Research Article

Assessment of river water–groundwater–seawater interactions in the coastal delta of Bangladesh based on hydrochemistry and salinity distribution

Sushanta Kumar Roy[1] · Anwar Zahid[2,3]

Received: 3 September 2020 / Accepted: 16 February 2021 / Published online: 4 March 2021

Abstract
A synchronization study among hydrochemistry, hydrochemical facies evaluation, EC observation, salinity distribution and groundwater flow direction has been addressed to assess river water–groundwater–seawater interactions in the coastal delta of southern Bangladesh. The findings show that river water, shallow groundwater and deep groundwater interact with seawater at various intensities within the complex dynamics of hydrochemical facies evaluation. Deep groundwater is intensively influenced by seawater, where shallow groundwater is moderately affected and river water is very negligibly affected. Major cation and anion have been plotted in the Piper diagrams and hydrochemical facies diagrams (HFE-D) to clarify the result. More than 60% of the water samples of the river lie on the Ca-HCO_3 (or Mg-HCO_3) facies quadrant, and more than 70% of the shallow groundwater samples and more than 95% of the deep groundwater samples lie on the Na-Cl facies quadrant of the HFE-D diagram. River water types are dissimilar, and approximately 82% of facies are characterized by freshening phases and 18% by intrusion phases. Mixed water types with predominate of Na-Cl were observed in shallow groundwater where the hydrochemical facies are characterized by 53 percent freshening phases and 47 percent intrusion phases. Deep groundwater hydrochemistry clearly indicates the dominant Na-Cl type of water in the study area where only four hydrochemical facies are observed and 78 percent correspond to the intrusion phases and 22 percent to the freshening phases. Both direct and reverse cation exchange reactions take place in shallow groundwater, where deep groundwater is predominantly characterized by reverse cation exchange reactions. Two end members: seawater of Bay of Bengal and freshwater, contribute to the exchange reactions in the coastal aquifer of the study area. In terms of nitrate contamination, river waters are affected by negligible to low concentrations, shallow groundwater is affected by moderate to high concentrations and deep groundwater is affected by moderate to very high nitrate concentrations. Dissimilarity in electrical conductivity (EC) values, variation of salinity distribution maps and groundwater flow direction suggest the possible interconnections among river water, groundwater and aquifer sediments. Significant concentrations of Na^+ and Cl^- ions lead to seawater contamination in groundwater, and HCO_3^- along with Na^+, Ca^{2+}, Mg^{2+} in river water suggests mixing of freshwater and seawater, which could have adverse effects both in coastal delta aquatic life and in agriculture.

Keywords River water · Groundwater · Seawater · Hydrochemistry · Salinity distribution · Coastal area · Bangladesh

✉ Sushanta Kumar Roy, sushanta.bwdb@gmail.com; Anwar Zahid, anwarzahidb@gmail.com | [1]Barapukuria Coal Mining Company Ltd, Chowhati, Parbatipur, Dinajpur, Bangladesh. [2]Ground Water Hydrology, Bangladesh Water Development Board, Dhaka, Bangladesh. [3]Department of Disaster Science and Management, University of Dhaka, Dhaka, Bangladesh.

SN Applied Sciences (2021) 3:411 | https://doi.org/10.1007/s42452-021-04389-8

1 Introduction

River water, groundwater and seawater interaction studies are often complex and difficult tasks to perform, particularly in complex coastal hydrogeological settings. The complexities are mainly due to discrepancies in catchment physiographic characteristics, such as variations in topography, geology, climate, river geomorphology, as well as the positioning of river water features relative to groundwater flow paths in catchments, and the availability of sampling sites.

Geologically, the coastal delta of Bangladesh is more complex and dynamic than is commonly accepted. Coastal erosion, subsidence, strong tidal activity and rising sea levels are causing rapid geomorphological changes here [1]. This dynamic geology causes the coastal region to have unpredictable hydrogeological framework. The regressions and transgressions of the sea and the nature of the river over the last thousands of years have produced a complex system of sedimentary deposits comprising fresh and saline water [1, 2]. Interactions among river water, groundwater and seawater in the coastal aquifers are influenced by a variety of factors, such as sea level rise, coastal geology and hydrogeology, cyclone and storm surge activity, tidal interaction, river navigability reduction, gradient between freshwater–seawater and groundwater well pumping rates. Rising sea levels may be one of the prime reasons for intrusion of seawater into the coastal aquatic system. Research indicates that the sea level in the twenty-first century could rise by one meter or more, which would raise the vulnerable population to about one billion by 2050 [3, 4].

A huge number of hydrological and hydrogeological studies have been carried out in the Bangladesh coastal area. Some of the seawater intrusion studies are: Islam et al. [5] reported salinization and increasing amounts of metals are becoming a major threat in the coastal aquifer of the country, Naus et al. [6] referred to palaeo- and current hydrological processes and their geographical or geological controls are responsible for the variation in groundwater salinity in the southwestern coast of Bangladesh, Zahid et al. [7] depicted salinity sources in the multilayer aquifers of the coastal belt of Bengal delta, Sanchez et al. [2] delineated the saltwater intrusion into coastal groundwater systems in the southwestern coast of Bangladesh, and Rahman and Bhattacharya [8] focused exclusively on the causes of salinity intrusion into Bangladesh's coastal aquifers and [3, 4] studied on climate change, groundwater salinization and river salinity in the Bangladesh coastal region and stated that climate change would cause substantial changes in river salinity in the coastal area of Bangladesh by 2050. A number of studies have also been conducted on the health issue due to salinity and other pollution in the coastal area of Bangladesh. For example, [5, 9–11] published studies on the scarcity of safe drinking water highlighting community health security impacted by saline water and other multi-hazards in coastal Bangladesh.

This study particularly focuses on the assessment of river water–groundwater–seawater interactions on the basis of hydrochemistry of water, hydrochemical facies analysis, EC observations, groundwater flow direction and salinity distribution in the coastal delta of Bangladesh. This study will provide an in-depth perception of the geological, hydrogeological and hydrochemical environments and will assess how these environments are interlinked by hydrochemistry and hydrogeology.

2 Study area

Ganges–Brahmaputra–Meghna (GBM) river catchment areas are one such catchment area that supplies a massive amount of runoff compared to adjacent lowland areas of the Bangladesh Coastal Delta. Major and minor rivers in the study area are considered to be significant sources of groundwater recharge; and these rivers are major components of the hydrogeological system. The coastal delta of Bangladesh is typically low-lying flood-plain land without any prominent undulating areas. Surface elevation ranges from 1.32 m at the southern region to 2.16 m at the northern region and elevation changes during both the monsoon and dry seasons, although positive elevation increases during the monsoon season due to vertical accretion of sediment [12].

Eleven upazilas (sub-district) of six districts in the south-central coastal area of Bangladesh have been considered for this study. The study area comprises the Ganges delta plain and tidal delta plain. Geographically, the study area lies between 22.00° and 23.50° north latitudes and between 90.15° and 90.80° east longitudes (Fig. 1). Two types of groundwater sampling piezometric well stations are located in the eleven distinct lines at the 11 sites of the six (6) districts. The districts are Barguna, Patuakhali, Barishal, Lakshmipur, Chandpur and Shariatpur extending from south coastal area to the central portion of Bangladesh. Each site consists of 30 m depth 5 shallow wells and 100 m depth 5 deep wells along the single line. Total groundwater sampling stations are 110, where 55 for shallow and 55 for deep groundwater. River water sampling stations positioned at seventeen points within twelve rivers. These north–south trending rivers are Meghna, Tentulia, Payra, Biskhali, Sandha, Sikarpur, Dhansiri, Andharmanik, Gab khan, Arial Kha, Karkhana and Naya vangani.

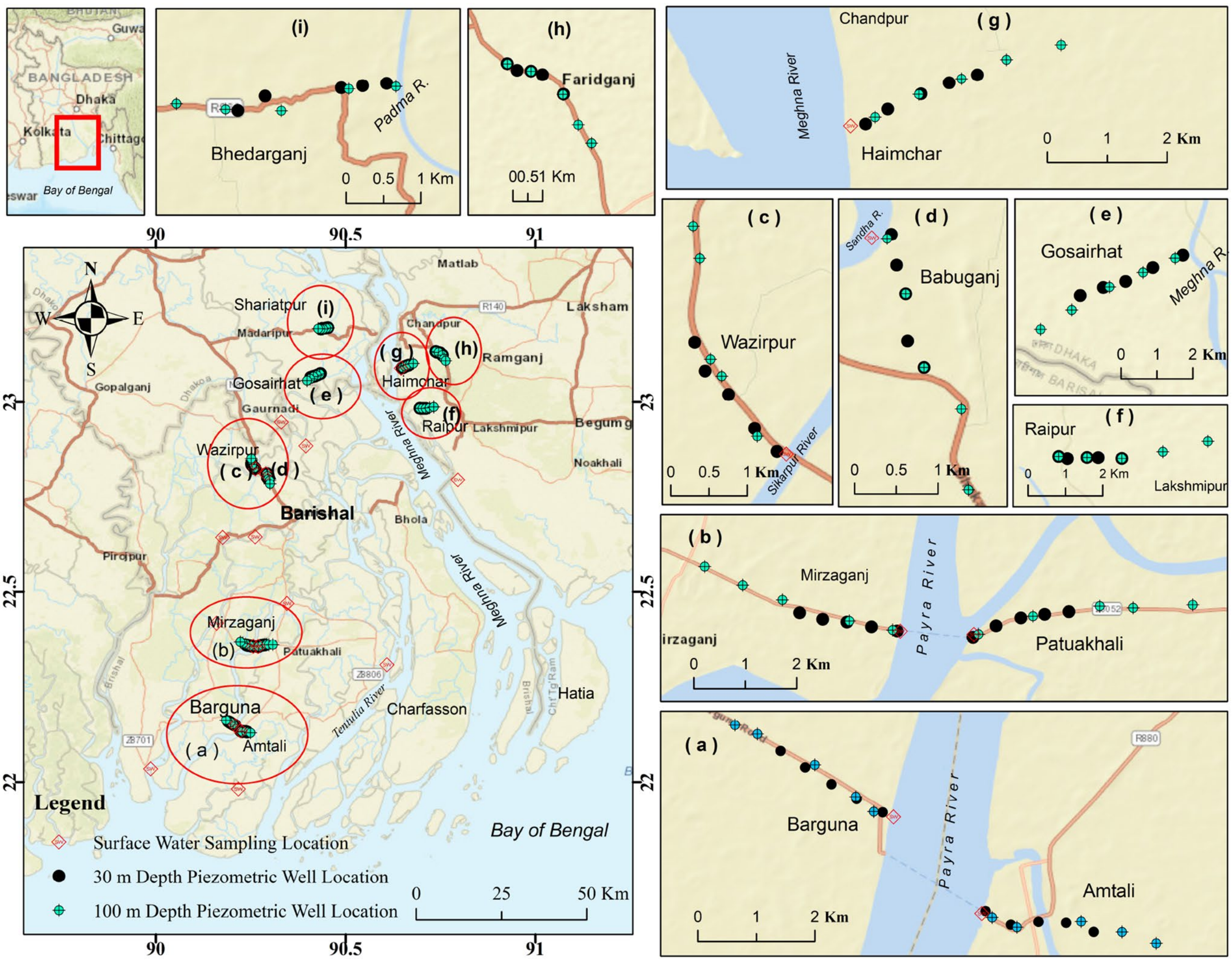

Fig. 1 Illustrating the location of groundwater sampling wells of 11 sites and 17 river water sampling stations in the coastal area of Bangladesh

3 Materials and methods

All data used in this study were obtained from Bangladesh Climate Change Trust (BCCT) project of Bangladesh Water Development Board (BWDB) under Ministry of Water Resources (MoWR). River water samples were collected in the months of February–March 2012 and groundwater samples collected in the months of October–November 2013. The parameters such as salinity, EC, Na, K, Ca, Mg, Cl, HCO_3, SO_4 and NO_3 have been measured in this study. Salinity and EC had been measured in the field during sampling using EC-meter and rest parameters were measured in the BWDB laboratory using the Atomic Absorption Spectrophotometer (AAS), UV–Vis Spectrophotometer and Volumetric Titration.

