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Groundwater of the Municipalities of Southwestern Coastal Bangladesh

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Abstract: Aquifers of the urban conglomerates in the southwestern coastal Bangladesh—situated at the heart of the Ganges delta—are susceptible to contamination and induced saltwater intrusion because of population pressure demanding for freshwater and other anthropogenic interventions and thus are vulnerable in terms of quality and quantity. This comprehensive review endeavours to elucidate the geochemistry of solute load of such aquifers for its monitoring, management and conservation. One hundred and seventy numbers of groundwater samples from the production tube wells, penetrating mostly the shallow coastal alluvial aquifers, collected in different periods from Bagerhat, Faridpur, Jhenaidah, Paikgacha and Satkhira municipalities and Khulna City Corporation (KCC) are analyzed for major cations and anions following standard methods. The results show that the abundance of cations follow the general trend Na>Ca>Mg>K for Bagerhat, Paikgacha and KCC and Ca>Mg>Na>K for Satkhira, Jhanaidah and Faridpur municipalities. The anions on the other hand follows the general trend of HCO_3>Cl>SO_4>PO_4 for Satkhira, Jhenaidah, Faridpur and KCC and Cl>HCO_3>SO_4>PO_4 for Bagerhat and Paikgacha. The spatial variation of soute load to the aquifers is statistically quite significant. Molar ionic ratio of chemical parameters suggests both carbonates and plagioclase silicates as their source rock. However seawater intrusion to the aquifers is quite revealing, may be due to localized upwelling of saline waters. Most of the groundwater is supersaturated with respect to both calcite and dolomite suggesting absence of nucleation for calcite precipitation.

The chemical mechanism responsible for the groundwater chemistry is rock weathering, however, is gradually commanded by the processes of evaporation and crystallization as is evident from Gibb's plot. The

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water type is both Na-HCO_3 and Na-Cl for Bagerhat and Paikgacha while it is mostly Ca-Mg-HCO_3 for Faridpur, Satkhira, Jhenaidah and KCC. Further most of groundwater from Faridpur, Satkhira and Jhenaidah occupies temporary hardness field of Chadha's plot. Almost all samples from Paikgacha and most samples from Bagerhat are saline as revealed from Chadha's plot. With respect to TDS, groundwater in most municipalities of southwestern coastal Bangladesh does not accord with standard and in few cases such as in Faridpur and Paikgacha almost 100% of the samples exceed desirable limit for safe drinking. From published reports on consequences of rapid climate change it may be envisioned that salinity front would move upwards and drainage congestion would increase which would create uncertainty in groundwater management. Thus conjunctive use of groundwater with surface water may be prescribed at this moment.

Key words: Ganges delta, hydrogeochemistry, municipalities of southwestern coastal Bangladesh, groundwater, coastal Bangladesh.

Introduction

Coastal groundwater, when fresh, is an important resource because of its potable, agricultural and industrial use. The ever increasing population density in coastal zones (Finkl, 1994; Vandenbohede et al., 2009) and the demand for potable freshwater globally (UNEP, 1999; Nickson et al., 2005) renders coastal groundwater supplies to ceaseless depletion worldwide (Barlow, 2003). Generally the coastal aquifers are shallower and fragile and are susceptible to contamination and pollution (Chidambaram et al., 2009). The major threat to coastal aquifers is saltwater intrusion, sometimes induced (due to over exploitation), due to their proximity to the sea (Nadler et al., 1981; Morell et al., 1996; Sukhija et al., 1996) and also there are many aquifers deposited in palaeo-saline environment, mostly in deltas. The variability in hydrochemistry of coastal aquifers is thus complex due to presence of conflicting processes in the geo-environment (Morell et al., 1996). This necessitates monitoring, management and conservation of coastal groundwater for its optimum utility.

Urban conglomerates in southwestern coastal Bangladesh are characterized by high population density (Ahmed, 2005, 2011), poorly maintained and dilapidated built environment (Ahmed, 2005), restricted and ineffective natural drainage system (SDP, 2011), water logging but limited recharge due to concrete envelope (Adri and Islam, 2012; Brammer, 2010). The aquifers in such locations are also susceptible to contamination and induced saltwater intrusion (Nobi and Gupta, 1997; Rahman and Bhattacharya, 2006). A number of generalized studies on groundwater of the southwestern coastal Bangladesh as a whole and also on specific issues may be found elsewhere (Nobi and Gupta, 1997; Yokota et al., 2002; Rahman and Bhatacharya, 2006; Bahar and

Reza, 2010; Burgess et al., 2010; Haque et al., 2010; Islam et al., 2011; Rahman et al., 2011; Adhikary et al., 2012; Ghosh et al., 2012; Khanom and Salehin, 2012; Rahman et al., 2012; Harun and Kabir, 2013). However understanding hydrochemistry is essential in coastal aquifer management. This compilation reviews few short-term researches on hydro-chemical nature of solute load of aquifers in urban conglomerates situated in the southwestern coastal Bangladesh and endeavours to decipher their geochemistry and vulnerability.

The Southwestern Coastal Bangladesh

Situated at the southwestern corner of Bangladesh and bordered on the north by the Ganges, on the east by the Gorai-Modhumati-Baleshwar river, on the south by the Bay of Bengal and by the Indo-Bangladesh international border on the west the southwestern coastal Bangladesh covers an area of ~16,000 sq km with topographic slope towards south (Nobi and Gupta, 1997). This region experience a subtropical climatic condition where more than 80% rainfall takes place during monsoon (May to October). There are at least twenty distributaries having a complex network of inlets connected to the Ganges-Brahmaputra-Meghna (GBM) river system criss-crossing the southwestern coastal Bangladesh (Barua, 1991) and represents one or the other of the four sub-systems such as Raimagal-Hariabhangha, Kobadak-Arpangasia-Malancha, Shibsha-Passur-Marjata and Madhumati-Haringghata all of which flow from north to south (Rasid, 1991). Freshwater from upstream (mainly from the Ganges) has ceased to flow along the former three sub-systems during recent times and only the Madhumati-Haringghata (in fact the Garai-Madhumati-Baleshwer) receives water from the Ganges. The other three, however, receive water from the upstream only during monsoon. Structurally the area represents the southern edge of the Faridpur Trough seperated from the Hatia Trough by a gravity and magnetic anomaly known as Barisal-Chandpur High on the southeast and by Hinge Zone on the northeast (Alam et al., 1990). Geomorphologically the area represents functional attributes of fluvial forms and processes along with recent human interventions and modifications in the form of inter-basin diversions, flow regulation and polderisation etc. Such features influence the groundwater quality and quantity in a variety of ways.

Records of heterogeneity in aquifer materials even within short distances have been observed throughout the coastal Bangladesh (Zahid et al., 2014) where the aquifers are recognized on their depth-based criteria by various authors (BWDB-UNDP, 1982; DPHE-BGS, 1999, 2001; Aggrawal et al., 2000; Zahid et al., 2009). The uppermost category made up of fine sands with clay lenses and extending from 50 to 100 metre from the surface and water within such aquifers have been estimated of about 100 years old (Aggrawal et al., 2000). The aquifer below the upper one is supposed to be the main aquifer (Zahid et al., 2014) which extends down from 250 to 350 metres from the surface composed mainly of fine to very fine sand and water and estimated to be of about 3000 years old (Aggrawal et al., 2000). The third aquifer below the main one (referred as deep aquifer) generally occurs below 250 to 350 metres and is absent in most of the southwestern coastal Bangladesh. Waters from these Late Pleistocene to Early Holocene aquifers have been dated about 20,000 years old. These are paleo-saline waters entrapped in geological formation during their deposition (Rahman et al., 2011).

Fluctuation of groundwater table in coastal Bangladesh is more conspicuous vertically than that of horizontally at least on regional scale (Zahid et al., 2014). This suggests noted contribution through recharge from rainfall and floodwaters, although variations in movement at local scale may be significant (BWDB, 2013) due to development stresses (Zahid et al., 2014) that in fact regulates impact of salinity. The physiography and geological characteristics of the aquifer systems also control the hydrograph as usual. Zahid et al. (2014) observed that ground water table responds to both recharge and irrigation abstraction as well as to tidal fluctuations in coastal Bangladesh. Zahid et al. (2009, 2012) also observed hydraulic connectivity among the aquifers as well. The production wells supplying water to the municipalities are affected by declining water table caused by over-abstraction (SDP, 2011).

The general water types in coastal aquifers of Bangladesh are Na-Cl and Na-Ca-Mg-HCO_3 (Zahid et al., 2008) and the widespread contamination of aquifers by salinity is represented by higher Total Dissolved Solids (TDS) such as Cl^-, Na^+, Mg^{2+} and SO_4^{2-} (BWDB, 2013 as mentioned in Zahid et al., 2014). The potable water along the coastal Bangladesh is restricted either within first 25 m or below about 150 to 200 m depth (Revenscroft et al., 2005); however such locations do not follow any pre-defined pattern. Zahid et al. (2014) noticed that in general the shallow aquifer in Satkhira, Jessore and Narail of southwest contains water with electrical conductivity (EC) $<1000\ \mu S.cm^{-1}$. Water from the main aquifers of Satkhira, Jessore and Narail districts are also fresh. However, deep aquifers of Khulna are mostly saline. Seasonal variation in water chemistry also has been noticed where higher EC is observed in dry season relative to that of wet season. There is control of tidal process in aquifer chemistry as well.

