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Tracing Groundwater Flow Systems with Hydrogeochemistry in Bengal Delta Aquifers, Bangladesh

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Abstract

Objective: In present study, hydrochemical data were used to characterize the hydrogeochemical processes and to identify groundwater flow systems in Bengal Delta aquifers, Bangladesh. **Methods:** Regarding this, 202 shallow, 26 intermediate and 100 deep groundwater samples were collected from the study area for major ion analyses. It is observed that the shallow and intermediate groundwater samples are dominantly Ca-Mg-HCO_3 type, and the deep groundwater is mainly of Na–Cl–HCO_3 and Na–Cl types. In deep groundwater, the loss of Ca^{2+} are ion exchanged for Na^+ along the flow paths, which are initially enriched in Ca^{2+}. The Na-HCO_3 type deep groundwater appear in the coastal confined aquifers, whereas Na-Cl type groundwater are found in wells depth ranging from 200-250m. With some local exceptions, electrical conductivity (EC), pH and Cl^- concentrations for both shallow and deep groundwater gradually increase generally from north-south direction in the study site. **Findings:** The observed results clearly indicate the presence of three groundwater systems: (i) the shallow groundwater characterized by low ionic concentration; (ii) intermediate groundwater with less evolved ionic chemistry; and (iii) the deep groundwater with higher ionic concentration. **Application:** This study enables to conceptualize three groundwater flow systems: namely shallow fast circulating fresh young water mixed and moderately mineralized groundwater representing a transition system between the overlying shallow and underlying deep aquifers and the highly mineralized deep groundwater.

Keywords: Bangladesh, Bengal Delta, Groundwater flow, Hydrogeochemistry

1. Introduction

Hydrogeochemical processes and reactions occurring within groundwater aquifer have a profound effect on groundwater quality. The geochemical properties of groundwater depend on the chemistry of water in the recharge area as well as on different geochemical processes taking place in the subsurface aquifer systems.

The quality of water along the course of its underground movement therefore depends on chemical and physical properties of surrounding rocks, quantitative and qualitative properties of through-flowing water bodies, and the products of human activity[1]. During the last two decades, several research groups[2,3]. Studied hydrogeochemistry and groundwater dynamics of the Bengal basin using a variety of techniques. Suggest that the water chemistry of the Ganges–Brahmaputra drainage system is controlled by the presence of carbonates, silicates and sulfides. They also suggest that weathering is dominated by H_2CO_3 derived from oxidation of Organic Matter (OM) in the soil and minor H_2SO_4 derived from the oxidation of sulfides. Furthermore, Galy and France-Lanord[2] advocate that Na^+ and K^+ are the dominant cations released by the weathering of the alkaline Himalayan silicates because

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of lower abundance of Ca-plagioclase in the Himalayas. Magnesium may be introduced from weathering of biotite to form hydrobiotite, vermiculite or smectite[4]. In [3] suggest that the Ganges–Brahmaputra floodplains have been dominated by carbonate weathering. However, other authors have argued that the development of the foreland basin in front of the Himalayas[5] has resulted in deposition of silt-dominated sediments in the Ganges–Brahmaputra flood plain, favoring silicate weathering[2]. Most of the recent studies of groundwater chemistry in the Bengal basin have strongly advocate that the redox-related processes in the aquifer are largely controlled by FeOOH reduction as catalyzed by microbially mediated oxidation of natural OM[6–8]. The OM may exist as dissolved organic carbon or peat layers[7]. Carbonic acid produced by OM oxidation reacts with aquifer sediments to produce high concentrations of HCO_3^-. The groundwater has been found to be anoxic[9], with frequent detections of sulfide and CH_4[7] and very little dissolved O_2.

Groundwater chemistry so far has been used to infer the groundwater flow systems in the Bengal Delta aquifers. In present study, groundwater chemistry data has evaluated to infer the active hydrogeochemical processes in the Bengal Delta aquifers. Hence, a detailed investigation was carried out to identify the hydrogeochemical process and its relation to groundwater flow system in the Bengal Delta aquifers of Bangladesh.

2. Study area

2.1 Geology, Hydrogeology and Rainfall

Bangladesh occupies the greater part of the Bengal Delta, which forms largely of alluvial and deltaic sediments of the Ganges-Brahmaputra-Meghna (GBM) rivers system. Excluding the eastern Tertiary Hill Range (Figure 1), the present study covers about 85% land area of Bangladesh. It is convenient to consider the regional geology in terms of five major subdivisions – Tertiary deposits, Residual deposits, Alluvial fan deposits, Alluvial deposits and Deltaic deposits (Figure 1)[10,11]. The residual deposits (the Pleistocene Madhupur and Barind Tracts) locally interrupt the flat topography of central Bangladesh rising by up to 20 m above the adjacent floodplains[11]. A generalized geological cross-section (Figure 1) shows the structure of Bengal Basin (Figure 2).

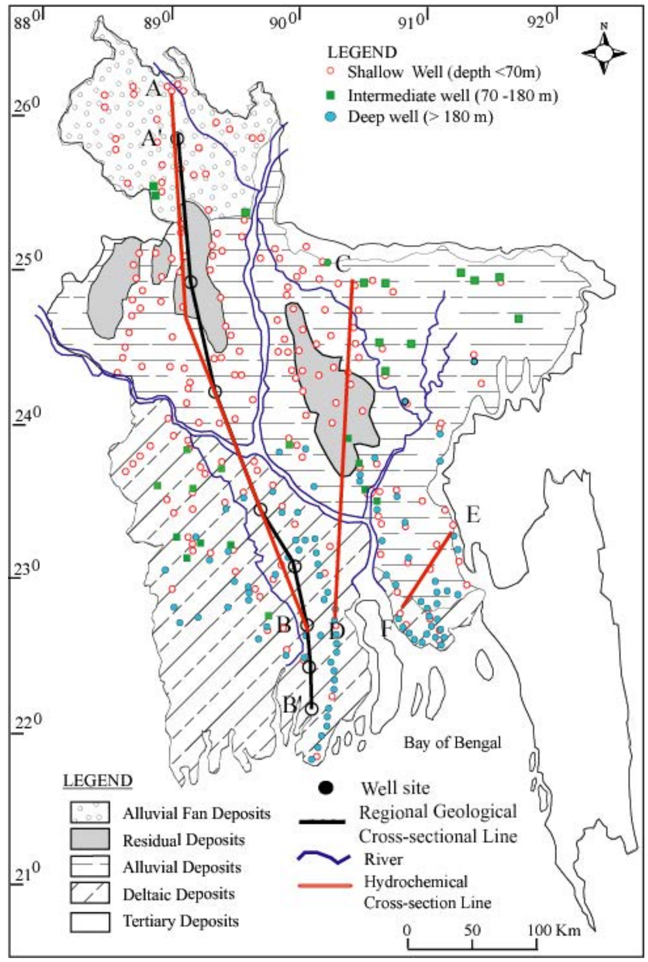

Figure 1. Sample location and surface geological map of Bangladesh (modified after[10-12]).

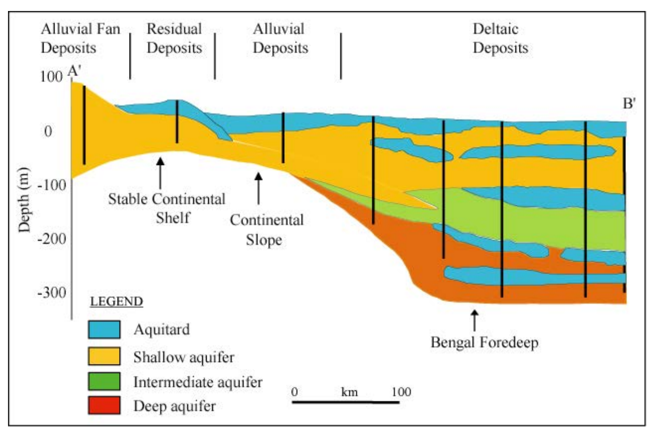

Figure 2. Geological cross-section A'-B' (as shown in Figure 1) through the study area showing borehole locations and the structure of Bengal Basin (modified from[13,32]).

The thick unconsolidated deposits of Pleistocene and Holocene alluvial sediments of the GBM delta system form one of the most productive aquifer systems in the world[12]. Silts and clays are predominate in the upper few meters of the GBM delta system, forming a surfacial aquitard, generally less than 10 m thick with typical specific yield values of 2–3%, and vertical permeability values in the range 3–8×10^{-3} m/d. The aquifers are mostly medium-to-fine and medium-to-coarse sands, with permeability of 40–80 m/d. Short-term pumping tests on the Holocene aquifers indicate a leaky response, but for longer pumping periods the aquifer is best described as regionally unconfined. The principal mineralogical components of the Holocene sands are quartz, plagioclase feldspars, potassium feldspars, micas (muscovite, biotite and chlorite), and clays (smectite, kaolinite and illite). Deep clayey aquitards exist in coastal regions and the sands below the aquitards are commonly referred to as the deep aquifer. In present study, based on the sampled well depths, the studied aquifers are considered as shallow (<70 m), intermediate (70 – 180 m) and deep (>180 m) aquifers[12].

The average annual rainfall in Bangladesh varies from a maximum of 5690 mm in the northeast of the country to minimum of 1110 mm in the west. Up to 95% of the annual rainfall occurs during the May to September monsoon.

3. Methodology

3.1 Groundwater Sampling

A total of 202 shallow, 26 intermediate and 100 deep groundwater samples were collected during the sampling campaigns (January – February, 2006; November – December, 2006; September – October, 2007 and March 2008). Sampled wells were chosen arbitrarily (Figure 1) and prior to sampling each well were pumped for several minutes until it purged out approximately twice the well volume, or until steady state chemical conditions (pH, electrical conductivity and Temperature) were obtained. The geographical location of each well was determined with a GARMIN handheld global positioning system (Kansas, USA) and the approximate depth of wells were noted from the well owner's records. The physical parameters electrical conductivity, pH and temperature were measured with a portable EC/pH meter (TOA EC/pH METER, WM-22EP). Samples for major ion analysis were collected in 100 mL High Density Polyethylene (HDPE) bottle. All the samples were stored at a temperature of 4^{o}C until analysis.

3.2 Laboratory Analyses

The major cations (Ca^{2+}, Mg^{2+}, K^+ and Na^+) and anions (Cl^-, NO_3^- and SO_4^{2-}) were analyzed with an ion chromatography (Metrohm 761 Compact IC). The instrument was linearly calibrated from 2.5 to 7.5 mg/L with standards (Wako Pure Chemicals Industries Ltd., Japan). All of the samples were diluted several times to adjust for the operating range. Alkalinity (as HCO_3^-) was determined by field titration with 1.6 N H_2SO_4 to pH ~ 4.5 using HACH Digital multi Sampler Model 1690.

The potential for a chemical reaction can be determined by calculating the chemical equilibrium of the water with the mineral phase[14]. The equilibrium state of water with respect to a mineral phase can be determined by calculating a saturation index (SI). The saturation indices were calculated using PHREEQC[15] with thermodynamic database of MINTEQA2[16] and the calculated SI values for calcite ($SI_{calcite}$) and dolomite ($SI_{dolomite}$) are given in Table 1. The SI is defined as the logarithm of the ratio of ion activity product (IAP) to the mineral equilibrium constant at a given temperature and given as: $SI = \log_{10}(IAP/K_{sp})$, where IAP = ion activity product and K_{sp} = solubility product at given temperature[14].

4. Results

4.1 Physical Parameters

Physical parameters and major ion concentrations of analyzed water samples are given in Table 1. The shallow and intermediate depth groundwater show low mineralization with EC ranging from 282 – 920 µS/cm (average 637 µS/cm) and 282 – 547 µS/cm (average 531 µS/cm) respectively, and the deep groundwater EC values varied from 117– 4870 µS/cm (average 1288 µS/cm). The shallow groundwater temperature ranges from 23‑30.2°C with an average value of 26°C, while the intermediate depth groundwater temperature varies from 22.4–28°C (average 25.9°C). However, the deep groundwater average temperature is 27.4°C varying from 24.8 – 29.5°C. The shallow groundwater pH values vary from 5.5 – 7.96 with an average value of 6.88. However, the intermediate depth groundwater average pH value is near neutral (7.07) and the deep groundwater average pH value (7.4) is higher than that of the shallow and intermediate well groundwater average pH values.