Groundwater flow directions have been observed through the contour map of the dry season groundwater table using contour segment of spatial analyst tools of the Arc-GIS 10.3. Interconnections between the river and the aquifers have also been assessed through graphs of electrical conductivity values.

Hydrochemical parameters have been used to determine the characterization of river water and groundwater hydrochemistry in order to assess the interaction between river water, groundwater and seawater. Ions exchange and chemical reactions among various sources of water have been identified from hydrochemistry represented by the plotting of major cations and anions in the Piper diagrams. These diagrams, plotted using Aquachem 2014.2 software, are used to determine the predominant water types of the study region. Hydrochemical Facies Evaluation Diagrams (HFE-D) have been constructed in configured excel sheets to assess freshening–intrusion phases and ion exchange processes [13]. Geostatistical analyst tools Arc-Gis 10.3 have also been used to illustrate the salinity distribution raster maps of river water, shallow groundwater and deep groundwater.

4 Results and discussion

4.1 Hydrogeological depiction

Eleven lithological cross sections have been constructed along the 100 m depth line wells at eleven sites based on washed borehole sediment data (Fig. 2). Detail lithological information suggests the study area is possessed with multilayer prolific heterogeneous aquifer system composed of deltaic sediments composed of complex mixture of sand, silt, and clay. These cross sections allow us to better understand the lithology of individual sites in order to evaluate river water–groundwater interactions. Cross sections along the line wells suggest the varying nature of the aquifers at different locations, consisting of distinct stratigraphy; some aquifers are confined in nature, some unconfined, some semi-confined or leaky. The lithological dissimilarity of eleven locations in the study area may indicate variations in the hydrochemical properties of the aquifer and the nature of the interconnection between rivers and aquifers.

4.2 Groundwater flow direction

Based on the contour map of the groundwater table, it is found that the groundwater flow is directed from the lower to the higher values of the groundwater table in the study area. Groundwater flows from the south to the north of the delta region, where all rivers follow the topography of the study area with a general trend from the north to the Bay of Bengal in the south (Fig. 3); and when rivers are influenced by frequent tidal action, regular seasonal inflows and storm surges, the flow path moves in the opposite direction. These phenomena related to the flow direction have implications for groundwater and river water interactions. Groundwater

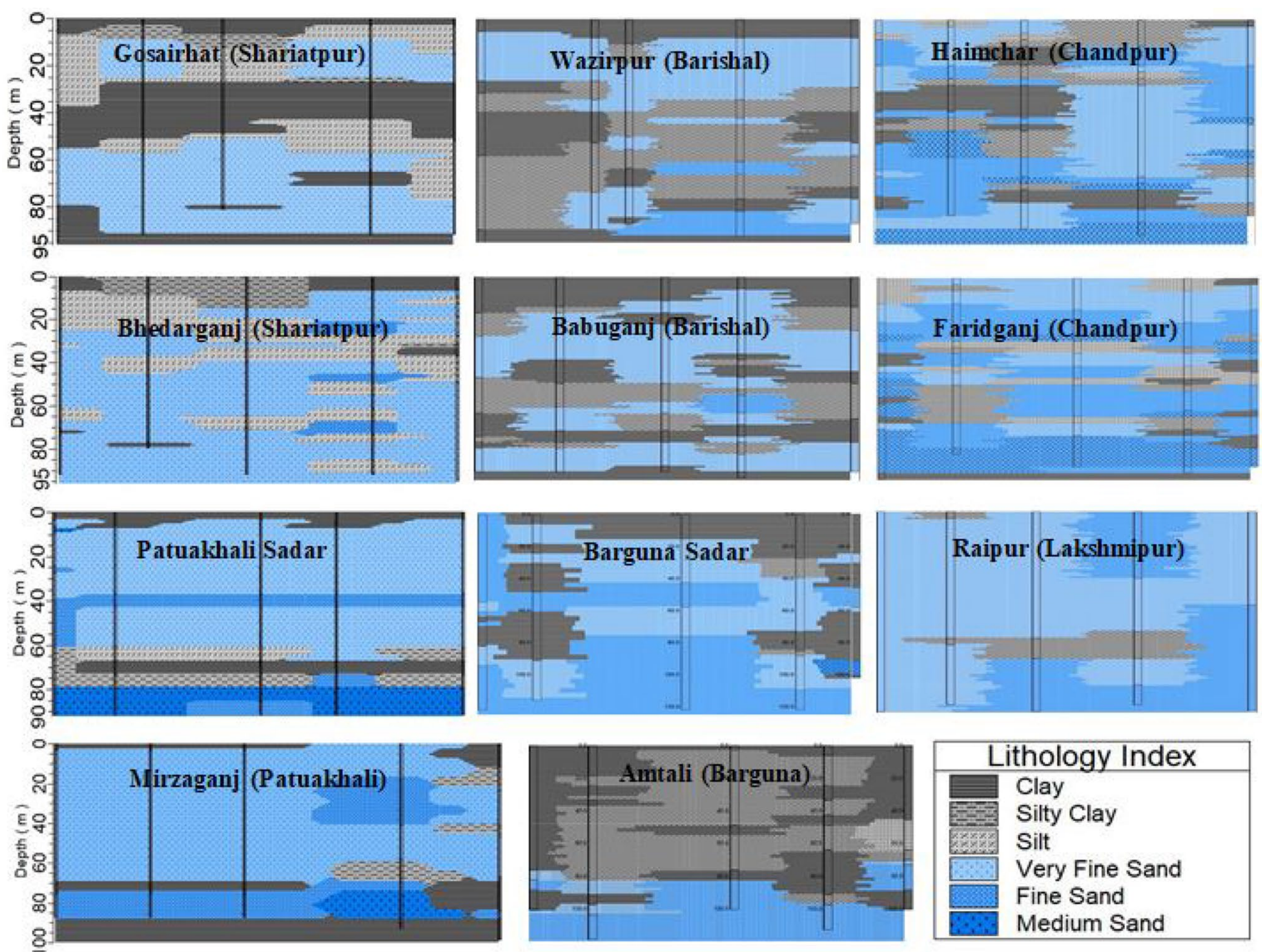

Fig. 2 Lithological cross sections along the line of approximate 100 m depth piezometric wells at eleven (11) locations in the study area

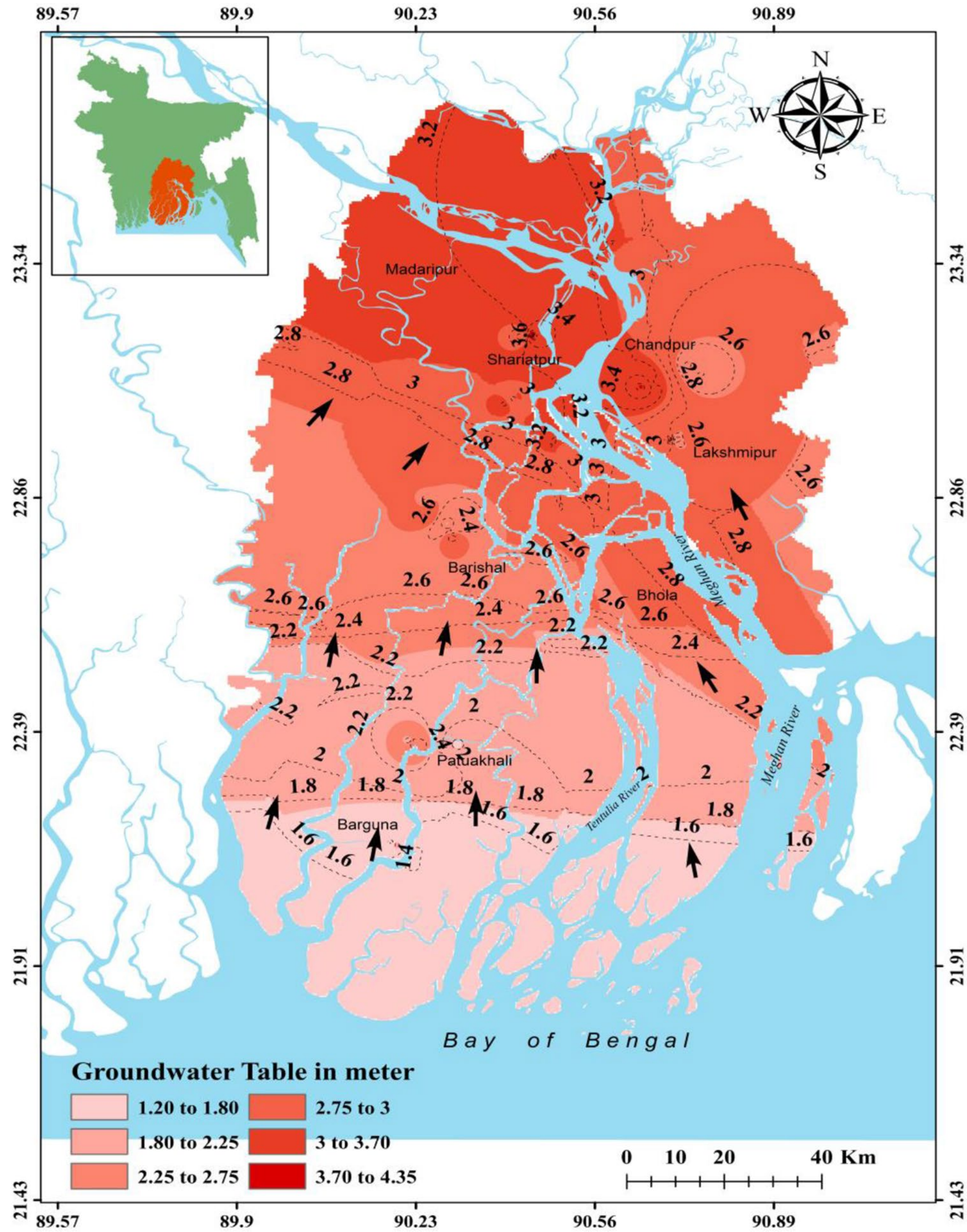

Fig.3 Groundwater table contour map showing the direction of the groundwater flow

flow direction in the contour map (Fig. 3) strongly indicates the possible entrance of seawater from the Bay of Bengal to the coastal delta aquifer. River water is directly connected to groundwater in most locations due to sandy-silt lithology; and rivers and of its floodplains are significant source of groundwater recharge. When aquifers are recharged through the process of infiltration and seepage, chemical reactions, such as ion exchange, may have occurred with an approach to the interaction between river water and groundwater.

