Chattogram, Bangladesh.*
[2]*Department of Geography and Environmental Studies, University of Chittagong, Chattogram, Bangladesh.*
[3]*Department of Chemistry, Jahangirnagar University, Savar, Dhaka, Bangladesh.*
[4]*Department of Chemical Engineering, University of Calcutta, 92, APC Road, Kolkata, India.*

The other issue is the scaling of $CaCO_3$ caused by the deposition of excess carbonates in the pipe network and other machine parts (Asghari et al., 2018). Divalent cations (Ca^{2+}, Mg^{2+}) react with other substances soluble in water to form a tinny layer that builds up inside the walls of water pipelines. This process is known as scaling. Generally, the scaling layers are made of $CaCO_3$. In addition to raising operating and maintenance expenses, the scaling process can result in issues like clogged tubes, decreased water pressure and discharge, and decreased water discharge in the distribution network (Mirzabeygi et al., 2017).

The two most common problems with water quality are corrosion and scaling. There are various causes for both of these processes, and the literature offers a variety of assessment techniques. The most popular methods for assessing the degree of these two processes are the Aggressive index (AI), Pukorious index (PI), Larson-Skold index (LS), Langelier saturation index (LI), and Ryznar index (RI). Numerous researchers worldwide employ these techniques (Kalyani et al., 2017; Alipour et al., 2015; Shams et al., 2012; Alsaqqar et al., 2014). As an illustration, Kumar (2019) claimed that the purpose of the Ryznar and Langelier indices was to show significant harm to the industries' machinery. Rabbani et al. (2012) looked into the agrarian water assets. They reported that almost all samples were extremely corrosive, increasing the risk of framing scales for the Ryznar, Langelier, and Puckorius indices. Kurdi et al. (2015) looked into the erosion and revealed particle-dependent scaling accounts. Additionally, corrosion and scaling records can be used to evaluate the corrosive activity of groundwater (Kurdi et al., 2015). Further research on water quality using the aforementioned stability indices was conducted in several countries, including Makou (Asghari et al., 2018), China (Zhang et al., 2018), India (Ahmed et al., 2021), Ecuador (Maroneze et al., 2014), Ethiopia (Gebremikael and Dawod, 2021), Iran (Gholizadeh et al., 2017), Jordan (Al-Rawajfeh and Al-Shamaileh, 2007), Iraq (Al-Qurnawi et al., 2022), Kenya (Baloïtcha et al., 2022), Niger (Weissbrodt et al., 2020), Nigeria (Egbueri, 2021), Romania (Gavriloaiei, 2016), Taiwan (Chien et al., 2009) and USA (Zhang et al., 2014). These studies show how important the topic is.

An investigation on the water supply lines in the Bangladeshi city of Sylhet was reported. In addition to the Surma River's BOD and COD, the study focused on four water quality indices such as the Aggressive Index (AI), the Pukorious Scaling Index (PSI), the Langelier Saturation Index (LSI), and the Ryznar Stability Index (RSI). Based on the stability indices, the findings suggested that the river water had a slightly corrosive effect (Uddin et al., 2020 a). A thorough investigation assessed the Karnaphuli River, Chattogram, for various water quality parameters. For continuous monitoring, water samples were specifically taken from ten locations during the hydrological year 2014–2015 at three distinct times of the year (winter, rainy, and spring). The reported values for the Water Quality Index (WQI), LSI, and RSI were 99.92, −3.06, and 12.36, respectively, indicating subpar water quality (Uddin et al., 2020 b).

The background research studies also showed no published literature on the valuation of the corrosion and scaling potential of Chattogram City, Bangladesh's supply water. The current study targets to address the knowledge gap in the literature by examining the corrosion and scaling potential of Chattogram city's (Bangladesh) supply water. This study aims to evaluate water quality parameters and associations within the indices using correlation analysis, assess the water supply according to physicochemical parameters, and estimate water's corrosion-scaling characteristics using the water stability indices. This study aims to ensure a safe domestic and industrial water supply in Chattogram, Bangladesh, by assessing its corrosive and scaling integrity for the first time. The study's rationale goes beyond simply checking the quality of water. The present findings of this study may be applied to more research to improve the regulatory decision support system.

Materials and methods

Study area

Bangladesh's second-biggest city is Chattogram (Mia et al., 2015). The 157 square kilometer Chattogram City Corporation (CCC) is situated between latitudes 22°13' and 22°27' north and longitudes 91°40' and 91°53' east. This metropolis is home to about 4 million people, according to the national census 2011 and Bangladesh Statistics from 2019. The city's uncontrollable population growth has raised sewage, water supply, and stormwater drainage demand. The Chattogram Water Supply and Sewerage Authority (CWASA) of Bangladesh uses its distribution network to supply water to Chattogram City's residents after treating water from the Karnafuli and Halda rivers, as well as a groundwater source (Debnath et al., 2022). According to CWASA, the maximum of 220 million liters of water per day is insufficient to meet the daily demand of 550 million liters for commercial, industrial, and residential users (Mia et al., 2015). Conversely, the annual average temperature in the Chattogram district varies from 13.5 °C to 32.5 °C (Ahmed et al., 2018). CWASA owns a 570 km water supply pipeline. The proportion of groundwater to surface water used is 52:48 (Amin, 2006).

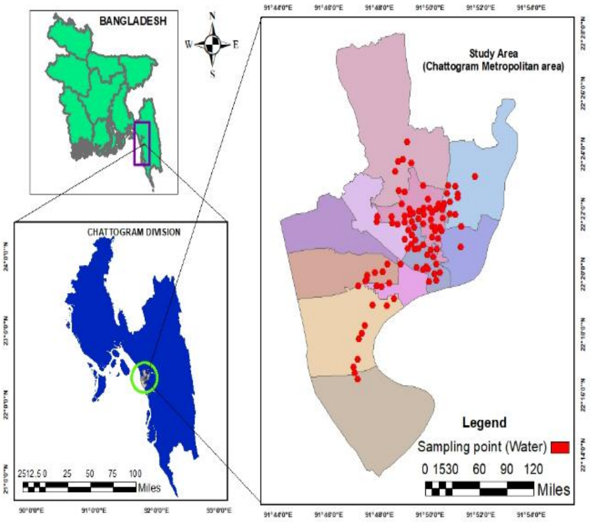

Fig. 1. Map of Chattogram and sampling sites.