Bangladesh Bureau of Statistics (BBS, 2011) estimated that 89.80% of the households in southwest coastal Bangladesh depend on tubewells (i.e., ground water) for their supply of potable water and 60.80% of the households have their potable water source within their premises. The Sector Development Plan (SDP, 2011) estimated that the usable groundwater recharge is 5600 Mm^3 in the southwestern coastal region and the demand for potable water is 289 Mm^3, environment is 620 Mm^3 and agriculture is 4196 Mm^3. That suggests a balance of 495 Mm^3 for the region; however, such estimate suggests a tremendous demand from agriculture for ground water and recently water quality issues in the southwestern region is increasingly being recognized (Yokota et al., 2002; Rahman and Bhattacharya, 2006; WHO, 2004).

Geophysically the southwestern coastal Bangladesh is interlinked with the development stresses such as polderization of the region (Brammer, 2010) that when coupled with water diversion at Farakka resulted in waterlogged conditions and imposed a conflicting drainage network with the natural system in the region. The consequence of such structural interference to natural system resulted in restricted freshwater inflow and increase in salinity of the area. Thus the quality and quantity of groundwater are stressed both from within and outside of the region.

Methods

The location of municipalities of the southwestern coastal Bangladesh where from the groundwater was collected and analyzed are shown in Fig. 1. The borehole depth and the study period are presented in Table 1.

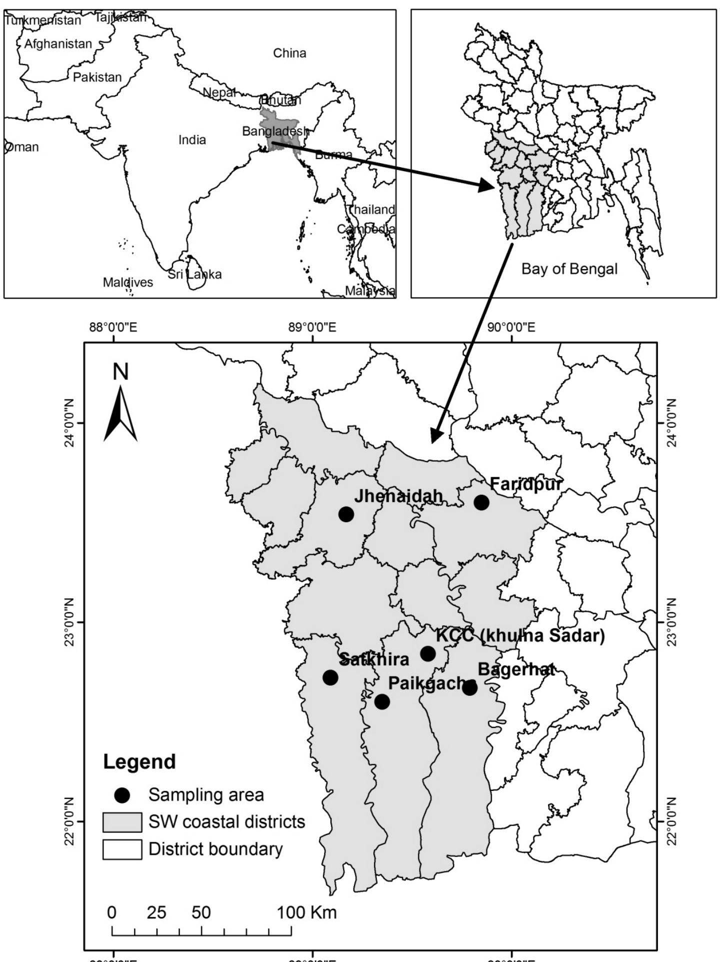

Fig. 1: South-western coastal area of Bangladesh.

Table 1: Inventory of the groundwater samples collected from southwestern coastal municipalities of Bangladesh

Municipality	*Latitude*	*Longitude*	*Study season and year*	*Range of borehole depth (m)*	*Reference*
Bagerhat	22º39′-22º41′N	89º46′-89º49′E	Winter, 2005	18.5-38.5	Das, 2006
Faridpur	23º35′-23º37′N	89º50′-89º53′E	Monsoon and winter, 2011	18.6-102.3	Paul, 2014
Jhenaidah	23º31′-23º34′N	89º08′-89º12′E	Winter, 2007	18-152	Sarkar, 2008
KCC	22º46′-22º58′N	89º28′-89º37′E	Monsoon, 2004	301-329	Biswas, 2004
Paikgacha	22º34′-22º39′N	89º19′-89º24′E	Monsoon, 2011	11.47-97.65	Ghosh et al., 2012
Satkhira	22º42′-22º45′N	89º04′-89º06′E	Post-monsoon, 2006	18-99	Dey, 2007

The depth of boreholes varies from ~12 m to ~150 m for Bagerhat, Faridpur, Jhenaidah, Paikgacha and Satkhira municipalities that represent the shallow aquifer; however the borehole depth for Khulna City Corporation (KCC) varies from ~300 m to ~330 m representing the main aquifer. The samples were collected during winter, monsoon and post-monsoon depending on logistics and other support system.

Samples were collected after pumping the tube well for few minutes when a relative stability of physico-chemical condition was achieved. The water samples from Bagerhat (n = 26), Faridpur (n = 30+30), Jhenaidah (n = 12), Paikgacha (n = 35), Satkhira (n = 25) and KCC (n = 12) were collected in pre-washed 1L polyethylene bottles and were air tightened. The temperature, pH, EC and bi-carbonate were estimated at the field and major cations and anions were estimated at the laboratory following standard procedures as mentioned in Table 2.

Table 2: Analytical methods followed to determine the major ion chemistry

Parameter	*Method*	*Reference*
pH	Glass electrode	Instrument manual
Na^+, K^+	Flame photometric method (Flame photometer PFP7)	Instrument manual
Ca^{2+}, Mg^{2+}	Titrimetric method using standard EDTA	Greenberg et al. (1995)
Alkalinity	Potentiometric method	Greenberg et al. (1995)
Chloride	Ion selective electrode methods (Cole-Palmer Model 27502-13)	Instrument manual
Sulphate	Turbidimetric method	Greenberg et al. (1995)
Silica	Molybdosilicate method	Greenberg et al. (1995)
Phosphate	Ascorbic Acid method	Greenberg et al. (1995)
Nitrate	Spectrophotometric method	Greenberg et al. (1995)

Nature of Solute Load to Groundwater

The physico-chemical nature of the municipality ground water of the southwest coastal Bangladesh is briefly presented in Table 3. The analytical precision was better than ±5% for Ca^{2+}, Mg^{2+}, K^+ and HCO_3^+ and within ±10% for Na^+, Cl^-, SO_4^{2+} and SiO_2. The estimated charge balance between cations (Tz^+) and anions (Tz^-) was within ±10% and the correlation coefficient r = 0.98 (n = 170) (Fig. 2). The cations and anions are related by the equation

$$Tz^+ \text{ (meq.L}^{-1}) = 1.034\ Tz^- \text{ (meq.L}^{-1}) - 1.295$$

This implies that contribution to the solute load by ions not measured in the analysis is negligible. The Normalized Inorganic Charge Balance (NICB) as defined in Huh et al. (1998) when plotted against Tz^+ (Fig. 3A) indicates

