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ORIGINAL PAPER

Hydrogeochemical investigation and qualitative assessment of groundwater resources in Bokaro district, Jharkhand, India

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Abstract

The present study is carried out in the Bokaro district of the Jharkhand state to identify the hydrogeochemical characteristic of the groundwater and assess its quality with reference to drinking, domestic, and agriculture purposes. In the study area, 102 groundwater samples were collected during the pre-monsoon season and post-monsoon season (51 samples per season) and analyzed for pH, electrical conductivity (EC), total dissolved solids (TDS), total hardness, F^-, Cl^-, HCO_3^-, SO_4^{2-}, NO_3^-, Ca^{2+}, Mg^{2+}, Na^+, and K^+. The analytical results show slightly acidic to slightly alkaline nature of the groundwater in the study area. Ca^{2+} and Na^+ are the dominant cations, while anion chemistry is dominated by HCO_3^- and Cl^- during both seasons, respectively. The data plotted on the Piper and Gibbs diagram, as well as statistical analysis, reveals that the chemistry of the groundwater in the study area is mainly controlled by rock weathering phenomenon with secondary contributions from anthropogenic sources. The water quality assessment indicated that TDS, hardness, Ca^{2+}, Na^+, HCO_3^-, and Cl^- are the major concern parameters in the study area during both seasons. Sodium adsorption ratio, sodium percent, residual sodium carbonate, magnesium hazard, Kelly's ratio, and permeability index are calculated to identify the suitability of water for irrigation purposes and revealed that most of the groundwater is suitable for irrigation purposes, except few sites. The present study will be useful in the future management of groundwater resources of the area.

Keywords Groundwater chemistry · Hydrogeochemical facies · Statistical analysis · Seasonal variation · Irrigation water

Introduction

Groundwater resources play a crucial role in meeting the water requirements of various sectors like drinking, irrigation, and industrial sectors because it is generally less prone contamination than surface water bodies. But at the present time, a concern about groundwater quality deterioration is increasing day by day, especially in developing countries such as India. In parts of the country, groundwater contamination and over-exploitation have resulted from the rapid growth in agricultural activity, industrialization, and urbanization. Poor groundwater quality may cause various problems such as ecosystem degradation, health impacts, treatment costs, and impacts on agriculture, industry, and tourism (Touhari et al. 2015). Each groundwater system under different hydrogeological conditions has unique geochemistry due to the geological and lithological factors such as precipitation, mineralogy of the aquifers, overlying land uses, proximity to the coast, the source of recharge water, soil type, and water flow. Human activities are also responsible for changing the geochemical properties of the groundwater with geogenic factors (Chitradevi and Sridhar 2011). Some of the previous studies carried out on hydrogeochemical characteristics and groundwater quality in different parts of Jharkhand state, India (Chatterjee et al. 2010; Shekhar et al. 2012; Singh et al. 2012a, 2013, 2014a, 2014b; Mondal et al. 2013; CGWB 2013; Prasad et al. 2014; Gautam et al. 2015; Tiwari et al. 2016; Mahato et al. 2016; Tirkey et al. 2017). However, such information is lacking for many other parts of Jharkhand state including Bokaro district. Thus, proper assessment and reporting of groundwater geochemistry and its quality is an

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important issue. The aim of present study is to determine the hydrogeochemical process, seasonal variation, and quality of the groundwater for suitability of drinking, domestic, and irrigation uses in the study area. This study will help to develop a suitable management plan for groundwater resources of the area.

Study area

The Bokaro district is a highly industrialized coal belt district in Jharkhand state, India. The Bokaro district is bounded by Giridih to the north by Purulia (West Bengal) to the south, Dhanbad to the east and Hazaribagh to the west. The study area covers 2861 sq.km and lies between 23^0 24’ 27” N to 23^0 57’ 24” N latitude and 85^0 34’ 30” E to 86^0 29’ 10” E longitude of Jharkhand state (Fig. 1). The study area is drained by the Damodar river and its tributaries and forms a part of the Damodar basin. In the central part of the district, the Damodar river flows from west to east on which are located two important reservoirs: the Tenughat reservoir in the south western part of the district and the Konar reservoir in the north western part of the district. The regional slope of the study area is from the west towards the east.

Rainfall and climate

The average annual rainfall of the study area is 1363.3 mm/year. Around 95% of the annual rainfall takes place during the monsoon season (i.e., from mid-June until the end of September) and rest of the rainfall takes place during summer and winter seasons. The highest monthly rainfall occurs during the month of July in the Chanadankiyari block and the lowest monthly rainfall is received in the Kasmar and Nawadih blocks of the district.

The climate of the study area is humid subtropical with three diverse seasons, i.e., summer, monsoon, and winter. The winter season occurs from the middle of November to end of February during which January is the coldest month where the average daily temperature from 25.9 to 10.2 °C. The summer season takes place from March to mid-June during which daily maximum temperature varies from 42 to 46 °C. Levels of humidity in the area are higher in July, August, and September than the period of March to June each year (CGWB 2013).

Geology and hydrogeology

The Bokaro district is located in the eastern part of the Chotanagpur Plateau which forms an undulating land surface that covers much of the district. Much of the study area (about 75%) is underlain by granitic gneiss and other metamorphic rocks of Precambrian age and remaining part of the study area is underlain by sedimentary rocks comprising sandstones, shales and coal (Satapathy and Syed 2015). A thin layer of alluvial deposits occurs in along the course of the Damodar river.

On the basis of lithology, the study area was categorized into three distinct classes: (1) consolidated rock formation in which groundwater occurs under confined to semi-confined conditions; (2) semi-consolidated formation, where groundwater occurs under confined to semiconfined conditions (mostly in the central part of the study area); and (3) unconsolidated formations where groundwater occurs in unconfined aquifers. Unconfined aquifers cover a major part of the area with recent alluvium deposited mainly by the Damodar, Konar, and Jamunia rivers (CGWB 2013). The stratigraphic sequence of various geological formations of the study area is presented in Table 1 and a hydrogeological map of the study area is shown in Fig. 1.