Sampling and analysis

Laboratory-grade sampling bottles were used to collect one hundred (100) samples, which were then moved to the Biomaterials Research Laboratory and kept fresh in a refrigerator. The samples were gathered in 2022 between August and September. With the sampling locations included, Fig. 1 depicts the study area. A variety of parameters, including temperature, electrical conductivity (EC), total dissolved solids (TDS), pH, bicarbonate (HCO_3^-), carbonate (CO_3^{2-}), total hardness (TH), calcium hardness (Ca-H), total alkalinity (Alk.), chloride (Cl^-), and sulfate (SO_4^{2-}) were measured to judge corrosion and scaling potential of the supply water. A portable combometer was employed at the sampling locations to monitor the pH, TDS, EC, and temperature. Furthermore, according to the American Public Health Association's (APHA) recommendation, Ca-H, HCO_3^-, CO_3^{2-}, and Cl^- were measured using a straightforward titration method (APHA, 2017). Alk. was also measured using titrimetric method (APHA, 2002). A UV-visible spectrophotometer (Shimadzu, UV1800ENG240V, SOFT, Japan) was used to analyze the SO_4^{2-} content (APHA, 2017). Every measurement was carried out in triplicate, and the average results were considered for further analysis.

Water stability indices

The LSI, RSI, PSI, LS, and AI are among the corrosion indices that have been calculated to measure water's corrosion and scaling potential. Table 1 displays the equations that were utilized to assess these indices.

Statistical analysis

SPSS software (version 29.0) computed descriptive statistical analysis parameters like mean, minimum, maximum, and standard deviation. The SPSS-29.0 program was also used to carry out correlation analysis. The OriginPro software (version 2021) was used to create the box plot. Additionally, the same program, Origin, was used for PCA analysis.

Table 1. Water stability indices for corrosion and scaling potential and water condition based on the index value.

Index	Index Formula	Index value	Water condition based on the index value	Reference
Langelier Saturation Index (LSI)	LSI=pH-pHs. Here, pHs=(9.3+A+B) -(C+D) A = (log [TDS] − 1)/10, B = −13.12 × log [˚C + 273] + 34.55, C = log [Ca^{2+} as $CaCO_3$] − 0.4, and D = log [alk. as $CaCO_3$].	LSI>0 LSI=0 LSI<0	Under saturated; Corrosion potential. Equilibrium: No Scaling potential. Supersaturated water; Scaling potential.	
Ryznar Stability Index (RSI)	RSI=2pHs-pH	RSI<6 6<RSI<7 RSI>7	Supersaturated Scaling potential. Saturated Equilibrium; No Scaling Potential. Under saturated; Corrosion potential.	
Puckorius Scaling Index (PSI)	PSI=2(pH_{eq})-pHs. pHs=1.465+log (Alk.) +4.54 pH_{eq}=1.465×log (Alk.) +4.54	PSI<6 6≤PSI≤7 PSI>7	Scaling potential. Equilibrium. Significant corrosion potential	(Tyagi and Sarma, 2020)
Larson-Skold Index (LS)	LS= (Cl^- +SO_4^{2-})/ (HCO_3^- +CO_3^{2-})	LS<0.8 0.8<LS<1.2 LS>1.2	Scaling potential. Corrosion potential. High corrosion rates.	
Aggressive Index (AI)	AI=pH+ log[(Alk.) (Ca-H)]	AI<10 10≤AI≤12 AI>12	Corrosion potential. Moderately corrosive. Scaling potential and non-aggressive.	

Note: pH: actual pH of water, **pHs:** pH at saturation state of $CaCO_3$, **TDS:** (mg/L), **°C:** Temperature, **Ca^{2+}:** (mg/L as $CaCO_3$), **Alk.: (**mg/L as $CaCO_3$), **pHeq:** pH at equilibrium, **Cl^-:** (mg/L), **SO_4^{2-}:** (mg/L), **HCO_3^-: (**mg/L as $CaCO_3$).

Results and discussion

The various physicochemical characteristics of the supplied water are statistically analyzed and are shown in Table 2. Every parameter was analyzed, and the results were compared to the standards stipulated by the World Health Organization (WHO, 2004), the United States Environmental Protection Agency (USEPA, 1994), and the Bureau of Indian Standards (IS, 10500: 2012).

Table 2. Physico-chemical properties of water analyses.

Parameters	Unit	Mean ± SD value	Min	Max	WHO standard	USEPA standard	IS standard	% of samples exceeded the limits
pH	-	6.70 ± 0.25	6.1	7.4	6.5-8.5	6.5-8.5	6.5-8.5	-
Temperature	°C	25.70 ± 0.83	24.1	27.2	20-30	-	-	-
TDS	mg/L	122.61 ± 136.93	32	736	500	500	500–2000	5 (WHO, USEPA)
EC	mS/cm	0.17 ± 0.27	0.06	1.57	0.5	-	1.5	5 (WHO, IS)
Turbidity	NTU	0.87 ± 1.07	0.05	5.13	5	-	10	1 (WHO)
Salinity	ppt	1.06 ± 1.43	0	5	-	-	-	-
Cl^-	mg/L	33.95 ± 77.06	2.61	438.51	250	-	250-1000	4 (WHO, IS)
TH	mg/L	65.97 ± 53.93	36	490	300	-	200-600	1 (IS)
CO_3^{2-}	mg/L	0±0	0	0	-	-	-	-
HCO_3^-	mg/L	71.52 ± 17.30	61	167.75	200	-	200-600	-
SO_4^{2-}	mg/L	12.70 ± 13.12	0.072	69.43	250	-	200-400	-
Ca-H	mg/L	56.60 ± 46.75	24.19	418.93	-	-	75-200	1 (IS)
Alk.	mg/L	36.53 ± 10.20	22	76	-	-	-	-

pH, TDS, EC, Salinity, and Turbidity

The pH in this investigation was 6.10 to 7.40, with an average value of 6.70 ± 0.25. The water in this area had a mean pH value almost precisely at the lowest value of 6.5 of the allowable range, according to WHO (2004) and IS (10500: 2012) standards. Free CO2 and HCO_3^- concentrations may mainly cause acidic pH (Isa et al., 2012; Zhuo et al., 2015; Mirzabeygi et al., 2017; Kalyani et al., 2017). For the supply water of Chittagong City, similar results of nearly neutral water were previously reported (Molla et al., 2014). The water may have become weakly acidic or indirectly acidic due to minuscule amounts of inorganic sediments or agricultural and household wastes (Sarker et al., 2019). Remarkably, the measured pH does not directly affect public health (Shabbir and Ahmad, 2015). Nevertheless, acidic water corrodes metals and lessens the efficacy of disinfection, which has unintended health effects on humans (Popoola et al., 2019). The average temperature was measured as 25.70 ± 0.83°C, with variations between 24.10 and 27.20 ºC (Table 2). This indicates that every sample stayed within the 20–30 ºC recommended range of the WHO (2004). TDS suggests the presence of both organic and inorganic materials (Rifat et al., 2021). The TDS varied from 32.00 to 736.00 mg/L, with a mean value of 122.61 ± 136.95 mg/L (Table 2). The observed values of TDS at five distinct locations (SS-13, SS-85, SS-90, SS-97, and SS-98) were higher than 500 mg/L as stipulated by the WHO (2004), while the observed values of TDS for all other samples were within 500 to 2000 mg/L as stipulated by the IS (10500: 2012) (Table 2). Thus, the water samples from each sampling station resembled freshwater, with a mean TDS concentration of less than 1000 mg/L (USEPA Region and Foia, 2008).

