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Drinking Water Insecurity in the Coastal Parts of Mirsharai, Sonagazi and Companiganj Areas of Bangladesh: Water Quality Analysis

Md. Bazlar Rashid[1*], Md. Rubel Sheik[1], A.J.M. Emdadul Haque[1],
Md. Ahosan Habib[1], Kamrul Ahsan[2]

[1]Geological Survey of Bangladesh, Segunbagicha, Dhaka, Bangladesh.
[2]Formerly Geological Survey of Bangladesh, Segunbagicha, Dhaka, Bangladesh.

[*]Corresponding author E-mail: bazlarrashid@ymail.com

Abstract: The people of the coastal parts of Bangladesh are insecure for safe drinking water. Present study is an attempt to delineate the water quality in the coastal parts of Mirsharai, Sonagazi and Companiganj areas. Various parameters of water quality such as free hydrogen (p^H), electrical conductivity (EC), total dissolved solids (TDS), oxidation reduction potential (ORP), salinity, turbidity, dissolved oxygen (DO), biological oxygen demand (BOD), chemical oxygen demand (COD), acidity, alkalinity, total hardness and nitrate, phosphate, sulphate, chloride, iron, manganese, cobalt, nickel, arsenic and chromium were determined through field work, available data and laboratory analysis. The results indicate that the arsenic concentration and electrical conductivity in shallow aquifers exceed WHO and Bangladesh standards limit. Additionally, chloride, total hardness, alkalinity, and lead exceed the WHO and Bangladesh standards in both shallow and deep aquifers. In many cases, the turbidity of surface water both inside and outside the coastal embankments also exceeds these limits. The lead, chloride and manganese contents, DO and BOD in the Feni River also exceed the BSTI limits. The analysis reveals that the deep aquifers are free from arsenic, while the shallow aquifers are significantly contaminated. Although, the deep aquifers need precaution for salinity, alkalinity, total hardness and lead contents. Correlation matrix analysis confirms that EC and TDS serve as reliable indicators of salinity levels in both shallow and deep aquifers. Principal Component Analysis (PCA) further supports this, showing that EC, TDS, and salinity are influenced by the saline water intrusion in these aquifers. Additionally, pollutants in both shallow and deep aquifers are positively associated with EC, TDS and salinity.

Keywords: Drinking water insecurity, water quality analysis, coastal areas, Bangladesh.

Introduction

The Bengal Delta in Bangladesh is one of the largest and most densely populated river deltas in the world, supporting approximately 180 million people. The coastal part of Bangladesh is highly vulnerable due to its geographic position, low elevation and different anthropogenic activities like non-scientific embankments and upstream barrages (Rashid et al., 2022b; Rashid, 2023; Rashid et al., 2024). This coast is frequently affected by tropical cyclones leading to significant loss of lives and properties (World Health Organization, 2011; Rashid et al., 2023c; Rashid et al., 2022a). In recent years the area is also threatened by the forthcoming effect of sea level rise due to global warming (Clarke et al., 2015; Ayers et al., 2016; Rashid et al., 2022a). Beyond these environmental challenges, the people of this coast are now insecure for safe drinking water (EPA, 2003; Ali, 2006; Hopenhayn, 2006; Williams et al., 2006; Khan et al., 2011; Mitchell, 2014; Benneyworth et al., 2016; Siddique et al., 2021; Rashid et al., 2023b). Despite the severity of this issue, limited research has been conducted to address water quality issues in this area, particularly the study area where the Government of Bangladesh started to build a sea connected first multi-sector economic zone of the country. Therefore, it is important to pay closer attention to studying water quality to develop effective solution measures. Hence, this study aims to delineate the water quality in the coastal areas of Mirsharai, Companiganj and Sonagazi to support future water resource management and protection efforts (Fig. 1).

Study Area and Regional Geologic Setting

Bangladesh constitutes the major portion of the Bengal Basin (BB) which is bounded by the Indian Shield to the west, the Arakan-Yoma-Chin geanticline in the east, the Shillong Massif to the north and the Bay of Bengal (BoB) in the south. The study area falls within the Folded Flank Tectonic Element of BB (Khan, 2002). A large number of sub-meridional trending structures in Chittagong, Chittagong Hill tracts, Comilla, Tripura and southeastern Sylhet occupy the folded flank. Neogene sediments are compressed into long, linear folds parallel to the Arakan-Yoma Mega-anticlinorium. These folds are characterized by an *en-echelon* position, box-like and ridge forms, high amplitude, and variable width of anticlines which are common features of folding of an intermediate type between platform and geosyncline regions. In terms of relief, these are represented by elongated hill ranges.

Gradual complications of structural features of these folds have been observed eastward. Neogene sedimentary sequences developed here are largely unfossiliferous and consist mainly of alternating shale, sandstone, siltstone, and occasional conglomerate beds. Bedrock sediments were deposited during the major development of the BoB and the present land configuration was the result of eastward plate convergence, during which the main uplift of the Himalayan and Indo-Burman Ranges occurred leading to overthrusting and wrench faulting.