Table 3: Physico-chemical parameters of municipality groundwater

Municipalities	*Statistical parameter*	*pH*	*EC* *($\mu S.cm^{-1}$)*	*Estimated TDS ($mg.L^{-1}$)*	*Cations ($mg.L^{-1}$)*				*Anions ($mg.L^{-1}$)*					*SiO_2 ($mg.L^{-1}$)*
					Na^+	*K^+*	*Ca^{2+}*	*Mg^{2+}*	*HCO_3^-*	*Cl^-*	*SO_4^{2-}*	*NO_3^-*	*PO_4^{3-}*	
Satkhira	Max	7.25	3540	1770	450	30.8	188	99	625	932	57.75	12	0.95	36.89
	Min	6.83	533	266	16	1.8	58	2	245	13	0.8	0.2	0.08	20.88
	Mean	7.02	1220.48	637.72	88.28	6.78	121.52	40.11	478.12	166.83	10.20	4.16	0.47	29.39
	St dev	0.09	685.84	374.72	103.30	5.74	29.84	28.75	101.51	238.88	16.14	3.33	0.20	4.92
Paikgacha	Max	6.49	12120.00	4303	1293.71	39.40	297.54	92.66	940.03	2084.75	17.20	0.14	0.10	11.88
	Min	6.00	709.00	444	28.25	2.81	42.10	9.44	189.60	35.45	0.57	0.04	0.01	2.94
	Mean	6.28	4763.60	2010.41	428.91	13.85	159.47	43.54	597.03	750.17	6.85	0.07	0.04	6.59
	St dev	0.11	2943.75	1009.76	318.77	8.30	59.60	25.99	185.90	500.38	4.86	0.03	0.02	2.01
Khulna City Corporation (KCC)	Max	8.20	2610	1738	295	7.9	90	24	780	757	38	-	0.69	36.88
	Min	7.70	855	870	84	3.2	25	6	497	57	3	-	0.26	29.38
	Mean	7.93	1421.75	1210.25	186.83	5.47	42.08	10.50	614.92	289.83	20.00	-	0.48	31.93
	St dev	0.14	549.20	297.42	78.92	1.65	23.50	5.04	75.76	230.53	11.47	-	0.125	2.65
Bagerhat	Max	7.90	3870	1950	514	60	122	63	661	595	94.8	-	2.31	1.24
	Min	7.50	796	398	27	3	17	13.8	315	50	1.4	-	0.06	0.38
	Mean	7.68	1940.42	1010.69	278.25	9.24	58.81	26.76	461.50	328.10	16.28	-	0.45	0.74
	St dev	0.11	889.60	461.05	154.64	10.61	25.99	12.66	103.98	179.97	28.00	-	0.46	0.21
Jhenaidah	Max	7.90	1097	548	46.02	4.9	182.12	30.67	600	61	31.5	12.6	0.37	29.14
	Min	7.22	474	237	8.92	1.95	26.18	10.65	300	5	0.9	0.21	0.02	6.25
	Mean	7.53	728.17	364.25	18.46	3.48	111.36	18.48	430.50	23.25	12.40	1.91	0.20	12.24
	St dev	0.22	192.59	96.23	10.30	0.92	48.77	5.91	104.50	18.22	12.59	3.44	0.11	5.805
Faridpur	Max	7.65	1670	1327	213.4	9.2	144.3	83.2	792.4	309.3	80.7	3.98	2.7	38.8
	Min	6.82	526	534	12.4	1.9	45.1	18.8	324.3	15.1	14.7	0.12	0.06	2.2
	Mean	7.35	971.92	880.58	60.11	5.04	104.46	39.24	535.32	71.92	46.02	1.08	1.00	16.39
	St dev	0.17	273.20	207.10	48.32	1.35	21.50	13.30	97.31	68.03	16.04	0.69	0.77	7.34

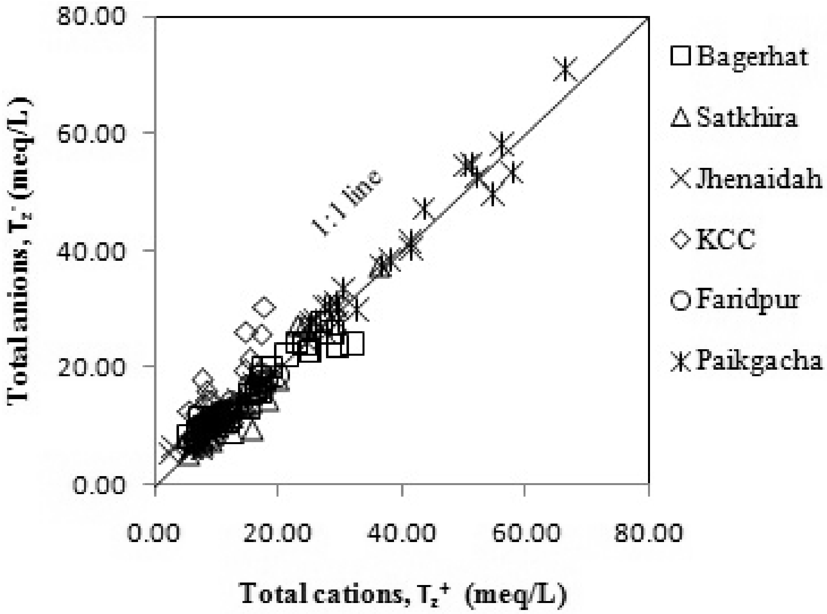

Fig. 2: Ionic charge balance for the municipality groundwater.

that anions not analyzed and may have been derived from organic acids are not significant. Similarly when NICB is plotted against Tz^- (Fig. 3B) indicates that metal pollution load other than the major cations analyzed are not significant in ground water from municipalities of southwestern coastal Bangladesh.

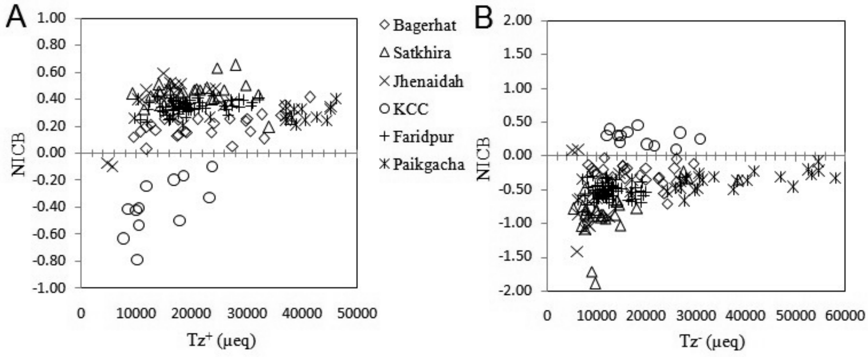

Fig. 3A-B: Normalized Inorganic Charge Balance (NICB) for the municipality groundwater.

Major Cations and Anions

The pH of the ground water varies within a narrow range of 6.00 to 8.20 as a whole and represents the abrasion pH of most of the rock forming minerals (Ollier, 1969) such as calcic plagioclase, micas, carbonates, clays and quartz etc. known to be abundant in the basin (Alam et al., 1990). The TDS of Satkhira municipality ranges from 266 $mg.L^{-1}$ to 1770 $mg.L^{-1}$, that of Paikgacha ranges from 444 $mg.L^{-1}$ to 4303 $mg.L^{-1}$, that of Bagerhat ranges from 398 $mg.L^{-1}$ to 1950 $mg.L^{-1}$, that of Jhenaidah ranges from 237 $mg.L^{-1}$ to 548 $mg.L^{-1}$ and for Faridpur the TDS ranges from 534 $mg.L^{-1}$ to 1327 $mg.L^{-1}$. The TDS of KCC main aquifers varies from 870 $mg.L^{-1}$ to 1738 $mg.L^{-1}$. The TDS, total anions and total cations among the municipalities having aquifers at shallow depth show statistically significant spatial variation at 1% significance level (F value = 23.845, 23.062 and 27.018 respectively at $p = 0.000$; df = 5). Such spatial heterogeneity in aquifer chemistry is well in southwestern coastal Bangladesh (Zahid et al., 2014 and references therein). In general the highest TDS is observed at Paikgacha municipality (2010 ± 1010 $mg.L^{-1}$) and the lowest TDS is observed at Jhenaidah municipality (364 ± 96 $mg.L^{-1}$). The relative abundance of alkali earth elements (calcium and magnesium) is evident in Fig. 4A; however contribution of (Na+K) is noticeable in high TDS samples presumably representing contribution from saline water particularly in Bagerhat and Paikgacha municipalities. This is recognizable in anion ternary diagram (Fig. 4B) where the samples cluster around ($Cl + SO_4$) apex. Figure 4B also suggests relative abundance of silica in groundwater and thus silicate weathering is evident in southwestern coastal aquifers as well.

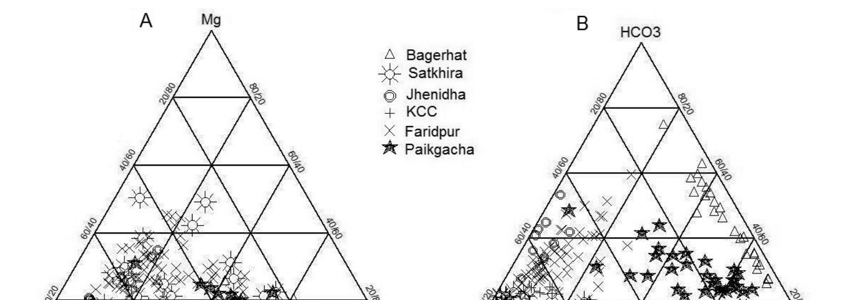

Fig. 4A-B: Ternary diagram showing relative abundance of cations and anions.

The abundance of cations follow the general trend of Na>Ca>Mg>K for Bagerhat, Paikgacha and KCC except Satkhira, Jhenaidah and Faridpur municipalities where the cation abundance follows the trend Ca>Mg>Na>K. The anions follow the trend $HCO_3>Cl>SO_4>PO_4$ for Satkhira, Jhenaidah, KCC and Faridpur municipalities and the anionic abundance follows $Cl>HCO_3>SO_4>PO_4$ trend at Bagerhat and Paikgacha. Such abundance of cations and anions suggest contribution from both rock weathering and seawater to the aquifer chemistry.