Table 1. Well site area, well depth, field physical parameters, major ionic concentration and calculated saturation index (SI) for Calcite ($SI_{calcite}$) and Dolomite ($SI_{dolomite}$)

ID.	Area	Well Depth (m)	pH	Temp. (°C)	EC (µS/cm)	HCO_3^- (mg/L)	Cl^- (mg/L)	NO_3^- (mg/L)	SO_4^{2-} (mg/L)	Na^+ (mg/L)	K^+ (mg/L)	Mg^{2+} (mg/L)	Ca^{2+} (mg/L)	$SI_{calcite}$	$SI_{dolomite}$
Shallow groundwater															
1	Fulchari	22	6.65	25	274	151	8.89	0.53	0.11	13.94	5.00	11.90	18.64	-2.63	-5.56
2	Nilphamari	8	6.37	24.3	190.7	79	3.43	2.09	8.80	8.00	4.32	3.56	15.30	-1.92	-4.13
3	Saidpur	12	6.52	25.6	1442	67	7.35	1.51	3.15	9.25	8.94	4.74	17.26	-1.77	-3.74
4	Parbatipur	24	6.63	24.2	188	67	14.51	0.40	3.73	19.35	2.46	3.20	6.63	-2.08	-4.14
5	Fulbari	13	6.64	25.5	215	99	13.24	0.45	1.01	19.21	1.78	5.69	14.42	-1.57	-3.18
6	Hakimpur	10	6.06	24.9	259	67	44.11	3.78	7.84	15.09	1.83	9.77	18.41	-2.24	-4.40
7	Joypurhat	20	7.02	25.2	379	162	40.42	0.60	5.49	25.33	2.43	11.72	30.75	-0.70	-1.46
8	Akkelpur	20	7	24.4	201	106	4.97	0.28	2.13	17.14	1.63	7.03	14.88	-1.18	-2.35
9	Adamdighi	16	6.54	26.3	726	245	107.93	1.15	17.63	50.36	5.07	23.34	28.65	-1.06	-1.84
10	Atrai	26	6.82	26.1	543	268	18.72	1.54	35.68	42.84	5.06	14.08	29.40	-0.72	-1.40
11	Natore	22	6.5	24.4	814	268	19.64	3.08	14.72	42.66	5.20	23.44	25.79	-1.12	-1.94
12	Baraigram	27	6.85	25.3	874	566	16.23	3.00	37.28	146.46	7.17	114.15	76.20	-0.10	0.34
13	Iswardi	26	7.2	26.3	789	455	18.51	4.85	0.24	21.21	5.57	23.88	39.79	0.00	0.14
14	Bheramara	21	6.99	26.6	823	517	7.28	4.80	0.24	25.36	11.57	24.31	16.04	-0.54	-0.53
15	Kushtia	38	6.60	26.20	852	565	3.86	4.99	0.62	23.56	6.89	23.58	25.10	-0.71	-0.18
16	Shailakupa	25	6.85	25.80	803	519	4.92	1.76	7.32	10.41	9.05	25.95	22.54	-0.55	-0.67
17	Jhenaidha	20	6.69	24.50	1075	543	78.25	1.89	29.29	52.76	10.39	24.23	34.12	-0.56	-0.92
18	Kaliganj	46	6.45	26.70	871	478	189.65	6.07	3.64	47.88	12.71	88.71	175.03	-0.19	-0.31
19	Jessore	45	7.20	25.00	562	360	4.00	2.64	0.34	6.92	4.83	15.02	45.39	-0.04	-0.20
20	Jessore	45	7.41	25.30	359	223	2.16	0.80	0.35	6.24	2.82	11.48	50.60	0.04	-0.21
21	Fultala	60	7.27	24.00	1006	619	41.51	1.60	0.94	73.47	9.24	36.50	26.78	-0.04	0.04
22	Khulna	34	6.94	26.20	4500	1186	1564.15	54.58	32.85	1027.35	35.13	116.68	70.50	0.12	0.84
23	Bagerhat	58	7.22	25.7	3000	522	827.19	19.79	42.92	412.08	21.09	34.01	132.03	0.42	0.62
24	Gopalganj	12	7.15	26.2	770	403	30.54	6.43	12.01	25.61	9.52	20.48	67.88	0.11	0.07
25	Kaliakoir	52	7.11	25.6	338	232	2.79	0.27	0.61	24.09	1.73	11.11	29.01	-0.47	-0.10
26	Mirzapur	20	6.61	26.0	850	188	109.64	75.12	67.32	52.34	7.55	17.26	51.31	-0.09	-1.92
27	Tangail	23	6.96	26.1	471	210	52.27	11.16	0.27	29.58	8.53	23.21	93.69	-0.21	-0.66
30	Madhupur	21	6.18	26.2	219	73	26.07	3.07	2.50	16.13	2.82	5.60	17.44	-2.07	-4.27

ID.	Area	Well Depth (m)	pH	Temp. (°C)	EC (µS/cm)	HCO_3^- (mg/L)	Cl^- (mg/L)	NO_3^- (mg/L)	SO_4^{2-} (mg/L)	Na^+ (mg/L)	K^+ (mg/L)	Mg^{2+} (mg/L)	Ca^{2+} (mg/L)	$SI_{calcite}$	$SI_{dolomite}$
32	Jamalpur	40	6.8	25.8	274	173	2.73	0.76	0.07	11.84	3.53	12.50	23.38	-0.98	-1.87
34	Jamalpur	22	6.98	24.3	287	156	13.52	0.70	4.62	23.37	2.23	10.04	22.96	-0.88	-1.77
35	Sherpur	22	6.89	26.6	190	112	1.34	0.85	1.53	2.78	1.34	8.68	18.60	-1.14	-2.24
36	Sherpur	15	6.61	25.5	363	132	37.99	1.26	10.08	12.92	3.36	15.57	26.73	-1.25	-2.37
37	Jhenaigati	40	7.07	24.9	248	159	0.84	1.73	0.10	20.43	2.54	8.09	21.20	-0.80	-1.66
39	Nakla	15	6.76	25.7	620	139	128.74	2.34	18.64	34.79	6.73	23.07	42.81	-0.91	-1.74
40	Fulpur	45	7.24	25.4	339	212	2.80	1.21	0.06	33.19	2.70	10.59	24.03	-0.46	-0.92
43	Netrokona	27	6.9	25.3	381	142	29.25	15.33	0.18	16.05	4.38	12.63	25.88	-0.94	-1.84
44	Tarakanda	12	6.52	25.8	608	146	124.57	13.18	12.94	50.69	5.34	20.62	35.95	-1.21	-2.29
46	Mymensing	58	7.24	25.1	340	220	1.64	1.91	0.02	24.43	2.50	11.80	28.03	-0.39	-0.79
48	Trisal	54	7.08	24.8	352	229	1.43	1.15	0.52	26.38	2.90	12.84	30.20	-0.50	-1.03
51	Sreepur	36	6.36	25.4	156.4	95	2.39	3.94	0.03	12.88	2.38	5.05	13.31	-1.89	-3.85
52	Joydevpur	46	6.8	25.7	233	137	3.02	6.94	0.29	16.63	2.11	7.85	20.79	-1.12	-2.31
54	N-ganj	25	6.97	25.5	961	232	111.80	0.66	5.61	68.68	7.44	9.20	26.13	-0.69	-1.47
56	Munshiganj	16	6.92	25.7	665	330	38.51	4.56	13.09	15.81	6.23	27.78	75.79	-0.16	-0.40
58	Chandpur	52	7.05	26	1951	354	388.89	1.73	10.87	131.24	0.20	31.63	75.33	-0.06	-0.12
59	Matlab	50	6.72	26.4	1344	146	597.72	2.70	25.19	158.63	12.01	49.39	106.23	-0.64	-1.24
60	Raigonj	32	6.88	29.7	310	69	6.50	2.87	0.30	10.81	5.62	9.34	24.45	-1.20	-2.42
61	Sherpur	21	6.3	26.1	517	37	126.29	0.54	8.81	22.36	7.52	17.60	36.51	-1.98	-3.91
62	Bogra	21	6.62	26.9	285	37	33.23	6.03	6.51	21.96	4.16	8.80	18.93	-1.89	-3.74
63	Gobindagonj	8	6.54	26.3	328	74	14.91	2.77	4.32	17.86	7.41	14.44	24.36	-1.58	-3.02
64	Palashbari	34	6.55	28	460	74	54.19	0.22	11.78	33.60	20.76	7.17	22.98	-1.58	-3.28
65	Gaibandha	15	6.64	25.5	270	31	16.03	3.72	0.32	10.75	2.55	4.29	15.37	-2.03	-4.25
66	Mithapukur	21	6.75	28	214	49	7.58	0.08	0.99	16.65	2.47	8.59	13.42	-1.75	-3.30
67	Kurigram	12	6.26	24.3	242	43	4.59	12.09	4.09	8.68	4.30	5.28	19.09	-2.20	-4.61
68	Lalmoni	24	6.45	23.8	158	18	12.59	18.49	4.85	11.02	7.63	3.17	11.32	-2.60	-5.42
69	Hatibandha	8	6.41	26.1	62	12	2.36	2.23	0.41	2.67	4.74	0.88	3.90	-2.63	-5.56
70	Dimla	11	6.38	26.1	240	25	22.67	43.84	9.02	13.01	15.38	2.87	14.28	-2.44	-5.22
71	Debigonj	21	6.3	26.5	106	25	4.51	6.45	4.09	3.50	3.95	1.25	14.20	-2.47	-5.63
72	Debigonj	38	6.8	24.9	92.7	25	0.61	0.41	0.26	10.15	3.69	1.83	6.23	-2.33	-4.85
73	Thakurgaon	27	6.57	23.2	74	49	2.86	0.19	5.31	8.36	1.65	0.95	5.16	-2.38	-5.16

ID.	Area	Well Depth (m)	pH	Temp. (°C)	EC (µS/cm)	HCO_3^- (mg/L)	Cl^- (mg/L)	NO_3^- (mg/L)	SO_4^{2-} (mg/L)	Na^+ (mg/L)	K^+ (mg/L)	Mg^{2+} (mg/L)	Ca^{2+} (mg/L)	$SI_{calcite}$	$SI_{dolomite}$
74	Birgoj	23	6.12	24.9	70	18	2.94	1.52	1.44	4.79	4.12	1.32	5.51	-3.18	-6.64
75	Dinajpur	12	6.3	25.2	95	25	5.79	4.01	3.28	7.50	4.26	2.70	5.42	-2.90	-5.57
76	Naogaon	29	6.6	24.1	245	31	28.06	0.16	3.62	21.99	3.47	7.12	16.18	-2.80	-4.18
77	Tarash	23	6.82	25.2	365	86	18.03	0.20	18.65	19.72	5.53	11.99	35.97	-1.10	-2.32
78	Ullapara	21	6.71	26.3	352	74	9.38	1.82	11.94	13.10	7.09	15.58	26.69	-1.37	-2.62
79	Sathia	30	6.68	26.8	505	129	2.42	5.92	0.33	14.85	7.25	20.52	46.03	-0.94	-1.87
80	Pangsha	44	7.12	25.5	915	253	31.66	2.97	0.52	49.34	10.75	31.10	68.88	-0.11	-0.21
81	Modhukhali	49	6.95	26.1	923	271	11.81	3.60	0.61	23.06	12.95	29.62	66.76	-0.25	-1.53
82	Magura	69	7	25.9	740	210	12.20	1.06	11.23	12.98	9.20	23.03	55.35	-0.37	-0.77
84	Narail	37	7	25.5	660	185	1.31	10.59	0.74	10.21	9.29	25.21	78.66	-0.29	-0.72
85	Joshore	55	7.2	25.6	1306	302	270.82	0.49	2.48	83.26	15.95	38.25	67.60	0.00	0.10
87	Bagerhut	21	7.07	25.3	733	197	6.58	22.01	0.60	19.52	11.04	23.58	78.57	-0.20	-0.57
88	Zianagar	14	7.12	24.5	2480	351	527.49	16.06	1.50	425.32	24.37	17.24	54.46	-0.18	-0.52
89	Bhandaria	26	7.12	25.7	3030	370	642.43	36.48	1.80	478.96	33.30	47.20	40.82	-0.30	-0.17
90	Jhalokathi	12	7.31	25.2	1375	290	175.24	4.94	5.61	75.06	18.28	63.96	77.94	0.13	0.53
91	Gouronadi	23	7.07	24.4	927	269	41.69	25.38	0.54	69.15	13.34	20.84	75.38	-0.12	-0.45
93	Ghatail	18	6.8	26.1	298	68	10.61	1.70	4.17	16.24	4.17	11.16	21.53	-1.40	-2.73
94	Dewangonj	23	6.56	24.3	312	62	15.93	0.86	4.98	11.92	5.15	10.69	20.90	-1.72	-3.39
95	Bakshigonj	12	6.36	25.7	295	31	41.74	87.07	31.59	20.84	23.94	19.25	41.60	-1.98	-3.95
96	Nalitabari	12	6.73	26.7	496	74	27.50	5.02	4.51	9.42	5.69	13.12	21.71	-1.43	-2.71
97	Purbodhala	12	6.8	25	335	43	25.04	35.10	13.62	15.85	6.57	10.68	25.06	-1.57	-3.17
98	Netrokona	27	6.85	23.2	428	100	10.23	24.08	0.81	11.29	2.51	13.46	40.06	-0.99	-2.12
99	Nandail	37	7	24.5	430	111	24.07	0.16	0.23	42.10	6.23	11.94	20.28	-1.05	-1.99
100	Pakundia	14	6.83	25.1	123	62	2.35	0.07	2.29	3.50	1.76	5.11	10.72	-1.69	-3.35
101	Kuliar Char	26	6.7	25.9	626	153	55.95	7.42	2.10	34.63	29.04	18.41	34.04	-1.01	-1.92
102	Chatok	64	6.93	23.7	612	136	17.79	7.37	8.29	54.53	6.82	12.39	25.20	-0.97	-1.92
103	Baniachong	67	6.85	26.2	316	80	3.72	6.07	0.21	41.99	1.22	6.35	15.14	-1.43	-2.87
104	Sayestagonj	65	6.8	25.2	260	78	0.94	3.00	0.10	36.33	1.26	5.53	10.95	-1.63	-3.21
105	B. Baria	30	6.9	24.5	234	31	1.87	5.18	0.21	10.39	2.35	13.17	17.07	-1.75	-3.27
106	Comilla	37	7.12	27	182	62	0.73	0.19	2.71	18.13	0.47	5.47	12.87	-1.31	-2.61
107	Laksham	20	7.15	26.7	316	92	10.40	14.02	0.28	21.89	9.32	21.91	15.40	-1.08	-1.63