The study area lies between the western limit of the Tertiary Hills and the Hatia Trough in the west (Khan, 2002). The area is covered with Holocene coastal deposits which are dominantly fluvio-tidal and tidal in nature. The remains are piedmont deposits between the Tertiary hills and the active coastal plain. The sediments are predominantly clayey silt and silty clay with minor sand, whereas the piedmont sediments are dominated by clayey sandy silt. Fluvio-tidal, tidal, and fluvial are the main depositional systems in this area dominated by humid tropical monsoon climate.

Materials and Methods

Water quality parameters assessed through field measurements included pH, electrical conductivity (EC), total dissolved solids (TDS), oxidation-reduction potential (ORP), salinity, dissolved oxygen (DO), and turbidity for both surface and groundwater samples using an HQ40d Multimeter. Well depths were obtained from well owners, and locations were recorded using the Global Positioning System (Garmin GPSMAP® 78s).

Additional parameters include biological oxygen demand (BOD), chemical oxygen demand (COD), acidity, alkalinity, total hardness, and concentrations of various ions and metals (nitrate-N, o-phosphate-P, sulfate-S, chloride, iron, manganese, cobalt, nickel, arsenic, and chromium) were collected from published documents. The water quality parameters were grouped in four different categories according to their sources- surface water (inside the embankments), surface water (outside the embankments), groundwater (shallow aquifer; <100 m depths), and groundwater (deep aquifer; >100 m depths).

Statistical Analysis

To evaluate trends and relationships among water quality parameters, a comprehensive statistical analysis was conducted which included descriptive statistics, correlation analysis, and principal component analysis (PCA). Mean, median, standard deviation, and range were calculated for each parameter in descriptive statistics through Microsoft Office Excel 2007 and OriginPro software. For correlation analysis Pearson's correlation coefficients were computed through SPSS 20 Software. PCA was applied separately for each water source (shallow and deep aquifer water) through the same software.

Results and Discussion

Conductivity

Conductivity measures water's ability to transmit electrical flow, which depends on the concentration of ions present (EPA, 2012). Higher ion concentrations result in greater conductivity. Typically expressed in micro- or millisiemens per centimeter (µS/cm or mS/cm) (EPA, 2012), conductivity, particularly specific conductance, is a widely used indicator of water quality (Miller et al., 1988).

Sudden changes in conductivity can signal pollution. For instance, agricultural runoff or sewage leaks raise conductivity by introducing chloride, phosphate, and nitrate ions (EPA, 2012), while oil spills and organic contaminants have lower conductivity since they do not form ions (LCRA, 2014). In both cases, these dissolved substances negatively affect water quality. In the study area, the conductivity (a proxy for salinity) of surface water inside the coastal embankment varies from 85µS/cm to 644 µS/cm, and in most cases, falls within the WHO and Bangladesh standard limits (Table 1; Fig. 2).

In case of surface water outside the embankment the conductivity varies from 130 µS/cm to10610 µS/cm, and in most cases, exceeds the WHO and Bangladesh standard limits (Table1; Fig. 3). The conductivity of shallow aquifer water varies from178 µS/cm to 4380 µS/cm and in most of the cases exceeded the WHO and Bangladesh standards (Table1; Fig. 4). The conductivity of deep aquifer water varies from 304 µS/cm to 2097 µS/cm, and in most cases, falls within the Bangladesh limits, although there are few exceptions (Table 1; Fig. 5). EC varies widely in all sources of water, suggesting significant variability in dissolved ionic content (Table 1; Figs. 2-5).

Salinity

Salinity refers to the total concentration of dissolved salts in water (Wetzel, 2001). The units used to measure salinity vary depending on application and reporting standards. Traditionally, it was expressed in parts per thousand (ppt) or grams per kilogram (g/kg), where 1 ppt equals 1 g/kg (EPA, 2003). Salinity plays a crucial role in dissolved oxygen solubility, as higher salinity levels reduce oxygen concentration (Miller et al., 1988). In fact, oxygen is approximately 20% less soluble in seawater than in freshwater at the same temperature (Miller et al., 1988), resulting in lower dissolved oxygen levels in marine environments.

Most aquatic organisms can only survive within specific salinity ranges (SWRCB, 2002; Myers, 1949), with many species experiencing declines when salinity exceeds 1,000 mg/L (McEvoy and Goodwin, 2003). Adaptation to salinity varies by species and is shaped by their natural habitat. In the study area, the salinity of surface water inside the embankment varies from 0.05 to 0.31‰. However, in case of surface water outside the embankment, the salinity varies from 0.06 to 6.03 ‰. The salinity of shallow aquifer water varies from 0.13 to 3.11‰, whereas the salinity of deep aquifer water varies from 0.12 to 1.07 ‰.