The water samples' observed EC varied from 0 to 157 mS/cm, with a mean value of 0.17 ± 0.27 mS/cm. Merely five samples (SS-13, SS-85, SS-90, SS-97, and SS-98) surpassed the WHO's permissible standards of 0.5 mS/cm and the IS's permissible standards of 1.5 mS/cm, while the remaining samples were significantly below these standards. The current investigation's observed EC values for 95% of the samples were less than 1000 μS/cm, indicating that the water samples had very little mineralization. However, the WHO defines "low salinity water" as having an EC of between 0 and 250 μS/cm; by this specification, the samples under study showed low salinity (USEPA, 1994). A lower EC indicated less nutrient content, salinity intrusion, and aquifer mineral dissolution (Rifat et al., 2021). The observed values of EC of less than 1000 μS/cm for 95% of the water samples taken for this study fit the Detay et al. (1997) definition of very weakly mineralized (Rifat et al., 2021).

The salinity of drinking water may be a factor in hypertension (Rifat et al., 2021). Few samples had salinities higher than 5 ppt. The current study's salinity ranged from 0.00 to 5.0 ppt, with an average value of 1.06 ± 1.43 ppt. Turbidity is a crucial criterion for drinking water quality because it can harm one's health if consumed (Rifat et al., 2021). The turbidity value went from 0.05 to 5.13 NTU, and the average value was 0.87 ± 1.07 NTU. Except for one sample (SS-13), all of the observed turbidity values fell between the WHO and IS's allowable limits (5.0 and 10.0 NTU). Turbidity may be caused by dissolved material accumulating in supply lines and water storage tanks.

TH, Ca-H, Cl^-, CO_3^{2}, HCO_3^-, SO_4^{2-}, Alk.

The total dissolved ion in the water is represented by its total hardness (TH). Carbonated or transitory ($CaCO_3$, $MgCO_3$, Ca $(HCO_3)_2$, Mg $(HCO_3)_2$) and non-carbonated or permanent ($CaCl_2$, $MgCl_2$, $CaSO_4$, $MgSO_4$) are the common two forms of hardness. Hard water use is indicated by the speed at which scaling develops. Scaling buildup in excess drinking water causes kidney illnesses and can frequently clog drip irrigation sprinklers, low-pressure boilers, and water heaters (Vasanthavigar et al., 2010). With a mean value of 65.97 ± 53.93 mg/L, the observed range of TH was 36.0 to 490.0 mg/L. The TH values of the

CWASA water samples range from 200 to 600 mg/L, which is within the IS standards; only the sample (SS-97) had a TH value that exceeded the WHO standards. It should be noted that the $CaCO_3$ concentration in soft water is less than 75 mg/L, while it varies from 75 to 150 mg/L in slightly hard water, from 150 to 300 mg/L in moderately hard water, and above 300 mg/L in very hard water (Tyagi and Sarma, 2020).

A little over 86% of samples fall into the soft category, 9% into the slightly hard, 4% into the moderately hard, and 1% into the very hard water category. The Ca-H values ranged from 24.19 to 418.93 mg/L, whereas the mean value of 56.60 ± 46.75 mg/L. It was observed that just one sample (SS-97) exceeded the IS requirement. The alk. acid-neutralizing ability of [HCO_3^-], [CO_3^{2-}], and [OH^-] ions, which are abundant in groundwater aquifer systems, determines the pH of water. The effects of CO_3^{2-} equilibrium characterize the presence of [HCO_3^-], whereas the temperature, pH, cations, dissolved CO_2, and other dissolved solids are the main factors that control the proportion of [HCO_3^- - CO_3^{2-}] in freshwaters (Krishna et al., 2015). All the examined water samples had CO_3^{2-} values of zero. The HCO_3^- ranged from 61.00 to 167.75 mg/L, with a mean value of 71.52 ± 17.30 ppm. Every sample in this investigation was recorded within the WHO, and IS recommended ranges. Table 2 shows that the average value of Cl^- was 33.95 ± 77.06 mg/L, with a range of values from 2.61 to 438.51 mg/L. It was found that four samples (SS-85, SS-90, SS-97, and SS-98) exceeded the all-out allowable level (250 mg/L) that the WHO and IS had recommended. Typically, soluble Ca, Mg, and Na complexes with SO_4^2 are found in groundwater. Within the present investigation, the average SO_4^{2-} concentration ranged between 0.07 and 69.43 mg/L with a variation of 12.69 ± 13.12 mg/L.

WHO and IS stipulated the highest allowable levels of SO_4^{2-} are 250 mg/L and 400 mg/L, respectively. SO_4^{2-} concentrations ranged from 0.07 to 69.43 mg/L, and the mean SO_4^{2-} value was 12.70 mg/L. The findings show that the sulfate concentration was below the acceptable levels. Alkalinity (Alk.) adversely affects the corrosion rate and causes it to decrease at alkalinity levels higher than 60 mg/L (Asghari et al., 2018). Water frequently contains hydroxides, phosphates, and carbonate, which increase its alkalinity (Gorde and Jadhav, 2013; Islam et al., 2017). The measured quantities of "Alk." were between 22 and 76 mg/L, with an average value of 36.53 ± 10.20 mg/L.

In the CWASA supply water, the average range of the indices for every sampling site is shown in Fig. 2 and Table 3. The box plot is a tool for showing the shape, median, and range of data distribution. For each supply water sample, the spatial variation in indices was independently analyzed using box plots, based on the physicochemical contents (Fig. 2). Box plots are utilized due to their visual attributes (outlier presence or absence, mean, median, and interquartile range, among others) when representing an entire dataset (Shil et al., 2019). As box plots show, the LSI values were all less than zero, suggesting that the water is corrosively susceptible. In contrast, there was a scale-forming tendency with the LS values. Indicators of the samples' corrosive tendencies included RSI, PSI, and AI, all of which fell within the same range.