ID.	Area	Well Depth (m)	pH	Temp. (°C)	EC (µS/cm)	HCO_3^- (mg/L)	Cl^- (mg/L)	NO_3^- (mg/L)	SO_4^{2-} (mg/L)	Na^+ (mg/L)	K^+ (mg/L)	Mg^{2+} (mg/L)	Ca^{2+} (mg/L)	$SI_{calcite}$	$SI_{dolomite}$
108	Sonaimuri	17	7.08	25.5	7120	191	3420.27	92.25	51.66	2456.60	100.31	151.25	58.64	-0.63	-0.58
109	Lakhipur	46	7.02	25.5	1460	154	318.13	14.49	9.27	74.53	15.37	74.87	69.67	-0.48	-0.57
110	Chandpur	18	6.85	25.3	1380	314	134.19	35.99	0.62	130.58	10.15	43.09	102.31	-1.18	-0.38
111	Kochua	24	7.07	26.4	2061	197	542.12	28.63	0.92	330.32	16.21	45.44	31.03	-0.69	0.84
112	Daudkandi	20	6.95	26.4	940	247	51.52	33.89	0.54	88.21	10.69	42.47	43.88	-0.49	-0.63
113	Araihazar	55	6.93	25.8	510	142	6.50	5.21	1.22	19.48	3.09	35.26	38.90	-0.76	-1.20
114	Manikgonj	18	6.6	24.4	556	160	3.82	7.76	0.29	12.20	3.98	18.38	23.50	-1.24	-2.25
115	Goalondo	18	6.9	26.3	926	234	53.73	1.96	23.84	24.87	10.29	19.56	78.60	-0.30	-0.83
116	Faridpur	18	7.08	27	548	154	9.67	4.99	0.60	8.94	8.03	16.69	62.95	-0.34	-0.89
117	Bhanga	21	7.04	27.3	1873	234	29.02	14.98	1.81	26.81	24.10	50.08	188.84	0.17	0.15
118	Bhanga	32	7.03	26.5	1047	345	9.02	22.79	0.56	29.07	8.79	37.40	106.04	0.10	0.12
128	Kurigram	38	6.55	24.3	260	55	0.68	0.32	2.42	10.77	2.45	7.47	19.62	-1.78	-3.65
129	Aditmari	61	6.23	24.8	114	37	0.58	0.01	8.75	8.61	1.15	3.06	9.92	-2.55	-2.26
130	Hatibandha	52	5.5	24.5	102	31	0.03	0.03	18.90	6.49	1.03	2.25	8.89	-3.41	-7.07
131	Dimla	73	6.62	26.2	88	25	1.22	0.02	27.72	3.67	2.29	1.46	8.91	-2.37	-5.15
132	Thakurgaon	55	6.45	23	101	31	0.86	0.06	15.02	9.75	1.66	1.79	8.06	-2.52	-5.37
133	Birgonj	61	6.26	25.1	145	43	0.35	0.29	4.60	14.55	1.51	3.05	11.34	-2.39	-5.00
136	Hakimpur	37	6.53	26.6	142	25	7.94	0.17	1.71	15.15	0.43	2.56	6.88	-2.54	-5.15
137	Badalgachi	30	6.5	23.9	173	31	2.28	0.05	45.80	7.19	3.82	3.31	14.22	-2.25	-4.81
138	Manda	32	6.57	25.1	291	92	4.91	0.63	0.53	25.45	2.71	10.47	22.69	-4.49	-2.97
139	Manda	73	6.58	25.6	305	80	7.52	0.29	0.42	24.75	2.24	9.28	20.81	-1.57	-3.13
140	Mohanpur	34	6.81	25.6	853	277	1.44	0.07	6.28	49.83	0.96	31.44	66.24	-0.39	-0.75
141	Mohanpur	55	6.96	25.4	755	228	3.93	0.04	9.50	33.63	0.22	30.31	79.72	0.25	-0.56
142	Amchori	61	7.07	26.6	812	240	3.50	0.02	259.39	21.14	0.38	24.39	66.87	-0.27	-0.61
143	Baraigram	32	7.07	24.8	512	142	3.25	0.02	81.31	8.13	0.24	15.34	51.36	-0.53	-1.25
144	Tarash	43	7.15	25.1	497	123	7.58	0.01	276.69	28.66	0.95	14.40	51.69	-0.60	-1.41
145	Ullapara	55	7.01	26.9	453	86	8.62	0.06	321.80	10.77	1.99	16.94	37.24	-1.02	-2.03
146	Ataikula	55	7.03	26.3	661	166	12.39	0.02	30.43	34.24	0.55	20.54	51.57	-0.47	-0.98
147	Pabna	46	6.96	26.1	860	259	5.72	0.04	131.86	6.00	1.60	27.13	1.30	-1.99	-2.30
163	Pathrail	64	6.71	26.7	457	105	41.44	0.70	0.84	69.53	0.93	3.17	8.31	-1.71	-3.48
164	Ghatail	64	6.71	25.5	474	113	6.99	1.75	3.06	18.06	1.94	18.47	52.86	-0.93	-1.96

ID.	Area	Well Depth (m)	pH	Temp. (°C)	EC (µS/cm)	HCO_3^- (mg/L)	Cl^- (mg/L)	NO_3^- (mg/L)	SO_4^{2-} (mg/L)	Na^+ (mg/L)	K^+ (mg/L)	Mg^{2+} (mg/L)	Ca^{2+} (mg/L)	$SI_{calcite}$	$SI_{dolomite}$
165	Jamalpur	46	6.33	23.4	412	49	19.18	2.59	7.29	14.07	3.47	16.30	39.67	-1.80	-3.67
166	Bokshigonj	60	6.78	26.1	280	80	22.35	1.37	7.07	8.26	1.53	8.44	22.58	-1.33	-2.72
168	Phulpur	55	7.17	26.4	328	99	2.84	7.56	1.09	16.44	4.13	22.98	65.89	-0.44	-0.96
180	B. Baria	61	7.96	24.6	198	62	0.55	7.43	0.11	43.09	0.64	3.92	5.21	-0.90	-1.59
192	Goalondo	61	6.95	26.4	1006	277	26.55	3.27	16.58	16.40	5.03	32.34	106.78	-0.60	-0.27
196	Bhaluka	67	6.86	27.2	273	86	0.85	0.46	0.41	18.84	1.11	10.38	25.01	-1.16	-2.32
197	Bhaluka	70	6.76	26	173	43	2.43	0.87	0.52	14.42	0.87	5.53	16.25	-1.73	-3.57
200	Raygonj	32	6.9	26.5	184	62	3.81	1.80	4.69	13.72	2.59	8.27	19.75	-1.36	-2.74
201	Sherpur	23	6.95	27.7	181	49	23.76	6.74	5.70	20.61	0.84	6.74	13.90	-1.55	-3.03
202	Bogra	27	6.8	26.9	141	37	8.90	3.13	1.50	7.18	2.56	5.54	22.11	-1.62	-3.47
203	Shibganj	15	7.12	26.9	166	55	10.46	0.25	2.59	8.04	3.63	8.44	19.59	-1.18	-2.36
204	Gobindaganj	9	6.72	26.9	193	74	9.24	3.17	0.61	11.21	3.00	9.54	24.62	-1.37	-2.78
205	Pirganj	23	6.4	26.6	127	31	12.79	11.00	4.08	11.86	1.61	4.84	13.41	-2.32	-4.71
206	Mithapukur	21	6.7	27.7	131	62	6.30	0.02	1.00	17.17	0.97	8.21	13.57	-1.70	-3.24
207	Rangpur	32	7.09	26.5	87	37	2.62	0.17	2.39	8.38	2.10	2.84	10.98	-1.61	-3.45
208	Mithapukur	23	6.61	25.5	119	43	3.76	1.19	0.08	7.31	1.86	3.44	19.08	-1.81	-4.02
209	Badarganj	23	6.87	25.9	154	55	2.47	0.49	0.09	14.24	1.56	7.32	18.09	-1.47	-2.98
210	Phulbari	14	6.33	26.2	189	43	19.08	25.56	13.48	14.45	6.39	5.74	20.70	-2.09	-4.38
215	Dhamoirhat	34	6.7	26.4	70	25	3.14	5.10	0.64	10.64	1.74	1.72	4.41	-2.56	-5.17
216	Dhamoirhat	20	6.6	26.5	139	43	7.70	0.43	1.63	11.91	2.76	6.01	14.66	-1.93	-3.88
217	Patnitala	20	6.55	27.2	176	68	12.09	0.17	1.02	14.09	3.51	9.64	19.24	-1.67	-3.28
218	Mahadevpur	26	6.56	27	164	62	1.67	0.17	2.10	20.50	1.81	7.58	14.95	-1.81	-3.54
219	Mahadevpur	34	7.09	26.5	310	111	20.25	0.17	4.64	28.34	2.78	11.72	38.62	-0.67	-1.49
220	Naogaon	29	6.66	26.7	210	80	32.55	0.17	3.23	23.39	1.83	8.02	18.65	-1.52	-3.04
221	Joypurhat	15	6.85	26.5	310	99	17.26	0.17	7.44	31.04	2.53	14.34	34.86	-1.00	-2.03
222	Manda	32	7.07	27.2	390	166	28.26	0.25	1.11	34.05	3.83	25.29	22.15	-0.76	-1.09
223	Paba	30	7.28	27.4	350	166	5.45	0.22	0.65	26.56	3.58	21.78	51.00	-0.20	-0.38
224	Rajshahi	37	7.16	26.5	510	216	54.68	0.90	7.98	37.14	3.90	39.65	34.69	-0.41	-0.40
225	Puthiya	35	7.14	24.4	510	247	3.43	3.30	0.06	29.51	6.87	36.69	56.94	-0.19	-0.23
226	Mirpur	37	7.34	26.8	350	148	15.76	1.90	12.58	21.18	2.88	17.23	59.94	-0.13	-0.43
228	Gangni	18	7.32	26.9	360	197	42.80	2.73	10.73	15.19	6.38	23.51	83.13	0.90	0.00

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229	Meherpur	12	7.3	27.3	530	216	27.01	5.87	0.36	28.83	12.21	24.81	48.04	-0.11	-0.12
230	Meherpur	38	7.22	26.8	530	240	2.05	6.23	0.27	21.97	10.01	27.82	34.65	-0.28	-0.28
232	Jibonnagar	9	7.33	26.9	370	142	32.25	58.12	11.41	20.92	4.58	19.04	73.49	-0.10	-0.42
233	Jibonnagar	55	7.09	26.9	520	173	48.38	0.87	4.11	16.14	3.59	29.59	62.68	-0.31	-0.57
236	Kalaroa	46	7.06	27.2	810	308	120.95	21.38	0.71	55.44	9.72	47.39	170.38	0.26	0.34
244	Jhalakathi	12	7.24	26.8	1110	832	194.08	5.33	5.50	84.24	17.26	78.28	136.35	0.71	1.55
253	Gopalganj	37	7.17	27.9	580	240	6.76	11.51	0.20	15.83	12.89	33.56	77.12	0.00	0.02
258	Madaripur	30	7.28	26.8	410	142	16.82	19.79	0.26	21.01	10.78	28.41	60.35	-0.22	-0.39
262	Burichong	58	7.48	27.6	310	136	10.78	14.23	0.07	21.75	12.83	37.49	25.05	-0.39	-0.23
263	C-gram	15	6.69	26.7	144	55	2.33	0.91	4.06	24.87	7.53	4.26	10.16	-1.89	-3.79
266	C-gram	35	6.92	26.7	147	62	1.56	0.53	0.78	13.13	5.52	6.14	14.73	-1.45	-2.92
268	D-bhuyan	18	7.43	26.9	910	154	239.30	52.85	1.60	90.61	20.47	57.86	46.74	-0.21	0.04
273	Suborna	8	7.46	27	870	327	58.16	3.34	16.58	70.73	22.42	65.17	57.23	0.23	0.90
277	Suborna	7	7.75	26.9	1090	296	167.74	3.45	45.11	223.15	24.37	39.98	37.49	0.27	0.95
279	Suborna	12	7.59	27	910	222	155.88	8.09	73.13	86.19	25.00	61.73	72.35	0.27	0.85
281	Suborna	7	7.88	27	2330	388	743.15	8.40	76.38	614.29	45.24	43.15	26.60	0.27	1.14
284	Maijdi	8	7.61	26.5	4100	357	1463.04	7.78	149.88	939.68	66.10	91.76	53.36	0.19	0.99
288	Ramgati	9	7.61	27.6	3100	462	1126.56	17.22	133.02	921.86	41.60	76.76	32.84	0.12	0.99
291	Ramgati	9	7.6	26.6	710	166	175.72	2.16	1.38	161.08	8.40	19.32	30.96	-0.15	-0.13
292	Kaliakoir	52	7.28	26.8	270	105	5.24	2.88	2.29	22.95	2.39	11.61	41.16	0.47	-1.12
293	Mirzapur	21	6.7	26.2	430	99	54.20	3.94	41.28	19.28	18.01	24.90	57.24	-0.99	-1.99
294	Basail	18	7.07	27.1	360	142	5.61	1.79	8.56	15.10	4.57	19.48	53.79	-0.45	-0.97
296	Kalihati	18	6.82	25.9	250	99	8.68	6.02	0.74	12.86	3.45	13.18	41.75	-0.96	-2.06
298	Bhuapur	37	7	26.7	310	123	2.18	5.91	0.35	19.45	5.26	19.47	42.98	-0.67	-1.32
299	Gopalpur	20	6.97	26.3	220	74	13.29	7.35	0.35	16.04	3.36	11.36	27.03	-1.00	-2.21
301	Madhupur	21	7.27	26.7	180	68	2.15	0.83	1.55	18.61	2.34	7.15	24.78	-0.86	-1.88
302	Muktagacha	27	7	26.6	270	105	5.03	0.45	6.10	19.83	1.90	12.66	40.84	-0.75	-1.65
304	Fulbaria	59	7.67	26.4	310	123	1.16	0.48	0.49	32.77	2.36	13.03	42.44	-0.01	-0.17
308	Joydevpur	46	6.8	26	199	68	1.35	1.45	0.01	14.34	4.71	13.79	22.58	-1.38	-2.61
309	Sreepur	36	6.4	26.5	114	25	7.40	1.97	0.12	7.19	5.55	4.00	11.92	-2.45	-5.00
310	Valuka	58	7.11	26.1	236	86	0.73	0.18	0.46	19.06	3.44	16.94	24.55	-0.94	-1.68