Materials and methods

One hundred two groundwater samples (51 samples in the pre-monsoon season and 51 samples in the post-monsoon season) were collected from 51 locations of the Bokaro district during the years 2014–2015 (Fig.1). For sample collection, preservation, and analysis, standard methods (APHA 1998) were followed. Before analysis, the water samples were filtered through 0.45-μm Millipore membrane filters to remove suspended particles. The pH and EC of water samples were measured in the field immediately after the collection of the samples by using a multiparameter probe (PCSTestr 35), and the major ions were analyzed using the standard methods suggested by the American Public Health Association (APHA 1998). Major cations (Ca^{2+}, Na^+, and K^+) were analyzed by using Systronics Flame photometer 128. Mg^{2+} was analyzed by the titration method. Total hardness (TH), bicarbonate (HCO_3^-), and chloride (Cl^-) were estimated using standard EDTA, HCl, and $AgNO_3$ as titration solution. Sulfates (SO_4^{2-}), fluoride (F^-), and nitrate (NO_3^-) were estimated by using the UV-Vis spectrophotometer. Calculated charge balance error (CBE) (Eg.1) is found within the permissible limit of ± 10% (Freez and Cherry 1979).

$$CBE = \left(\frac{\sum cations - \sum anions}{\sum cations + \sum anions} \right) \times 100 \quad (1)$$

The hydrogeochemical facies (Piper trilinear diagram), Gibbs diagram, scatter plots, saturation index (SI), Wilcox plots, sodium percent, and the permeability index were plotted using the AqQA and Grapher software. In this study, the correlation analyses were carried out by using the Statistical

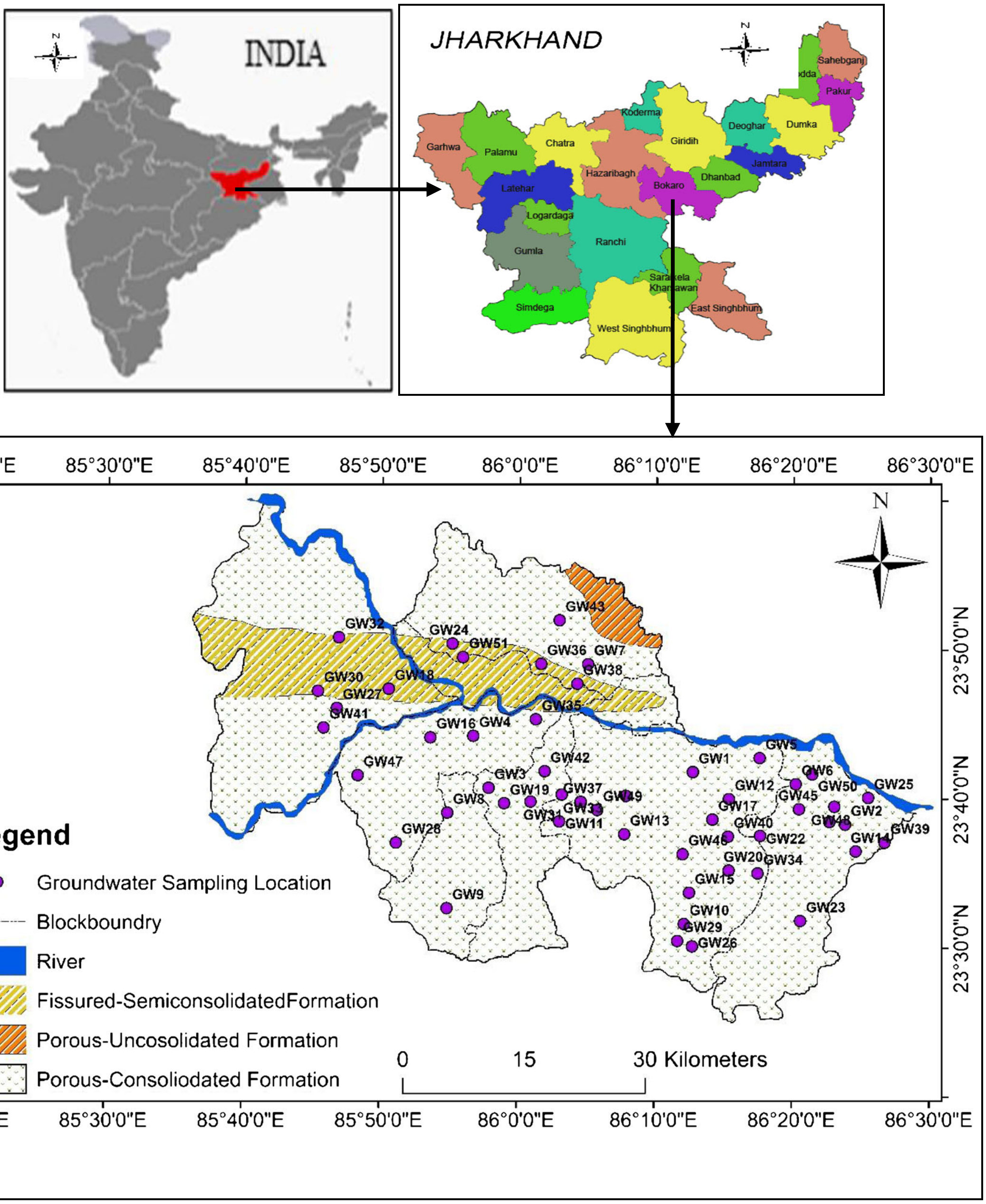


Fig. 1 Groundwater sampling locations and hydrological condition of the study area

Package of Social Studies (SPSS) software to reduce the number of variables in a data set to a smaller number without loss of essential information.

Results and discussions

Chemistry of groundwater

Tables 2 and 3 show data of various physico-chemical parameters with descriptive statistical measures, and are compared to drinking water limits established by the World Health Organization (WHO 2006) and the Bureau of Indian Standards (BIS 2012) to consider the suitability for drinking and domestic uses. The pH values of the samples varied from 5.67 to 8.09 (mean 7.42) and 6.88 to 7.92 (mean 7.44) during the pre- and post-monsoon seasons, respectively. The pH values indicate that the groundwater is slightly acidic to slightly alkaline nature. The electrical conductivity (EC) values ranged between 520 and 1961 μS cm^{-1} (mean 1142.22 μS cm^{-1}) in the pre-monsoon, while during the post-monsoon, its values varied from 304 to 1620 μS cm^{-1} (mean 860.80 μS cm^{-1}), respectively. Langenegger (1990) classified water on the basis of EC value (Table 4); the

Table 1 Geological succession of the study area (CGWB 2013)