The salinity of surface water inside the embankments and shallow aquifer are highly variable (Table 1; Figs. 2-5). Salinity range indicates fresh reservoir of surface water within the embankments with no seawater intrusion, whereas, saline reservoir of surface water outside the embankments shows seawater intrusion. The shallow aquifer water is predominantly saline, whereas the deep aquifer generally contains fresh water, except for one site, where salinity was detected-potentially indicating seawater intrusion.

Salinization of surface water and groundwater is a significant issue in coastal Bangladesh, leading to adverse health effects and reduced agricultural productivity (Clarke et al., 2015; Worland et al., 2015; Benneyworthet al., 2016; Rashid et al., 2023a, b; Siddique et al., 2021; Rashid et al., 2024). Prolonged consumption of saline drinking water has been associated with hypertension (EPA, 2003).

In this region, high salinity levels in drinking water have been linked to increased cases of preeclampsia and gestational hypertension, with the latter being more prevalent during the dry season compared to the wet season (Khan et al., 2011). Additionally, elevated salinity in irrigation water and soil negatively impacts crop yields, with reductions ofup to 50% when irrigation water salinity exceeds 5 ppt (Ali, 2006; Clarke et al., 2015).

pH

It measures the concentration of free hydrogen ions (H^+) in water and is expressed as pH is = -log(H^+). It indicates the acid-base balance influenced by dissolved compounds and in most natural waters, primarily regulated by the CO_2-HCO_3^--CO_3^{2-} equilibrium system. In typical raw water sources, pH ranges between 6.5 and 8.5.

In this area, the pH concentration of surface water inside the embankment varies from 6.62 to 8.67 (Table 1) and in most of the cases, it falls within the WHO and Bangladesh standard limits (Fig. 2). In case of surface water outside the embankment the pH concentration varies from 7.08 to 8.49, and in most of the cases, it falls within the WHO and Bangladesh standards (Fig. 3).

The pH concentration of shallow aquifer water varies from 6.52 to 7.73 and also in most of the cases, it falls within the WHO and Bangladesh guidelines (Fig. 4). The pH concentration of deep aquifer water varies from 6.72to 7.37, and is within the WHO and Bangladesh standards (Fig. 5). The pH is indicating mostly neutral to slightly alkaline water in the study area (Adenovaet al., 2025).

ORP

Oxidation-Reduction Potential (ORP), also known as Redox Potential, measures an aqueous system's ability to accept or release electrons through chemical reactions (Axel et al., 2009). A system that accepts electrons functions as an oxidizing system, while one that releases electrons acts as a reducing system. ORP can fluctuate with the introduction of new substances or changes in the concentration of existing ones. Similar to pH, ORP is used as an indicator of water quality. While pH reflects a system's tendency to donate or accept hydrogen ions, ORP represents its ability to gain or lose electrons. Unlike pH, ORP values are influenced by all oxidizing and reducing agents, not just acids and bases. In water treatment, ORP is commonly used to regulate disinfection processes involving chlorine or chlorine dioxide in applications such as cooling towers, swimming pools, and potable water supplies.

Research has shown that bacterial survival in water is closely linked to ORP levels. Additionally, ORP monitoring plays a key role in waste water treatment, where biological treatment processes rely on controlled redox conditions to remove contaminants effectively.

In this study, ORP values show a wide range across different water sources (Table 1; Figs. 2-5), reflecting spatial variation in redox conditions.

Surface water inside the embankment shows ORP values ranging from 10.50 to 140.6 mV, whereas surface water outside the embankment varies from 17.4 to 70 mV. Shallow aquifer water shows an even broader range, from –122 to 36.2 mV, and deep aquifer water shows strongly reducing conditions with ORP values from –84.6 to –42.2 mV. These ORP variations have significant implications for contaminant mobility and groundwater quality. Negative ORP values, observed predominantly in deep aquifer water and parts of the shallow aquifer, indicate reducing conditions (Adenova et al., 2025) which can facilitate the mobilization of redox-sensitive contaminants. Under such reducing environments, certain elements like arsenic, iron, and manganese can be released from mineral surfaces in aquifer sediments into groundwater through reductive dissolution processes.

Turbidity

Turbidity refers to the cloudiness or haziness of water, which can range from highly turbid conditions, such as a river carrying mud and silt, to clear spring water with low turbidity. Monitoring turbidity is essential for domestic water supplies, as it can impact water treatment processes. During the rainy season, increased turbidity from mud and silt can clog filters, reducing their effectiveness, and also obstructing tanks, pipes, valves, and taps. In chlorinated water systems, even moderately high turbidity can hinder chlorine’s ability to disinfect water efficiently. Turbidity is typically measured in nephelometric turbidity units (NTU) or Jackson turbidity units (JTU), which are roughly equivalent. The World Health Organization (WHO) sets a turbidity limit of 5 NTU/JTU for drinking water, while Bangladesh standard allows up to 10 NTU/JTU.