Source Rock

Molar ionic ratios are good in deciphering source minerals that helps in explaining coastal processes controlling coastal groundwater geochemistry (Kim et al., 2003). Following Haunslow (1995) the plots of ionic molar ratios are constructed in Fig. 5A-D and Fig. 6A-D. The plot of TDS vs Na^+:Cl^- (in $meq.L^{-1}$) (Fig. 5A) suggests that a significant number of groundwater samples have contributions from seawater (because these samples are also having TDS >500 $mg.L^{-1}$; Haunslow, 1995); however most of the high TDS waters having Na source other than halite such as plagioclase feldspars and/or natural softening (Haunslow, 1995). This is also supported by the plot of TDS vs (Mg^{2+}:Ca^{2+}) (Fig. 5B) where few samples—those lie above the Mg^{2+}:Ca^{2+} = 1 line—might have seawater contribution. Figures 5C and 5D suggest major contribution of carbonate weathering to the groundwater chemistry and the source of calcium is mostly carbonates.

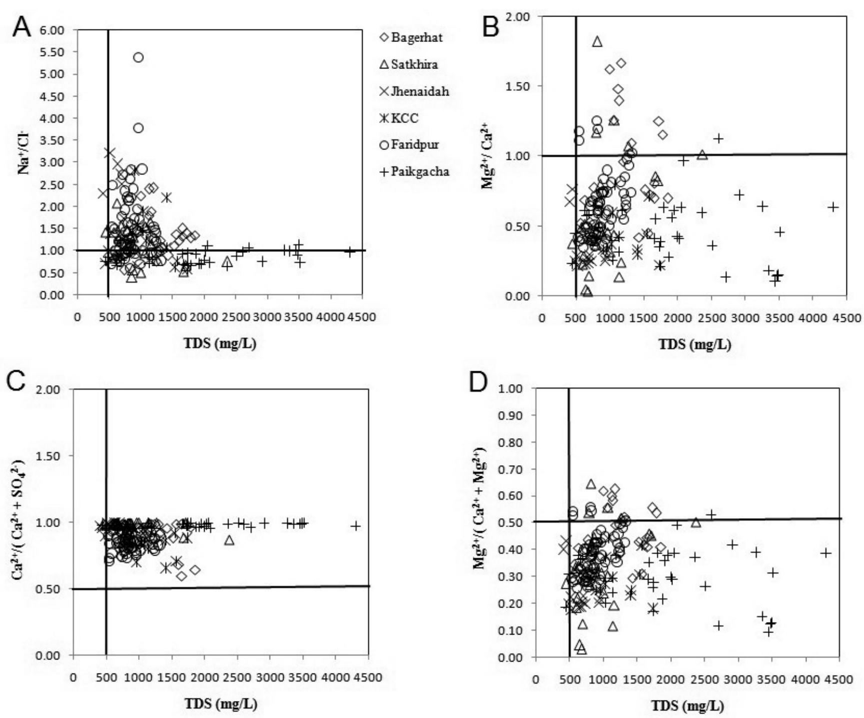

Fig. 5A-D: Molar ionic ratio: (A) TDS *vs* Na^+/Cl^-, (B) TDS *vs* Mg^{2+}/Ca^{2+}, (C) TDS *vs* $Ca^{2+}/(Ca^{2+} + SO_4^{2-})$ and (D) TDS vs $Mg^{2+}/(Ca^{2+} + Mg^{2+})$.

The plot of TDS vs Cl^{-1}: (sum of anions) (Fig. 6A) and TDS vs HCO_3^{-1}: (sum of anions) (Fig. 6B) suggests contribution both from rock weathering and sea water in the aquifer chemistry of southwestern municipalities of Bangladesh. The plot of TDS vs Na^+: ($Na^+ + Cl^-$) in $meq.L^{-1}$ (Fig. 6C) suggests sodium sources both from seawater (41%) and plagioclase such as albite

(59%). Figure 6D suggests both albite weathering and cation exchange as major geochemical processes occurring in the groundwater chemistry. Thus molar ratios among different parameters and their combinations indicate that the dominant process controlling the groundwater chemistry is rock weathering and the source rocks are both carbonates and plagioclase silicates; however, seawater intrusion to the groundwater is quite revealing.

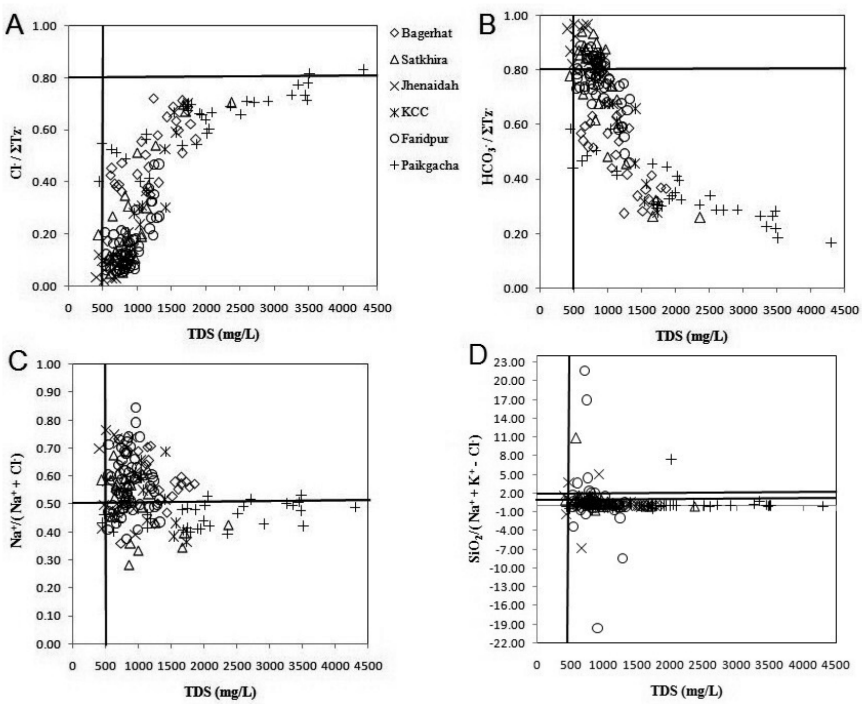

Fig. 6A-D: Molar ionic ratio: (A) TDS *vs* $Cl^-/\Sigma Tz^-$, (B) TDS *vs* $HCO_3^-/\Sigma Tz^-$, (C) TDS *vs* $Na^+/(Na^+ + Cl^-)$ and (D) TDS *vs* $SiO_2/(Na^+ + K^+ - Cl^-)$.

Concentration of alkali earth elements such as Ca and Mg (27% - 88% of total cation) and the concentration of alkalinity (bicarbonates 37% - 89% of total anions) and the (Ca+Mg):(Na+K) and HCO_3: SiO_2 ratio (0.15 to 14.77 and 8.62 to 1587.80 respectively) in the aquifer chemistry of the southwestern municipalities suggest that dominance of carbonate weathering is not always expected although records show that carbonate weathering is dominant in the Bengal delta (Datta and Subramanian, 1997). Such variation may be due to the location of the municipalities at the proximity to sea at the coastal zone where saline water may intrude the aquifers. Further the southwest region of Bangladesh is experiencing waterlog condition during the last about four decades because of construction of enclosures (called polders) and the tidal processes are restricted to the river valley. Such physical alteration to the natural processes might have bearing on the processes of salinization because of the processes that exists between ground and surface waters (Margat, 1994). Moreover, the municipalities are locations where overexploitation of groundwater takes place. In this case localized upwelling of saline water may also be responsible for high TDS Na-Cl rich water in the wells.

The TDS does not show good correlation with borehole depth ($r = 0.205$) and also the correlation coefficient of TDS with Na^+:Cl^- ratio ($r = -0.259$) and with Ca^{2+}: Mg^{2+} ratio ($r = 0.034$) at 1% significance level is poor suggesting that contribution to TDS from saline water of oceanic origin is not significant. On the contrary Na^+ and Cl^- ions show perfect correlation ($r = 0.96$) at 1% level suggesting their co-origin. Significant correlation also may be observed (Table 4) between Ca^{2+} with Mg^{2+} and HCO_3^- ($r = 0.491$ and 0.463 respectively) suggesting their co-origin as well.

Saturation Index

The plot of calcite saturation index (CSI) *vs* the dolomite SI (DSI) in Fig. 7 suggests that most of the municipality groundwater (Bagerhat 100%, Faridpur 96%, KCC 100%, Satkhira 88% and Jhenidah 100%) are super-saturated with respect to both calcite and dolomite. Lack of nucleation for calcite precipitation may be responsible for this general supersaturation (Huh et al., 1998). While most of the Paikgacha (97%) ground water are under-saturated with respect to both calcite and dolomite.