Age	Series	Lithology	Hydrogeological conditions	Formation	Groundwater potential
Upper carboniferous to middle Jurassic	Gondwana supergroup	Sandstone, shale, grit, coal Seams Amphibolite, epidiorite	Moderately thick regionally extensive confined/unconfined aquifers.	Fissured/Semi-consolidated	Limited yield prospects below 10 Cu m/h
Middle to upper proterozoic	Chotanagpur granite gneiss	Granite and granite gneiss, micaschist and phyllite	Groundwater restricted to weathered residuum and fractured zone down to 125 m.	Fissured/Consolidated	Limited yield prospects below 30 Cu m/h
Lower to middle proterozoic	Unclassified metasediments	Quartzites, fine to coarse grained sand, silt, clay, recent stream sediments	Moderately thin restricted unconfined aquifers down to 50 m.	Porous/unconsolidated	Limited yield prospects below 30 Cu m/h

majority of the water samples (55 and 49%) falls within the permissible category in the pre- and post-monsoon seasons, respectively. Moreover, 17.6 and 23.5% of the samples are under brackish water category and 27.4 and 8.0% of the samples belong to saline water category during the pre- and post-monsoon seasons, respectively. However, 19.5% of the samples belong excellent to good water category in the post-monsoon season (Table 4). Higher EC value shows the high volume of dissolved salts in the water samples. TDS of the water samples varied between 414 and 1735 mg/L (mean 961.69 mg/L) in the pre-monsoon and from 258 to 1454 mg/L (mean 702.96 mg/L) in the post-monsoon season. Davis and Wiest (1966) proposed four classes on the basis of TDS concentrations for suitability of drinking and irrigation purposes (Table 5). The results, as shown in this table indicate that 12 and 31% of the samples are falls in the desirable for drinking uses, while 47 and 43% of the samples are under the permissible limit in the pre- and post-monsoon seasons, respectively. Rest of the samples of both seasons are under the suitability for irrigation purposes (Table 5). However, according to desirable limits of TDS established by the BIS (2012) and WHO (2006), most of the water samples are beyond the desirable limit in the study area, making unfit for domestic and drinking uses in both seasons, respectively. Total hardness (TH) in the groundwater samples ranged from 172.62–973.72 mg/L and 121.30–817.77 mg/L with the average value of 488.49 and 371.07 mg/L during the pre- and post-monsoon seasons, respectively. Sawyer and McCarthy (1967) suggested four classes to classify the water on the basis of total hardness (Table 6). Based on this classification, data show that about 74.6% of the samples in the pre-monsoon season and 52.9% of the samples during the post-monsoon season are very hard type of water (Table 6). Moreover, 25.4 and 35.1% of the samples belong hard type of water in the study area during the pre- and post-monsoon seasons, respectively (Table 6). High TH value causes various problems encrustation on water supply distribution systems. There is some suggestive evidence that long-term consumption of extremely hard water might lead to an increased incidence of urolithiasis, anecephaly, prenatal mortality, some types of cancer, and cardio-vascular disorders (Durvey et al. 1991; Agrawal and Jagetia 1997).

Major cations chemistry

Ca^{2+} and Na^{+} are the dominant cations in the groundwater samples of the study area followed by Mg^{2+} and K^{+} in both seasons, respectively. Calcium ion in the groundwater samples of the study area varied from 31.80 to 218.74 mg/L with the average value of 101.80 mg/L in the pre-monsoon season and from 24.20 to196.72 mg/L with the mean value of 83.47 mg/L in the post-monsoon season, which accounts 37 and 43% of the total cationic content (TZ^{+}) in the pre- and post-monsoon seasons, respectively. The concentrations of Ca^{2+} exceeded the drinking water acceptable limit of the WHO (2006) and BIS (2012) in 60.7% (pre-monsoon season) and 47.0% (post-monsoon season) of the samples in the study area. Magnesium in the groundwater samples ranged from 21.35 to 106.93 mg/L (mean 56.93 mg/L) and from 13.6 to 87.95 mg/L (mean 39.51 mg/L), which accounts 21 and 20% of the TZ^{+} in the pre- and post-monsoon seasons, respectively. Mg^{2+} about 84.31% in the pre-monsoon season and 58.82% in the post-monsoon season of the groundwater samples are above the acceptable limits of the WHO (2006) and BIS (2012) for drinking water. Weathering and dissolution of calcium carbonate (limestone and dolomite), calc-silicate minerals (amphiboles, pyroxenes, olivine, biotite, etc.), and magnesium carbonate (dolomite) in sedimentary rock are the most common source of calcium and magnesium in water (Singh et al. 2012b). Na^{+} concentration in the samples during the pre- and post-monsoon seasons ranged from 39.7 to 235.9 mg/L (mean 102.56 mg/L) and from 14.2 to 172.8 mg/L (mean 65.57 mg/L), respectively and it accounts for 38 and 34% of

Table 2 Physico-chemical characteristics of the groundwater of the Bokaro district