LSI, RSI, PSI, LS and AI:

The values of LSI, RSI, PSI, LS, and AI for the CWASA water samples were calculated based on the values of physic-chemical parameters. The values associated with these indices are shown in Table 3. Based on the observed results, the LSI, RSI, PSI, and AI indices showed that every water resource was corrosive. The values calculated were -1.93 ± 0.36 for LSI, 10.56 ± 0.56 for RSI, 10.45 ± 0.64 for PSI, 0.58 ± 0.86 for LS, and 10.01 ± 0.36 for AI.

With a standard deviation of 0.36 and a mean LSI of -1.93, it was predicted that the water samples were under-saturated with $CaCO_3$. The corrosion affinity was supported by the water samples' slightly acidic pH (Table 3). The maximum measured value of the LSI

Table 3. Water quality characteristics, associated with corrosion and scaling tendency.

Indices	Mean±SD	Maximum	Minimum	Status
LSI	-1.93±0.36	-0.83	-2.49	Corrosive
RSI	10.56±0.56	11.43	8.87	Corrosive
PSI	10.45±0.64	11.52	8.38	Corrosive
LS	0.58±0.86	4.76	0.05	Scaling
AI	10.01±0.36	11.19	9.4	Moderately aggressive

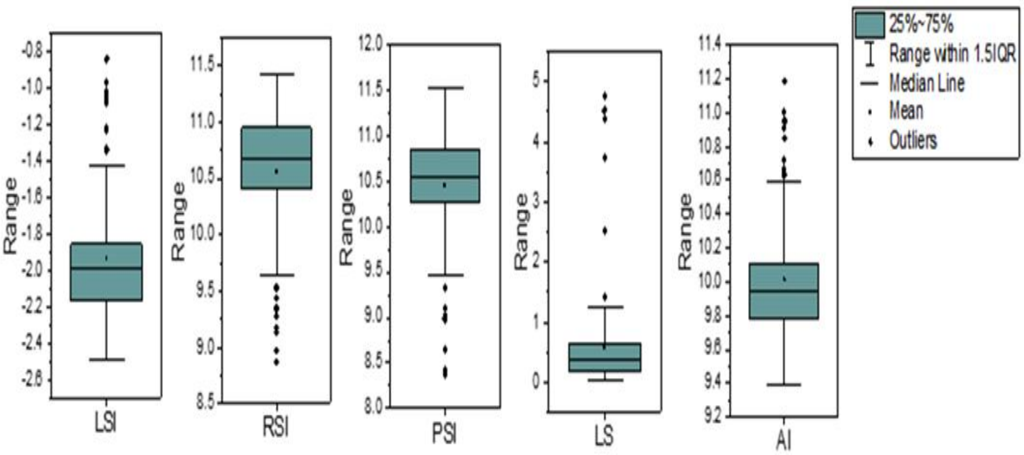

Fig. 2. Box plots show the range of five indices (LSI, RSI, PSI, LS, and AI).

was less than zero, or -0.83. Each sample exhibited corrosive tendencies based on the data in Table 4. There was a balance regarding the corrosive nature, as indicated by a mean RSI of 10.56 in Table 3. According to Table 4, every water sample tends toward corrosion with an RSI > 7. The corrosion nature indicated by the LSI index was also found to be the source of the corrosive tendency. The alkalinity and pH of the water are most likely determining factors. As per Table 4, the PSI mean values for all the water samples were 10.45 in the current investigation, suggesting a corrosive tendency (>7). The LS index comprises Cl^-, HCO_3^-, CO_3^{2-}, SO_4^{2-}, and "alk.". Higher Cl^- or ions with chlorine concentrations will likely promote pitting corrosion of stainless steels in neutral to acidic solutions (Tyagi and Sarma, 2020). Water is predicted to form a scale (LS< 0.8) based on the observed LS mean value of 0.58, as illustrated in Table 4. Eighty-three percent (83%) of the samples support the scaling tendency (Table 4). A high corrosion rate was present in 7 percent of the samples (LS> 1.2). The AI uses Ca-H, alk., and pH to assess water's level of aggressive condition. The LSI, RSI, and PSI results are consistent with the reported mean value of AI of 10.01 (Table 4). All the samples within the study area were aggressive or moderately aggressive, with an AI of less than 12.

The supply of water for drinking purposes should contain essential minerals. However, it is noteworthy that de-mineralized water has a high corrosive tendency, though it does not contribute to scale formation in water supply networks (WSN). It is reasonable to expect drinking water to contain dissolved minerals while minimizing the risk of corrosion and scale formation. Studies have shown that when dissolved oxygen is present and the pH of water is close to 7, pipeline corrosion increases, requiring extra precaution (Larson, 1963; McFarland et al., 2024). Additionally, a higher concentration of dissolved salts in water enhances the likelihood of scale buildup in WSN (Hoang, 2022). Experiments conducted on drinking water samples from the Chittagong region indicate that the supply water's corrosive nature and scale-forming tendency are significantly high. It is worth mentioning that CaH and Alk are the determining factors for LSI, RSI, and PSI

Table 4. Percentage of water samples showing corrosion and scaling potential in CWASA.

Index	Water condition		% of samples
LSI	LSI<0	Under saturated; Corrosion potential.	100
	LSI=0	Equilibrium: No Scaling potential.	0
	LSI>0	Supersaturated water; Scaling potential.	0
RSI	RSI<6	Supersaturated Scaling potential.	0
	6<RSI<7	Saturated Equilibrium; No Scaling Potential.	0
	RSI>7	Under saturated; Corrosion potential.	100
			0
PSI	PSI<6	Scaling potential.	0
	6≤PSI≤7	Equilibrium.	100
	PSI>7	Significant corrosion potential	
LS	LS<0.8	Scaling potential.	83
	0.8<LS<1.2	Corrosion potential.	10
	LS>1.2	High corrosion rates.	7
AI	AI<10	Corrosion potential.	66
	10<AI<12	Moderately corrosive.	44
	AI>12	Scaling potential and non-aggressive.	0

values, whereas Cl^- and SO_4^{2-} are the determining factors for LS value. Thus, the dissolved oxygen and minerals levels in drinking water must be controlled according to standard guidelines to prevent pipeline corrosion while minimizing scale formation (Table 4).