Controlling Mechanism

Gibb's plot (Fig. 8) as suggested by Gibbs (1970) shows that all the water samples have a tendency to cluster along the line transitional between the processes of rock weathering and evaporation and crystallization as representing mechanism controlling the water chemistry. However the Paikgacha samples are heading more towards the evaporation-crystallization apex of the boomerang along with few samples from other municipalities. Thus the control of water chemistry is gradually commanded by the processes of evaporation and crystallization and consequently the processes of salinization that may be due to the proximity of the municipalities to the sea.

Water Type

The hydrogeochemical facies of the municipality groundwater may be deciphered by trilinear diagrams (Fig. 9) following Piper (1944). Such diagram also provides knowledge on chemical relationships among samples in more definite terms (Walton, 1970). Figure 9 suggests that the Bagerhat and Paikgacha ground water are of both Na-HCO_3 and Na-Cl type while ground water from Faridpur, Satkhira, Jhenaidah and Khulna City Corporation (KCC) are of Ca-Mg-HCO_3 type. Also few samples from Satkhira are of Ca-Cl type. Such variation in water type suggests that groundwater of Bagerhat

Table 4: Pearson correlation coefficient (*r*) matrix for different chemical parameters of groundwater of the municipalities of the southwestern coastal Bangladesh (*n* = 170)

	pH	*TDS*	*EC*	Na^+	K^+	Ca^{2+}	Mg^{2+}	HCO_3^-	Cl^-	SO_4^{2-}	PO_4^{3-}	SiO_2
pH	1											
TDS	-0.504**	1										
EC	-0.592**	0.967**	1									
Na^+	-0.411**	0.952**	0.944**	1								
K^+	-0.388**	0.531**	0.535**	0.498**	1							
Ca^{2+}	-0.659**	0.579**	0.593**	0.384**	0.319**	1						
Mg^{2+}	-0.398**	0.387**	0.328**	0.217**	0.216**	0.491**	1					
HCO_3^-	-0.233**	0.671**	0.544**	0.520**	0.354**	0.463**	0.365**	1				
Cl^-	-0.521**	0.971**	0.972**	0.953**	0.515**	0.528**	0.328**	0.488**	1			
SO_4^{2-}	0.309**	-0.143	-0.248**	-0.215**	-0.169*	-0.078	0.175*	0.133	-0.246**	1		
PO_4^{3-}	0.267**	-0.275**	-0.316**	-0.279**	-0.213**	-0.238**	0.051	-0.028	-0.334**	0.414**	1	
SiO_2	-0.159*	-0.247**	-0.320**	-0.345**	-0.239**	-0.118	-0.018	0.028	-0.301**	0.143	0.189*	1

** Correlation significant at 1% level estimated using 2-tailed t-test statistic; * Correlation significant at 5% level estimated using 2-tailed t-test statistic.

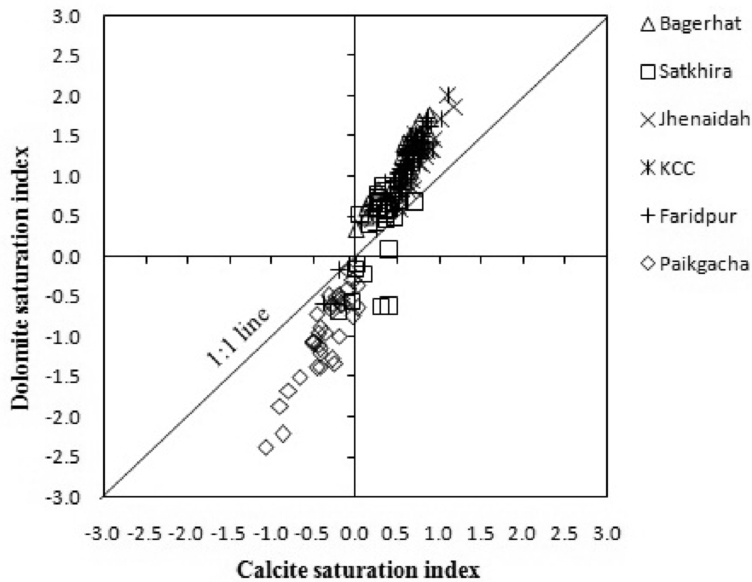

Fig. 7: Plots of CSI *vs* DSI in groundwater of southwestern coastal municipalities of Bangladesh.

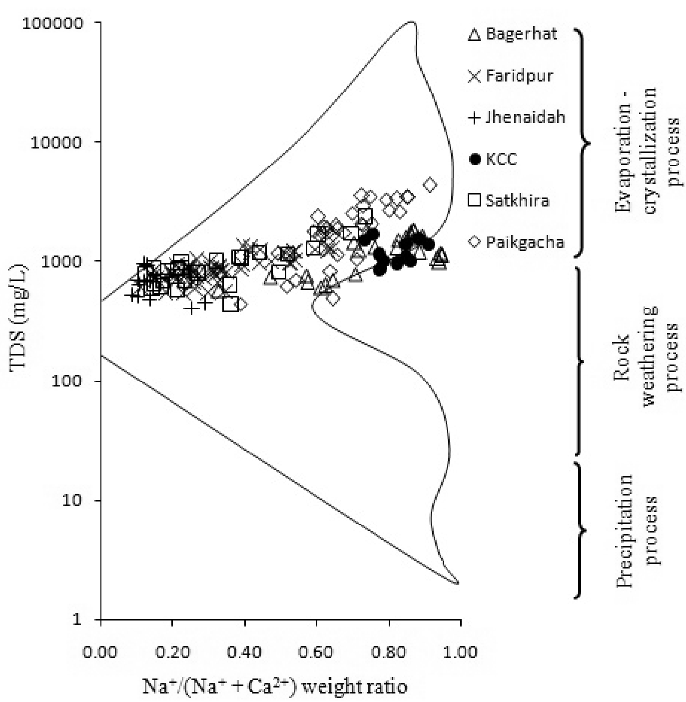

Fig. 8: Gibb's plot with groundwater from southwestern coastal municipalities of Bangladesh as suggested by Gibbs (1970) deciphering mechanism controlling water chemistry.

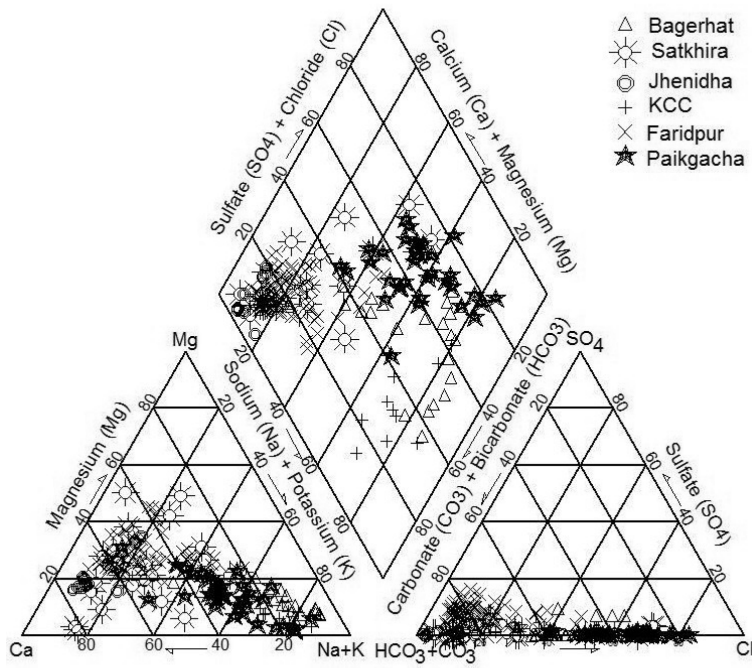

Fig. 9: Piper plots for the municipality groundwater.

and Paikgacha and few locations of Satkhira municipalities are vulnerable to salinization.

Plotting samples in Chadha's diagram (Fig. 10) following Chadha (1999) is also useful in characterising the chemical nature of the solute load. Figure 10 shows that most of the groundwater samples from Faridpur, Satkhira and Jhenaidah occupies the temporary hardness field. Alkaline earths (Ca and Mg) and the weak acidic ions (such as HCO_3) exceed both alkali metals (Na and K) and strong acidic ions (such as SO_4) respectively in this field and represent Ca^{2+}-Mg^{2+}-HCO_3^--type, Ca^{2+}-Mg^{2+}- dominant HCO_3^- -type or HCO_3^- -dominant Ca^{2+}-Mg^{2+}- type waters (Chadha, 1999).

Most of the samples from KCC and few Bagerhat samples occupy the field where alkali metals > alkaline earth and weak acidic anions > strong acidic anions. Such waters are prone to deposit residual sodium carbonate and represent Na^+-HCO_3^- -type, Na^+-dominant HCO_3^- -type, or HCO_3^--dominant Na^+- type water (Chadha, 1999). They are not good quality water for irrigation and potable purpose. Almost all the samples from Paikagacha and most of the samples from Bagerhat and few samples from KCC occupies the field where alkali metals > alkaline earths and strong acidic anions > weak acidic anions. Such waters are saline and represent Na^+-Cl^--type, Na_2SO_4-type, Na^+-dominant Cl^--type or Cl^--dominant Na^+-type waters (Chadha, 1999). Few Satkhira samples occupy the permanent hardness field as well.