Sample Code	Type of water	Latitude	Longitude	pH	EC	TDS	Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	Cl^{-}	HCO_3^{-}	SO_4^{2-}	F^{-}	NO_3^{-}	TH
(a) Pre-monsoon season																
GW1	Hand pump	23.696	86.212	6.99	1023	894	107.31	58.70	74.70	8.70	129.96	434	54.75	0.92	29.65	509.54
GW2	Dug Well	23.638	860.397	7.92	656	524	74.39	26.38	48.20	3.60	109.00	204	23.87	0.69	37.20	294.38
GW3	Dug Well	23.677	85.964	7.50	960	779	105.25	45.78	79.80	5.60	111.97	302	110.83	1.34	13.54	451.27
GW4	Dug Well	23.735	85.945	7.10	884	699	67.46	35.83	80.90	4.40	138.99	302	54.34	0.58	12.16	315.93
GW5	Hand pump	23.671	86.283	7.30	1196	1047	144.38	52.37	108.10	9.50	121.99	470	76.89	0.81	57.94	576.21
GW6	Hand pump	23.683	86.337	7.80	1608	1416	157.62	76.40	145.60	18.70	285.94	594	87.59	1.79	46.30	708.05
GW7	Hand pump	23.826	86.034	7.44	1772	1529	105.17	96.19	235.90	15.20	289.97	605	125.13	1.86	51.59	658.29
GW8	Hand pump	23.649	85.914	7.35	794	704	43.51	38.05	81.50	8.20	107.99	326	77.92	1.03	15.45	265.17
GW9	Dug Well	23.542	85.914	6.96	977	822	78.20	65.32	87.50	5.60	117.98	423	32.5–4	0.61	8.47	463.97
GW10	Dug Well	23.643	86.202	7.35	1423	1266	167.28	72.21	107.10	7.90	196.70	555	87.38	1.36	67.68	714.98
GW11	Hand pump	23.663	86.017	7.70	1133	946	81.75	51.26	142.20	11.80	131.96	446	52.91	0.73	23.29	415.06
GW12	Dug Well	23.666	86.256	7.80	698	598	55.54	37.59	44.60	5.40	73.96	318	31.94	0.46	27.05	293.35
GW13	Hand pump	23.641	86.111	7.15	1923	1727	218.74	101.35	163.50	24.20	297.98	750	111.52	1.77	54.21	963.40
GW14	Dug Well	23.610	86.383	6.85	1732	1501	168.33	92.44	154.50	14.90	239.89	692	98.04	1.73	35.74	800.77
GW15	Dug Well	23.561	86.208	8.00	560	456	33.95	21.35	72.90	4.80	64.97	225	21.83	0.56	6.82	172.62
GW16	Hand pump	23.733	85.893	6.80	669	544	48.05	28.57	70.80	4.40	79.99	264	32.93	0.64	11.40	237.56
GW17	Dug Well	23.643	86.204	7.78	1660	1449	193.11	87.15	109.00	14.30	224.99	636	81.16	1.51	97.68	840.94
GW18	Hand pump	23.787	85.842	7.75	1764	1521	174.16	97.29	133.20	15.70	234.96	659	106.52	1.77	96.03	835.24
GW19	Dug Well	23.660	85.983	7.33	1098	916	130.91	60.26	54.80	8.50	176.00	389	66.10	1.36	24.79	574.96
GW20	Dug Well	23.604	86.239	7.00	848	704	64.96	47.87	80.30	7.40	79.98	358	47.22	0.84	12.87	359.14
GW21	Hand pump	23.630	86.394	7.10	1591	1358	119.82	76.41	175.70	10.20	189.40	616	77.19	1.52	87.26	613.59
GW22	Dug Well	23.620	86.194	7.80	1961	1735	213.70	106.93	186.80	24.70	328.99	666	97.52	1.89	103.4	973.73
GW23	Dug Well	23.576	86.358	7.69	1582	1349	133.88	89.20	153.00	14.90	216.50	570	106.90	1.53	59.10	701.33
GW24	Dug Well	23.819	85.857	7.40	520	414	35.91	28.38	50.00	5.30	51.94	202	29.80	0.51	7.51	206.43
GW25	Hand pump	23.663	86.404	7.58	1692	1394	112.39	88.70	180.20	16.20	222.99	635	57.19	1.66	76.80	645.54
GW26	Hand pump	23.515	86.204	7.88	1484	1238	147.39	73.79	90.50	9.40	193.97	536	157.76	1.46	24.50	671.74
GW27	Dug Well	23.777	86.770	7.22	1270	1115	129.19	54.73	134.50	15.10	139.93	427	120.74	1.23	88.96	547.90
GW28	Dug Well	23.615	85.852	7.43	1585	1326	109.62	70.69	208.40	19.90	204.96	535	78.60	1.65	94.40	564.57
GW29	Dug Well	23.515	86.204	7.86	1786	1508	202.30	83.89	133.30	14.90	229.98	680	95.42	1.75	63.70	850.54
GW30	Hand pump	23.781	85.815	7.17	1237	1083	77.97	46.75	184.70	11.30	177.93	489	60.42	0.89	31.28	387.07
GW31	Dug Well	23.662	86.015	7.02	963	746	88.88	48.69	59.50	8.60	108.99	357	53.65	0.79	15.01	422.30
GW32	Hand pump	23.844	85.781	6.77	750	603	53.18	35.16	71.40	8.70	97.96	280	36.32	0.66	16.78	277.46
GW33	Hand pump	23.670	86.053	7.05	1384	1193	136.57	58.93	108.40	15.30	218.99	540	84.35	1.46	25.09	583.62
GW34	Dug Well	23.513	86.204	7.74	1574	1326	141.67	69.74	132.50	17.20	205.93	593	92.54	1.43	68.74	640.79
GW35	Hand pump	23.754	86.021	7.16	573	448	48.40	28.41	52.40	4.60	65.99	216	24.08	0.49	5.47	237.77
GW36	Hand pump	23.801	86.015	7.43	1192	998	88.00	83.82	105.10	7.10	144.98	456	62.24	0.60	46.22	564.50
GW37	Dug Well	23.640	86.087	7.20	1068	898	131.98	60.87	57.30	9.40	155.99	437	31.84	1.32	9.51	580.12

Table 2 (continued)