In this study, the turbidity of surface water both inside and outside the embankment varied from 7.42 to 402 NTU (Table 1), and in most of the cases exceeded the WHO and Bangladesh standards. The turbidity of the shallow and deep aquifers varies from 0.57 to 67.1 NTU and in most of the cases falls within WHO and Bangladesh limits. Turbidity is also a highly variable in all sources of water (Figs. 2-5).

TDS

Total dissolved solids (TDS) consist of inorganic salts and organic matter. Common dissolved mineral salts can influence water’s taste, hardness, corrosion, and encrustation (Ahmed and Rahman, 2000). High levels of dissolved inorganic substances may negatively impact aquatic plants and animals, and contribute to irrigation challenges. In this study, surface water TDS both inside and outside the embankment varies from 40.40 to 6190mg/l, and in most of the cases are within the WHO and Bangladesh standard limits. Groundwater TDS in both the shallow and deep aquifers varies from121 to 330mg/l (Table 1) and in most of the cases also falls within the WHO and Bangladesh guidelines. TDS are highly variable in all sources of water (Figs. 2-5). TDS indicate fresh surface water inside the embankment (Fetter, 2014).

However, surface water outside the embankment and shallow aquifer water are subsaline, and deep aquifer water is generally fresh, except for one deep aquifer site, where elevated salinity may be indicative of localized seawater intrusion.

Arsenic (As)

In the 1990s it was discovered that groundwater from 6 to 10 million tubewells in Bangladesh had As concentrations higher than the World Health Organization guidelines for drinking water of 10 μg/L (WHO, 2011). Khan et al. (2010) carried out a study on As concentration in shallow and deep aquifers in this area. In their study, it was revealed that the arsenic concentration distribution in the shallow aquifer at Companiganj Upazila varies from 0 to 0.35 mg/l.

Among 56 samples from the shallow aquifers, only 12 samples show arsenic concentration below 0.05 mg/l (BSTI limit) and others exceed the tolerable limit of the Bangladesh Standard (0.05 mg/l). However, in the deep aquifers, 100% of the samples fall within 0.01 mg/l arsenic concentration. In case of Sonagazi Upazila, the arsenic concentration distribution of the shallow aquifer varies from 0.06 mg/l to 0.45mg/l.

A total of sixteen (16) samples were collected from the shallow aquifer, showing that all the tubewells exceeded the BSTI limit. However, the tubewells reaching the deep aquifer are free from arsenic contamination. In the case of Mirsharai Upazila, in shallow aquifers the arsenic concentration varies from 0 to 0.35 mg/l. But the deep aquifer is free from arsenic contamination. Arsenic is a carcinogen to humans and exposure through drinking contaminated water can increase the risk of skin, lung, bladder and kidney cancers, hypertension, diabetes, peripheral vascular disease, and skin lesions (Hopenhayn, 2006).

Arsenic present in soil and irrigation (such as in paddy field) water can also be incorporated into rice, presenting another exposure risk (Williams et al., 2006; Mitchell, 2014). Ayers et al. (2016) stated that the causes of arsenic contamination in groundwater resources in the coastal areas of Bangladesh are from connate water, where sedimentary arsenic was mobilized through reductive dissolution of ferric oxyhydroxides.

Other Parameters

The specific parameters such as lead, chloride and manganese content, DO, and BOD in the Feni River exceeded WHO and BSTI limits (Table 2; Ahmed et al., 2011). Additionally, in ground water total hardness and lead exceed the Bangladesh standards and BSTI limits (Table 2; Ahmed et al., 2011).

Pollution Source Identification

Correlation matrix analysis of shallow aquifer

Correlation matrices analysis of shallow aquifer water shows that TDS and salinity are strongly positively correlated ($.916^{**}$; Table 3). EC and TDS are also strongly positively correlated ($.902^{**}$). Similarly, EC and salinity are strongly positively correlated ($.902^{**}$).

Therefore, it confirms that EC and TDS are reliable proxies for salinity levels in the shallow aquifers. Similar findings are also found in the southwestern coast of the country (Rashid et al., 2023b). Resistivity is strongly negatively correlated with TDS ($-.569^{*}$), salinity ($-.714^{**}$) and EC ($-.598^{*}$).

Correlation matrix analysis of deep aquifer

Correlation matrices analysis of deep aquifer water shows that TDS and salinity are strongly positively correlated 1.000^{**}; (Table 4). EC and TDS are also strongly positively correlated (1.000^{**}). Similarly, EC and salinity are also strongly positively correlated ($.902^{**}$).