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313	Ghatail	26	6.11	27	50	12	2.18	10.36	0.10	4.87	3.60	0.02	3.64	-3.52	-8.88
314	Shakhipur	27	6.6	26.2	76	18	1.58	12.00	0.30	7.29	3.29	1.43	8.10	-2.54	-5.46
320	Bhaluka	70	6.74	26.1	141	49	3.12	0.63	0.72	13.11	2.71	4.80	14.55	-1.74	-3.59
321	Gobindaganj	59	7.1	26.5	164	62	0.46	3.33	0.07	1.57	0.39	1.07	2.47	-2.01	-4.02
322	Dinajpur	12	6.07	25.4	40	25	0.57	1.07	0.17	1.20	0.78	0.66	1.86	-3.55	-7.21
324	Obhaynagar	55	7.1	27.1	610	271	12.27	1.76	0.53	65.00	7.24	19.43	65.17	-0.09	-0.34
326	Khulna	61	7.07	28.2	3810	271	1574.15	6.06	12.03	953.59	43.78	53.33	99.16	-0.15	-0.17
328	Patuakhali	14	6.96	26.3	1810	247	558.30	2.87	1.65	363.31	36.39	43.23	37.95	-0.62	-0.82
334	Kuakata	6	7.86	30.2	455	136	25.99	0.77	16.29	25.00	9.81	21.30	21.18	-0.04	0.32
343	Ramganj	14	7.04	27.6	755	173	98.52	2.12	0.08	120.08	13.33	35.72	24.08	-0.78	-1.00
347	Noakhali	15	7.2	24.8	2390	296	621.48	8.50	68.13	393.29	32.99	68.44	11.39	-0.88	-0.63
348	Suborna	8	7.53	27.3	1170	357	71.82	2.80	19.20	73.66	22.18	77.59	60.12	0.35	1.19
351	Kachua	24	7.06	26.5	1667	617	237.32	4.18	24.47	157.00	10.58	48.90	36.80	-0.13	0.24
352	Singair	12	7.14	27.50	444	255	7.12	1.11	11.92	6.97	6.85	20.57	56.88	-0.12	-0.30
353	Singair	12	6.98	25.3	432	271.16	7.78	0.31	7.11	6.63	5.01	17.02	35.98	-0.46	-0.90
354	Singair	14	7.08	26.00	553	238	24.73	1.22	36.36	12.77	5.79	21.46	59.92	-0.22	-0.53
355	Singair	14	6.9	26.1	456	184.88	9.43	0.72	12.82	15.70	5.48	20.64	48.92	-0.57	-1.15
363	Shahjadpur	62	6.91	27.8	470	235	11.49	159.49	0.51	311.00	20.60	85.50	61.40	-0.44	-0.36
365	Sarisabari	26	6.38	26	365	204	14.36	58.29	2.65	22.00	2.53	26.30	84.60	-0.83	-1.81
Intermediate groundwater															
42	Netrokona	80	7.21	24.5	397	198	33.49	0.55	0.01	38.93	2.31	12.52	26.91	-0.38	0.14
53	Sonagaon	80	7.09	26.6	980	283	127.57	40.58	5.18	93.65	56.55	31.14	34.00	-4.35	-4.21
55	N-ganj	85	7.05	27	933	227	88.07	0.66	2.99	63.73	3.54	5.83	16.49	-0.46	-0.90
57	Munshiganj	90	6.98	26.2	720	273	101.43	1.43	0.16	70.70	5.78	16.63	37.13	-0.19	-0.52
83	Narail	91	7.12	25	625	185	2.78	12.14	0.74	12.30	9.62	24.25	77.05	-0.29	-0.48
86	Fakirhati	78	7.05	27.6	293	197	491.30	25.20	0.90	268.42	27.73	40.88	78.96	-0.19	-0.03
120	Jessore	132	7.27	25.70	629	394	12.30	0.85	0.39	24.97	6.02	23.90	24.68	-1.43	-2.86
127	Gaibandha	76	6.54	25.4	313	86	1.64	0.08	1.77	4.27	2.58	13.22	29.71	-1.46	-3.04
135	Phulbari	107	6.78	26.3	282	55	0.81	0.35	7.18	21.51	1.14	7.64	23.70	0.08	-0.05
148	Kustia	88	7.22	25.6	777	240	2.28	0.12	4.66	12.88	1.35	23.80	87.36	-0.38	0.14

ID.	Area	Well Depth (m)	pH	Temp. (°C)	EC (µS/cm)	HCO_3^- (mg/L)	Cl^- (mg/L)	NO_3^- (mg/L)	SO_4^{2-} (mg/L)	Na^+ (mg/L)	K^+ (mg/L)	Mg^{2+} (mg/L)	Ca^{2+} (mg/L)	$SI_{calcite}$	$SI_{dolomite}$
149	Pangsha	128	7.06	25.8	920	277	14.00	0.05	8.74	47.95	2.51	32.82	1.35	-1.80	-1.85
152	Jhinaidah	134	7.11	26.6	740	243	1.64	0.05	2.58	10.47	1.30	27.44	60.65	-0.16	-0.29
153	Joshore	98	7.15	26.4	915	259	9.86	0.06	3.98	21.37	3.09	23.72	17.91	-0.60	-0.70
169	Purbodhola	85	7.05	25	330	92	1.23	7.55	1.05	80.00	3.63	11.32	23.97	-1.01	-2.00
171	Nandail	91	6.98	24	323	105	2.95	3.70	0.44	37.99	0.89	9.27	22.19	-1.06	-2.16
172	Tarail	107	7.22	25.8	1180	230	2.75	9.77	0.82	191.88	4.08	13.11	35.92	-0.32	-0.72
173	Pakundia	85	7.06	25.7	264	74	15.35	0.13	0.05	15.76	1.82	5.34	13.16	-1.30	-2.64
175	Sunamgonj	168	6.82	22.4	361	127	3.01	0.35	1.30	20.66	2.79	22.62	52.59	-0.82	-1.64
176	Madanpur	122	6.95	23.3	409	123	0.95	8.90	0.23	40.66	2.45	8.33	20.23	-1.07	-2.20
177	Chatok	149	7.11	23.6	500	142	3.39	10.81	0.10	36.47	1.70	11.67	25.48	-0.76	-1.53
178	Balagonj	152	7.1	26.4	474	154	13.53	2.79	0.14	67.51	1.65	6.53	15.88	-0.89	-1.81
191	Manikgonj	152	6.7	25.3	630	197	6.80	3.43	19.89	23.78	4.21	25.44	76.02	-0.59	-1.30
199	Tongi	137	6.98	27.6	317	68	17.28	0.94	1.87	26.40	1.39	9.02	25.56	-1.13	-2.33
212	Phulbari	107	7.05	27	230	89	1.51	0.52	0.48	23.39	3.21	8.18	24.39	-0.96	-2.03
227	Gangni	73	7.25	27.2	310	179	2.52	2.64	0.12	13.18	5.17	20.27	74.24	-0.05	-0.28
231	Chuadanga	107	7.51	27.2	460	210	10.90	2.56	3.73	14.42	4.77	21.26	70.39	0.25	0.36
234	Chowgacha	107	7.5	28	360	173	2.09	10.04	0.10	3.96	3.64	6.90	24.72	-0.23	-0.62
267	Feni	91	7.07	27.5	182	86	1.70	0.56	2.50	18.63	6.69	8.78	22.48	-0.99	-2.00
Deep groundwater															
121	Fultala	280	7.63	27.00	1643	406	371.18	4.88	11.23	139.50	13.70	49.40	56.42	-0.38	0.14
122	Khulna	270	8.88	28.8	847	449	38.12	3.40	0.70	159.90	7.98	9.59	17.37	-2.80	-6.38
124	Sonagaon	300	6.92	25.5	520	210	74.92	0.41	1.26	44.67	5.32	16.20	34.79	-0.33	-0.75
125	Sonagaon	220	7.20	26	972	234	213.69	1.78	4.40	137.86	3.57	13.22	37.54	-1.15	-2.27
126	Matlab	210	6.52	25.9	1931	71	597.72	2.70	25.19	158.63	12.01	49.39	106.23	-0.19	-0.23
150	Madhukhali	213	7	26.3	1071	302	15.52	0.17	21.20	31.95	2.22	39.06	63.04	0.08	0.09
151	Magura	250	7.4	26.1	684	207	5.47	0.01	16.16	8.70	1.61	23.43	64.03	0.00	0.10
154	Narail	238	6.98	25	3335	247	271.62	0.06	18.40	270.41	7.42	96.45	170.08	0.06	0.13
155	Joshore	244	7.3	26	1342	207	263.79	0.69	2.33	73.49	3.64	39.61	89.51	0.08	0.36
156	Khulna	310	7.62	27.3	1553	173	326.23	6.52	3.47	192.20	6.25	34.86	52.24	0.29	0.59
157	Bagerhut	305	7.48	27	2890	185	450.62	5.23	1.74	99.26	18.61	51.37	120.28	-0.38	0.14