4.3 Hydrochemical characterization of river water and groundwater

Tables 1, 2 and 3 represent the ten hydrochemical parameters of river water samples, shallow groundwater samples and deep groundwater samples, respectively. Samples were collected during dry season of different year and period. River water sampling was performed at various times on the same day. That's why the same river exhibits different salinity levels in different sampling times. Low

Table 1 Measured hydrochemical data of the river water samples

Sampling location	Sampling date	Salinity (ppt)	EC (µS/cm)	Na (mg/l)	K (mg/l)	Mg (mg/l)	Ca (mg/l)	Cl (mg/l)	SO_4 (mg/l)	HCO_3 (mg/l)	NO_3 (mg/l)
Haimchar (Meghna)	05.02.2012	0.1	263	7.5326	1.709	0.43	8.32	20.25	30.2584	91.5	0.6034
Ramgati (Meghna)	22.03.2012	0.2	464	12.278	16.022	17.83	38.2	22	30	103.7	3.9
Gaurnadi (Arial Kha)	04.02.2012	0.1	264	6.92	1.86	10.26	10.12	22	28.9241	109.8	0.8442
Muladi (Naya Vangani)	06.02.2012	0.1	276	11.169	3.54	10.85	9.94	15	33.2059	85.4	3
Wazirpur (Sikarpur)	04.02.2012	0.1	271	10.6	3.24	18.4	16.96	14.75	32.2921	103.7	1.4251
Babuganj (Sandha)	03.02.2012	0.1	266	6.49	2.21	9.09	0.16	21.25	31.6056	103.7	2.9
Nalcity (Dhanshiri)	01.02.2012	0.1	238	7.42	2.89	6.63	10.87	15.5	36.7626	85.4	2.2
Bakerganj (Karkhana)	03.02.2012	0.1	260	5.94	2.104	8.85	6.11	22.5	28.552	91.5	2.3
Jhalokathi Sadar (Gab Khan)	01.02.2012	0.1	239	2.41	2.81	4.67	11.48	15	30.4429	73.2	2.4016
Patuakhali Sadar (Payra)	12.03.2012	0.2	433	32.5	3.94	12.23	13.86	90	40.6754	85.4	0.243
Mirzaganj (Payra)	12.03.2012	0.1	422	25.09	4.17	9.17	14.46	85	35.8	103.7	2.3
Amtali (Payra)	09.03.2012	0.2	515	53.58	4.73	13.78	15.64	75	44.4852	97.6	3.1
Barguna Sadar (Payra)	08.03.2012	2.3	4320	23.42	23.385	111	55.64	1132.5	605.512	115.9	1.7
Barguna Sadar (Bishkhali)	10.03.2012	0.2	371	14.65	3.47	8.78	13.16	28.75	41.3318	97.6	2.2
Betagi (Bishkhali)	08.03.2012	0.1	268	27.41	3.05	10.76	14.74	18	22.5358	109.8	6.953
Dasmina (Tentulia)	15.03.2012	0.5	987	128.1	6.47	24.89	22.89	205	61.5307	97.6	0.0956
Kalapara (Andharmanik)	13.03.2012	17.2	27,900	146.2	188.5	41.7	118.75	10,500	1272.744	97.6	1.9926

Table 2 Measured hydrochemical data of the collected shallow groundwater samples in the study area

Sampling sites	Sampling wells	Sampling date	Salinity (ppt)	EC (µS/cm)	Na (mg/l)	K (mg/l)	Mg (mg/l)	Ca (mg/l)	Cl (mg/l)	SO_4 (mg/l)	HCO_3 (mg/l)	NO_3 (mg/l)
Bhedarganj	SPBGSLW1	11.10.2013	0.4	860	109.73	7.2	28.14	53.12	57.5	2	298.9	10
	SPBGSLW2	11.10.2013	0.4	837	99.62	13.82	38.52	34.66	250	85.49	292.8	13
	SPBGSLW3	11.10.2013	0.4	917	70.24	4.83	57.08	11.46	307.5	83.4	323.3	10
	SPBGSLW4	11.10.2013	0.4	839	131.36	4.69	20.14	44.23	465	84.1	268.4	7
	SPBGSLW5	11.10.2013	0.2	539	33.76	3.63	38.96	27.04	225	80	359.9	8
Gosairhat	SPGHSLW1	11.10.2013	1.4	2660	55	3	45	53	220	80	329.4	0.2
	SPGHSLW2	11.10.2013	1.4	2750	503.9	14.78	63.42	61.33	290	81.84	323.3	70.2
	SPGHSLW3	11.10.2013	1	2070	408.3	16.28	37.18	51.91	240	93.05	97.6	5.5
	SPGHSLW4	11.10.2013	0.7	1401	219.73	9.49	28.88	42.27	310	81.38	268.4	38
	SPGHSLW5	11.10.2013	0.5	1126	116.08	4.27	31.74	57.37	400	80.74	359.9	35
Wazirpur	BSUPSLW1	27.10.2013	0.3	602	44.76	6.38	18.66	58.13	6725	7.25	292.8	19.2
	BSUPSLW2	27.10.2013	0.5	1123	160.88	15.82	22.66	61.55	5075	83.94	616.1	23.7
	BSUPSLW3	27.10.2013	1.3	2560	434.7	4.71	43.78	51.89	4075	7.4	378.2	8.6
	BSUPSLW4	27.10.2013	1.8	3470	710.6	6.66	56.82	75.76	6750	7.7	390.4	20.13
	BSUPSLW5	27.10.2013	1.7	3210	659.7	10.56	59.04	122.4	2385	7.47	97.6	51.9
Babuganj	BSBBSLW1	27.10.2013	1.4	2780	468.6	22.16	49	99.1	7450	3.95	414.8	60.7
	BSBBSLW2	27.10.2013	0.1	383	72.2	15.34	8.52	17.36	1525	27.8	640.5	15.2
	BSBBSLW3	27.10.2013	1	2010	288.5	11.99	67.82	32.15	1460	7.6	525	24
	BSBBSLW4	27.10.2013	2.1	4010	889.7	15.6	53.24	122.86	1252	0	363	5
	BSBBSLW5	27.10.2013	2.6	4840	889.2	21.93	93.72	97.99	1150	7.53	310	33.7
Haimchar	CDHCSLW1	15.11.2013	0.5	1059	37.76	4.63	36.74	102.86	51	63.7	201.3	46.2
	CDHCSLW2	15.11.2013	0.8	1677	64.13	8.42	54.3	207.08	222.5	64.4	195.2	42.45
	CDHCSLW3	15.11.2013	0.9	1895	109.75	10.07	60	173.41	685	63.9	256.2	40.8
	CDHCSLW4	15.11.2013	1.2	2450	184.3	10	68.7	208.35	725	3	207.4	47.5
	CDHCSLW5	15.11.2013	0.9	1811	109.24	10.3	50.56	108.23	775	65.3	244	40.2
Faridganj	CDFGSLW1	15.11.2013	0.8	1591	194.19	12.53	44.54	77.96	537.5	3	408.7	38.45
	CDFGSLW2	15.11.2013	0.3	725	61.68	5.62	27.54	43.66	50	4	305	46.95
	CDFGSLW3	15.11.2013	0.2	494	21.91	5.3	1.08	18.43	435	1	225	47.7
	CDFGSLW4	15.11.2013	0.1	365	17.7	2.49	16.72	19.82	875	3	481.9	44.4
	CDFGSLW5	15.11.2013	0.2	508	48.88	6.87	16.94	20.64	1050	2	201.3	42.6
Raipur	LKRPSLW1	16.11.2013	0.4	951	289.1	9.58	27.72	89.16	48	4	292.8	10.1
	LKRPSLW2	16.11.2013	0.7	1455	199.35	4.56	61.42	70.02	68	2	286.7	12.9
	LKRPSLW3	16.11.2013	0.1	291	59.8	9.94	7.22	6.5	107	5	237.9	13.6
	LKRPSLW4	16.11.2013	0.4	895	310.05	4.36	22.2	133.79	33	3	359.9	4.7
	LKRPSLW5	16.11.2013	0.7	1455	189.4	4.43	61.52	96.99	49	4	244	19.8

Table 2 (continued)

Sampling sites	Sampling wells	Sampling date	Salinity (ppt)	EC (µS/cm)	Na (mg/l)	K (mg/l)	Mg (mg/l)	Ca (mg/l)	Cl (mg/l)	SO_4 (mg/l)	HCO_3 (mg/l)	NO_3 (mg/l)
Mirzaganj	PKMGSLW1	28.10.2013	10.3	17,580	2928.6	53.45	381.36	208.28	290	40	305	12
	PKMGSLW2	28.10.2013	8.1	13,810	2269.6	65.35	341.68	187.36	72	123	244	9
	PKMGSLW3	28.10.2013	7.7	13,420	2479.5	44.53	270.04	89.05	37	1050	158.6	8
	PKMGSLW4	28.10.2013	10.8	18,350	2777.7	74.92	416.96	142.76	21	56	61	28
	PKMGSLW5	28.10.2013	4	7360	813.4	30.06	293.76	374.91	37	3	317.2	40
Patuakhali Sadar	PKPKSLW1	28.10.2013	11.7	19,660	3715.2	152.39	405.6	125.6	625	3	300	28
	PKPKSLW2	28.10.2013	3.5	6450	1730.5	43.49	69.94	44.81	532.5	5	347.7	0.5
	PKPKSLW3	28.10.2013	2.3	5200	1530	39.6	65	34	327.5	4	390.4	30
	PKPKSLW4	28.10.2013	2.2	4260	1187.5	35.83	63.7	17.63	235	4	305	42
	PKPKSLW5	28.10.2013	2.2	4000	1070	28.2	60	18	240	5	244	15
Amtali	BNAMSLW1	15.11.2013	3.9	7160	5568.6	70.68	79.7	56.42	2700	450	500.2	9.77
	BNAMSLW2	15.11.2013	4.6	8230	5243	69	96.34	77.15	2900	502	317.2	9.7
	BNAMSLW3	15.11.2013	4.6	8240	5226.6	86.58	109.24	92.19	2880	505	317.2	13.2
	BNAMSLW4	15.11.2013	4.1	7530	5182.4	73.85	90.42	67.96	2450	503	463.6	7.6
	BNAMSLW5	15.11.2013	6.3	11,120	5853	59.3	224.02	102.38	4000	520	268.4	8.4
Barguna Sadar	BNBNSLW1	29.10.2013	16.4	26,800	4965.8	118.23	79.7	122.71	10,100	543.7	536.8	17
	BNBNSLW2	29.10.2013	17	27,700	2788.8	81.37	226.1	59.35	5325	932.2	298.9	8
	BNBNSLW3	29.10.2013	8.3	14,380	4510.6	149.51	690.08	278.78	10,325	993.8	176.9	17.8
	BNBNSLW4	29.10.2013	14.2	23,500	4861.2	156.41	519.6	141.01	9550	79.32	494.1	6
	BNBNSLW5	29.10.2013	16.1	26,400	4690.6	179.58	732.88	292.66	9700	1130	244	4