Table 1. Water quality of different sources of water.

	pH	EC (μs/cm)	Resistivity (Ω-cm)	TDS (mg/l)	Salinity (‰)	ORP (mV)	Turb. (NTU)
Surface water inside the embankment							
Max.	8.67	644	11620	313	0.31	140.6	402
Min.	6.62	85.6	1555	40.40	0.04	10.50	7.42
Mean	7.43	252	5638	121.57	0.12	65.95	63.67
Median	7.18	171	5895	81.90	0.08	66.60	22.2
SD	0.62	176	2827	86.36	0.09	37.32	96.89
Surface water outside the embankment							
Max.	8.5	10610	7880	6190	6.0	70.0	380
Min.	7.1	130	95	68.8	0.1	-17.4	14.2
Mean	7.7	2794	2949	2519.3	1.5	30.3	163.3
Median	7.6	781	1304	1347.5	0.4	33.5	105.7
SD	0.46	3778.19	3182.12	2570.2	2.15	25.96	143.73
Shallow aquifer							
Max.	7.73	5720	3770	3030	3.11	36.2	67.1
Min.	6.52	178	176	126	0.13	-122	0.57
Mean	7.25	2103	815	1058	1.14	-62.37	9.484
Median	7.36	1572	555	793	0.91	-72.6	5.21
SD	0.33	1513	846	797	0.78	45.97	15.38
Deep aquifer							
Max.	7.37	2097	3960	1056	1.07	-42.2	5.61
Min.	6.72	253	476	121	0.12	-84.6	0.63
Mean	7.03	500	2787	244	0.25	-64.23	1.71
Median	7.04	320	3160	152	0.15	-64	0.96
SD	0.19	509	869	258	0.26	12.87	1.61

Table 2. Water quality of the area (after Ahmed et al., 2011).

Parameters	Surface Water (Feni River)	Groundwater (In Feni District)	BSTI Limit	WHO Bangladesh Limit
DO/mgL^{-1}	7.45	1.25-3.34	Max 6	-
T. hardness /mgL^{-1}	52	26-554	Max 500	-
Chloride/mgL^{-1}	2720	8.17-481.76	Max 600	-
BOD/mgL^{-1}	1.97	-	0.2	-
Mn/mgL^{-1}	0.25	BDL	0.1	0.4
Pb/mgL^{-1}	0.07	0.02-0.07	Max 0.05	0.01

Table 3. Pearson's correlation matrix of shallow aquifer water physicochemical parameters.

	pH	EC (µs/cm)	Resist. (Ω-cm)	TDS (mg/l)	Sal. (‰)	ORP (mv)	Turb. (NTU)
pH	1						
EC (µs/cm)	.070	1					
Resist. (Ω-cm)	-.176	-.598*	1				
TDS (mg/l)	.077	.902**	-.569*	1			
Sal. (‰)	.062	.902**	-.714**	.916**	1		
ORP (mv)	.138	-.059	.339	-.071	-.068	1	
Turb. (NTU)	.106	.135	-.188	-.205	-.057	-.055	1

*. Correlation is significant at the 0.05 level (2-tailed). **. Correlation is significant at the 0.01 level (2-tailed).

Table 4. Pearson's correlation matrix of deep aquifer water physicochemical parameters.

	EC (µs/cm)	Resist. (Ω-cm)	TDS (mg/l)	Sal. (‰)	ORP (mv)	Turb. (NTU)
EC (µs/cm)	1					
Resist. (Ω-cm)	-.900**	1				
TDS (mg/l)	1.000**	-.898**	1			
Sal. (‰)	1.000**	-.896**	1.000**	1		
ORP (mv)	.142	.216	.145	.148	1	
Turb. (NTU)	-.155	.049	-.155	-.157	-.511	1

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

Table 5. Varimax rotated factor loadings & communalities of different physicochemical parameters of shallow aquifers.

	PC1	PC2	PC3	Communalities
pH	.133	-.252	.754	.650
EC (µs/cm)	.936	.031	.076	.883
Resist. (Ω-cm)	-.793	.366	.077	.768
TDS (mg/l)	.932	.288	.004	.951
Sal. (‰)	.967	.138	.016	.954
ORP (mv)	-.186	.471	.724	.781
Turb. (NTU)	.023	-.836	.222	.748
Eigenvalue	3.361	1.221	1.155	
% of total variance	48.017	17.439	16.495	
Cumulative % of variance	48.017	65.456	81.950	

Table 6. Varimax rotated factor loadings and communalities of different physicochemical parameters of deep aquifers.