ID.	Area	Well Depth (m)	pH	Temp. (°C)	EC (µS/cm)	HCO_3^- (mg/L)	Cl^- (mg/L)	NO_3^- (mg/L)	SO_4^{2-} (mg/L)	Na^+ (mg/L)	K^+ (mg/L)	Mg^{2+} (mg/L)	Ca^{2+} (mg/L)	$SI_{calcite}$	$SI_{dolomite}$
158	Zia Nagor	300	7.93	26.1	4870	234	1078.50	12.80	1.76	569.75	20.25	102.05	154.47	0.81	1.82
159	Bhandaria	292	7.91	26.1	2996	216	615.50	3.06	1.00	357.25	10.62	56.23	84.63	0.58	1.35
160	Jhalokathi	300	7.86	27.3	1436	222	458.55	3.90	0.41	340.09	6.11	4.94	11.31	-0.24	-0.46
161	Gouronodi	300	7.68	25.1	1630	197	526.53	6.38	0.75	524.03	4.34	9.90	21.75	0.25	-0.48
167	Nalitabari	213	7.1	26.8	283	74	17.30	1.19	4.77	12.66	0.71	6.47	17.89	-1.12	-2.32
174	Kuliar Chor	244	7.03	27.1	332	49	34.81	0.22	1.16	96.47	1.08	1.63	8.16	-1.72	-3.76
179	Baniachong	210	6.9	25.1	297	92	5.39	5.98	0.09	31.59	1.37	7.15	15.14	-1.33	-2.63
181	B. Baria	244	6.98	25.4	355	68	4.50	2.93	0.02	54.85	2.77	19.68	39.79	-1.00	-1.95
182	Kosba	183	6.92	26.4	488	123	4.99	0.26	0.17	27.29	3.67	14.71	45.17	-0.73	-1.58
183	Laksum	213	7.24	27.1	1382	68	354.76	1.57	31.63	222.32	3.87	12.79	15.08	-1.22	-2.14
184	Begumgonj	244	6.87	25.9	2510	43	712.97	17.03	27.30	219.17	6.06	67.34	140.09	-0.93	-1.82
185	Lakkhipur	244	7.1	25.2	1219	105	284.83	0.81	4.56	83.35	5.04	39.89	74.26	-0.51	-0.94
186	Raipur	259	7.19	26	417	111	17.22	2.05	0.29	34.68	3.77	15.52	27.12	-0.72	-1.33
187	Chandpur	229	6.83	25.6	746	68	185.02	1.19	0.01	61.89	3.37	18.68	50.90	-1.08	-2.23
188	Kochua	227	7.07	25.2	2420	170	599.55	15.50	1.16	336.99	8.83	37.20	41.39	-0.64	-0.97
189	Daudkandi	213	7.01	27.4	750	105	138.05	1.37	4.06	44.44	7.14	24.18	55.97	-0.65	-1.28
190	Araihazar	274	6.92	26	432	68	63.04	1.53	1.02	23.90	7.34	15.65	30.44	-1.16	-2.25
193	Faridpur	206	7.07	27.6	2185	216	482.83	4.01	1.52	226.15	5.73	39.84	50.47	-0.40	-0.53
194	Bhanga	244	7.16	28.1	2850	256	660.72	2.29	2.01	364.45	26.80	39.17	115.82	0.08	0.07
195	Bhanga	234	7.26	27	804	203	53.26	1.60	3.30	83.11	3.48	24.57	55.60	-0.13	-0.24
235	Nvaron	250	7.78	27.3	600	216	149.22	3.45	0.41	117.47	10.58	33.29	69.56	0.47	1.01
237	Sathkhira	198	8.1	27.5	1860	277	578.00	2.19	1.24	491.49	23.63	11.05	16.22	0.20	0.62
238	Sathkhira	238	7.8	27.2	2500	302	883.38	14.27	1.68	654.32	27.48	44.48	65.24	0.48	1.18
239	Tala	183	8.06	28.1	1630	160	595.52	14.62	1.98	324.01	24.11	68.65	46.39	0.37	1.31
240	Dumuria	305	8.06	29.2	420	166	18.88	4.69	3.92	74.09	7.93	18.41	36.86	0.44	0.99
241	Kaukhali	274	7.98	27.6	1410	247	477.31	8.76	1.55	431.03	19.40	13.40	23.35	0.21	0.56
242	Rajapur	259	8.21	27.1	930	277	245.13	0.67	0.54	313.94	9.81	5.79	5.95	-0.07	0.22
243	Jhalakathi	300	8.17	27.8	1030	247	254.29	5.66	1.08	305.80	11.97	5.57	9.75	0.06	0.27
245	Nalchiti	305	8.11	27	1170	185	431.17	8.66	0.79	526.37	13.82	13.00	31.43	0.33	0.65
246	Nalchiti	290	8.28	28.7	1610	234	603.35	1.41	2.86	534.25	19.31	9.35	15.99	0.31	0.78
247	Bakerganj	305	8.27	27.6	430	210	47.97	2.65	1.03	188.13	5.76	2.97	5.25	-0.12	-0.10

ID.	Area	Well Depth (m)	pH	Temp. (°C)	EC (µS/cm)	HCO_3^- (mg/L)	Cl^- (mg/L)	NO_3^- (mg/L)	SO_4^{2-} (mg/L)	Na^+ (mg/L)	K^+ (mg/L)	Mg^{2+} (mg/L)	Ca^{2+} (mg/L)	$SI_{calcite}$	$SI_{dolomite}$
248	Dumki	305	8.47	27.4	580	259	14.87	2.78	0.84	199.85	6.19	3.07	4.61	0.09	0.39
249	Patuakhali	299	8.45	34	560	240	9.28	2.99	0.92	182.07	5.43	1.99	3.33	-0.01	0.20
250	Patuakhali	305	8.29	28.3	610	253	6.20	7.11	0.24	226.22	8.78	4.62	10.49	0.27	0.58
251	Babuganj	259	7.74	27.1	750	191	144.66	4.36	0.40	251.06	10.58	5.84	13.78	-0.29	-0.58
252	Gopalganj	198	7.34	27	2200	339	748.14	21.91	0.70	563.75	46.78	58.92	117.93	0.33	0.73
254	Gopalganj	183	7.66	27.1	1790	370	579.78	7.52	11.42	557.78	28.54	42.46	79.91	0.54	1.18
255	Moksedpur	213	7.59	26.4	1050	394	92.70	18.93	0.80	358.51	20.85	27.07	25.77	0.07	0.54
256	Rajoir	213	7.46	26.9	1810	166	686.59	3.93	1.60	484.50	24.61	43.16	88.30	0.05	0.17
257	Madaripur	229	7.51	26.7	1030	160	353.51	1.12	0.60	207.08	17.97	38.17	79.08	0.09	0.25
259	Madaripur	227	6.84	26.2	790	370	167.74	3.45	45.11	223.15	24.37	39.98	37.49	-0.55	-0.70
260	Bhanga	259	7.47	27	550	166	80.78	1.04	14.00	74.53	11.22	29.31	51.52	-0.05	0.04
261	Lohajanj	305	7.38	30.6	770	129	221.73	3.26	1.04	102.22	13.52	46.51	69.35	-0.10	0.03
264	C-gram	198	6.9	25.8	143	68	1.59	0.79	0.90	14.74	6.23	5.24	13.31	-1.49	-3.02
265	C-gram	259	6.47	27.6	117	37	2.48	0.68	1.94	10.84	5.74	5.10	10.56	-2.24	-4.42
269	D-bhuyan	213	7.02	27	1430	68	548.09	2.75	39.45	132.50	20.97	80.12	119.26	-0.63	-1.05
270	Begumganj	226	7.06	27	510	99	135.05	1.91	3.10	55.32	9.75	25.46	35.50	-0.82	-1.41
271	Noakhali	279	7.07	25.9	1890	99	731.30	1.92	36.77	450.49	28.73	36.29	44.89	-0.86	-1.44
272	Suborna	277	7.44	27.6	670	117	175.69	11.06	1.05	53.42	21.73	34.86	50.28	-0.24	-0.25
274	Suborna	256	7.12	28.8	1500	99	549.42	4.08	2.46	82.44	33.87	87.03	118.67	-0.33	-0.41
275	Suborna	244	7.47	27	550	129	108.84	8.80	1.36	50.09	17.34	32.70	34.26	-0.32	-0.28
276	Suborna	256	7.45	27.4	410	129	23.92	4.53	0.84	45.59	10.15	21.86	24.68	-0.44	-0.55
278	Suborna	287	7.12	27.2	1770	99	665.02	6.19	5.50	71.49	26.21	124.39	199.10	-0.18	-0.18
280	Suborna	310	7.06	27.2	1740	92	655.91	7.69	10.82	124.05	26.99	105.55	167.45	-0.33	-0.48
282	Maijdi	259	7.07	26.7	770	111	271.08	0.85	4.88	101.62	13.30	31.18	49.64	-0.66	-1.15
283	Maijdi	290	7.45	28.2	350	62	62.36	0.63	1.05	36.24	7.16	16.80	26.68	-0.70	-1.22
285	Ramgati	293	7.43	27.5	270	105	5.91	1.04	0.72	27.27	5.86	12.66	28.92	-0.45	-0.89
286	Ramgati	274	7.26	27.4	650	105	196.16	0.77	1.05	62.03	12.20	31.79	56.36	-0.41	-0.70
287	Ramgati	310	7.07	27.9	1190	80	460.57	2.62	2.15	141.35	11.38	52.84	105.50	-0.51	-0.94
289	Ramgati	262	7.2	27.2	860	136	282.49	2.85	1.73	103.37	11.97	40.10	62.55	-0.35	-0.52
290	Ramgati	305	7.5	27.2	1110	160	378.76	2.60	2.06	257.64	14.56	21.97	35.08	-0.24	-0.31
323	Obhaynagar	229	7.03	27.7	935	173	14.37	1.28	0.08	5.18	1.93	4.83	13.68	-0.94	-1.95

ID.	Area	Well Depth (m)	pH	Temp. (°C)	EC (µS/cm)	HCO_3^- (mg/L)	Cl^- (mg/L)	NO_3^- (mg/L)	SO_4^{2-} (mg/L)	Na^+ (mg/L)	K^+ (mg/L)	Mg^{2+} (mg/L)	Ca^{2+} (mg/L)	$SI_{calcite}$	$SI_{dolomite}$
325	Khulna	290	7.44	29.5	1416	123	503.39	15.11	25.79	283.54	26.68	41.86	68.49	-0.14	-0.09
327	Patuakhali	244	7.89	27.8	804	259	2.17	1.39	0.63	12.36	8.14	0.90	3.62	-0.49	-1.41
329	Amtali	317	7.88	29.2	856	283	24.67	1.47	0.56	253.68	10.82	4.19	8.78	-0.15	-0.21
330	Amtali	305	7.86	26.9	920	296	21.22	2.45	0.08	280.88	9.87	4.38	8.47	-0.20	-0.31
331	Amtali	311	7.6	28.5	1030	333	34.91	3.06	0.11	316.01	15.75	7.84	12.23	-0.24	-0.28
332	Kalapara	274	7.7	32.6	1146	345	88.05	1.91	0.13	345.88	8.93	10.08	16.87	0.05	0.31
333	Kalapara	300	7.45	29.1	2140	308	661.22	3.21	0.19	580.65	29.17	21.14	25.42	-0.19	-0.07
335	Kuakata	310	7.66	28.8	2005	394	27.57	3.55	1.67	29.37	9.48	10.68	240.85	1.12	1.29
337	Patuakhali	312	8.01	32.2	737	234	11.66	1.15	0.91	213.88	6.42	2.44	15.16	0.19	0.01
338	Barisal	244	7.9	28.1	862	234	184.90	2.09	0.59	239.30	8.93	4.23	10.59	-0.15	-0.32
339	Uzirpur	259	7.7	27.5	1116	160	312.22	1.61	1.04	339.30	12.14	5.66	4.62	-0.90	-1.34
340	Gournadi	259	7.12	29.5	1405	173	497.89	2.32	0.93	185.93	17.57	46.87	96.22	-0.16	-0.22
341	Rajoir	213	7.3	28.4	2410	160	942.07	3.86	0.32	501.41	25.03	42.82	92.15	-0.10	-0.14
342	Haziganj	244	7.4	29.1	535	74	89.80	0.96	0.10	45.89	7.34	17.49	42.95	-0.48	-0.95
344	Ramganj	244	7.21	27.1	312	123	7.68	1.28	0.11	30.27	7.49	16.00	28.28	-0.63	-1.13
345	Noakhali	244	7.09	24.8	4230	173	1670.84	6.72	36.75	1035.41	77.93	39.75	32.84	-0.84	-1.24
346	Noakhali	311	7.48	26.2	4460	160	1757.58	7.02	61.67	1063.30	54.91	434.50	41.98	-0.47	0.46
349	Subornachar	287	7.6	29.8	1852	86	660.80	9.38	0.21	93.62	38.50	95.97	109.79	0.05	0.45
356	Laksham	251	6.04	25.5	3790	51	1120.00	0.21	89.20	309.00	6.57	95.00	220.00	-1.56	-3.13
357	Shib Char	213	6.72	26.8	1425	292	292.09	0.05	3.30	67.00	5.77	47.20	87.20	-0.38	-0.66
358	Kachua	191	6.7	28.4	722	154	122.72	0.26	2.12	59.60	2.15	8.11	15.40	-1.30	-2.49
359	Shib Char	213	6.78	26.5	1327	321	262.68	0.22	22.02	79.80	4.93	37.30	70.60	-0.37	-0.65
360	Kuliarchar	284	7.02	29.1	334	156	5.75	0.08	1.71	266.00	3.28	18.20	15.70	-1.00	-1.54
361	Singair	247	6.61	27.20	827	275	26.05	2.18	7.11	21.56	16.56	28.64	90.20	-0.45	-1.02
362	Singair	218	6.79	28.00	536	243	7.21	1.59	0.01	25.93	5.65	13.20	45.29	-0.56	-1.27
364	Rampal	260	8.22	33.1	2675	444	491.28	1.51	0.26	5.87	2.37	4.88	13.40	0.56	1.14
366	Ghior	210	6.94	28.8	810	385	114.92	41.71	0.85	48.80	1.01	33.10	43.10	-0.28	-0.28

Table 2. Summery statistics of major ion chemistry

	Collected water samples	Na^+ (mg/L)	Ca^{2+} (mg/L)	Mg^{2+} (mg/L)	K^+ (mg/L)	HCO_3^- (mg/L)	Cl^- (mg/L)	SO_4^{2-} (mg/L)	NO_3^- (mg/L)
Shallow groundwater									
Min.	202	1.20	1.30	0.02	0.00	12.00	0.04	0.01	0.00
Max.		2456.60	188.84	151.25	100.31	1186.00	3420.27	321.80	159.49
Avg.		75.50	38.80	21.89	8.21	172.32	100.18	14.49	8.08
Intermediate depth groundwater									
Min.	26	3.95	1.34	5.24	0.88	55	0.80	0	0
Max.		268.42	87.36	40.88	56.55	394	491	19.89	40.58
Avg.		46.69	35.07	16.31	6.16	173.39	34.71	2.49	5.15
Deep groundwater									
Min.	100	5.18	3.32	0.9	0.71	37	1.59	0.01	0.01
Max.		1063.3	240.85	434.5	54.91	449	1757.58	180.04	41.71
Avg.		212.33	56.22	38.43	12.65	198.17	322.45	8.52	4.28