Sample Code	Type of water	Latitude	Longitude	pH	EC	TDS	Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	Cl^{-}	HCO_3^{-}	SO_4^{2-}	F^{-}	NO_3^{-}	TH
(a) Pre-monsoon season																
GW38	Hand pump	23.794	86.071	7.54	835	674	61.59	43.35	66.30	5.20	68.98	290	100.49	0.80	33.70	332.16
GW39	Hand pump	23.617	86.388	7.93	562	446	37.71	36.82	39.70	5.80	74.96	155	48.96	0.59	44.46	245.60
GW40	Hand pump	23.624	86.255	7.44	802	670	47.83	29.44	109.30	5.60	87.99	304	55.11	0.94	27.09	240.57
GW41	Hand pump	23.794	85.841	7.61	955	775	65.23	43.30	95.00	7.40	134.99	332	77.54	0.90	15.43	341.06
GW42	Dug Well	23.696	86.032	6.97	561	419	31.80	28.44	51.20	6.40	43.99	225	24.67	0.34	5.09	196.40
GW43	Hand pump	23.844	86.041	7.72	885	698	67.62	39.24	85.10	9.30	63.98	320	60.06	0.78	48.74	330.32
GW44	Dug Well	23.641	86.110	7.80	1378	1203	96.83	81.78	111.60	11.70	174.98	576	82.59	1.43	62.47	578.18
GW45	Dug Well	23.628	86.395	7.78	597	492	49.22	26.20	44.70	11.10	59.88	265	24.67	0.87	6.22	230.72
GW46	Dug Well	23.616	86.186	7.72	893	684	59.16	32.14	92.20	7.70	154.98	295	24.40	0.92	13.51	280.00
GW47	Hand pump	23.643	85.752	5.67	887	666	84.76	36.84	50.70	4.90	134.96	305	35.14	0.94	8.66	363.30
GW48	Dug Well	23.653	86.404	7.88	1638	1444	185.96	75.47	129.20	16.90	238.99	640	84.37	1.42	66.80	775.08
GW49	Dug Well	23.756	86.212	7.43	935	715	70.53	56.40	44.87	4.20	111.81	331	51.07	0.77	39.99	408.13
GW50	Dug Well	23.684	86.337	7.69	898	702	83.21	35.89	62.90	8.90	103.97	277	115.43	0.76	9.14	355.55
GW51	Dug Well	23.823	85.932	8.09	837	684	59.38	40.82	88.90	10.00	95.00	342	37.25	0.58	5.93	316.21
(b) Post-monsoon season																
GW1	Hand pump	23.696	86.212	7.30	566	498	65.60	24.68	26.90	3.10	47.00	285	20.02	0.62	21.85	265.44
GW2	Dug Well	23.638	860.397	7.12	453	405	51.39	20.21	41.80	2.80	71.30	167	19.55	0.65	27.52	211.54
GW3	Dug Well	23.677	85.964	7.30	576	469	61.12	34.59	38.32	4.20	62.99	201	59.34	1.03	4.65	294.97
GW4	Dug Well	23.735	85.945	7.78	612	525	59.71	24.53	43.20	3.60	51.99	286	48.60	0.36	3.83	250.10
GW5	Hand pump	23.671	86.283	7.12	674	532	57.01	34.00	28.20	3.30	37.00	309	33.97	0.54	26.22	282.27
GW6	Hand pump	23.683	86.337	7.84	1092	864	134.57	39.87	65.30	7.00	154.96	384	60.42	0.90	15.09	500.28
GW7	Hand pump	23.826	86.034	7.70	1234	1005	87.85	59.96	142.90	7.40	173.98	426	79.68	1.15	21.46	466.04
GW8	Hand pump	23.649	85.914	7.19	524	389	36.17	22.08	56.20	2.10	43.40	169	49.34	0.42	7.09	181.17
GW9	Dug Well	23.542	85.914	7.40	769	567	73.64	47.46	33.10	3.10	86.99	296	20.37	0.75	2.47	379.16
GW10	Dug Well	23.643	86.202	7.70	1187	929	126.07	58.48	69.80	5.40	160.00	419	40.03	0.94	47.58	555.55
GW11	Hand pump	23.663	86.017	7.50	966	764	78.50	38.22	108.90	3.00	105.00	385	35.04	0.59	5.43	353.33
GW12	Dug Well	23.666	86.256	7.40	498	388	49.81	25.14	27.90	1.70	42.97	192	21.50	0.24	19.99	227.86
GW13	Hand pump	23.641	86.111	7.60	1620	1454	193.64	81.18	135.50	13.20	256.98	654	76.46	1.58	38.57	817.77
GW14	Dug Well	23.610	86.383	7.09	1521	1251	154.40	87.95	90.10	8.50	210.00	593	84.03	1.57	18.74	747.46
GW15	Dug Well	23.561	86.208	7.67	318	275	26.17	13.60	35.50	1.50	33.00	146	10.42	0.39	2.93	121.30
GW16	Hand pump	23.733	85.893	7.20	386	331	27.30	14.31	44.60	2.60	51.60	161	13.23	0.43	6.80	127.06
GW17	Dug Well	23.643	86.204	7.54	1283	1009	161.58	41.26	63.10	3.80	136.99	476	58.99	1.11	61.94	573.51
GW18	Hand pump	23.787	85.842	7.92	1327	1097	167.89	56.75	66.20	11.90	171.92	490	60.43	1.54	66.03	652.97
GW19	Dug Well	23.660	85.983	7.10	876	708	109.44	58.58	23.30	5.10	143.00	322	35.75	0.97	5.66	514.36
GW20	Dug Well	23.604	86.239	7.46	533	477	48.03	28.26	59.30	1.90	46.00	256	27.92	0.45	6.92	236.22
GW21	Hand pump	23.630	86.394	7.10	1252	1049	102.46	41.27	150.90	5.30	157.96	493	43.94	1.33	49.32	425.76
GW22	Dug Well	23.620	86.194	7.70	1618	1439	196.72	69.12	147.80	14.20	288.93	582	57.54	1.61	73.43	775.87
GW23	Dug Well	23.576	86.358	7.22	1339	1073	120.61	64.68	97.10	7.70	194.97	449	82.21	1.45	51.10	567.36

Table 2 (continued)