	PC1	PC2	Communalities
EC (µs/cm)	.996	-.003	.992
Resist. (Ω-cm)	-.925	.284	.937
TDS (mg/l)	.996	-.001	.991
Sal. (‰)	.995	.002	.991
ORP (mv)	.116	.889	.804
Turb. (NTU)	-.198	-.817	.706
Eigenvalue	3.882	1.539	
% of total variance	64.706	25.642	
Cumulative % of variance	64.706	90.348	

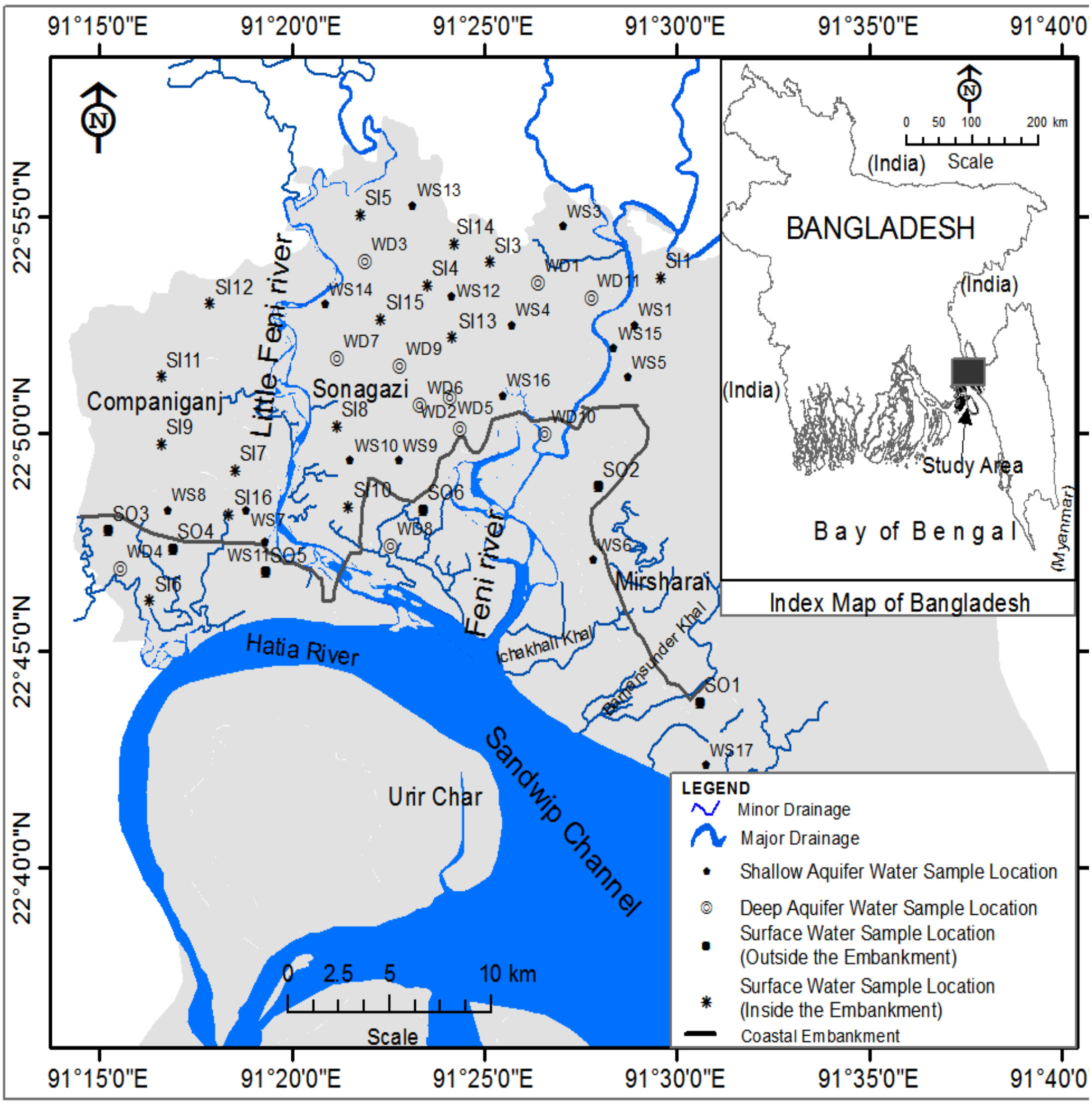

Fig. 1 Sample location map of the study area.