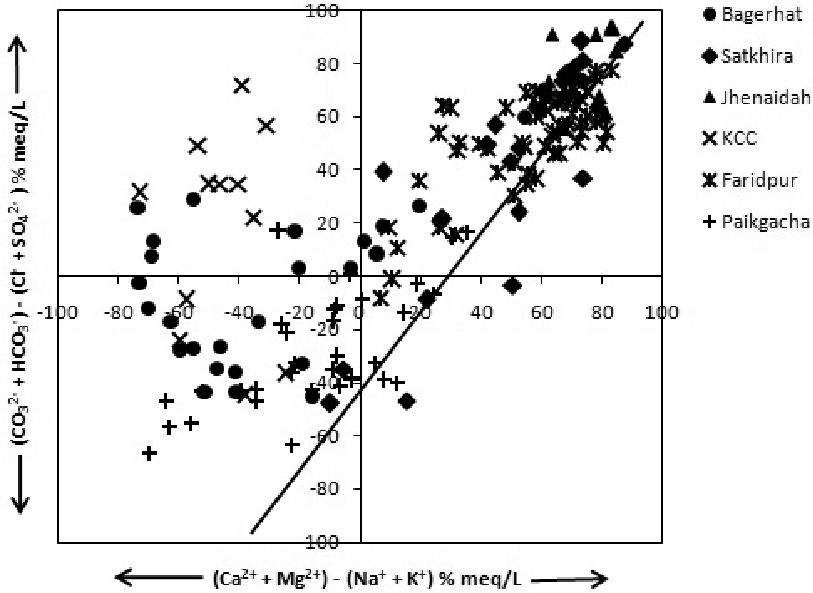

Fig. 10: Chadha's plots for the municipality groundwater.

Quality of Groundwater

Water quality is of definite concern worldwide and the chemical analysis of potable water ultimately leads to answer the suitability of groundwater for specific purposes. The water quality for potable purpose in the present compilation is assessed with respect to the standard as defined in Bangladesh (Huq, 2002) and that of World Health Organization (WHO, 1993) and presented in Table 5.

With respect to TDS, groundwaters in most municipalities of southwestern Bangladesh do not accord with standard and in few cases such as in KCC, Faridpur and Paikgacha almost 100% of the samples exceed desirable limit for safe drinking water. Similarly considerable number of samples in most municipalities exceed the desirable limit with respect to other estimated parameters as shown in Table 5. This suggests that groundwater in municipalities of the southwestern Bangladesh is experiencing vulnerability due to their chemical assembly.

Such vulnerabilities to groundwater resources in municipalities of southwestern Bangladesh may result from over-exploitation due to increase in population density and growth, due to consequences of rapid climate change and on transnational relationships with neighbouring countries (Chowdhury, 2010). It has been estimated that per annum water availability will decrease by 7670 m^3 from 12,162 m^3 in 1991 because of the enhanced water demand for a hefty mass of population by 2025 (Ahmed et al., 2001 as mentioned in

Table 5: Groundwater quality of the municipalities of southwestern coastal Bangladesh

Chemical parameters of groundwater	*DoE (Bangladesh) standard*	*WHO standard*		*Sample status for Bangladesh standard*	*Sample status for WHO standard*	
		Desirable limit	*Maximum allowable limit*	*Percentage of samples exceeding the standard*	*Percentage of samples exceeding the desirable limit*	*Percentage of samples exceeding the maximum allowable limit*
				Bagerhat municipality (*n* = 26)		
pH	6.5-8.5	7.0-8.5	6.5-9.2	Nil	Nil	Nil
EC (µS/cm)	–	750	1500	–	100%	65.39%
TDS (mg.L^{-1})	1000	500	1500	46.15%	88.45%	19.23%
Na^+ (mg.L^{-1})	200	–	200	62.23%	–	62.23%
K^+(mg.L^{-1})	12	–	12	7.70%	–	7.70%
Ca^{2+} (mg.L^{-1})	75	75	200	19.23%	19.23%	Nil
Mg^{2+} (mg.L^{-1})	30-35	50	150	26.92%	3.85%	Nil
HCO_3^- (mg.L^{-1})	–	300	–	–	100%	–
Cl^- (mg.L^{-1})	150-600	200	600	Nil	57.70%	Nil
SO_4^{2-} (mg.L^{-1})	400	200	400	Nil	Nil	Nil
PO_4^{3-} (mg.L^{-1})	6	–	–	Nil	–	–
				Satkhira municipality (*n* = 25)		
pH	6.5-8.5	7.0-8.5	6.5-9.2	Nil	40%	Nil
EC (µS/cm)	–	750	1500	–	76%	20%
TDS (mg.L^{-1})	1000	500	1500	16%	52%	4%
Na^+ (mg.L^{-1})	200	–	200	12%	–	12%
K^+(mg.L^{-1})	12	–	12	12%	–	12%

(*Contd*)

Table 5: (*Contd*)

Chemical parameters of groundwater	*DoE (Bangladesh) standard*	*WHO standard*		*Sample status for Bangladesh standard*	*Sample status for WHO standard*	
		Desirable limit	*Maximum allowable limit*	*Percentage of samples exceeding the standard*	*Percentage of samples exceeding the desirable limit*	*Percentage of samples exceeding the maximum allowable limit*
Ca^{2+} (mg.L^{-1})	75	75	200	96%	96%	Nil
Mg^{2+} (mg.L^{-1})	30-35	50	150	48%	32%	Nil
HCO_3^- (mg.L^{-1})	–	300	–	–	96%	–
Cl^- (mg.L^{-1})	150-600	200	600	16%	16%	16%
SO_4^{2-} (mg.L^{-1})	400	200	400	Nil	Nil	Nil
NO_3^- (mg.L^{-1})	–	45	–	–	Nil	–
PO_4^{3-} (mg.L^{-1})	6	–	–	Nil	–	–
Khulna City Corporation (KCC) (n = 12)						
pH	6.5-8.5	7.0-8.5	6.5-9.2	Nil	Nil	Nil
EC (µS/cm)	–	750	1500	–	100%	41.67%
TDS (mg.L^{-1})	1000	500	1500	75%	100%	66.67%
Na^+ (mg.L^{-1})	200	–	200	41.67%	–	41.67%
K^+(mg.L^{-1})	12	–	12	Nil	–	Nil
Ca^{2+} (mg.L^{-1})	75	75	200	16.67%	16.67%	Nil
Mg^{2+} (mg.L^{-1})	30-35	50	150	Nil	Nil	Nil
HCO_3^- (mg.L^{-1})	–	300	–	–	100%	–
Cl^- (mg.L^{-1})	150-600	200	600	16.67%	50%	16.67%
SO_4^{2-} (mg.L^{-1})	400	200	400	Nil	Nil	Nil
PO_4^{3-} (mg.L^{-1})	6	–	–	Nil	–	–

(*Contd*)

Table 5: (*Contd*)

				Jhenaidah municipality (*n* = 12)		
pH	6.5-8.5	7.0-8.5	6.5-9.2	Nil	Nil	Nil
EC (μS/cm)	–	750	1500	–	41.67%	Nil
TDS ($mg.L^{-1}$)	1000	500	1500	Nil	16.67%	Nil
Na^{+} ($mg.L^{-1}$)	200	–	200	Nil	–	Nil
K^{+}($mg.L^{-1}$)	12	–	12	Nil	–	Nil
Ca^{2+} ($mg.L^{-1}$)	75	75	200	83.34%	83.34%	Nil
Mg^{2+} ($mg.L^{-1}$)	30-35	50	150	Nil	Nil	Nil
HCO_3^- ($mg.L^{-1}$)	–	300	–	–	91.67%	–
Cl^- ($mg.L^{-1}$)	150-600	200	600	Nil	Nil	Nil
SO_4^{2-} ($mg.L^{-1}$)	400	200	400	Nil	Nil	Nil
NO_3^- ($mg.L^{-1}$)	–	45	–	–	Nil	–
PO_4^{3-} ($mg.L^{-1}$)	6	–	–	Nil	–	–
				Faridpur municipality (*n* = 60)		
pH	6.5-8.5	7.0-8.5	6.5-9.2	Nil	Nil	Nil
EC (μS/cm)	–	750	1500	–	81.67%	16.67%
TDS ($mg.L^{-1}$)	1000	500	1500	43.33%	100%	Nil
Na^{+} ($mg.L^{-1}$)	200	–	200	3.34%	–	3.34%
K^{+}($mg.L^{-1}$)	12	–	12	Nil	–	Nil
Ca^{2+} ($mg.L^{-1}$)	75	75	200	95%	95%	Nil
Mg^{2+} ($mg.L^{-1}$)	30-35	50	150	56.67%	16.67%	Nil
HCO_3^- ($mg.L^{-1}$)	–	300	–	–	100%	–
Cl^- ($mg.L^{-1}$)	150-600	200	600	Nil	6.67%	Nil
SO_4^{2-} ($mg.L^{-1}$)	400	200	400	Nil	Nil	Nil