Sample Code (a) Pre-monsoon season	Type of water	Latitude	Longitude	pH	EC	TDS	Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	Cl^{-}	HCO_3^{-}	SO_4^{2-}	F^{-}	NO_3^{-}	TH
GW24	Dug Well	23.819	85.857	7.45	304	275	24.20	20.34	29.70	2.90	32.98	148	10.75	0.35	2.43	144.09
GW25	Hand pump	23.663	86.404	7.57	1260	1037	98.23	60.13	135.20	11.20	179.98	456	37.17	1.51	53.00	492.72
GW26	Hand pump	23.515	86.204	7.77	1113	872	132.05	69.28	52.50	9.30	150.95	319	125.69	1.23	7.50	614.89
GW27	Dug Well	23.777	86.770	7.38	992	773	108.50	21.66	85.70	8.60	64.98	336	95.05	0.98	46.15	360.26
GW28	Dug Well	23.615	85.852	7.50	1365	1109	97.66	55.59	172.80	9.70	168.97	495	55.02	1.43	49.47	472.63
GW29	Dug Well	23.515	86.204	7.30	1543	1199	155.51	62.22	80.50	10.80	201.96	552	76.84	1.64	53.30	644.49
GW30	Hand pump	23.781	85.815	7.80	892	756	60.56	31.86	115.50	7.26	129.99	346	42.55	0.62	17.95	282.35
GW31	Dug Well	23.662	86.015	7.50	764	565	67.85	39.26	23.50	5.80	87.99	291	37.58	0.67	7.62	330.98
GW32	Hand pump	23.844	85.781	6.88	487	387	37.10	23.71	26.90	2.10	39.99	225	21.82	0.55	6.01	190.20
GW33	Hand pump	23.670	86.053	7.54	1154	939	118.19	43.20	73.10	9.30	155.97	463	53.95	1.21	18.73	473.00
GW34	Dug Well	23.513	86.204	7.10	1234	1013	121.05	57.13	82.70	9.80	161.99	475	50.05	1.32	47.02	537.43
GW35	Hand pump	23.754	86.021	6.90	387	297	34.76	14.17	37.30	1.10	31.99	156	16.95	0.35	2.03	145.15
GW36	Hand pump	23.801	86.015	7.50	986	803	75.32	62.59	90.10	3.70	122.99	359	50.73	0.46	32.73	445.57
GW37	Dug Well	23.640	86.087	7.20	866	764	106.91	53.11	45.60	6.40	114.95	404	22.88	1.02	5.58	485.57
GW38	Hand pump	23.794	86.071	7.40	654	568	57.85	38.64	41.10	3.80	35.95	279	89.38	0.62	20.02	303.44
GW39	Hand pump	23.617	86.388	7.30	342	304	28.22	26.00	14.20	3.00	23.99	138	39.37	0.31	24.31	177.42
GW40	Hand pump	23.624	86.255	7.50	563	469	39.53	17.61	69.90	4.30	44.99	241	30.78	0.76	16.73	171.20
GW41	Hand pump	23.794	85.841	7.47	726	587	49.44	32.28	65.30	3.10	85.99	293	41.83	0.64	11.00	256.25
GW42	Dug Well	23.696	86.032	7.62	326	258	25.01	15.47	29.50	2.60	24.99	138	12.51	0.24	3.88	126.09
GW43	Hand pump	23.844	86.041	7.44	683	503	49.44	26.44	67.60	3.40	38.99	247	42.19	0.53	24.17	232.27
GW44	Dug Well	23.641	86.110	7.70	1032	899	78.23	52.75	66.50	8.00	134.99	444	60.42	1.03	49.74	412.39
GW45	Dug Well	23.628	86.395	7.60	354	309	34.01	13.76	28.40	8.10	26.40	178	14.93	0.59	1.44	141.60
GW46	Dug Well	23.616	86.186	7.50	751	555	58.87	20.18	70.40	2.90	110.00	267	12.87	0.62	7.59	230.11
GW47	Hand pump	23.643	85.752	7.62	719	522	74.11	24.59	34.10	2.50	95.99	263	19.13	0.78	4.17	286.31
GW48	Dug Well	23.653	86.404	7.71	1267	1042	155.64	55.35	84.40	7.70	193.87	448	46.44	1.12	45.87	616.59
GW49	Dug Well	23.756	86.212	7.29	726	551	56.91	42.01	32.10	2.90	69.98	291	32.54	0.58	19.74	314.94
GW50	Dug Well	23.684	86.337	7.30	654	545	76.54	24.14	43.30	4.90	85.93	228	74.01	0.49	4.15	290.54
GW51	Dug Well	23.823	85.932	7.50	533	452	45.69	25.47	50.20	3.00	43.99	256	21.10	0.32	2.01	218.90

Unit concentrations are in mg/L except EC (μS cm^{-1}), and pH

the TZ^{+}. A higher sodium intake may cause hypertension, congenial heart diseases, nervous disorder, and kidney problems (Singh et al. 2008). Among the cations, K^{+} concentration is very low in the groundwater samples of the study area. The concentrations of K^{+} varied between 3.6 and 24.7 mg/L (mean 10.33 mg/L) in the pre-monsoon season and 1.1 to 14.2 mg/L (mean 5.5 mg/L) in the post-monsoon season, respectively. Although Na^{+} and K^{+} could be associated with NO_3^{-} and Cl^{-} in sewage and fertilizer, weathering of silicate minerals such as albite, orthoclase microcline, and muscovite also may be a source (Gaofeng et al. 2010; Singh et al. 2012a). Evaporate encrustations of Na^{+} and K^{+} salts, which develop due to cyclic wetting and drying of the Damodar River and cause the formation of alkaline/saline soils, also serve as a local source of Na^{+} and K^{+} (Singh et al. 2005).

Table 3 Statistics summary of the analytical data and compare with the WHO and Indian Standard (IS 10500) for domestic purposes

Parameters	Pre-monsoon				Post-monsoon				WHO (2006)	BIS (2012)		No of samples exceeding acceptable limit	
	Min.	Max.	Avg.	SD	Min.	Max.	Avg.	SD		Acceptable limit	Highest permissible	Pre	Post
pH	5.67	8.09	7.42	0.43	6.88	7.92	7.44	0.24	7.0–8.5	6.5–8.5	No relaxation	1	–
EC	520.00	1961.00	1142.22	420.31	304.00	1620.00	860.80	381.02	750	–	–		
TDS	414.00	1735.00	961.69	383.49	258.00	1454.00	702.96	318.37	500	500	2000	45	35
F^-	0.34	1.89	1.08	0.45	0.24	1.64	0.84	0.42	0.6–1.5	1.0	1.5	28	18
Cl^-	43.99	328.99	151.37	71.70	23.99	288.93	105.70	66.40	250	250	1000	4	2
HCO_3^-	155.00	750.00	428.33	159.52	138.00	654.00	330.92	133.58	200	–	–	–	–
SO_4^{2-}	21.83	157.76	68.03	32.55	10.42	125.69	44.57	25.49	200	200	400	–	–
NO_3^-	5.09	103.42	38.06	29.05	1.44	73.43	22.92	20.32	50	45	No relaxation	19	13
Hardness	172.62	973.73	488.49	216.49	121.30	817.77	371.07	185.43	500	200	600	49	41
Ca^{2+}	31.80	218.74	101.80	51.26	24.20	196.72	83.47	46.25	75	75	200	31	24
Mg^{2+}	21.35	106.93	56.93	23.69	13.60	87.95	39.51	19.12	30	30	100	43	30
Na^+	39.70	235.90	102.56	47.87	14.20	172.80	65.57	38.56	200	–	–	–	–
K^+	3.60	24.70	10.33	5.21	1.10	14.20	5.50	3.33	–	–	–	–	–