Table 3 Measured hydrochemical data of the collected deep groundwater samples in the study area

Sampling sites	Sampling wells	Sampling date	Salinity (ppt)	EC (µS/cm)	Na (mg/l)	K (mg/l)	Mg (mg/l)	Ca (mg/l)	Cl (mg/l)	SO_4 (mg/l)	HCO_3 (mg/l)	NO_3 (mg/l)
Bhedarganj	SPBGLW-01	11.10.2013	0.6	1287	390.7	5.117	20.7	1.47	287.5	0	549	6.9
	SPBGLW-02	11.10.2013	0.41	750	165.6	2.583	19.62	21.8	61	0	408.7	8.5
	SPBGLW-03	11.10.2013	2.5	4780	605.3	6.818	63.91	65.53	1300	17	262.3	18.5
	SPBGLW-04	11.10.2013	3.3	6020	821.5	8.852	12.105	70.43	2670	0	225.7	29.9
	SPBGLW-05	11.10.2013	0.1	6120	871.8	10.99	98.16	52.24	5450	0	213.5	36.8
Gosairhat	SPGHLW-01	11.10.2013	5.1	9070	1814	18.64	5.32	15.78	3300	0	189.1	10.2
	SPGHLW-02	11.10.2013	3.6	6660	1356.8	21.71	143.6	31.31	2290	39	494.1	26.9
	SPGHLW-03	11.10.2013	4.1	7380	1483.3	14.57	139.81	84.43	2650	0	542.9	24.2
	SPGHLW-04	11.10.2013	4.4	7940	1269.5	24.72	135.99	20.17	2770	0	481.9	8
	SPGHLW-05	11.10.2013	7.5	13,070	2050.5	21.344	7.78	3.8121	2270	0	518.5	19.2
Wazirpur	BSUPLW-1	27.10.2013	0.538	945	205.9	4.13	52.02	82.56	101	0	317.2	15.1
	BSUPLW-2	27.10.2013	2	3330	894.2	6.83	146.66	277.56	1820	0	189.1	13.7
	BSUPLW-3	27.10.2013	1.6	3100	766.8	4.61	104.28	144.2	1140	0	195.2	17.4
	BSUPLW-4	27.10.2013	2.8	4860	854.7	14.75	250.5	238.46	1770	0	317.2	125
	BSUPLW-5	27.10.2013	2.3	4180	589.1	17.8	164.5	121.84	1400	0	481.9	236
Babuganj	BSBBLW-1	27.10.2013	2.7	4910	659.7	21.07	245.72	84.8	1700	0	469.7	18.2
	BSBBLW-2	27.10.2013	2.97	5510	694.4	17.66	254.5	56.3	1650	0	457.5	14.3
	BSBBLW-3	27.10.2013	3.59	6310	1121.8	8.97	211.6	263.96	2660	0	176.9	119
	BSBBLW-4	27.10.2013	2.66	4760	865.4	3.43	117.38	172.1	2130	0	219.6	191
	BSBBLW-5	27.10.2013	4.31	7710	1413.9	17.23	243.76	306.68	2820	0	256.2	51.4
Haimchar	CDHCLW-1	15.11.2013	3.62	8581	468.83	15.12	290	60	2800	0	189.1	27.3
	CDHCLW-2	15.11.2013	3.15	7660	72.825	1.08	230	50	2600	0	122	31.2
	CDHCLW-3	15.11.2013	2.57	4970	1427.8	18.278	240	120	2250	0	128.1	13.5
	CDHCLW-4	15.11.2013	4.1	7110	1141	15.621	350	160	2420	0	67.1	17.3
	CDHCLW-5	15.11.2013	1.34	2670	564.3	21.038	65	60	887.5	0	91.5	13.1
Faridganj	CDFGLW-1	15.11.2013	3.2	5580	659.45	16.735	300	150	1900	0	176.9	2.6
	CDFGLW-2	15.11.2013	1.8	5230	958.55	21.087	240	40	1730	0	61	27.9
	CDFGLW-3	15.11.2013	2.9	6020	603.4	12.614	250	190	2200	0	61	15.7
	CDFGLW-4	15.11.2013	3.6	6320	767.05	12.915	250	200	2400	0	54.9	2.1
	CDFGLW-5	15.11.2013	4.3	7490	1079	14.587	238.22	270	2500	1	79.3	12.2
Raipur	LKRPLW-1	16.11.2013	4.1	7290	1318	7.3	224.7	156.58	2700	0	396.5	6.2
	LKRPLW-2	16.11.2013	6.5	11,150	1994	16.8	400.84	116.36	4150	0	134.2	10.8
	LKRPLW-3	16.11.2013	4.3	7480	1375	6.27	206.32	99.62	3120	0	36.6	9
	LKRPLW-4	16.11.2013	3.4	5910	715.6	1.26	236.74	316.14	2450	0	115.9	0.8
	LKRPLW-5	16.11.2013	3.6	6180	1450	5.93	186.86	257.52	2200	1	414.8	39

Table 3 (continued)

Sampling sites	Sampling wells	Sampling date	Salinity (ppt)	EC (µS/cm)	Na (mg/l)	K (mg/l)	Mg (mg/l)	Ca (mg/l)	Cl (mg/l)	SO_4 (mg/l)	HCO_3 (mg/l)	NO_3 (mg/l)
Mirzaganj	PKMGLW-1	28.10.2013	5	9040	1447	6.68	189.45	103.05	3490	1	146.4	0.4
	PKMGLW-2	28.10.2013	6.2	11,930	1815.8	8	249.95	274.7	5800	4	225.7	0.5
	PKMGLW-3	28.10.2013	7.8	14,430	2246.3	6	463.7	353.65	6125	87	158.6	0.3
	PKMGLW-4	28.10.2013	10.6	18,020	2100	7	460	350	6000	86	155	0.4
	PKMGLW-5	28.10.2013	0.6	1330	2000	8	450	345	5945	85	156	0.5
Patuakhali sadar	PKPKLW-1	28.10.2013	1.8	3540	396.3	5.92	149.7	218.05	1440	9	48.8	0.4
	PKPKLW-2	28.10.2013	5.2	9370	1481.3	4.93	310.35	544.2	3610	0	42.7	0.3
	PKPKLW-3	28.10.2013	4.6	8240	1125.3	16.16	366.5	419.05	3600	0	61	0.3
	PKPKLW-4	28.10.2013	5.5	9780	1318.9	17.79	360.35	392.4	3700	0	79.3	0.3
	PKPKLW-5	28.10.2013	6.3	11,110	1832.3	28.13	367.65	457.7	4260	1	73.2	0.3
Amtali	BNAMLW_1	15.11.2013	0.5	1000	255.4	1.472	5	20	135	0	463.6	0.7
	BNAMLW_2	15.11.2013	0.9	1840	452.7	4.041	10	10	277.5	0	475.8	0.4
	BNAMLW_3	15.11.2013	1.7	3270	375.5	27.58	70	90	682.5	0	213.5	5.5
	BNAMLW_4	15.11.2013	2.5	4630	672.1	11.88	120	140	1870	0	207.4	2.2
	BNAMLW_5	15.11.2013	3.3	5960	1098	17.67	75	40	2290	3	146.4	5.2
Barguna sadar	BNBN1LW_1	29.10.2013	3.1	5830	1029.5	18.82	85	70	1930	0	170.8	4.4
	BNBN1LW_2	29.10.2013	1.1	2190	229	6.36	50	40	482.5	0	268.4	1.7
	BNBN1LW_3	29.10.2013	1.4	2720	350.2	8.98	60	60	650	5	244	2.2
	BNBN1LW_4	29.10.2013	2.9	5440	787.2	14.69	135	90	1960	1	292.8	2.7
	BNBN1LW_5	29.10.2013	6.32	12,160	1963.4	19.99	210	120	5000	0	286	3.6

tide and high tide effects are responsible for differences in salinity values. Mg^{2+} and HCO_3^- ions are dominant in river water with an average concentration of 37.41 percent of the total cation and 43.20 percent of the total anion, respectively. The shallow and deep groundwater have excess levels of Na^+, K^+ and Cl^- ions; where the average concentrations of $Na^+ + K^+$ and Cl^- ions in shallow groundwater are 63.84 percent and 63.61 percent of the total cations and anions, respectively. Deep groundwater is very highly concentrated by $Na^+ + K^+$ and Cl^- ion, with an average of 66.27% of total cations and 88.25% of total anions, respectively. Excessive concentrations of Na^+, K^+ and Cl^- ions lead to seawater contamination in groundwater, and HCO_3^- along with Na^+, Ca^{2+}, Mg^{2+} in river water suggest a mixture of freshwater and seawater.

Hydrochemistry of river water and groundwater has been characterized by hydrochemical classification of waters. Hydrochemical water types, phases and facies were categorized among three sources by plotting major cations and anions using piper diagrams and HFE-D diagrams. According to Arthur M. Piper [14], Groundwater can be classified into 6 types occurring in 6 fields in the Piper diagram. These fields are 1. Ca–HCO_3 type 2. Na–Cl type 3. Ca–Mg–Cl type, 4.Ca–Na–HCO_3 type 5. Ca–Cl type and 6. Na–HCO_3 type. In some cases, Mg^{2+} replaces the Ca^{2+} and forms the Mg–HCO_3 water type. Freshening and intrusion phases denote the direct cation exchange and reverse cation exchange, respectively. In HFE-D diagram freshening phase points are placed on the left of the mixing line and intrusion phase points are placed on the right of the mixing line [13]. The term facies is measured relative to the percentage of Ca^{2+} and Na^+ cations, and HCO_3^- (or SO_4^{2+}) and Cl^- anions in regards to the sum of cations and anions, respectively. The facies are recognized using the term Mix to indicate that the percentage of cation or anion is less than 50%. There are four major facies in HFE-D: NaCl, CaCl, Na–HCO_3, and Ca–HCO_3. And each major facies also comprise four other facies that are related to it [15]. Detailed hydrochemical facies and phases of water are shown in Tables 4 and 5 illustrating the phases and facies among three sources of water.

The Piper diagram of river water indicates the dissimilar water types. The seventeen river water samples lie on four quadrants (1,2,3 and 5) of the Piper diagram, where about 60% samples are Ca–HCO3 type, about 30% are Ca–Mg–Cl type and about 10% are Na–Cl and Ca–Cl types (Fig. 4a). This dissimilarity clearly indicates mixing of different sources water. The percentage trends of cations in river water are $Mg^{2+} > Na^+ + K^+ > Ca^{2+}$ and $HCO_3^- > Cl^- > SO_4^{2-}$ for anion. It is assumed that the percentage of Mg^{2+} ion is greater than of Ca^{2+} and Na^+ which may indicate dissolved clay sediments in the river water. HFE-D diagram suggests that the most samples are characterized by freshening phases indicating recharge or mixing freshwater into river water except three samples (Fig. 4b). Among sixteen facies, there are eleven hydrochemical facies have been recognized where about 82% facies are characterized by freshening phases and 18% by intrusion phases (Table 4). More than 60% river water samples lie on Ca-HCO_3 (or, Mg–HCO_3) facies quadrant of HFE-D diagram. The facies number of river water are relatively wide than groundwater may imply recharge of freshwater in the existing water and show intermediate stage facies recognized by mixing ions.