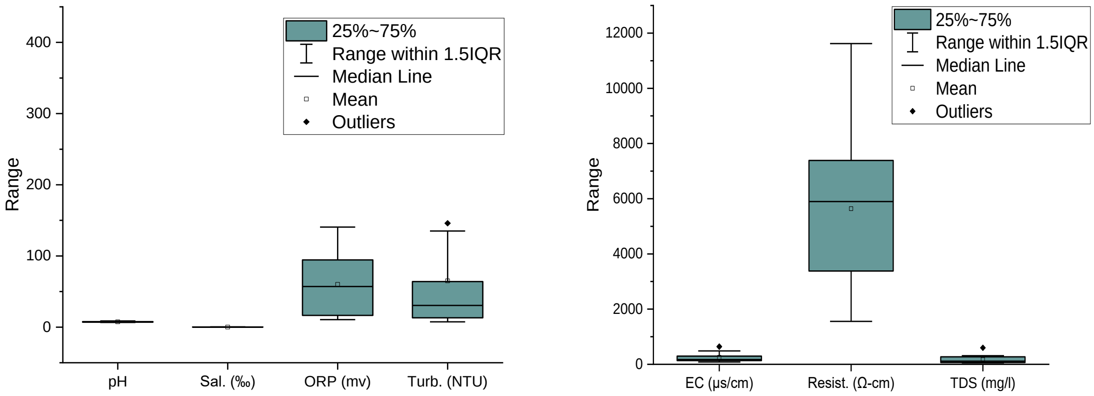

Fig. 2 Shows the corresponding box plots for pH, salinity (‰), ORP (mV), EC (µS/cm), TDS (mg/L), Resistivity (Ω-cm) and turbidity (NTU) of surface water inside the embankment. The x-axis represents different water quality parameters.

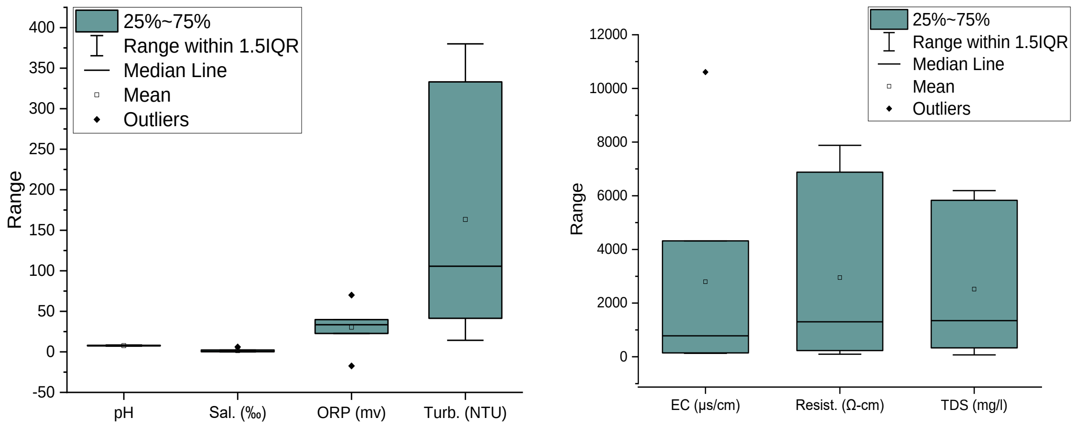

Fig. 3 Shows the corresponding box plots for pH, salinity (‰), ORP (mV), EC (μS/cm), TDS (mg/L), Resistivity (Ω-cm) and turbidity (NTU) of surface water outside the embankment. X-axis represents different water quality parameters.

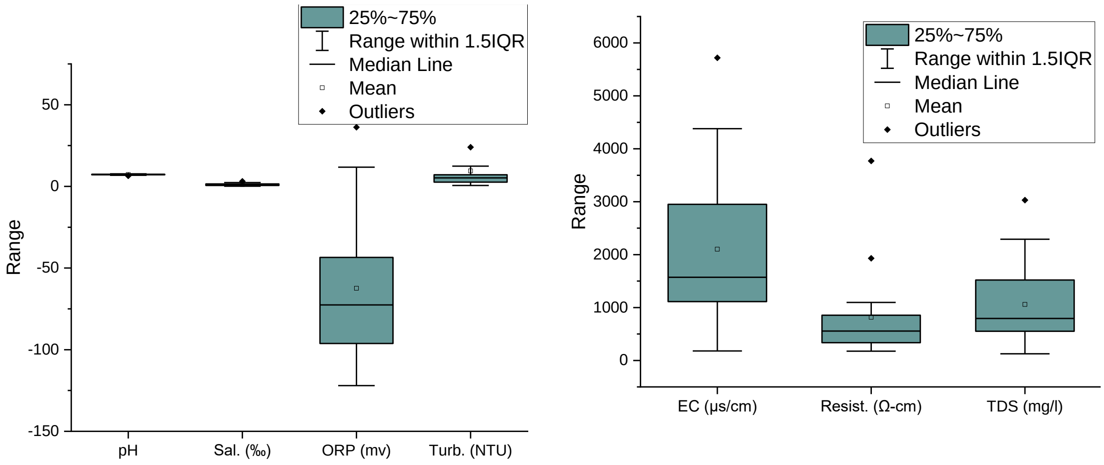

Fig. 4 Shows the corresponding box plots for pH, salinity (‰), ORP (mV), EC (μS/cm), TDS (mg/L), Resistivity (Ω-cm) and turbidity (NTU) of shallow aquifer water. The x-axis represents different water quality parameters.