Unit concentrations are in mg/L except EC (μS cm^{-1}), and pH

Major anion chemistry

In the groundwater samples, HCO_3^- is the dominant anion among the other anions of the study area. The HCO_3^- concentrations varied from 155 to 750 mg/L with the mean value of 428.33 mg/L in the pre-monsoon season and from 138 to 654 mg/L with the mean value 330.92 mg/L in the post-monsoon season, respectively, which contributes 62% in the pre-monsoon season and 65% in the post-monsoon season of the total anionic content (TZ^-). In the groundwater samples, higher concentrations of HCO_3^- are due to the carbonate weathering as well as the dissolution of carbonic acid in the aquifers and decay of organic matter in the soil zone (Canter 1997; Jeong 2001; Zilberbrand et al. 2001). Chloride is second major anion in the groundwater samples of the study area. The concentration of Cl^- varied from 43.99 to 328.99 mg/L (mean 151.37 mg/L) and from 23.99 to 288.93 mg/L (mean 105.70 mg/L), which accounts 21 and 22% of the TZ^- in the pre- and post-monsoon seasons, respectively. Concentrations of Cl^- exceeded the acceptable limits of 7.8 and 3.9% of the samples during the pre- and post-monsoon seasons, respectively. Nitrate concentrations varied from 5.09 to 103.42 mg/L (mean 38.67 mg/L) in the pre-monsoon season and from 1.44 to 73.4 mg/L (mean 22.92 mg/L) in the post-monsoon season, which contributing 6 and 5% in the pre- and post-monsoon seasons of the TZ^-, respectively. About 37.2 and 25.4% of the samples in the pre- and post-monsoon seasons have high NO_3^- concentrations in the study area. Excessive NO_3^- in drinking water can cause a number of disorders including methaemoglobinaemia in infants, gastric cancer, goiter, birth malformations, and hypertension (Majumdar and Gupta 2000). The chief sources of NO_3^- and Cl^- are atmospheric precipitation, application of fertilizers, and discharges of municipal or domestic sewage (Appelo and Postma 1996). Sulphate concentrations in the groundwater of the study ranged between 21.83 and 157.76 mg/L with the mean of 68.03 mg/L and from 10.42 to 125.69 mg/L with the mean of 44.57 mg/L in the pre- and post-monsoon seasons, respectively, which accounts for 10 and 9% of the TZ^-. In both seasons, the concentrations of SO_4^{2-} are within the respective acceptable limit established by the WHO (2006) and BIS (2012) in the study area. Concentrations of fluoride in the study area ranged from 0.34 to 1.89 mg/L and from 0.24 to 1.64 mg/L with the mean of 1.08 and 0.84 mg/L in the pre- and post-monsoon seasons, respectively. F^- concentrations exceeded the drinking water acceptable limit in 54.9 and 35.2% of the samples during the pre- and post-monsoon seasons, respectively. Excessive intake of F^- can cause various forms of

Table 4 Classification of the groundwater samples according to EC value (Langenegger 1990)

S. No.	Electrical conductivity (μS cm^{-1})	Category	Groundwater samples	
			Pre-monsoon season	Post-monsoon season
1	0–333	Excellent	–	5.8%
2	333–500	Good	–	13.7%
3	500–1100	Permissible	55.0%	49.0%
4	1100–1500	Brackish	17.6%	23.5%
5	1500–10,000	Saline	27.4%	8.0%

fluorosis (Meenakshi and Maheshwari 2006; Tiwari et al. 2017).

Hydrogeochemical facies

The trilinear plots and corresponding diamond-shaped Piper (1944) diagram reveal that the groundwater of the study area is the primarily Ca-Mg-HCO_3 type and secondarily Ca-Mg-Cl type in the pre- and post-monsoon seasons, respectively (Fig. 2). The data plot on the trilinear diagram shows that most of the groundwater samples fall into no dominant zone in the cation facies, while the HCO_3 zone in the anion facies during both seasons, respectively (Fig. 2). However, few samples fall into no dominant zone in the anion facies and the Ca zone in the cation facies, respectively. The plot of geochemical data of both the years on diamond-shaped field reveals that majority of the plotted points fall in zone 1, 2, 3, 5, and 9 (Fig. 2). Most of the groundwater samples fall in the zone 5, suggesting carbonate hardness, while some sample falls in the zone 9, with no dominant cation-anion in the study area.

Statistical analysis

Correlation analysis is an important tool to understand the relationships between individual parameters and various controlling factors of the water samples (Li et al. 2013). A high correlation coefficient (near 1 or − 1) means a good positive relationship between two variables and its value around zero means no relationship between them at a significant level of $p < 0.05$. A correlation coefficient of > 0.7 exhibits strong correlation whereas r value between 0.5 and 0.7 shows moderate correlation and < 0.5 exhibits poor correlation (Manish et al. 2006). Calculated correlation matrix of the 102 groundwater samples is shown in Table 7. In the pre- and post-monsoon seasons, EC and TDS show a high positive and strong correlation with Ca^{2+}, Mg^{2+}, Na^+, K^+, Cl^-, HCO_3^-, F^-, and total hardness (TH). A high positive correlation between Ca^{2+}-Mg^{2+} (0.84 and 0.81), Ca^{2+}-HCO_3^- (0.88 and 0.89), Mg^{2+}-Na^+ (0.72 and 0.55), HCO_3^--Mg^{2+} (0.93 and 0.85), HCO_3^--Na^+ (0.79 and 0.73), Ca^{2+}-TH (0.97 and 0.97), and Mg^{2+}-TH (0.94 and 0.93) indicating similar sources and similar geological process during ionic mineralization in the study area. The positive relation between HCO_3^--F^- (0.86 and 0.87) in the pre-and post-monsoon seasons indicates that when both calcite and fluorite are in contact with water (Rafique et al. 2008; Mamatha and Rao 2010).