Table 4 Freshening–intrusion phases and hydrochemical facies of different river water samples

River water sampling stations	Phases	Hydrochemical facies	
Haimchar (Meghna)	Freshening	Ca	HCO_3
Ramgati (Meghna)	Freshening	MixCa	HCO_3
Gaurnadi (Arial Kha)	Freshening	MixMg	HCO_3
Muladi (Naya Vangani)	Freshening	MixMg	HCO_3
Wazirpur (Sikarpur)	Freshening	Mg	HCO_3
Babuganj (Sandha)	Intrusion	Mg	HCO_3
Nalcity (Dhanshiri)	Freshening	MixMg	HCO_3
Bakerganj (Karkhana)	Freshening	Mg	HCO_3
Jhalokathi sadar (Gab Khan)	Freshening	Ca	HCO_3
Patuakhali sadar (Payra)	Freshening	MixNa	Cl
Mirzaganj (Payra)	Freshening	MixNa	MixCl
Amtali (Payra)	Freshening	Na	MixCl
Barguna sadar (Payra)	Intrusion	Mg	Cl
Barguna sadar (Bishkhali)	Freshening	MixNa	MixHCO_3
Betagi (Bishkhali)	Freshening	MixNa	HCO_3
Dasmina (Tentulia)	Freshening	Na	Cl
Kalapara (Andharmanik)	Intrusion	Na	Cl

Nitrate (NO_3^-) concentrations ranging from 0.0956 to 6.953 mg/l indicate a negligible to low concentration in river water samples (Table 1). Denitrification, regular interval tidal activity and river current in the coastal area cause a very low concentration of nitrate in river water.

Table 5 shows detail of hydrochemical phases and facies of all groundwater samples collected from two different depths. There are five quadrants (1,2,3,4 and 5) exhibit the shallow groundwater samples plotting on the Piper diagram, where more than 70% samples are Na–Cl types and other types are Ca–Na–HCO_3, Ca–Mg–Cl, Ca–Cl and Na–HCO_3 (Fig. 5a). This plotting suggests that alkali earths exceed alkaline earths; and strong acids exceed weak acids in shallow groundwater. The trends of ions concentration in shallow groundwater are $Cl^- > HCO_3^- > SO_4^{2-}$ for anion and $Na^+ + K^+ > Mg^{2+} > Ca^{2+}$ for cation.

Hydrochemical facies evaluation (HFE-D) diagram (Fig. 5b) of shallow groundwater samples notices that

Table 5 Hydrochemical facies and freshening–intrusion phases of the two depths groundwater samples

Sampling sites	Shallow groundwater				Deep groundwater			
	Sampling wells	Phases	Hydrochemical facies		Sampling wells	Phases	Hydrochemical facies	
Bhedarganj	SPBGSLW1	Freshening	MixNa	HCO_3	SPBGLW-01	Freshening	Na	HCO_3
	SPBGSLW2	Intrusion	MixNa	Cl	SPBGLW-02	Freshening	Na	HCO_3
	SPBGSLW3	Intrusion	Mg	Cl	SPBGLW-03	Intrusion	Na	Cl
	SPBGSLW4	Intrusion	Na	Cl	SPBGLW-04	Freshening	Na	Cl
	SPBGSLW5	Intrusion	Mg	MixCl	SPBGLW-05	Intrusion	Na	Cl
Gosairhat	SPGHSLW1	Intrusion	MixMg	MixCl	SPGHLW-01	Freshening	Na	Cl
	SPGHSLW2	Freshening	Na	Cl	SPGHLW-02	Freshening	Na	Cl
	SPGHSLW3	Freshening	Na	Cl	SPGHLW-03	Freshening	Na	Cl
	SPGHSLW4	Freshening	Na	Cl	SPGHLW-04	Freshening	Na	Cl
	SPGHSLW5	Intrusion	MixNa	Cl	SPGHLW-05	Freshening	Na	Cl
Wazirpur	BSUPSLW1	Intrusion	MixCa	Cl	BSUPLW-1	Freshening	Na	HCO_3
	BSUPSLW2	Intrusion	Na	Cl	BSUPLW-2	Intrusion	Na	Cl
	BSUPSLW3	Intrusion	Na	Cl	BSUPLW-3	Intrusion	Na	Cl
	BSUPSLW4	Intrusion	Na	Cl	BSUPLW-4	Intrusion	Na	Cl
	BSUPSLW5	Intrusion	Na	Cl	BSUPLW-5	Intrusion	Na	Cl
Babuganj	BSBBSLW1	Intrusion	Na	Cl	BSBBLW-1	Intrusion	Na	Cl
	BSBBSLW2	Intrusion	Na	Cl	BSBBLW-2	Intrusion	Na	Cl
	BSBBSLW3	Intrusion	Na	Cl	BSBBLW-3	Intrusion	Na	Cl
	BSBBSLW4	Freshening	Na	Cl	BSBBLW-4	Intrusion	Na	Cl
	BSBBSLW5	Freshening	Na	Cl	BSBBLW-5	Intrusion	Na	Cl
Haimchar	CDHCSLW1	Intrusion	Ca	MixHCO_3	CDHCLW-1	Intrusion	MixNa	Cl
	CDHCSLW2	Intrusion	Ca	Cl	CDHCLW-2	Intrusion	Na	Cl
	CDHCSLW3	Intrusion	MixCa	Cl	CDHCLW-3	Intrusion	MixNa	Cl
	CDHCSLW4	Intrusion	MixCa	Cl	CDHCLW-4	Intrusion	Na	Cl
	CDHCSLW5	Intrusion	MixCa	Cl	CDHCLW-5	Intrusion	Na	Cl
Faridganj	CDFGSLW1	Intrusion	Na	Cl	CDFGLW-1	Intrusion	Na	Cl
	CDFGSLW2	Freshening	MixNa	HCO_3	CDFGLW-2	Intrusion	Na	Cl
	CDFGSLW3	Intrusion	Na	Cl	CDFGLW-3	Intrusion	Na	Cl
	CDFGSLW4	Intrusion	MixMg	Cl	CDFGLW-4	Intrusion	Na	Cl
	CDFGSLW5	Intrusion	MixNa	Cl	CDFGLW-5	Intrusion	Na	Cl
Raipur	LKRPSLW1	Freshening	Na	HCO_3	LKRPLW-1	Intrusion	MixNa	Cl
	LKRPSLW2	Freshening	Na	HCO_3	LKRPLW-2	Intrusion	Na	Cl
	LKRPSLW3	Freshening	Na	HCO_3	LKRPLW-3	Intrusion	MixNa	Cl
	LKRPSLW4	Freshening	Na	HCO_3	LKRPLW-4	Intrusion	Na	Cl
	LKRPSLW5	Freshening	MixNa	HCO_3	LKRPLW-5	Intrusion	Na	Cl
Mirzaganj	PKMGSLW1	Freshening	Na	Cl	PKMGLW-1	Intrusion	Na	Cl
	PKMGSLW2	Freshening	Na	MixHCO_3	PKMGLW-2	Intrusion	Na	Cl
	PKMGSLW3	Freshening	Na	SO_4	PKMGLW-3	Intrusion	Na	Cl
	PKMGSLW4	Freshening	Na	MixSO_4	PKMGLW-4	Intrusion	MixNa	Cl
	PKMGSLW5	Freshening	MixNa	HCO_3	PKMGLW-5	Intrusion	Na	Cl
Patuakhali sadar	PKPKSLW1	Freshening	Na	Cl	PKPKLW-1	Intrusion	Mg	Cl
	PKPKSLW2	Freshening	Na	Cl	PKPKLW-2	Intrusion	Mg	Cl
	PKPKSLW3	Freshening	Na	Cl	PKPKLW-3	Intrusion	Na	Cl
	PKPKSLW4	Freshening	Na	Cl	PKPKLW-4	Intrusion	Na	Cl
	PKPKSLW5	Freshening	Na	Cl	PKPKLW-5	Intrusion	Na	Cl

Table 5 (continued)

Sampling sites	Shallow groundwater				Deep groundwater			
	Sampling wells	Phases	Hydrochemical facies		Sampling wells	Phases	Hydrochemical facies	
Amtali	BNAMSLW1	Freshening	Na	Cl	BNAMLW_1	Freshening	Na	HCO_3
	BNAMSLW2	Freshening	Na	Cl	BNAMLW_2	Freshening	Na	Cl
	BNAMSLW3	Freshening	Na	Cl	BNAMLW_3	Intrusion	Na	Cl
	BNAMSLW4	Freshening	Na	Cl	BNAMLW_4	Intrusion	Na	Cl
	BNAMSLW5	Freshening	Na	Cl	BNAMLW_5	Freshening	Na	Cl
Barguna sadar	BNBNSLW1	Freshening	Na	Cl	BNBN1LW_1	Intrusion	Na	Cl
	BNBNSLW2	Freshening	Na	Cl	BNBN1LW_2	Intrusion	Na	Cl
	BNBNSLW3	Intrusion	Na	Cl	BNBN1LW_3	Intrusion	Na	Cl
	BNBNSLW4	Intrusion	Na	Cl	BNBN1LW_4	Intrusion	Na	Cl
	BNBNSLW5	Intrusion	Na	Cl	BNBN1LW_5	Intrusion	Na	Cl

there are fourteen facies exist and characterized by 53% freshening phases and 47% by intrusion phases (Table 5). Shallow groundwater types and facies for individual sites along shallow wells are of a dissimilar nature: considering the first shallow well nearest to the river, six wells are affected by freshening phases and five other sites are affected by intrusion phases. Six sites whose first well are recognized by freshening phases are Bhedarganj, Raipur, Mirzaganj, Patuakhali Sadar, Amtali and Barguna Sadar. These wells may be influenced either by freshwater or rainwater or by direct cation exchange with aquifer sediments.

More than 70 percent of the shallow groundwater samples are found on the Na–Cl quadrant facies of the HFE-D diagram. The intrusion of seawater into shallow aquifers and the mixing of fresh groundwater with seawater are prominent from HFE-D, which is clearly seen from the Na-Cl facies quadrant in which both intrusion and freshening phases are characterized by Na-Cl.

Five other shallow well locations at: Gosairhat, Wazirpur, Babuganj, Haimchar and Faridganj, whose first wells (nearest to river) are experienced by intrusion phases. Several causes may be responsible for the hydrochemical phase variation among the wells in the different locations. These variations may be due to either lithology of aquifers or tidal activity or percolation of rain water. Overall it is said that the shallow groundwater of the study area are interacted to river water as well as to seawater.

Nitrate contamination in shallow groundwater is moderate to high; and both the lowest and highest values found in Gosairhat; 0.2 mg/l at the first well and 70.2 mg/l at the second well near the river, respectively (Table 2). Most shallow groundwater samples exceed the Bangladesh standard of nitrate (10 mg/l), indicating shallow aquifers of the coastal area are influenced by anthropogenic activities.