Table 3. Average ionic composition of major hydrochemical species

Groundwater group	Water type	Cl- (mg/L)	HCO3- (mg/L)	Na+ (Mg/L)	Ca2+ (mg/L)
Shallow groundwater					
Group-1	Ca-Mg-HCO_3	9.9	215.0	13.8	51.7
Group-2	Na-Ca-Mg-HCO_3	12.5	132.9	42.5	21.8
Group-3	Na-Cl	910.5	304.0	632.0	43.5
Group-4	Ca-Mg-Na-HCO_3-Cl	73.0	148.0	24.0	42.0
Intermediate depth groundwater					
Group-1	Ca-Mg-HCO_3	5.6	203	18.2	45.5
Group-2	Na-Ca-Mg-HCO_3	3.7	133.0	67.5	23.7
Group-3	Na-Cl	491.0	197.0	268.0	78.9
Group-4	Ca-Mg-Na-HCO_3-Cl	54.0	173.0	47.5	25.3
Deep groundwater					
Group-1	Ca-Mg-HCO_3	12.08	178.0	29.0	35.3
Group-3	Na-Cl	460.05	145.5	370.0	41.0
Group-4	Ca-Mg-Na-HCO_3-Cl	160.0	210.5	71.0	49.0
Group-5	Na-Ca-Mg-Cl	485.0	173.0	241.0	84.0
Group-6	Na-HCO_3	32.0	296.0	228.0	11.0

4.2 Major Ion Chemistry

Summery statistics of groundwater major ion chemistry are given in Table 2. The average concentrations of Na^+, Ca^{2+} and Cl^- in deep groundwater display a clear difference with shallow and intermediate depth groundwater (Table 2). The trend of major cation concentrations in shallow and deep groundwaters are $Na^+>Ca^{2+}>Mg^{2+}>K^+$ and for intermediate depth groundwater is $Ca^{2+}>Na^+>Mg^{2+}>K^+$. The anionic trend of shallow and intermediate depth groundwaters is $HCO_3^-> Cl^->SO_4^{2-}>NO_3^-$ and deep groundwater is $Cl^->HCO_3^->SO_4^{2-}>NO_3^-$.

4.3 Hydrochemical Grouping

Piper plots (Figure 3) for shallow, intermediate and deep groundwater are classified into six major groups, namely Group-1: Ca-Mg-HCO_3, Group-2: Na-Ca-Mg-HCO_3, Group-3: Na-Cl, Group-4: Ca-Mg-Na-HCO_3-Cl, Group-5: Na-Ca-Mg-Cl and Group-6: Na-HCO_3. The spatial distribution of groundwater hydrochemical species at different depths are show in Figure 3. The relevant chemical parameters for the shallow, intermediate and deep groundwater groups are depicted in Table 3. Figure 3a illustrates that the shallow groundwater is dominantly of Ca-Mg-HCO_3 type low mineralized water characterizing the chemical composition of rainfall and major river water in Bangladesh, which indicates the initial source of water recharging into the aquifer systems. This type of water (Group-1) is distributed in most sites of the study area (Figure 4a) indicating preferential recharge area. Group-2 shallow groundwater is observed in the northern-eastern site of the study area (Figure. 3a), which shows slightly increase of Na^+ concentration with respect to Ca^{2+} and Mg^{2+}. The increase in Na^+ exchange for Ca^{2+} and Mg^{2+} suggest softening process, which may indicate rapid recharge and/or much more water-rock interactions along the flow paths. Group-3 water shown in the central and north-western site (Figure 4a) are characterized by SO_4^{2-} and NO_3^- rich mixed water, which may be from anthropogenic sources. In contrast, the Na-Cl type water from the coastal area is characterized by high concentrations of chloride, which is possibly due to mixing with seawater[17].

The intermediate depth groundwater is also dominated in Ca-Mg-HCO_3 type water (Figure 3b) and surprisingly in spatial distribution (Figure 4b) the intermediate depth groundwater aquifer with water types Ca-Mg-HCO_3, Na-Ca-Mg-HCO_3 and Na-Cl respectively are underlain by the similar type water in shallow groundwater aquifers (Figure 4a). This phenomenon indicates possible connectivity between shallow and intermediate depth aquifers as well as rapid recharge to the intermediate aquifers without changing the chemical characteristics of recharging water. The intermediate depth groundwaters are also affected by softening process giving rise to Na-Ca-Mg-HCO_3 type water adding more Na^+ in groundwater exchanged for Ca^{2+} and Mg^{2+}. In the coastal region, the intermediate depth groundwaters are characterized by Na-Cl chloride type saline water with an average Cl^- concentration of 491 mg/l (nearly 3% salinity). Similar to shallow groundwater, the intermediate groundwater is also affected by sea spry or mixed with seawater[17].

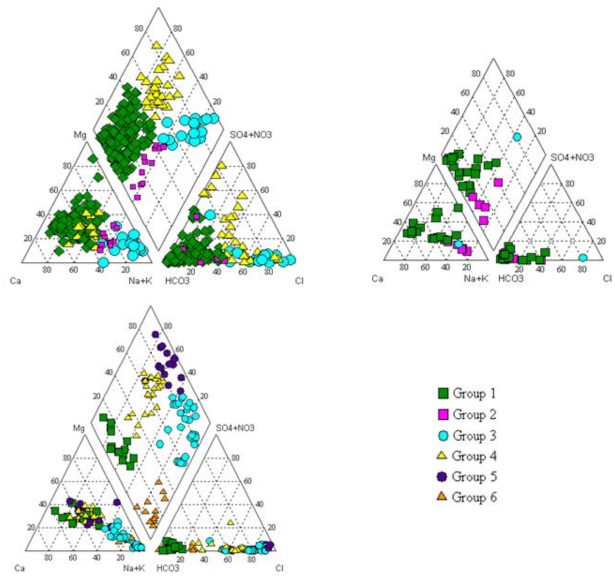

Figure 3. Piper plots showing the major ions composition of groundwater: (a) shallow well (<70 m), (b) intermediate well (70–180 m) and (c) deep well (>180 m). Based on this diagram, groundwaters are classified into six different groups, which are: Group-1 (Ca-Mg-HCO_3), Group-2 (Na-Ca-Mg-HCO_3), Group-3 (Na-Cl), Group-4 (Ca-Mg-Na-HCO_3-Cl), Group-5 (Na-Ca-Mg-HCO_3-Cl) and Group-6 (Na-HCO_3).

The Piper plot for deep groundwater (Figure 3c) shows distinct groundwater types both in compositions and in spatial distributions (Figure 4c). Ca-Mg-HCO_3 type water is observed in deep wells lying in the northern site of the study area. The Na-Cl and Na-Ca-Mg-Cl type deep groundwaters are restricted in the coastal region (Figure 4c) having ~0.9 to 6% salinity. This brackish high chloride content water probably represents relic seawater trapped in sediments during deposition under marine regressive conditions that have later undergone certain modifications (e.g., cation exchange, diluting by mixing with fresh meteoric water) during its period of confinement. Similar type of deep saline groundwater was also observed by[18] in West Bengal, India. The Ca-Mg-Na-HCO_3-Cl (Group-4) type deep groundwater shows increase in chloride and bicarbonate concentrations. The gradual increase in deep groundwater Cl^- and Na^+ concentrations thus suggest groundwater flow from the area of Group-1 type water towards the mixed type Group-4 area (Figure 4c).

The Na-HCO_3 type low chloride content (average 32 mg/L) groundwaters are observed in the coastal deep aquifers. It indicates that the Ca-HCO_3 groundwaters progressively evolve into the Na-HCO_3 type water at greater depth and the concentrations of chemical constituents in the water increase with prolonged water-rock interactions[19]. The presence of Na-HCO_3 type water in deep aquifers usually represents the end member of the groundwater flow system[20]. The Na-HCO_3 type deep groundwater observed in the coastal aquifers of Bangladesh are of stagnant water, which probably reflects the effect of incomplete flushing in a buried estuary aligned on an old course of the Ganges and/or Brahmaputra rivers when they flow directly south from their present confluence[21].

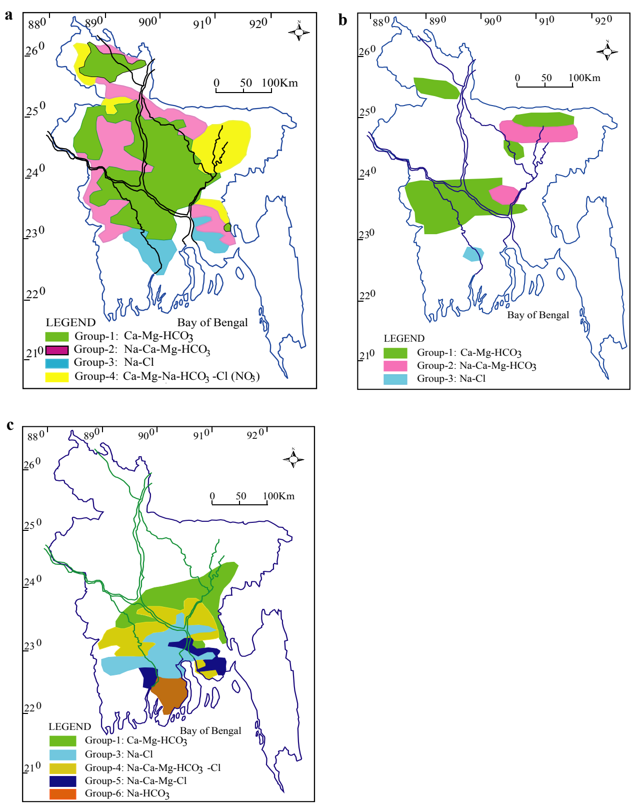

Figure 4. Plots showing the spatial distribution of groundwater hydrochemical species at different depths (a) shallow well (<70 m), (b) intermediate well (70–180 m) and (c) deep well (>180 m).

4.4 Stiff Diagram

Stiff diagrams are widely used to infer the trend of groundwater mineralization along the groundwater flow paths in spatial distribution. The spatial distribution of shallow groundwater chemical types represented in the Stiff diagrams (Figure 5a) denotes the generalized progressive increase of shallow groundwater mineralization from north to south. The increase in sodium and chloride concentration is prominent in the coastal region, which is affected by mixing with seawater. Stiff diagrams (Figure 5b) for intermediate depth groundwater show low mineralized water, which indicates rapid recharge into the aquifers without any significant chemical change in the initial recharging water (Group-1 type) as well as indicates low residence times for water-rock interactions or relatively short flow paths. The spatial distribution of deep groundwater Stiff diagrams (Figure 5c) shows notably high-mineralized water than those of shallow and intermediate groundwater. The chemical pattern of deep groundwater progressively increases from north to south. Following this direction, a gradual decrease in calcium and increase in sodium is noticeable. The chloride concentration increases in accordance with the pattern, which can be specified as flow directions.

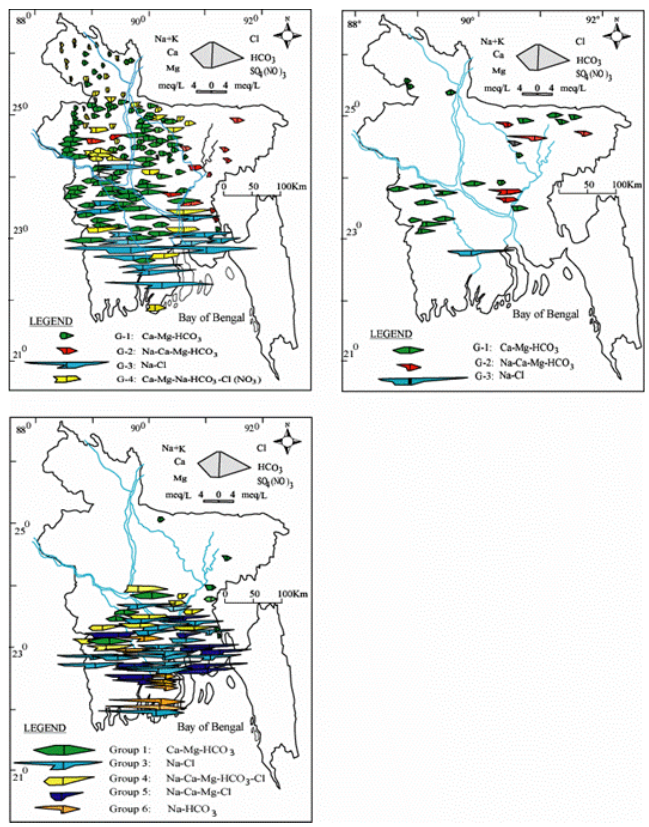

Figure 5. Stiff diagram showing (a) shallow, (b) intermediate and (c) deep groundwater hydrochemical types distributed over the study area.