(*Contd*)

Table 5: (*Contd*)

Chemical parameters of groundwater	*DoE (Bangladesh) standard*	*WHO standard*		*Sample status for Bangladesh standard*	*Sample status for WHO standard*	
		Desirable limit	*Maximum allowable limit*	*Percentage of samples exceeding the standard*	*Percentage of samples exceeding the desirable limit*	*Percentage of samples exceeding the maximum allowable limit*
NO_3^- ($mg.L^{-1}$)	–	45	–	–	Nil	–
PO_4^{3-} ($mg.L^{-1}$)	6	–	–	Nil	–	–
Paikgacha municipality (n = 35)						
pH	6.5-8.5	7.0-8.5	6.5-9.2	100%	100%	Nil
EC (µS/cm)	–	750	1500	–	97.14%	80%
TDS ($mg.L^{-1}$)	1000	500	1500	82.85%	94.28%	71.42%
Na^+ ($mg.L^{-1}$)	200	–	200	71.42%	–	71.42%
K^+($mg.L^{-1}$)	12	–	12	51.42%	–	51.42%
Ca^{2+} ($mg.L^{-1}$)	75	75	200	88.57%	88.57%	20%
Mg^{2+} ($mg.L^{-1}$)	30-35	50	150	54.28%	31.42%	Nil
HCO_3^- ($mg.L^{-1}$)	–	300	–	–	88.57%	–
Cl^- ($mg.L^{-1}$)	150-600	200	600	65.71%	85.71%	54.28%
SO_4^{2-} ($mg.L^{-1}$)	400	200	400	Nil	Nil	Nil
PO_4^{3-} ($mg.L^{-1}$)	6	–	–	–	Nil	–

Chowdhury, 2010). This would expedite over-exploitation of groundwater for potable purposes and would increase possibility of upwelling and the coastal area is most prone to such phenomenon.

The second important factor that may jeopardize groundwater management in coastal cities of southwestern Bangladesh can be envisioned from reports on climate change and its consequences that salinity front would move upwards into the coastal areas and drainage congestion would increase (World Bank, 2000), thus such driving force may create uncertainty in groundwater management.

Salinity intrusion into the southwestern coastal aquifers is of great concern in recent years particularly during dry season (Rahman and Bhattacharya, 2006) and such phenomenon has amplified after Ganges water diversion at Farrakka in West Bengal. The low water flow along the river system between India and Bangladesh is supposed to be the major reason for this salinization of alluvial aquifers. More than 93% of the river flow have been estimated to enter Bangladesh from upper riparian countries (Ahmad et al., 2001). Thus the transnational relationship of Bangladesh with countries within the GBM drainage basin, particularly with India would have vital bearing on groundwater management of the southwestern coastal Bangladesh.

The National Water Policy of Bangladesh was developed in 1999 where water demands for potable purposes in municipalities were given due priority (MWR, 1999; WARPO, 1999). The deep aquifers in the southwestern coastal Bangladesh are most vulnerable to salinity intrusion because of excessive draw-down (Brammer, 2010) and are at risk from arsenic contamination infiltrating from shallow aquifers in long run (Ravenscroft et al., 2005). Thus the National Water Policy deserves restrictions and implementing embargo of groundwater withdrawal and a conjunctive use with surface water may be prescribed. Further there could be surface water reserves in abandoned river channels (called baors) that may supplement the water demand during lean period.

Conclusion

The geochemical analysis and interpretation of groundwater from major municipalities of southwestern coastal Bangladesh suggest that the aquifers are vulnerable geochemically and in risk of salinity intrusion. Although the geochemical mechanism controlling the chemistry of groundwater is rock weathering but is gradually commanded by the processes of evaporation and crystallization and most groundwaters have a propensity towards saline environment. These waters do not accord with standard good for potable purposes. Thus the aquifers need to be managed suitably following water use regulations.

REFERENCES

Adhikary, S.K., Manjur-A-Elahi, M. and A.M.I. Hossain (2012). Assessment of shallow groundwater quality from six wards of Khulna City Corporation, Bangladesh. *Int. Journal of Applied Sciences and Engineering Research*, **1(3):** 488-498.

Adri, N. and I. Islam (2012). Vulnerability and Coping Strategies in Waterlogged Area: A Case Study from Keshabpur, Bangladesh. *International Journal of Environment*, **2(1):** 48-56.

Aggarwal, P.K., Basu, A.R., Poreda, R.J., Kulkarni, K.M., Froehlich, K., Tarafdar, S.A., Ali, M., Ahmed, N., Hussain, A., Rahman, M. and S.R. Ahmed (2000). A Report on Isotope Hydrology of Groundwater in Bangladesh: Implications for characterization and mitigation of arsenic in groundwater. Report prepared within the IAEA-TC project BGD/8/016.

Ahmad, M. (2005). Living in the Coast-Urbanization. PDO-ICZMP, Ministry of Water Resources and Water Resources Planning Organization (WARPO), Government of the People's Republic of Bangladesh, Dhaka.

Ahmad, Q.K., Biswas, A.K., Rangachari, R. and M.M. Sainju (eds) (2001). Gange-Brahmaputra-Meghna Region: A Framework for Sustainable Development. University Press Limited, Dhaka, Bangladesh.

Ahmed, A. (2011). Some of the major environmental problems relating to land use changes in the coastal areas of Bangladesh: A review. *Journal of Geography and Regional Planning*, **4(1):** 1-8.

Alam, M.K., Hasan, A.K.M.S., Khan, M.R. and J.W. Whitney (1990). Geological Map of Bangladesh. Geological Survey of Bangladesh (GSB), Dhaka.

B.B.S. (2011). Population and Housing Census – Socio-economic and Demographic Report. National Report, Volume 4, Bangladesh Bureau of Statistics, Statistics and Informatics Division (SID), Ministry of Planning**,** Government of the People's Republic of Bangladesh.

Bahar, M.M. and M.S. Reza (2010). Hydrochemical characteristics and quality assessment of shallow groundwater in a coastal area of southwest Bangladesh. *Environ Earth Sci*, **61:** 1065-1073.

Barlow, P.M. (2003). Groundwater in Freshwater-Saltwater Environments of the Atlantic Coast. U.S. Geological Survey Circular: 1262.

Barua, D.K. (1991). The coastline of Bangladesh – An overview of processes and forms. Proceedings of 7th symposium on Coastal and Oceanic Management, ASCE/Long Beach, CA.

Biswas, D. (2004). Chemical vulnerability of aquifers in Khulna City Corporation Area. Unpublished B.Sc. thesis. Environmental Science Discipline, Khulna University, Khulna - 9208, Bangladesh.

Brammer, H. (2010). After the Bangladesh Flood Action Plan: Looking to the future. *Environmental Hazards*, **9:** 118-130.

Burgess, W.G., Hoque, M.A., Michael, H.A., Voss, C.I., Breit, G.N. and K.M. Ahmed (2010). Vulnerability of deep groundwater in the Bengal aquifer system to contamination by arsenic. *Nature Geoscience*, **3:** 83-87.

BWDB (2013). Hydrogeological study and mathematical modeling to identify sites for installation of observation well nests, selection on model boundary, supervision of pumping test, slug test, assessment of different hydrological parameters collection and conduct chemical analysis of surface water and ground water. Main Report, Bangladesh Water Development Board and Institute of Water Modelling.

BWDB-UNDP (1982). Groundwater Survey: The Hydrogeological Conditions of Bangladesh. UNDP Technical Report DP/UN/ BGD–74-009/1.

Chadha, D.K. (1999). A proposed new diagram for geochemical classification of natural waters and interpretation of chemical data. *Hydrogeology Journal*, **7:** 431-439.

Chidambaram, S., Kumar, G.S., Prasanna, M.V., Peter, A.J., Ramanthan, AL. and K. Srinivasamoorthy (2009). A study on the hydrogeology and hydrogeochemistry of groundwater from different depths in a coastal aquifer: Annamalai Nagar, Tamilnadu, India. *Environ Geol*, **57:** 59-73.

Chowdhury, N.T. (2010). Water management in Bangladesh: An analytical review. *Water Policy*, **12:** 32-51.

Das, R. (2006). Nature of dissolved solute load in the water from aquifer of Bagerhat municipality. Unpublished B.Sc. thesis. Environmental Science Discipline, Khulna University, Khulna-9208, Bangladesh.

Datta, D.K. and V. Subramanian (1997). Nature of solute loads in the rivers of Bengal drainage basin, Bangladesh. *J Hydrol*, **198:** 196-208.

Dey, S.K. (2007). Nature of solute load from aquifers in and around the Satkhira municipality, southwest Bangladesh. Unpublished B.Sc. thesis. Environmental Science Discipline, Khulna University, Khulna - 9208, Bangladesh.