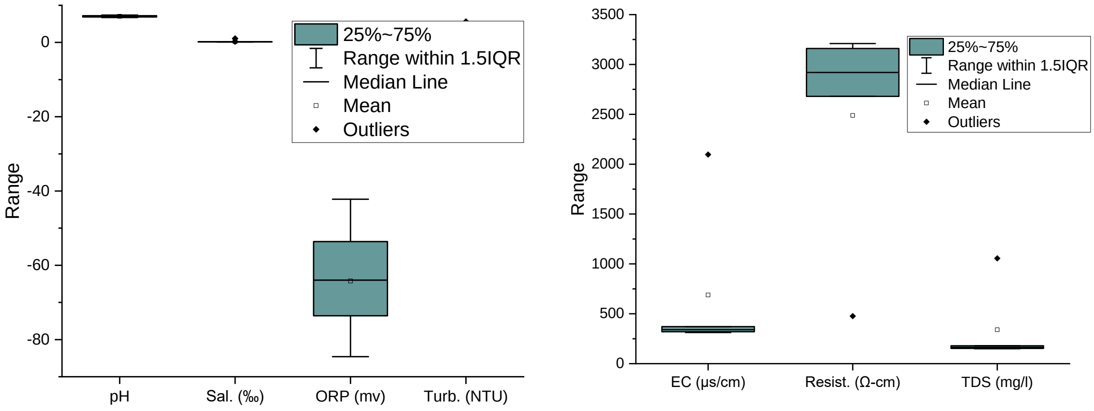

Fig. 5 Shows the corresponding box plots for pH, salinity (‰), ORP (mV), EC (μS/cm), TDS (mg/L), Resistivity (Ω-cm) and turbidity (NTU) of deep aquifer water. The x-axis represents different water quality parameters.

It shows that EC and TDS are reliable proxies for salinity levels in the deep aquifer. Similar findings are found in the southwestern coast of the country (Rashid et al., 2023b). Resistivity is strongly negatively correlated with TDS (-.898**), salinity (-.896**) and EC (-.900**). Due to higher TDS, higher salinity (meaning more dissolved salts) directs to lower resistivity.

Principal component analysis

Principal Component Analysis (PCA) is a basic reduction method usually used in data scrutiny and machine erudition. It helps to reduce the number of variables in a dataset while maintaining the most significant information. It also helps to reduce multifaceted datasets to two or three main components.

The results of the PCA of water quality parameters for both shallow and deep aquifers are shown in Tables 5-6 which explained the cumulative variance of 81.950% and 90.348%, respectively. In the PCA of water quality parameters for shallow aquifers, three principal components are identified (Table 5) as accountable for controlling the water quality. The loading of PCA is referred to as weak, moderate, and strong for the variable scores of 0.30-0.50, 0.50-0.75, and >0.75, respectively (Ahsan et al., 2019). PC1 represents 48.017% of the total variance, which was strongly loaded with EC, TDS and salinity. The strong loading of EC, TDS and salinity can be corroborated by the imposition of saline water in the shallow aquifers of the area (Rashid et al., 2023b). The PC2 accounts for 17.44% of the total variance where positive loadings are observed for resistivity and ORP. The PC3 accounts for 16.50% of the total variance where positive loadings are observed for pH and ORP.

In the PCA of water quality parameters for deep aquifers, two principal components are identified (Table 6) as accountable for controlling the water quality. PC1 represents 64.71% of the total variance, which is strongly loaded with EC, TDS and salinity. The PC2 accounts for 25.64% of the total variance where positive loadings are observed for ORP. Thus, the pollutants in both shallow and deep aquifers can be positively triggered by EC, TDS and salinity.

Conclusion

This multi-parameter water quality study highlights several critical concerns in the coastal areas of Mirsharai, Sonagazi and Companiganj. Conductivity levels in surface water outside the coastal embankment and in shallow aquifers frequently exceed WHO and Bangladesh standards. Similarly, salinity levels surpass acceptable limits in both water sources. Surface water turbidity, both inside and outside the embankment, consistently exceeds these standards. The Feni River shows elevated BOD and DO levels beyond BSTI limits, along with excessive chloride concentrations. Groundwater samples also show chloride, total hardness, alkalinity, and lead levels exceeding national BSTI standards. Most notably, the analysis confirms significant arsenic contamination in shallow aquifers, while deep aquifers remain arsenic-free. Correlation matrix analysis confirms that EC and TDS serve as reliable indicators of salinity levels in both shallow and deep aquifers. PCA analysis further supports this, showing that EC, TDS, and salinity are influenced by the intrusion of saline water in these aquifers. Additionally, pollutants in both shallow and deep aquifers are positively associated with EC, TDS, and salinity. These findings are crucial for guiding effective water management strategies and ensuring safe drinking water access for coastal communities. Future research should explore temporal variations in water quality, the geochemical processes influencing contaminant mobility, and the development of sustainable water treatment technologies tailored to these coastal regions.

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