Statistical analyses

A Pearson correlation matrix was generated by combining and analyzing corrosion indices and physicochemical parameters to appraise the interconnection among the variables (Table 5). It is essential to point out that the degree of relationship among the variables is, in general, clarified by the weak (r<0.500) and the strong (r>0.500) correlations. The strong and positive correlations between EC and TH (r = 0.873), Ca-H (r = 0.879), HCO_3^- (r = 0.506), Cl^- (r = 0.979), and SO_4^{2-} (r = 0.765) show that there are dissolved ionic species in the supply water, according to the results. These correlations, which show weak correlations with temperature, turbidity, salinity, and alkalinity, are significant at p<0.01. Additionally, the TDS showed a highly positive link with EC, TH, Ca-H, Cl^-, and SO_4^{2-} and a weak correlation with temperature, turbidity, salinity, alk., and HCO_3^-, indicating that each variable contributes to dissolved forms. Significantly, it was observed that TH and Ca-H had a robust positive relationship (r = 0.989). A strong positive relationship (p < 0.01) was also observed with Cl^- and SO_4^{2-}. These results support the hypothesis that Ca $(HCO_3)_2$ and Mg $(HCO_3)_2$ cause the supply water to become temporarily hard rather than permanently hard due to Cl^- and SO_4^{2-}. Furthermore, alk. and HCO_3^- had a significant positive correlation (r = 0.597).

The water stability indices were connected with the parameters and each other to measure their utility for corrosion and scaling potential. Due to its pH dependence, LSI displayed a significant positive correlation with alk. (r = 0.680), HCO_3^- (r = 0.651), and pH (r = 0.724). Additionally, AI and LSI had a strong correlation (0.984, p < 0.01). For corrosive indications of waterways, AI is generally used occasionally in place of LSI (Kalyani et al., 2017). Conversely, LSI demonstrated a negative correlation with PSI (r = -0.733) and RSI (r = -0.952), both of which were statistically significant (p<0.01). These differences in the underlying factors that each index considers may cause a negative correlation between LSI and PSI. In the end, the selection of an index is contingent upon the particular system in question and the intended emphasis on scaling tendency and corrosion when evaluating water quality (Hernández-Suárez and León, 2021). As opposed to this, RSI displayed a powerful positive correlation with PSI (r = 0.901, p < 0.01) and a negative correlation with strong LS magnitude (r = -0.516, p < 0.01). A negative correlation (r = -0.07) was found between pH and PSI.

A strong negative correlation between EC and the two indices, which measure the alk. of the water and pH, because EC is a constant for both RSI and PSI. The LS index sets off the supply water's aggressive potential. It had a very positive correlation at p < 0.01 with TH (r = 0.813), TDS (r = 0.941), EC (r = 0.948), SO_4^{2-} (r = 0.747), Ca-H (r = 0.797), and Cl^- (r = 0.981). The Cl^- and SO_4^{2-} are the main constituents promoting the scaling behavior discernible from this index, which makes sense given LS's strong correlation with these dissolved constituents. Furthermore, the influence of Cl^- salts determines the salinity, a prerequisite for EC. Moreover, adding bleaching agents for disinfection or the presence of Cl^- salts in the water from subsurface sources affects EC, which is a function of salinity (Tyagi and Sarma, 2020).

A weak positive correlation (r = 0.459) between the LS and AI, but a negative but weak correlation with the RSI and PSI, was observed. Table 4 indicates that most parameters exhibited statistically significant differences and weak correlations with AI (such as pH, EC, TDS, TH, Cl^-, SO_4^{2-}, and Ca-H).

With minimal harm to the total dataset, principal component analysis (PCA) can extract information about a particular variable (Singh et al., 2020; Nayak et al., 2022). It typically reduced the dataset to extract highly influential components by eliminating unnecessary data (Rifat et al., 2021; Sharma et al., 2015). By generating scree plots (Fig. 3a) with eigenvalues greater than 1, which analyze the compositional pattern of the variables, PCs were found using the Kaiser normalization technique. Fig. 3b shows the loading plot of the parameters significantly involved in the PCA analysis.

Table 5. Correlation among the physicochemical parameters and stability indices.

Correlations																		
	Temp.	TDS	EC	Turbidity	pH	Salinity	TH	CaH	Alk.	CO_3^-	HCO_3^-	Cl^-	SO_4^{2-}	LSI	RSI	PSI	LS	AI
Temp.	1																	
TDS	-0.128	1																
EC	-0.118	.960**	1															
Turbidity	-0.191	.348**	.284**	1														
pH	-0.179	-0.069	-0.017	-0.08	1													
Salinity	-0.132	.264**	.279**	.363**	-0.118	1												
TH	-0.062	.848**	.873**	.273**	-0.178	.216*	1											
CaH	-0.093	.842**	.879**	.285**	-0.137	.264**	.989**	1										
Alk.	-0.184	.427**	.428**	0.178	0.135	0.111	.438**	.444**	1									
CO_3^-	-	-	-	-	-	-	-	-	-	-								
HCO_3^-	-0.144	.464**	.506**	0.075	.260**	0.018	.511**	.556**	.597**	-	1							
Cl^-	-0.035	.942**	.979**	.259**	-0.03	.229*	.839**	.836**	.339**	-	.403**	1						
SO_4^{2-}	-0.049	.728**	.765**	-0.013	-0.008	-0.124	.720**	.714**	.353**	-	.610**	.725**	1					
LSI	-.251*	.451**	.500**	0.146	.724**	0.076	.415**	.459**	.680**	-	.651**	.433**	.383**	1				
RSI	.241*	-.605**	-.643**	-.221*	-.479**	-0.149	-.607**	-.645**	-.806**	-	-.713**	-.564**	-.491**	-.952**	1			
PSI	0.187	-.659**	-.675**	-.267**	-0.07	-.205*	-.710**	-.729**	-.910**	-	-.667**	-.590**	-.507**	-.733**	.901**	1		
LS	-0.005	.941**	.948**	.266**	-0.038	0.144	.813**	.797**	.289**	-	.346**	.981**	.747**	.392**	-.516**	-.537**	1	
AI	-.253*	.515**	.544**	0.159	.685**	0.028	.469**	.491**	.700**	-	.644**	.486**	.433**	.984**	-.949**	-.750**	.459**	1

* Correlation is significant at the 0.05 level (2-tailed).