Deep Groundwater chemistry on piper plot (Fig. 6a) specifically indicates the dominant Na–Cl type of water in the study area. Almost 95% deep groundwater samples lie on the Na–Cl type fields of the piper diagram (Fig. 6a). In this case, alkali earths exceed alkaline earths; and strong acids exceed weak acids in deep groundwater. Ions concentration trends in deep groundwater are $Cl^- > HCO_3^- > SO_4^{2-}$ for anion and $Na^+ + K^+ > Mg^{2+} > Ca^{2+}$ for cation. HFE-D diagram for deep groundwater reveals that there only four hydrochemical facies are identified, and 78% corresponding to intrusion phases and 22% to freshening phases (Fig. 6b and Table 5). All deep groundwater samples except six lie in the Na-Cl substages of the HFE-D diagram. Approximately more than 95% of the deep groundwater samples lie on the Na–Cl facies quadrant and the maximum is characterized by intrusion phases.

The deep groundwater with dominant Na–Cl indicates the presence of sea or brine water. Concentrations of Ca decrease, while the concentrations of Na increase in deep groundwater which may indicate the reverse ion exchange process between aquifer and saline water. This also could be due to mixing of shallow groundwater to deep groundwater.

Groundwater types and facies for individual sites along deep wells are of two natures: considering the first shallow well closest to the river, the first four wells of four sites are affected by refreshing phases and seven wells from other sites are affected by intrusion phases. Most wells are affected by intrusion phases and intrusion of seawater may be the main cause of this condition. Deep aquifer of the coastal region potentially interconnected with seawater.

Ca, Mg, and HCO_3 are the most abundant ions in natural waters, while Na and Cl provide an indicator of the deposition and dissolution of halite from hydrologically derived Na–Cl ions in areas along the coast. In addition,

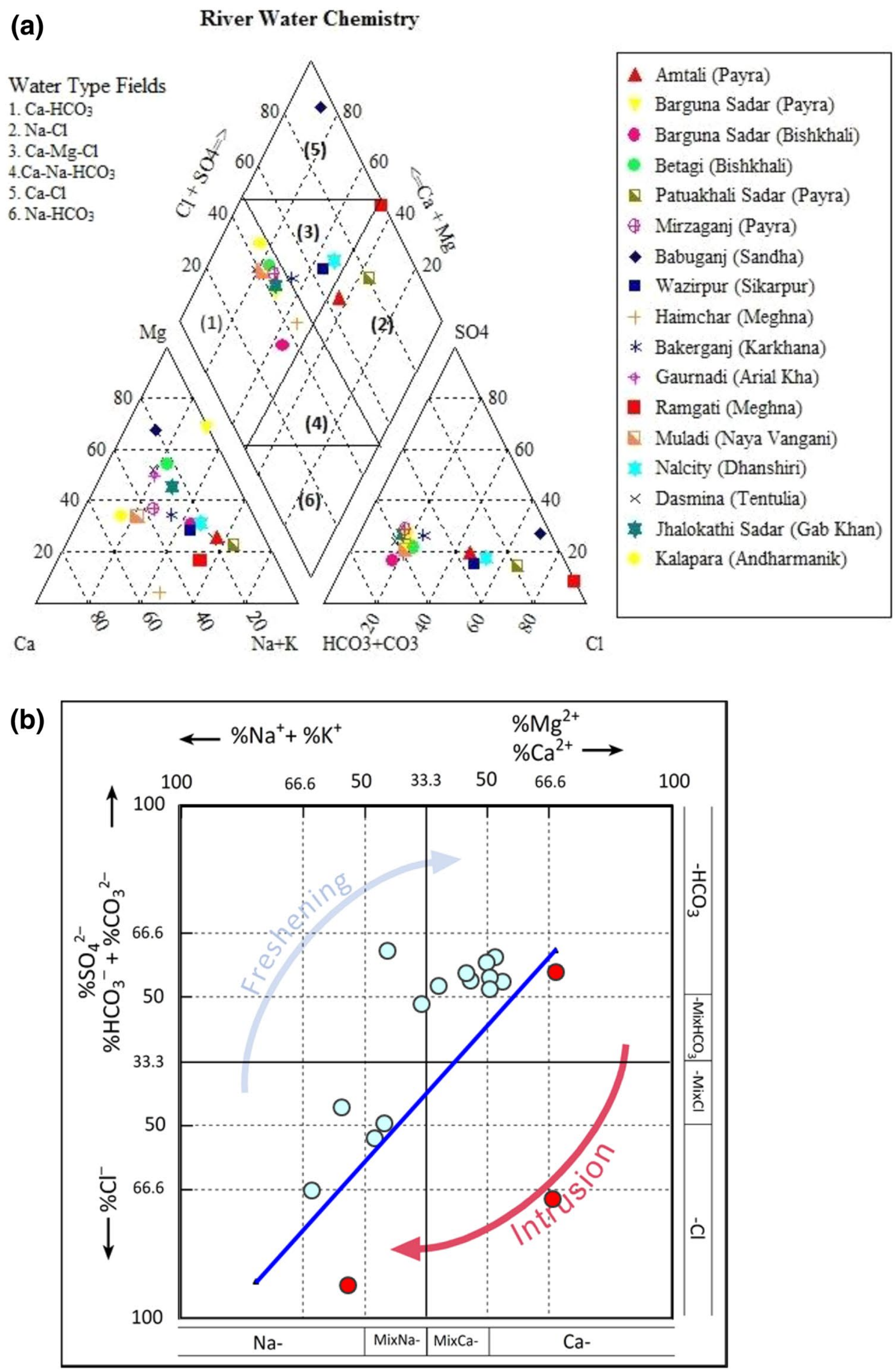

Fig. 4 **a** Piper diagram shows the river water types; **b** HFE-D diagram depicts the freshening–intrusion phases of river water samples in the coastal delta of Bangladesh

the dominance of Na–Cl and Ca–Mg–HCO_3 water indicates the mixing of new water with ancient/old saline groundwater. The very high positive correlation between Na and Cl indicates the dominance of Na–Cl rich recharge water from coastal origin [16, 17].

Deep aquifers in the southern region are moderately contaminated and the middle to northern portion of the coastal area is very highly contaminated with nitrate (Table 3). Some deep groundwater samples show extremely high nitrate levels; 236 mg/l and 125 mg/l in Wazirpur; 191 mg/l and 119 mg/l in Babuganj. Pronounced nitrate levels in deep aquifers indicate either organic compounds in aquifers or leaching from the upper sedimentary layers.

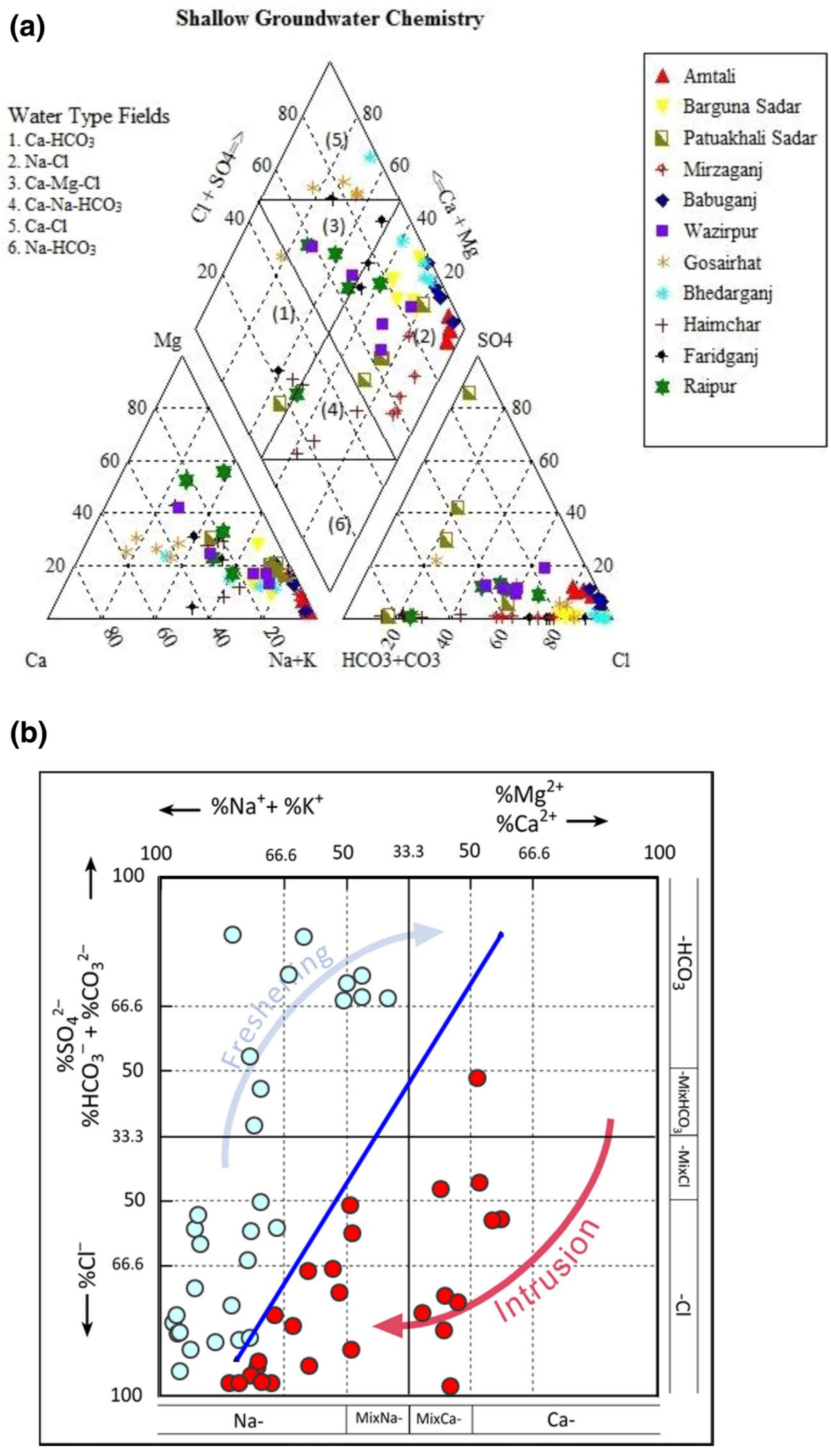

Fig. 5 **a** Piper diagram shows the shallow groundwater types; **b** HFE-D depicts the freshening–intrusion phases of shallow groundwater samples in the coastal delta of Bangladesh

The study area aquifers are mainly recharged from river water, surface runoff and precipitation. The dominance of Na–Cl dissolution in both shallow and deep groundwater suggests that there is an input of Na–Cl into groundwater from possible sources such as seawater of Bay of Bengal. The study area adjacent to the sea and the dominant nature of sandy-clayey lithology make NaCl inputs from seawater sources the most relevant.