4.5 Carbonates Dissolution

Bicarbonate in Bengal Delta groundwaters may derive mainly from the soil zone CO_2 and weathering of parent minerals. The soil zone in the subsurface contains elevated CO_2 pressure (produced by decay of organic matter and root respiration), which in turn combines with rainwater to form bicarbonate[22] following the reactions given below:

$CO_2 + H_2O \rightarrow H_2CO_3$ ---------------------------------(i)

$H_2CO_3 \rightarrow H^+ + HCO_3^-$ -------------------------------(ii)

Bicarbonate may also be derived from the dissolution of carbonates minerals (calcite and dolomite) by the carbonic acid according to:

$CaCO_3 + H_2CO_3 \rightarrow Ca^{2+} + 2HCO_3^-$ ------------------------(iii)

(calcite)

$CaMg(CO_3)_2 + 2H_2CO_3 \rightarrow Ca^{2+} + Mg^{2+} + 4HCO_3^-$ --------(iv)

(dolomite)

If Ca^{2+} and Mg^{2+} in groundwater may come from the dissolution of calcite and dolomite according to the equations (iii) and (iv) respectively, there would be straight positive correlation between Ca^{2+} and HCO_3^- and, Mg^{2+} and HCO_3^-. A bi-variant plot (Figure 6a) of Ca^{2+} versus HCO_3^- shows poor correlation ($r^2 = 0.30$) for shallow, intermediate ($r^2 = 0.03$, regression line not shown in Figure 6a) and deep groundwater ($r^2=0.009$, regression line not shown in Figure 6a). It is evident that Ca^{2+} in all observed groundwaters may not come from calcite dissolution. Besides[23] observed poor amount of calcite (average 0.8 wt%) in Bengal Delta sediments and thus this minor amount of calcite in host sediments may not be responsible releasing higher concentrations for Ca^{2+} in Bengal Delta groundwater.

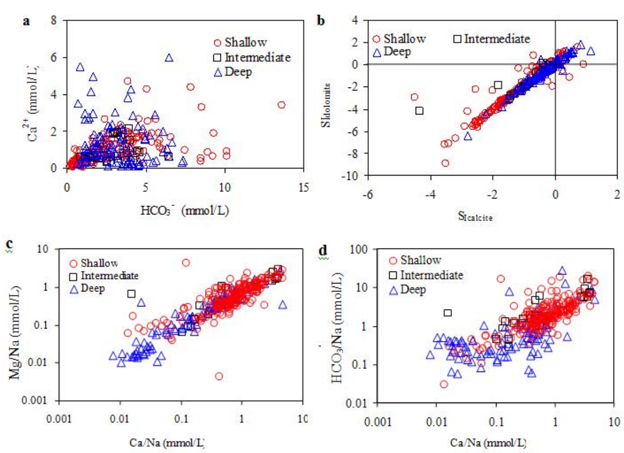

Figure 6. Bivariate plots showing the correlation between (a) HCO_3^- versus Ca^{2+}, (b) Saturation Index for calcite versus dolomite, (c) Ca/Na versus Mg/Na and (d) Ca/Na versus HCO_3/Na.

Assuming pure water equilibrated with sedimentary calcite and assuming $10^{-3.5}$ atm soil CO_2 gas in an open system at 25°C, the geochemical properties mainly saturation index for calcite and dolomite have been simulated, as given in Table 1. The plot of saturation indices of calcite ($SI_{calcite}$) versus dolomite ($SI_{dolomite}$) demonstrates that most of the groundwaters are under-saturated with respect to dolomite and calcite (Figure 6b). According to Figure 6b, about 86% of the analyzed groundwater samples are under-saturated with calcite and dolomite. It represents that the water comes from an environment where calcite and dolomite are impoverished. It also indicates that in the Bengal Delta groundwater, Ca^{2+} and Mg^{2+} partially come from carbonate dissolution.

Surprisingly, only 25% deep groundwaters (out of 100 nos.) are saturated with calcite and it indicates precipitation of calcium as calcite and/or dolomite.

4.6 Silicate Weathering

Weathering reactions of Ca and Mg-silicates are also responsible releasing Ca^{2+} and Mg^{2+} transforming CO_2 from the atmosphere to HCO_3^- in groundwater as:

$2NaAlSi_3O_8 + 2H_2CO_3 + 9H_2O \rightarrow Al_2Si_2O_5(OH)_4 + 2Na^+ + 4H_4SiO_4 + 2HCO_3^-$ ----(v)

(Na-silicate)

$Mg_2SiO_4 + 4CO_2 + 4H_2O \rightarrow 2Mg^{2+} + 4HCO_3^- + H_4SiO_4$ -------------------------------(vi)

(Mg-silicate)

Therefore, the Na-normalized[24] ratios for Ca^{2+} and Mg^{2+} might have relationship to each other. Accordingly, in the plot of molar ratios of Ca/Na versus Mg/Na are shown in a log–log space in Figure 6c, both shallow and deep groundwater show moderate correlation with regressions $r^2 = 0.54$ and $r^2 = 0.55$ respectively, whereas intermediate depth groundwater shows higher correlation ($r^2 = 0.85$). Recharging waters flowing through carbonates rich aquifer show high Ca/Na and Mg/Na rations (Figure 6c). The end member having lower Na-normalized ratios is that of water draining silicates. The molar Ca/Na ratio of average crustal continental rocks is close to 0.6[25], and due to the higher solubility of Na relative to Ca, lower Ca/Na molar ratio are expected in groundwater, which are related to weathering of silicates. In Figure 6c, the observed shallow groundwater with high Ca/Na molar ratios are being influenced by carbonate dissolution, whereas the intermediate and deep groundwaters are influenced by silicate weathering rather than carbonate dissolution. Similarly, the plot (Figure 6d) for HCO_3/Na and Ca/Na molar rations, high molar rations for half of the shallow and intermediate depth groundwaters are an indication of carbonate dissolution, meanwhile low molar ratios of HCO_3/Na and Ca/Na for the deep groundwaters are the indication of silicate weathering.

If groundwater mainly recharged by the recent atmospheric precipitation, its circulation remains active[26]. This being so, the most likely mechanism that can increase concentrations of Na^+ and HCO_3^- in groundwater is the alteration of silicates (like albite) as per the following reaction:

$$NaAlSi_3O_8 + CO_2(aq) + 11/2H_2O \rightarrow Na^+ + 1/2Al_2Si_2O_5(OH)_4 + 2H_4SiO_4 + HCO_3^- \text{----(vii)}$$

This reaction leads to increase in Na^+ and HCO_3^- concentrations consuming CO_2(aq), and thus decreases the partial pressure of carbon dioxide (pCO_2) and increases pH. The high average Na^+ (212.33 mg/L) content in observed deep groundwater with high pH (>7.5) values comply with the above-mentioned argument.

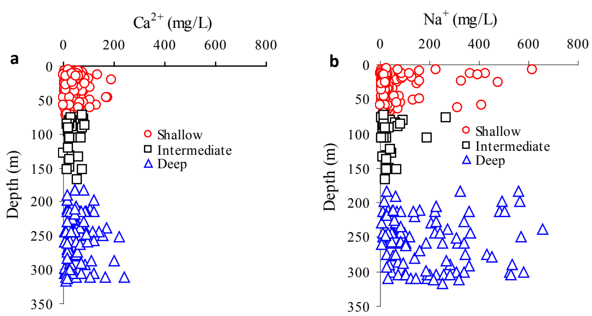

Figure 7. Depth dependence plots showing variations between (a) Ca^{2+} versus depth and (b) Na^+ versus depth.

4.7 Cation Exchange

Cation exchange reaction is also responsible for Na^+ enrichment in groundwater as[27]:

$$1/2Ca^{2+} + Na\text{-}X \rightarrow 1/2Ca\text{-}X_2 + Na^+ \quad \text{(viii)}$$

where, X denotes cation-exchange sites. This reaction explains the increase in Na^+ concentration without an associated increase in Cl^- concentration along the flow path and the clay particles of aquifer exchange calcium against sodium to elevate sodium concentrations[26]. It represents a process whereby a brackish aquifer is flushed with fresh water.

Considering the depth dependence of Na^+ and Ca^{2+} (Figure 7a, 7b), it is found that both Ca^{2+} and Na^+ has shown low concentrations up to the base of the intermediate depth aquifer. Only few shallow groundwater samples show slightly high Na^+ concentrations. Meanwhile, in deep groundwater Ca^{2+} concentrations remain nearly unchanged, whereas Na^+ concentrations become high. In Bengal delta, the Na^+ concentration increases in deep groundwater aquifers in response to cation exchange for Ca^{2+}.

4.8 Mixing of Groundwater

In general, chloride is a conservative component, and evaporation and mixing are considered as the main factors controlling its concentration in groundwater. Solubility of Na^+ compounds is high, so Na^+ remains dissolved in water in a very wide range of concentration[28]. In Na^+ versus Cl^- plot, most of the shallow and intermediate depth groundwater lie along the 1:1 evolution line (Figure 8a and Figure 8b) and it indicates that these water have mainly originated from rainfall and/or flood water maintaining the evolutionary ratio between Na^+ and Cl^- (1:1). Nevertheless, the deep groundwater scattered in three groups as samples along the Na-axis, above the seawater line (slope 0.86) and below the seawater line (Figure 8c). Those water scattered close to Na-axis (Y-axis in Figure 8c) are of Na-HCO_3 groundwater observed in coastal deep aquifers and these are of stagnant water having low concentration of chloride (<48 mg/L). Whereas, the deep groundwaters scattered above the seawater line show Na^+ excess and Na^+ excess suggest the presence of deep groundwater flow which gives rise to excess Na^+ along the flow paths due to cation exchange of Na^+ for Ca^{2+} as per the equation (viii). The deep groundwater lies below the seawater line (Figure 8c) are mainly of Na-Cl and Na-Ca-Mg-Cl type water with residence time of about 8500 year BP. If it is considered that the deep groundwater scattered below the seawater line is influenced by present seawater, then the process will have followed the equation[27] given below:

$$Na^+ + 1/2Ca\text{-}X_2 \rightarrow Na\text{-}X + Ca^{2+} \quad \text{(ix)}$$

Where, X indicates the soil exchanger.

This reaction will lead to increase in Ca^{2+} in coastal aquifers having Ca-Cl_2 type water. Surprisingly observed deep groundwater do not show any Ca-Cl_2 type water. Besides, the deep groundwater falls along the seawater line show long residence time (~ 6000 to 25000 year BP)[12], and these are also Na-Cl and Na-Ca-Mg-Cl type water. This water may partially mix with remnant seawater maintaining maxing ratios[29]. Thus, it may conclude that the Na-Cl and Na-Ca-Mg-Cl type deep groundwater are not influenced by the present seawater intrusion in the coastal aquifers of Bangladesh. The Na-Cl salinity may come from leaching of marine sediments, which are often dominated in coastal aquifers[29]. Alternatively, this brackish deep groundwater is probably of remnant seawater trapped within lower-permeability sediments[29]. Furthermore[18] observed similar type brackish connate water pockets in the western site of Bengal Delta, West Bengal, India.

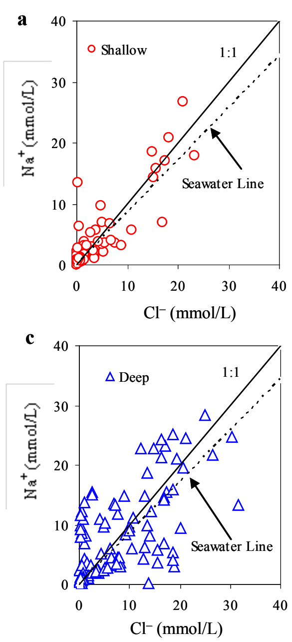

Figure 8. Bivariate plots showing relationship between (a) shallow groundwater Na^+ versus Cl^-, (b) intermediate groundwater Na^+ versus Cl^- and (c) deep groundwater Na^+ versus Cl^-.

5. Discussions

Ca-Mg-HCO_3 type shallow groundwater (Figure 4a) is widely distributed in most of the study area, which indicates infiltration of modern meteoric water as rain or flood in to the shallow groundwater aquifers. The Ca-Mg-HCO_3 type groundwater is also available in the intermediate depth aquifers up to the depth 180 m in the west-central and north-eastern region (Figure 4b) of Bangladesh. It is a clear indication of active recharge to the intermediate aquifers, which may ultimately feed the deeper aquifers. In the west-central and eastern sites of the study area, low mineralized Ca-Mg-HCO_3 type groundwater is observed at deep aquifers underlying the shallow and intermediate aquifers with similar water type (Ca-Mg-HCO_3) (Figure 4c). This implies active recharge to the deep aquifers from the west-central and eastern mountainous regions of the study area.

In shallow or local flow systems, the flow path is relatively short and thus shallow groundwater does not show distinct hydrochemical changes, i.e., change in water type. The presence of Na-Ca-Mg-HCO_3 water in intermediate aquifers (Figure 5b) is mainly evolved from Ca-Mg-HCO_3 water. It may indicate vertical groundwater and/or local groundwater flow within both the shallow and intermediate depth groundwaters with low water-rock interaction, i.e., short residence time. Along the flow path, significant change in concentration of major cations takes place[28]. The Ca-Mg-HCO_3 type deep groundwater observed in the west-central, middle and eastern (recharging area) part of the study area corresponds to the beginning of the flow path of the deep flow system (Figure 5c). As deep groundwater flows, the initial Ca-Mg-HCO_3 water evolves into Na-Cl type water mixing with connate paleo-seawater with low concentrations of Ca^{2+} and Mg^{2+}, and the high Na^+ concentrations in the central and southern coastal region of Bangladesh.