** Correlation is significant at the 0.01 level (2-tailed).

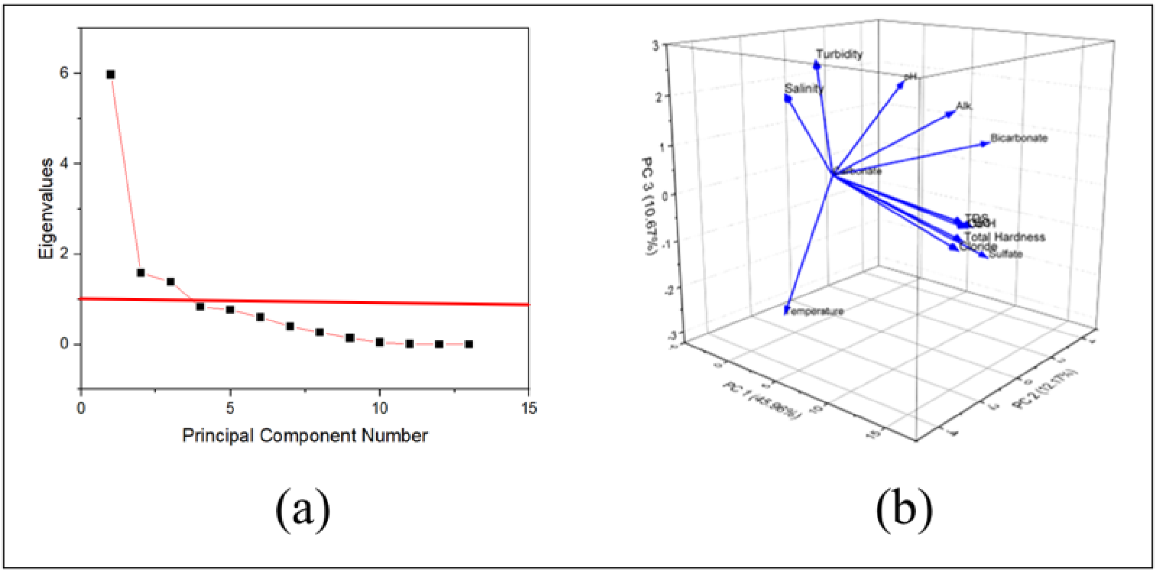

Fig. 3. (a) Scree plot of PCA analysis and (b) Loading plot of PCA analysis.

Table 6. Principal component analysis of CWASA supply water quality parameters.

Parameters	Coefficients of PC1	Coefficients of PC2	Coefficients of PC3
pH	-0.017	0.516	0.307
Temperature	-0.059	-0.194	-0.551
TDS	0.386	-0.095	-0.034
EC	0.395	-0.056	-0.053
Turbidity	0.134	-0.359	0.503
Salinity	0.106	-0.467	0.395
Chloride	0.376	-0.096	-0.135
Total Hardness	0.383	-0.086	-0.101
Carbonate	0	0	0
Bicarbonate	0.260	0.427	0.133
Sulphate	0.329	0.239	-0.261
Ca-H	0.386	-0.073	-0.056
Alk.	0.224	0.273	0.268
Eigenvalue	5.974	1.582	1.387
Percentage of Variance	45.96%	12.17%	10.67%
Cumulative	45.96%	58.13%	68.80%

The number of major components that need to be kept is ascertained by identifying the parameter structure with the scree plot. Table 6 displays the observed factor weight values associated with each PC. The top three components account for 68.80% of the total variation.

The principal components' weak, moderate, and strong classifications were built on their factor loading values of 0.30 to 0.50, 0.50 to 0.75, and >0.75, respectively (Nayak et al., 2022; Liu et al., 2003). The TDS (0.386), EC (0.395), TH (0.383), Ca-H (0.386), Cl^- (0.376), and SO_4^{2-} (0.329) were found to be correlated with a weak positive and weak negative loading of 45.96% variance, respectively, with the PC1. The temperature (-0.194), TDS (-0.095), turbidity (-0.359), salinity (-0.467), and Cl^- (-0.096), variables during PC2 synthesis are weakly loaded with negative weight, while pH (0.516), HCO_3^- (0.427), SO_4^{2-} (0.239) and alk. (0.273) indicated a positive factor weight with a variance of 12.17%. While pH (0.516) is moderately loaded, the following have weak loading: HCO_3^- (0.427), SO_4^{2-} (0.239) and alk. (0.273). In PC3, the variables displaying negative weight factors were temperature (-0.551), SO_4^{2-} (-0.261), TH (-0.101), and Cl^- (-0.135), while the variables showing positive weight factors were turbidity (0.503), salinity (0.395), alk. (0.268) and pH (0.307), with percentage variances of 10.67%. Remarkably, all variables are weakly loaded except temperature (-0.551) and turbidity (0.503). Exceptionally, no strong loading was observed for any variables. Together, these observations pointed to several artificial and natural sources that could contaminate the area, such as erosion or weathering of soil, bio-fertilizer runoff, deposition from the atmosphere, and agricultural runoff (Nayak et al., 2022). The higher ion loading may have been caused by ions being leached through weathering, dissolving, exchanging ions, and leaching as the pipeline's main mechanisms, in addition to human interaction as a secondary factor subsidizing variations in the supplied water quality. In addition, the PCA and correlation matrix support the findings of chemical features and physicochemical correlations, both impacting the quality of water provided.

Conclusions

Assessments of the water quality showed almost all of the samples satisfied the requirements for characteristics like EC, TDS, TH, Cl^-, HCO_3^-, and SO_4^{2-}. The supplied water inclinations were classified based on the qualitative factors in the water stability indices of scaling formation and corrosion. The high correlation of the LSI, RSI, and PSI indices with pH, EC, TDS, and alk. indicated that all of the samples exhibited corrosive properties. The AI index showed that the sample has moderately aggressive and corrosive properties at 44% and 66%, respectively. However, with 83% of all samples in the supplied water, LS showed a scaling trend that differed from the other indices. In terms of saturation, the samples lacked equilibrium. It was found that the corrosive estimations had a clear impact on the index, which included LSI, RSI, PSI, and AI. An alternative to another index is the LS, which shows a scaling tendency. The PCA indicated three main components representing 45.96%, 12.17%, and 10.67% of variation. Higher ion loadings indicated ion leaching from the parent material. Although sulfate and chloride ions can influence how corrosive or prone to scaling the water is, Ca and Mg ions are the primary determinants of hardness. To prevent significant contamination of the source water and the consequent aftereffects that would follow, regular checking and corrective actions are mandatory to protect the quality of the supplied water.

Acknowledgments

The authors gratefully acknowledge the support from the Research and Publication Cell (University of Chittagong), and Ministry of Education (Bangladesh).

Author Contributions

U. Sadia: Data curation, investigation, formal analysis, methodology, software, writing original draft; Md. A. H. Rifat: Investigation, resources, software, resources; A. Hasan: Data curation, formal analysis, validation; N. Sarker and S. Islam: Methodology, resources, software, visualization; M. F. Haque and M. A. Sabur: Methodology, resources, visualization; a. bandyopadhyay: methodology, resources, validation, writing–review and editing, supervision; S. Ganguli: Conceptualization, project administration, writing – review and editing, supervision.