4.4 Observations of ion exchange

Generally, cations and anions are in balance conditions in the most natural waters. When river water or groundwater moves underground, chemical reactions with of its environments tend to develop a chemical balance. Chemical water balance can also be formed through ion exchange. Ion exchange involves replacing ions adsorbed on the

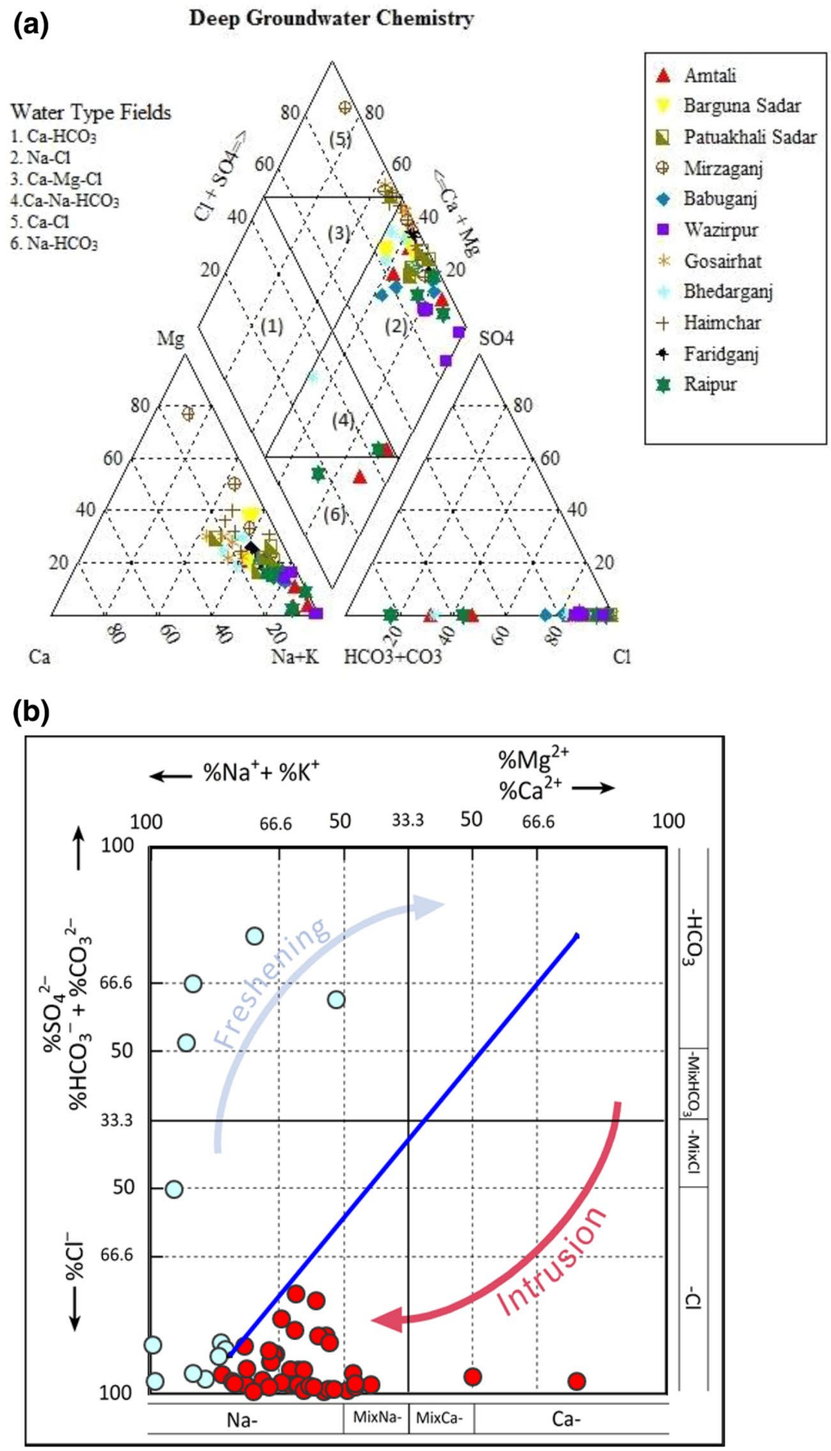

Fig. 6 **a** Piper diagram shows the deep groundwater types; **b** HFE-D depicts the freshening–intrusion phases of deep groundwater samples in the coastal delta of Bangladesh

surface of fine-grained sediments in aquifers with solution ions. Cations Na, Ca and Mg are primarily associated in the exchange. The direction of the exchange is toward the equilibrium of cations present in the water and on the finer sediments of the aquifer [11].

The intrusion and freshening process takes multiple steps. The final facies in intrusion phases are Na–Cl, which evolves from Ca–HCO_3 facies via the intermediate Ca–Cl facies. This hydrochemical appearance is characterized by reversing cation exchange reactions. During the freshening process, the Na–Cl water was gradually replaced by Ca–HCO_3 water through the intermediate Na–HCO_3 facies or other equivalent facies. When salt water enters a freshwater aquifer, it triggers a reverse cation exchange reaction. The reaction releases Ca^{2+} ion in previously existing water and Na ions are adsorbed by aquifer sediments.

Direct cation exchange occurs during freshening, when the salt water affected aquifer is washed away by presence of fresh calcium bicarbonate water [18].

In this study, HFE-D diagrams facilitate the observation of ion exchange in where four facies Na–Cl, Ca–Cl, Ca–HCO_3 (or, Mg–HCO_3) and Na–HCO_3 were considered. The HFE-D diagram for river water demonstrate dominant Ca–HCO_3 and Mg–HCO_3 facies in the central to northern alluvial portion indicating direct cation exchange; and the Na–Cl facies in the southern coastal portion denotes reverse cation exchange (Fig. 4b). Shallow groundwater is nearly similarly affected by reverse and direct cation exchange reactions, where deep groundwater is predominantly characterized by reverse cation exchange reactions (Figs. 5b and 6b). Two end members: the seawater of the Bay of Bengal and the freshwater of the river and aquifer, have participated in mixing visualized in the HFE-D diagram. Dissimilarities in mixing nature of two end members have been observed in river water and groundwater hydrochemistry. In river water HFE-D plotting, the prominent end members are freshwater with respect to seawater and are composed predominantly of Ca–HCO_3 (or Mg–HCO_3), where the shallow and deep groundwater is mainly characterized by seawater transgression and comprises the Na–Cl composition (Figs. 4, 5 and 6).

4.5 EC observations between rivers and aquifers

Electrical conductivity (EC) in both shallow and deep groundwater was observed by measuring the EC value along geodesic distances using a line well position map. Geodesic distances are computed from the river to the line wells in eleven locations where line wells are almost installed across the river (Fig. 1). EC pattern values in two graphs (Fig. 7) have been observed to delineate potential interconnections between river water to shallow groundwater; and shallow to deep groundwater.

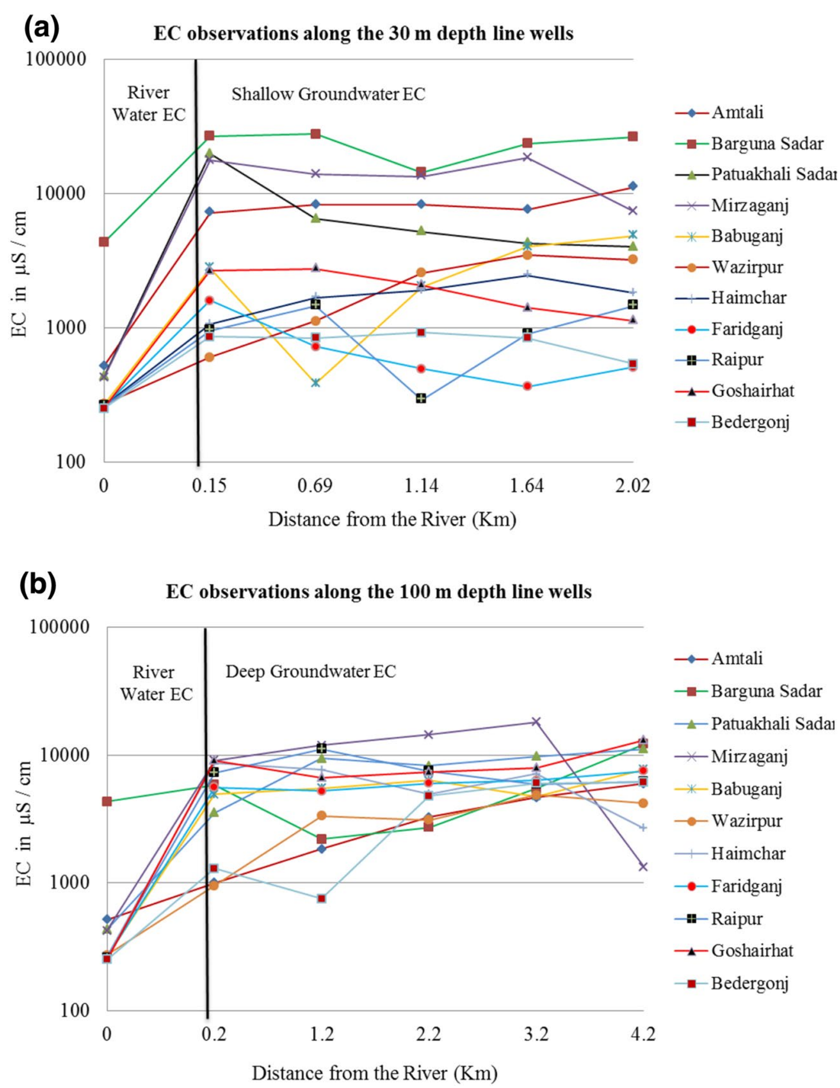

Fig. 7 Two graphs showing the comparison of electrical conductivity (EC): **a** river water to shallow groundwater and **(b)** river water to deep groundwater

EC values show dissimilar trends from rivers to shallow aquifers in the study locations. In Fig. 7a all groundwater samples of nearest wells to river show higher EC values than river water samples and other groundwater samples show irregular pattern suggesting mixing up of freshwater and saline water.

In Fig. 7b, most groundwater samples of nearest wells to river show higher EC values than river water samples, while only one groundwater sample has less value. Other groundwater samples shows irregular pattern in EC values suggesting mixing facies of cation–anion through the groundwaters, seawater and aquifers material. The lithology of the study area is mainly composed of sand and clay; and, sand is very resistant to weathering, while clay can affect the salt contents by absorption or desorption of ions from groundwater.

4.6 Salinity distribution

A sharp variation in salinity distribution has been observed in river water, shallow groundwater and deep groundwater, respectively (Fig. 8). Most of the river waters in the sample region contain salinity levels ranging from 0.10 to 4.45 ppt, except for the Kalapara upazila in the Patuakhali district, which shows this value > 4.45 ppt. It seems that the salinity distributions are almost dissimilar between shallow and deep groundwater. The salinity concentration range in shallow groundwater is 0.1 to 16 ppt, which is higher than the deep groundwater range of 0.4–10 ppt. The concentration rate of salinity is higher in the southern portion of the study region and decreases gradually from coast to inland in both rivers and shallow groundwater. In the extreme southern portion, the deep groundwater salinity concentration is very low, which may imply a lack of salinity data in the southernmost portion.