As per Figure 5a and Figure 5c, in the study area groundwater flows from the Ca-Mg-HCO_3 rich unconfined to Na-Cl rich confined (deep) aquifer and results in the evolution of Ca-Mg-HCO_3 groundwater to Na-Cl type water. Hydrochemical data plot (Figure 8c) suggests that the excess Na^+ is due to cation exchange of Na^+ for Ca^{2+}. Besides, the excess Na^+ in the deep flow system at the end of the flow path indicates an additional Na^+ source, which is attributed to silicate weathering (Figure 6c, 6d). Meanwhile, additional Na^+ in the deep groundwater may come from clay deposited from the marine episodes which acts as a long-term source of Na^+ and Cl^- to the underlying aquifer[30].

Considering the depth dependence of Na^+ and Ca^{2+}, it is found that the average Ca^{2+} concentration is low (38.14 mg/L) in shallow groundwater, while Na^+ concentrations are more than two times higher (74.75 mg/L) than that of Ca^{2+} concentrations (Figure 7a, 7b). In Figure 7b, the relatively high Na^+ concentrations are observed in the coastal shallow wells, which is due to mix with seawater (Figure 8a). In intermediate depth aquifers, the composition of Ca^{2+} and Na^+ become homogeneous and the concentrations of dissolved Ca^{2+} (37.25 mg/L) and Na^{+} (46.66 mg/L) are low (Figure 7a, b). Going downward, it is found that Ca^{2+} concentrations remain unchanged (Figure 7a), while Na^{+} concentrations become high in deep aquifers (Figure 7b). It implies that the Na^{+} concentration in groundwater increases in the deep aquifers in response to ion exchange of Na^{+} for Ca^{2+} and this phenomenon is also supported by the presence of clay minerals in the deep aquifer materials[30]. Appelo and Postma[27] explain that mineral dissolution and precipitation is a well-known category of chemical reactions that can have an important impact on solute concentrations.

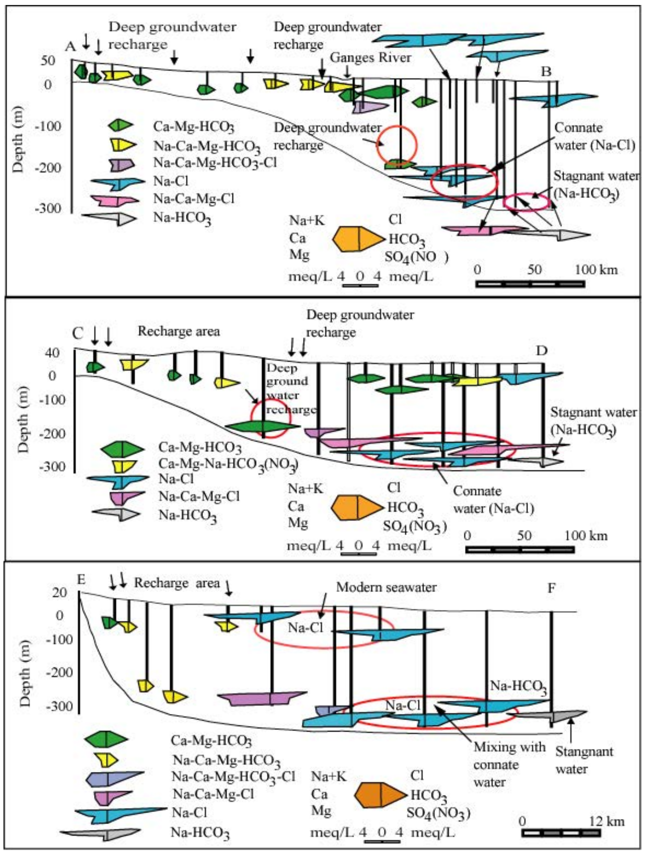

Figure 9. Distribution of chemical species in groundwater at different depths along cross-section lines (a) A-B, (b) C-D and (c) E-F shown in Figure 1.

In present study area, according to the hydrochemical cross-sections (Figure 9), the observed groundwater samples show significant change in major cation (Ca^{2+} and Na^{+}) concentrations. The shallow wells with Ca-Mg-HCO_3 type groundwater situated in the northern, west-central and eastern site of the study area correspond to the beginning of the shallow flow system and thus ultimately feeds both the intermediate and deep groundwater systems (Figure 9a, b, c). Meanwhile, deep groundwater recharges in the northern (Figure 9a, b), central (Figure 9a, b) and eastern (Figure 9c) sites of the study area with Ca-Mg-HCO_3 water.

Above-mentioned arguments comply with the statement of Kinniburgh and Smedley[12] and they state that there has been incision of the main Brahmaputra valley along with basal fan-delta sediments, which are deposited between uplifted Pleistocene Residual deposits (Figure 1). These coarse-grained sediments thin and pinch out south (Figure 2) of the Continental Slope (Hinge Zone) (Figure 2) and pass laterally into sandy deltaic deposits within the subsiding Faridpur Trough (Bengal Foredeep) (Figure 2). This coarse-grained layer would be the possible source of recharge through which low mineralized Ca-Mg-HCO_3 type water enters in to the deep aquifer system. Furthermore, deep groundwater moves towards south (Figure 9a, b) or south-west (Figure 9c) and mixes with Na-Cl type connate water with excess Na^{+}. The deep Na-HCO_3 type water along the coastal belt (Figure 9a, b) probably reflects an incomplete flushing in a buried estuary[21].

In the recharge area, the Ca^{2+} concentration is decreasing from the shallow to the deep layers along the flow paths (Figure 9a, b, c). In infiltrating water, the source of Ca^{2+} is the dissolution of carbonate minerals, which is controlled by local partial pressure of CO_2 and the CO_2 originates from the transformation of organics. In shallow groundwater, differences in concentrations of Ca^{2+} reflect different local partial pressures of CO_2. As groundwater moving downward, CO_2 partial pressure becomes homogeneous. In the discharge areas, changing of Na^{+} is the mirror image of Ca^{2+} due to ion exchange. The excess Na^{+} in the deep flow system at the end of the flow path indicates an additional Na^{+} source, which is attributed to weathering of Na^{+} feldspars. As per the hydrochemical sections (Figure 9a, b, c), the possible geochemical processes involved within Bengal Delta aquifers are silicate weathering with partial carbonate dissolution in the shallow aquifers giving rise to Ca-Mg-HCO_3 and Na-Ca-Mg-HCO_3 type waters; Na^{+} for Ca^{2+} ion exchange and finally mixing with deep Na-Cl type connate water possibly originated from the diffusion of marine clay[30]. The Na-Cl rich deep saline waters are probably trapped within lower-permeability sediments reflecting incomplete mixing and flushing[31]. Furthermore, DPHE[32] states that the shallow aquifer in the west-central region (Figure

1) is very thick where there is no deep aquifer up to about 250m depth. Kinniburgh and Smedley[13] also affirm that the south-central region (Figure 1) of Bangladesh is underlain by stacked sequences of coarse sands and gravels between 50–240m below the ground surface. These coarse sediments appear to have been deposited in the former main channel of the Ganges River. It is evident that the coarse grained thick aquifers in the west-central region of Bangladesh facilitate recharge in to the deep aquifers having similar groundwater type (Ca-Mg-HCO_3) both in shallow and deep groundwater (Figure 9a) and it is a clear indication of deep groundwater recharge in the west-central region of Bangladesh.

Fining-upward sequences of gravels and coarse to medium sands with basal conglomerate occur within the Residual deposits (Figure 1) of the Brahmaputra main channel beneath the central region of Bangladesh (Figure 9b), which pinch out south of the Continental Slope (Hinge Zone) (Figure 2) and pass laterally (Figure 2) into the sandy deltaic deposits[13]. In the central region of Bangladesh (Figure 1), recharge to the deep aquifers (Figure 9b) is due to the presence of aforementioned coarse grained sequence with Ca-Mg-HCO_3 type low mineralized water. Meanwhile, the deep aquifers may recharge from the overlying shallow aquifers through stratigraphic short-cut[18].

5.1 Conceptual Groundwater Flow Model

In present study, a conceptual groundwater flow model has been constructed for the Bengal Delta aquifers, Bangladesh considering all observed observations. The source and recharge processes of different types of groundwater with their chemical compositions are used to delineate the groundwater flow dynamics to represent a conceptual groundwater flow model for the Bengal Delta aquifers (Figure 10). The model takes into account the following observations: (a) basement structure and boundary condition, (b) lithology as revealed through a generalized hydrogeological cross-section, (c) surface geologic variations, and (d) change in groundwater chemical types. Rainfall or floodwater infiltrating in to the Bengal Delta shallow aquifer through the ground, it dissolves carbon dioxide and the acidic solution (H_2CO_3) formed reacts with carbonates in the sediments giving solutions of Ca^{2+}, Mg^{2+} and HCO_3^-. Silicate weathering also gives rise to Ca^{2+} and Mg^{2+} ions in solution. These hydrogeochemical reactions are responsible for the formation of Ca-Mg-HCO_3 type water. The initial Ca-Mg-HCO_3 type water tends to change in to Na-Ca-Mg-HCO_3 type water due to preferentially silicate weathering, which helps to add Na^+ within the solution in increase with the length of the flow path. At great depths, where the residence time is long due to extremely slow flow, groundwater tends to be Na-Cl type diluted water due to cation exchange of Na^+ for Ca^{2+}. The excess Na^+ comes from silicate weathering giving rise to high pH.

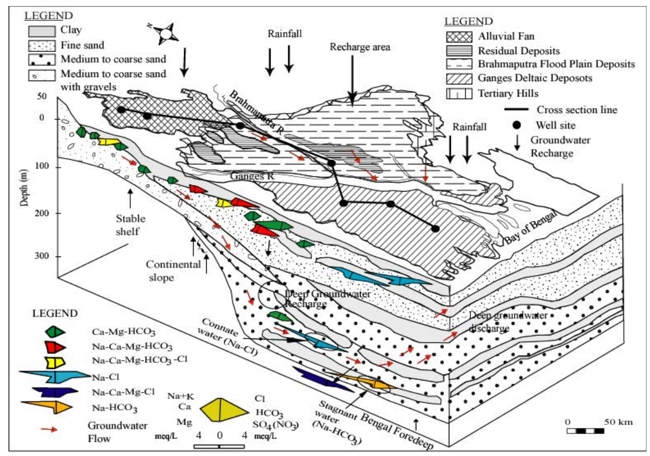

Figure 10. Conceptual groundwater flow model for Bengal delta aquifers (modified after[12]).

As per conceptual flow model (Figure 10), rainfall and/or floodwater infiltrating in the ground recharge the shallow groundwater. The shallow groundwater recharges the intermediate depth aquifers to some extend without changing its chemical facies (Figure 9b). It indicates short residence time within the intermediate depth aquifers. Thus, low water-rock interaction, which may not give rise to diluted water chemistry. Deep aquifers are recharged from the peripheral part of the study area and the recharge is possibly influenced by basement structure, surface geology and subsurface hydrogeological systems. The deep groundwater becomes chemically diluted along the flow paths to form Na-Cl type water due to cation exchange and/or diffusion from marine clay lying within the aquifer systems. The deep groundwater aquifers of Bengal Delta are characterized by layered zones[12]. In Bengal Delta aquifers, as the thickness of the confining clay layers increasing down gradient (Figure 10), the deep groundwater may be squeezed out of compacting clay and the pressure of the confined water it contain increases. As a result deep groundwater discharges from confined aquifers by slow upward seepage through the overlying clays. Finally, deep groundwater discharges in to the Bay of Bengal as submarine groundwater discharge and this argument is supported by enriched $\delta^{18}O$ values and long residence time[12] as well as the upward heat flow in the coastal aquifers[33].

6. Conclusions

Present study has clearly demonstrated the wide spatial and depth dependence variations of the hydrochemical composition of groundwater in the Bengal Delta aquifers, Bangladesh illustrating different flow systems and aquifers. Groundwater chemistry data constrain a complex flow generally from north to south following the basement structure, topographic gradient as well the boundary conditions. By Converging all evidences based on groundwater depth of circulation, generalized hydrogeological section and hydrochemistry, three groundwater flow systems can be conceptualized with depth.

[a] A shallow flow system is observed in the west-central and southern coastal regions of the study area, where shallow groundwater shows Ca-Mg-HCO_3 type low mineralized water.

[b] Intermediate flow system is less dominant, which acts as a transition zone between the shallow and deep aquifers and gets vertical recharge from the shallow flow system. In this system, groundwater is of less diluted due to low water-rock interactions because of short residence time.

[c] The deep groundwater flow system is enriched in chemically diluted Na-Cl type water along the flow paths due to cation exchange and/or diffusion from marine clay lying within the aquifer systems. It possibly emerges in to the Bay of Bengal in the form of Submarine Groundwater Discharge (SGD). But the stagnant deep fresh groundwater (Na-HCO_3 type) along the coastal region is completely different from the above mentioned three groundwater flow systems and it seems to be remnant of paleo-groundwater flow system persisted during past regression era.

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