Declaration of Conflict Interest

The authors declare that they have no conflict of interest.

References

Ahmed B, Rahman MS, Islam R, Sammonds P, Zhou C, Uddin K and Al-Hussaini TM. Developing a dynamic web-GIS based landslide early warning system for the Chittagong metropolitan area, Bangladesh. *ISPRS Int. J. Geo-Inf.* 2018; 7(12): 485.

Ahmed S, Sultan MW, Alam M, Hussain A, Qureshi F and Khurshid S. Evaluation of corrosive behaviour and scaling potential of shallow water aquifer using corrosion indices and geospatial approaches in regions of the Yamuna river basin. *J. King Saud Univ. Sci.* 2021; 33(1): 101237.

Alipour V, Dindarloo K, Mahvi AH and Rezaei L. Evaluation of corrosion and scaling tendency indices in a drinking water distribution system: a case study of Bandar Abbas city, Iran. *J. Water Health,* 2015; 13(1): 203-209.

Al-Qurnawi WS, Ghalib HB, Alabadi MA and Hawash AB. Corrosion-scaling potentially of domestic water pipelines and evaluate the applicability of raw water sources in Basrah, Iraq. *Iraqi J. Sci*. 2022; 63(5): 2089-2102.

Al-Rawajfeh AE and Al-Shamaileh EM. Assessment of tap water resources quality and its potential of scale formation and corrosivity in Tafila Province, South Jordan. *Desalination,* 2007; 206(1-3): 322-332.

Alsaqqar AS, Al-Rawajfeh AE, Al-Shamaileh EM, Khudair BH and Ali SK. Evaluating water stability indices from water treatment plants in Baghdad City. *J. Water Resour. Prot*. 2014; 6(14): 1344-1351.

Amin MO. Status of water and sanitation services in Chittagong Water Supply and Sewerage Authority, Bangladesh. In Capacity-building Workshop on Partnerships for Improving the Performance of Water Utilities in Asia and the Pacific Region, organized by UNDESA and UNESCAP 2006 Jul (pp. 25-27).

APHA, Standard Methods for the Examination of Water and Wastewater, 20th edn, American Public Health Association, Washington DC, 2002.

APHA, Standard Methods for the Examination of Water and Wastewater, 23rd edn, American Public Health Association, Washington DC, 2017.

Asghari FB, Jaafari J, Yousefi M, Mohammadi AA and Dehghanzadeh R. Evaluation of water corrosion, scaling extent and heterotrophic plate count bacteria in asbestos and polyethylene pipes in drinking water distribution system. *Hum. Ecol. Risk Assess. Int. J.* 2018; 24(4): 1138-1149.

Baloïtcha GM, Mayabi AO and Home PG. Evaluation of water quality and potential scaling of corrosion in the water supply using water quality and stability indices: A case study of Juja water distribution network, Kenya. *Heliyon*, 2022; 8(3): e09141.

Chien CC, Kao CM, Chen CW, Dong CD and Chien HY. Evaluation of biological stability and corrosion potential in drinking water distribution systems: a case study. *Environ. Monit. Assess.* 2009; 153: 127-138.

Debnath P, Al Mamun MA, Karmakar S, Uddin MS and Nath TK. Drinking water quality of Chattogram city in Bangladesh: An analytical and residents' perception study. *Heliyon,* 2022; 8(12): e12247.

Detay M and Carpenter M. Water wells: implementation, maintenance and restoration. John Wiley & Sons, Chichester, UK, 1997; 379.

Egbueri JC. Signatures of contamination, corrosivity and scaling in natural waters from a fast-developing suburb (Nigeria): insights into their suitability for industrial purposes. *Environ. Dev. Sustain*. 2021; 23(1): 591-609.

Gavriloaiei T. Study of corrosion tendency of drinking water in the distribution system of Lasi City, Romania. *Analele Stiintifice de Universitatii AI Cuza din Iasi. Sect. 2, Geologie.* 2016; 62(1/2): 19-27.

Gebremikael GH and Dawod AH. Assessment of corrosion and scale forming potential of groundwater resources: Case study of Dire Dawa City, Ethiopia. *Momona Ethiopian J. Sci*. 2021; 13(1): 110-133.

Gholizadeh A, Mokhtari M, Naimi N, Shiravand B, Ehrampoush MH, Miri M and Ebrahimi A. Assessment of corrosion and scaling potential in groundwater resources; a case study of Yazd-Ardakan Plain, Iran. *Groundw. Sustain. Dev*. 2017; 5: 59-65.

Gorde SP and Jadhav MV. Assessment of water quality parameters: a review. *J. Eng. Res. Appl*. 2013; 3(6): 2029-2035.

Hernández-Suárez M and León FA. Indirect calculation of Langelier saturation index and sodium adsorption ratio for remineralised waters from data on electrical conductivity and pH prior to and following remineralisation. *Desalin. Water Treat*. 2021; 230: 33-37.

Hoang TA. Mechanisms of scale formation and inhibition. In: *Water-formed deposits*. 2022. pp. 13-47.

IS 10500: 2012, Indian Standard Drinking Water-Specification (Second Revision), Standards for Drinking Water Specification. New Delhi: Bureau of Indian Standards; 2012.

Isa NM, Aris AZ and Sulaiman WN. Extent and severity of groundwater contamination based on hydrochemistry mechanism of sandy tropical coastal aquifer. *Sci. Total Environ.* 2012; 438: 414-425.

Islam M, Polash AG and Fahim SA. Analysis of groundwater quality in Sylhet district. *J. Sylhet Agril. Univ*. 2017; 4(2): 325-330.

Kalyani DS, Rajesh V, Reddi EU, Kumar KC and Rao SS. Correlation between corrosion indices and corrosiveness of groundwater: a study with reference to selected areas of Krishna District, Andhra Pradesh, India. *Environ. Earth Sci*. 2017; 76 (16): 568.

Krishna Kumar S, Logeshkumaran A, Magesh NS, Godson PS and Chandrasekar N. Hydro-geochemistry and application of water quality index (WQI) for groundwater quality assessment, Anna Nagar, part of Chennai City, Tamil Nadu, India. *Appl. Water Sci*. 2015; 5: 335-343.

Kumar PJS. Assessment of corrosion and scaling potential of the groundwater in the Thanjavur district using hydrogeochemical analysis and spatial modeling techniques. *SN Appli. Sci*. 2019; 1(5): 395.