According to the Department of Water, Government of Western Australia [19], freshwater contains

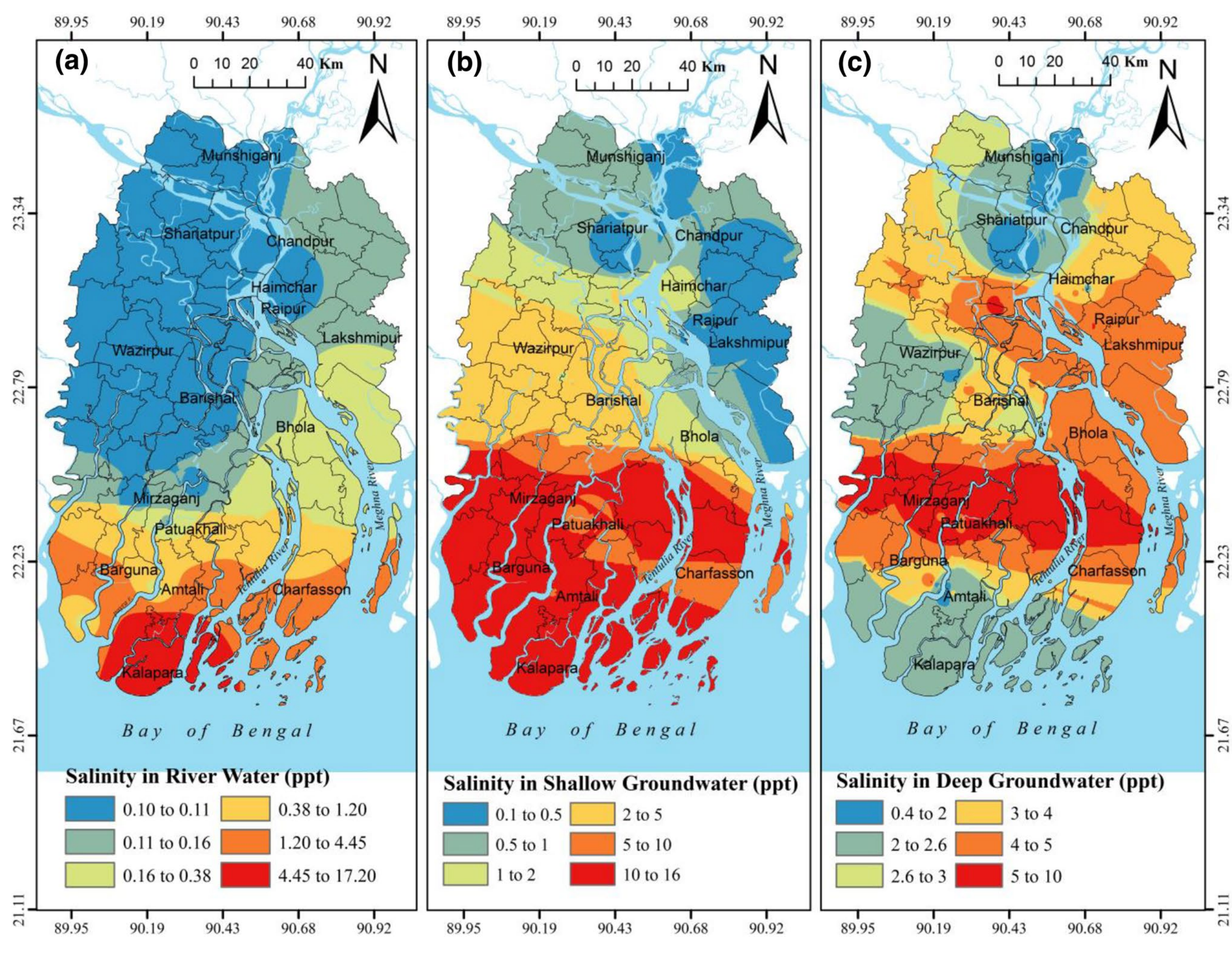

Fig. 8 Illustrating the salinity distribution maps of the river water, shallow groundwater and deep groundwater

salinity values < 0.5 ppt, 0.5–1 ppt in marginal water, 1–2 ppt in brackish water, 2–10 ppt in ordinary saline water, 10–35 ppt in extremely saline water and seawater contains salinity values > 35 ppt. In this research, it appears that the brackish water in the shallow aquifer reaches the Barishal district, and passes the Shariatpur district in the deep aquifer (Fig. 8).

5 Conclusions

Interactions between river water and groundwater have been identified on the basis of multiple perspectives, and it has been found that river water and shallow groundwater are less affected by seawater than deep groundwater. Hydrochemistry, hydrochemical facies evaluation and salinity distributions justify these interactions among river water, groundwater and seawater. Groundwater flow and electrical conductivity (EC) also enhance an understanding of their interactions.

Piper and HFE-D diagram indicates the three sources are interconnected by hydrochemical facies dynamics. Both HFE-D diagrams for shallow groundwater and deep groundwater clearly suggest that a transgression of seawater of the Bay of Bengal has taken place into the coastal aquifer of Bangladesh. In the assessment of river water samples, approximately 82 percent of facies are characterized by freshening phases and 18 percent by intrusion phases suggesting the predominance of freshwater recharge and the insignificant mixing of seawater. Shallow groundwater samples exhibit that there are 14 facies characterized by 53 percent freshening phases and 47 percent intrusion phases indicating the mixing of freshwater and seawater in the shallow aquifer. Finally, deep groundwater reveals that there are only four hydrochemical facies identified and 78 percent corresponding to intrusion phases and 22 percent to freshening phases, strongly suggested intrusion of seawater by reverse cation exchange reactions. Observations of irregular trends of electrical conductivity (EC) values, dissimilar salinity distribution of three sources water, multiple ion exchange process and direction of groundwater flow are also likely to follow the interactions of river water to shallow groundwater and shallow to deep groundwater. Excess concentration of Na^+ and Cl^- ions alerts about saline pollution in groundwater specially in deep groundwater, and HCO_3^- along with Na^+, Ca^{2+}, Mg^{2+} in river water indicates mixing of freshwater and saline seawater, which could have harmful effects both in coastal delta aquatic life and in agriculture. Nitrate concentrations in both shallow and deep groundwater warn the drinking standard and also notify us that anthropogenic activities are leading up to this pollution.

The coastal aquatic system of Bangladesh is regularly experiencing frequent cyclones and storms, sea level rising, tidal activity and excess freshwater pumping which are key causes of salinization and other harmful contamination in fresh groundwater and river water.

Research was conducted on the basis of data from a single dry season, and the related geomorphological and structural data for rivers and aquifers could not be provided in this report. This study further exacerbates the need for a combination of field methods with other advance hydrogeological studies for identifying, explaining and evaluating river water–groundwater interactions in the Bangladesh Coastal Delta.

Acknowledgements Authors would like to express gratitude to Bangladesh Water Development Board (BWDB), Ministry of Water Resources (MoWR) and Bangladesh Climate Change Trust (BCCT), Ministry of Forest, Environment and Climate Change for implementing the project under which the data have been generated and used for this study. The authors are also thankfully acknowledged to the review and editorial team of SN Applied Sciences.

Compliance with ethical standards

Conflict of interest The authors declare that there is no conflict of interests to submit this article in this journal.

References

1. Brammer H (2014) Bangladesh's dynamic coastal regions and sea-level rise. J Clim Risk Manag 1:51–62. https://doi.org/10.1016/j.crm.2013.10.001
2. Faneca Sanchez M, Bashar K, Janssen GMCM, Vogels M, Snel J, Zhou Y, Stuurman R, Dude Essink GHP (2015) SWIBANGLA: Managing salt water intrusion impacts in coastal groundwater systems of Bangladesh, p 153
3. Dasgupta S, Hossain MM, Huq M, Wheeler D (2014) Climate change, groundwater salinization and road maintenance costs in coastal Bangladesh, Policy Research Working Paper 7147, World Bank Group
4. Dasgupta S, Kamal FA, Khan ZH, Choudhury S, Nishat A (2014) River salinity and climate change: evidence from coastal Bangladesh, Policy Research Working Paper 6817, World Bank Group
5. Islam ARMT, Siddiqua MT, Zahid A, Tasnim SS, Rahman MM (2020) Drinking appraisal of coastal groundwater in Bangladesh:

an approach of multi-hazards towards water security and health safety. J Chemosphere. https://doi.org/10.1016/j.chemosphere.2020.126933
6. Naus FL, Schot P, Groen K, Ahmed KM, Griffioen J (2019) Groundwater salinity variation in Upazila Assasuni (southwestern Bangladesh), as steered by surface clay layer thickness, relative elevation and present-day land use. J Hydrol Earth Syst Sci 23:1431–1451. https://doi.org/10.5194/hess-23-1431-2019
7. Zahid A, Rahman A, Hassan MR, Ali MH (2016) Determining sources of groundwater salinity in the multi-layered aquifer system of the Bengal Delta, Bangladesh. BRAC Univ J 11(2):37–51
8. Rahman MM, Bhattacharya AK (2014) Saline water intrusion in coastal aquifers: a case study from Bangladesh. J Eng, Int Organ Sci Res 04(01):07–13
9. Rahman MA, Islam MN (2018) Scarcity of safe drinking water in the South-West Coastal Bangladesh. J Environ Sci Nat Res 11(1 & 2):17–25
10. Shammi M, Rahman MM, Bondad SE, Bodrud-Doza M (2019) Impacts of salinity intrusion in community health: a review of experiences on drinking water sodium from coastal areas of Bangladesh. J Healthc 7:50
11. Todd DK (1995) Groundwater hydrology, 2nd edn. John Wiley, New York, pp 515–516
12. Bomer EJ, Wilson CA, Hale RP, Hossain ANM, Rahman FMA (2020) Surface elevation and sedimentation dynamics in the Ganges-Brahmaputra tidal delta plain, Bangladesh: evidence for mangrove adaptation to human induced tidal amplification. J Catena 187:104312
13. Giménez-Forcada E (2010) Dynamic of seawater interface using hydrochemical facies evolution diagram (HFE-D). Ground Water 48(2):212–216. https://doi.org/10.1111/j.1745-6584.2009.00649.x
14. Piper AM (1944) A graphic procedure in the geochemical interpretation of water-analyses. EOS, Am Geophys Union 25(6):914–928
15. Giménez-Forcada E (2019) Use of the hydrochemical facies diagram (HFE-D) for the evaluation of salinization by seawater intrusion in the coastal Oropesa plain: comparative analysis with the coastal Vinaroz plain, Spain. Hydro Res 2:76–84
16. Kura NU, Ramli MF, Sulaiman WNA, Ibrahim S, Aris AZ, Mustapha A (2013) Evaluation of factors influencing the groundwater chemstry in a small tropical island of Malaysia. J Environ Res Publ Health 10:1861–1881
17. Younger PL (2007) Groundwater in the environment: an introduction, 1st edn. Blackwel Publishing, Newcastle
18. Giménez-Forcada E (2014) Space/time development of seawater intrusion: a study case in Vinaroz coastal plain (Eastern Spain) using HFE-Diagram, and spatial distribution of hydrochemical facies. J Hydrol 517:617–627
19. Department of Water: Government of Western Australia (2020) Understanding salinity, http://wadow.clients.squiz.net/watertopics/water-quality/managing-water-quality/understanding-salinity. Cited 02 March 2020