DPHE-BGS (1999). Groundwater studies for arsenic contamination in Bangladesh. Final Report, Rapid investigation phase. Department of Public Health Engineering, Government of Bangladesh, Mott MacDonald and British Geological Survey.

DPHE-BGS (2001). Arsenic contamination of groundwater in Bangladesh. Vol 2. Final Report, BGS Tech. Report WC/00/19.

Finkl, C.W. Jr. (1994). Coastal hazards, perception, susceptibility and mitigation. *J Coast Res*, **12:** 372 (special issue).

Ghosh, P.K., Sikder, M.S., Parvin, R. and A.K. Bhattacharjee (2012). Drinking quality assessment of south-western coastal groundwater – An indication of shallow groundwater quality deterioration in Bangladesh. *Bangladesh Journal of Public Administration*, **XXI(II):** 105-114.

Gibbs, R.J. (1970). Mechanisms controlling world's water chemistry. *Science*, **170:** 1088-1090.

Greenberg, A.E., Cleseceri, L.S. and A.D. Eaton (1992). Standard Methods for the Examinations of Water and Waste Water. 18th edition, APHA, Washington DC, USA.

Haque, A.K.M.M., Jahan, M.S. and M.A.K. Azad (2010). Shrimp culture impact on the surface and ground water of Bangladesh. *Iranian Journal of Earth Sciences*, **2:** 125-132.

Harun, M.A.Y.A. and G.M.M. Kabir (2013). Evaluating pond sand filter as sustainable drinking water supplier in the Southwest coastal region of Bangladesh. *Appl Water Sci*, **3:** 161-166.

Hounslow, A.W. (1995). Water Quality Data: Analysis and Interpretation. Lewis Publisher, Boca Raton, USA.

Huh, Y., Tsoi, M.Y., Zaitsev, A. and J.M. Edmond (1998). The fluvial geochemistry of the rivers of Eastern Siberia: I. Tributaries of the Lena River draining the sedimentary platform of the Siberian Craton. *Geochimica et Cosmochimica Acta*, **62(10):** 1657-1676.

Huq, M.E. (2002). Poribesh Ain Sangkalan (Compilation of Environmental Law). Department of Environment and Bangladesh Environmental Management Project (BEMP), Dhaka, Bangladesh.

Islam, M.A., Sakakibara, H., Karim, M.R. and M. Sekine (2011). Evaluation of risk communication for rural water supply management: A case study of a coastal area of Bangladesh. *Journal of Risk Research*, **14(10):** 1237-1262.

Khanom, S. and M. Salehin (2012). Salinity constraints to different water uses in coastal area of Bangladesh: A case study. *Bangladesh Journal of Scientific Research*, **25(1):** 33-42.

Kim, J.H., Kim, R.H. and H.W. Chang (2003). Hydrogeochemical characterization of major factors affecting the quality of shallow groundwater in the coastal area at Kimje in South Korea. *Environmental Geology*, **44:** 478-489.

M.W.R. (1999). National Water Policy. The Ministry of Water Resources, Government of the People's Republic of Bangladesh, Dhaka, Bangladesh.

Margat, J. (1994). Groundwater operations and management. *In:* Gibert, J., Danielopol, D. and Stanford, J. (eds), Groundwater ecology. Academic Press, San Diego.

Morell, I., Gime'nez, E. and M.V. Esteller (1996). Application of principal components analysis to the study of salinization on the Castellon Plain (Spain). *Science of the Total Environment*, **177:** 161-171.

Nadler, A., Magaritz, M. and E. Mazor (1981). Chemical reactions of seawater with rocks and freshwater experimental and field observations on brackish waters in Israel. *Geochemica et Cosmotica Acta*, **44:** 879-886.

Nickson, R.T., McArthur, J.M., Shrestha, B., Kyaw-Nyint, T.O. and D. Lowry (2005). Arsenic and other drinking water quality issues, Muzaffargarh District, Pakistan. *Appl Geochem*, **20:** 55-68.

Nobi, N. and A.D. Gupta (1997). Simulation of regional flow and salinity intrusion in an integrated stream-aquifer system in coastal region: Southwest region of Bangladesh. *Groundwater*, **35(5):** 786-796.

Ollier, C. (1969). Weathering. Oliver and Boyd, Edinburgh.

Paul, S.K. (2014). Hydrogeochemical characterization of ground and surface water in Faridpur Municipality area. Unpublished M.Sc. thesis. Environmental Science Discipline, Khulna University, Khulna - 9208, Bangladesh.

Piper, A.M. (1944). A graphical procedure in the geochemical interpretation of water. *Am Geophys Union Trans*, **25:** 914-928.

Rahman, M.A.T.M.T., Majumder, R.K., Rahman, S.H. and M.A. Halim (2011). Sources of deep groundwater salinity in the southwestern zone of Bangladesh. *Environ Earth Sci*, **63:** 363-373.

Rahman, M.A.T.M.T., Rahman, S.H. and R.K. Majumder (2012). Groundwater quality for irrigation of deep aquifer in southwestern zone of Bangladesh. *J Sci Technol*, **34(3):** 345-352.

Rahman, M.M. and A.K. Bhattacharya (2006). Salinity intrusion and its management aspects in Bangladesh. *Journal of Environmental Hydrology*, **14(14):** 1-8.

Rashid, H.E. (1991). Geography of Bangladesh. University Press Limited, Dhaka.

Ravenscroft, P., Burgess, W.G., Ahmed, K.M., Burren, M. and J. Perrin (2005). Arsenic in groundwater of the Bengal Basin, Bangladesh: distribution, field relations, and hydrogeological setting. *Hydrogeol J*, **13:** 727-751.

S.D.P. (2011). Water Supply and Sanitation Sector in Bangladesh. Sector Development Plan (FY 2011-25), Ministry of Local Government, Rural Development and Cooperatives, Government of the People's Republic of Bangladesh.

Sarkar, D.K. (2008). Nature of solute load from aquifers in and around Jhenaidahmunicipality, southwest Bangladesh. Unpublished B.Sc. thesis. Environmental Science Discipline, Khulna University, Khulna - 9208, Bangladesh.

Sukhija, B.S., Varma, V.N., Nagabhushanam, P. and D.V. Reddy (1996). Differentiation of paleomarine and modern seawater intruded salinities in coastal groundwaters (of Karaikal and Tanjavur, India) based on inorganic chemistry, organic biomarker fingerprints and radiocarbon dating. *Journal of Hydrology*, **174:** 173-201.

UNEP (1999). Global Environment Outlook 2000. United Nations Environment Program, Earthscan, UK.

Vandenbohede, A., Houtte, E.V. and L. Lebbe (2009). Sustainable groundwater extraction in coastal areas: A Belgian example. *Environ Geol*, **57:** 735-747.

W.A.R.P.O. (1999). National Water Management Plan. Water Resources Planning Organization, Dhaka, Bangladesh.

Walton, W.C. (1970). Groundwater Resources Evaluation. McGraw Hill Book Co., New York, USA.

WHO (1993). Guidelines for Drinking Water Quality. World Health Organization, volume 1, recommendations, 2nd edition, Geneva.

WHO (2004). Occurrence of Cyanobacterial Toxins (microcystins) in Surface Waters of Rural Bangladesh. Water, Sanitation and Health Protection of the Human Environment, World Health Organization, Geneva.

World Bank (2000). Bangladesh: Climate Change and Sustainable Development. Bangladesh Report No. 21104-BD, Rural Development Unit, South Asia Region, Document of the World Bank.

Yokota, H., Tanabe, K., Sezaki, M., Yano, Y., Hamabe, K., Yabuuchi, K., Tokunaga, H., AAN, RGAG and NIPSOM (2002). Arsenic contamination in groundwater of Samta, Bangladesh. *Water Science and Technology*, **46(11-12):** 375-380.

Zahid, A., Hasan, M.R., Jahan, K., Ahmed, N. and S. Afrin (2014). Groundwater salinity distribution in the coastal aquifers of Bangladesh and sustainable use of limited fresh water. Proceedings of the 2nd Regional Conference on Disaster Risk Reduction and Climate Change Adaptation – 2013, JJS, Khulna.

Zahid, A., Hassan, M.Q. and K.M.U. Ahmed (2012). Model simulation on groundwater development stresses to determine sustainable zones of multi-layered aquifer system in Bengal basin. *In:* Zahid et al. (eds), Impact of Climate Change on Water Resources and Food Security of Bangladesh. German Academic Exchange Service (DAAD) and AAGUB.

Zahid, A., Hassan, M.Q., Balke, K.D., Flegr, M. and D.W. Clark (2008). Groundwater chemistry and occurrence of arsenic in the Meghna floodplain aquifer, southeastern Bangladesh. *Environ Geol*, **54:** 1247-1260.

Zahid, A., Hassan, M.Q., Imes, J.L. and D.W. Clark (2009). Hydraulic characterization of aquifers and pump test data analysis of deep aquifer in the arsenic affected Meghna river floodplain of Bangladesh. *Environmental Research Journal*, **3(2/3):** 325-355.