Kurdi M, Ferdows MS and Maghsoudi A. Sensitivity of corrosion and scaling indices based on ions; case study Iran. *Water Qual. Expo. Health*. 2015; 7(3): 363-372.

Larson TE. Corrosion phenomena, causes and cures. Proceedings Fifth Sanitary Engineering Conference, Quality Aspects of Water Distribution Systems. University of Illinois Bulletin, 1963: 9-14.

Liu CW, Lin KH and Kuo YM. Application of factor analysis in the assessment of groundwater quality in a blackfoot disease area in Taiwan. *Sci. Total Environ.* 2003; 313(1-3): 77-89.

Maroneze MM, Zepka LQ, Vieira JG, Queiroz MI and Jacob-Lopes E. A tecnologia de remoção de fósforo: Gerenciamento do elemento em resíduos industriais. *Rev. Ambient. Água.* 2014; 9: 445-458.

McFarland ML, Provin TL and Boellstorff DE. Drinking water problems: Corrosion. Texas A & M AgriLife Extension Service Department, 2024; 1-5.

Mia MA, Nasrin S, Zhang M and Rasiah R. Chittagong, Bangladesh. *Cities*, 2015; 48(10): 31-41.

Mirzabeygi M, Yousefi N, Abbasnia A, Youzi H, Alikhani M and Mahvi AH. Evaluation of groundwater quality and assessment of scaling potential and corrosiveness of water supply networks, Iran. *J. Water Supply: Res. Technol. AQUA*, 2017; 66(6): 416-425.

Molla MH, Chowdhury MA, Ali KMB, Bhuiyan MH, Mazumdar RM and Das S. Supply water quality in urban Bangladesh: a case study of Chittagong metropolitan city. *Asian J. Water, Environ. Pollut.* 2014; 11(4): 27-38.

Nayak A, Matta G and Uniyal DP. Hydrochemical characterization of groundwater quality using chemometric analysis and water quality indices in the foothills of Himalayas. *Environ. Dev. Sustain*. 2022; 25(12): 14229-14260.

Popoola LT, Yusuff AS and Aderibigbe TA. Assessment of natural groundwater physico-chemical properties in major industrial and residential locations of Lagos metropolis. *Appl. Water Sci*. 2019; 9(8): 191.

Rabbani D, Miranzadeh MB and Paravar A. Evaluating the corrosive and scale-forming indices of water in the villages under the coverage of Kashan rural water and wastewater company during 2007-9. *Feyz*, 2012; 15(4): 382-388.

Rifat MA, Howlader S, Alam MA, Islam MN, Afrin A, Ali F, Islam S and Ganguli S. Hydrogeochemical characteristics, quality assessment and health impact analysis of groundwater for drinking in the university of Chittagong, Bangladesh. *Malaysian J. Chem*. 2021; 23(1): 74-102.

Sarker S, Mahmud S, Sultana R, Biswas R, Sarkar PP, Munayem MA, Ali MR, Wasim M, Ali MF, Faruque MO and Evamoni FZ. Quality assessment of surface and drinking water of Nakla paurosova, Sherpur, Bangladesh. *Adv. Microbiol.* 2019; 9(8): 703-727.

Shabbir R and Ahmad SS. Use of geographic information system and water quality index to assess groundwater quality in Rawalpindi and Islamabad. *Arabian J. Sci. Eng.* 2015; 40: 2033-2047.

Shams M, Mohamadi A and Sajadi SA. Evaluation of corrosion and scaling potential of water in rural water supply distribution networks of Tabas, Iran. *World Appl. Sci. J.* 2012; 17(11): 1484-1489.

Sharma M, Kansal A, Jain S and Sharma P. Application of multivariate statistical techniques in determining the spatial temporal water quality variation of Ganga and Yamuna rivers present in Uttarakhand State, India. *Water Qual. Expo. Health*. 2015; 7(4): 567-581.

Shil S, Singh UK and Mehta P. Water quality assessment of a tropical river using water quality index (WQI), multivariate statistical techniques and GIS. *Appl. Water Sci*. 2019; 9(7): 168.

Singh KK, Tewari G and Kumar S. Evaluation of groundwater quality for suitability of irrigation purposes: a case study in the Udham Singh Nagar, Uttarakhand. *J. Chem.* 2020; 2020(1): 6924026.

Tyagi S and Sarma K. Qualitative assessment, geochemical characterization and corrosion-scaling potential of groundwater resources in Ghaziabad district of Uttar Pradesh, India. *Groundw. Sustain. Dev*. 2020; 10: 100370.

Uddin M, Munna G, Uddin AS and Islam M. Assessment of water quality of Surma river in perspective of water distribution system in Sylhet City. *Int. J. Eng. Sci.* 2020a; 9: 8-13.

Uddin MR, Hossain MM, Akter S, Ali ME and Ahsan MA. Assessment of some physicochemical parameters and determining the corrosive characteristics of the Karnaphuli estuarine water, Chittagong, Bangladesh. *Water Sci.* 2020b; 34(1): 164-180.

USEPA, Method 200.8: *Determination of Trace Elements in Waters and Wastes by Inductively Coupled Plasma-Mass Spectrometry, Cincinnati, OH*, 1994.

USEPA Region and Foia. *Guidelines for drinking-water quality. Third, edition incorporating the first and second addenda Volume 1 Recommendations Geneva 2008 WHO Library Cataloguing-in-Publication Data*. 2008

Vasanthavigar M, Srinivasamoorthy K, Vijayaragavan K, Rajiv Ganthi R, Chidambaram S, Anandhan P, Manivannan R and Vasudevan S. Application of water quality index for groundwater quality assessment: Thirumanimuttar sub-basin, Tamilnadu, India. *Environ. Monit. Assess.* 2010; 171: 595-609.

Weissbrodt DG, Winkler MK and Wells GF. Responsible science, engineering and education for water resource recovery and circularity. *Environ. Sci. Water Res. Technol*. 2020; 6(8): 1952-1966.

WHO, Guidelines of drinking water quality, Geneva, Switzerland, 2004.

Zhang H, Wang K, Zhou X, Zhu W and Wang W. Water quality characteristics and corrosion potential in blending zones in X city drinking water distribution system. *Environ. Monit. Assess*. 2018; 190(9): 524.

Zhang L, Theregowda RB and Small MJ. Statistical model for scaling and corrosion potentials of cooling-system source waters. *Environ. Eng. Sci*. 2014; 31(10): 570-581.

Zhou X, Shen Y, Zhang H, Song C, Li J and Liu Y. Hydrochemistry of the natural low pH groundwater in the coastal aquifers near Beihai, China. *J. Ocean Univ. China*, 2015; 14: 475-483.