Evolution of rock-water interaction behavior

Rock-water interaction behavior is important to evaluate the weathering, ion exchange process, and dissolved constituent that consequences in the groundwater quality. Gibbs (1970) proposed a diagram that is widely used to recognize the functional sources of the dissolved chemical element of the water with their relevant aquifer lithologies, such as precipitation dominance, evaporation dominance, and rock–water interaction dominance. Gibbs's diagram representing the ratio of $Na^+ + K^+/(Na^+ + K^+ + Ca^{2+})$ and $Cl^- + NO_3^-/(Cl^- + NO_3^- + HCO_3^-)$ as a function of TDS to understand the functional

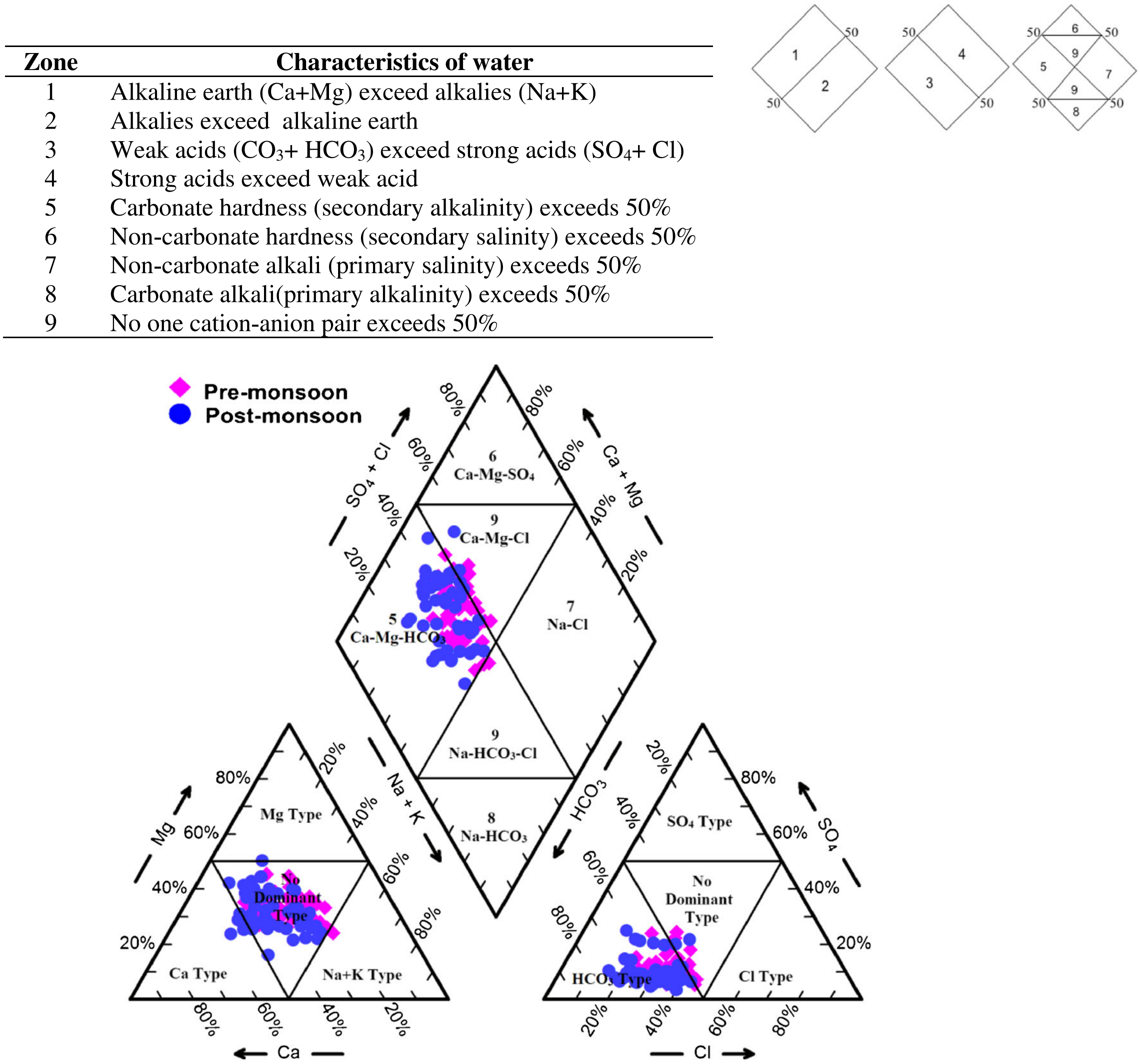
Table 5 Water quality classification based on TDS concentrations (Davis and Wiest 1966)

S. No.	TDS (mg/L)	Water quality	Percentage of sample	
			Pre-monsoon season	Post-monsoon season
1	< 500	Desirable for drinking	12.0%	31.0%
2	500–1000	Permissible for drinking	47.0%	43.0%
3	< 3000	Useful for irrigation	41.0 0%	26.0%
4	> 3000	Unfit for drinking and irrigation	–	–

Table 6 Categorization of the groundwater based on total hardness (Sawyer and McCarthy 1967)

S. No	Total hardness (mg/L)	Water quality	Percentage of sample	
			Pre-monsoon season	Post-monsoon season
1	< 75	Soft	–	–
2	75–150	Moderately hard	–	12.0%
3	150–300	Hard	25.4%	35.1%
4	> 300	Very hard	74.6%	52.9%

sources of dissolved chemical constituents. The plot of geochemical data on Gibbs's diagrams (Fig. 3) suggests rock weathering as the major driving force controlling the groundwater chemistry of the area in both seasons. The weathering dominance field indicates the interaction between the rock chemistry and groundwater chemistry. The relationship between Na^+ and Cl^- has often been used to identify the mechanism for acquiring salinity in semiarid or arid regions and to quantify the atmospheric contribution (Sarin et al. 1989; Sami 1992). The observed higher Na^+/Cl^- ratio (avg. 1.12 and 1.13) in the groundwater during the pre- and post-monsoon seasons as compared with marine aerosols ($Na^+/Cl^- = 0.85$) suggests that high levels of major ions are derived most likely by weathering of rock-forming minerals and anthropogenic sources. The higher Na^+/Cl^- ratio (> 1.0) indicate the non-halite source and suggest silicate weathering as a possible



Zone	Characteristics of water
1	Alkaline earth (Ca+Mg) exceed alkalies (Na+K)
2	Alkalies exceed alkaline earth
3	Weak acids (CO_3+ HCO_3) exceed strong acids (SO_4+ Cl)
4	Strong acids exceed weak acid
5	Carbonate hardness (secondary alkalinity) exceeds 50%
6	Non-carbonate hardness (secondary salinity) exceeds 50%
7	Non-carbonate alkali (primary salinity) exceeds 50%
8	Carbonate alkali(primary alkalinity) exceeds 50%
9	No one cation-anion pair exceeds 50%

Fig. 2 Piper trilinear diagram for hydrogeochemical facies of the study area groundwater

Table 7 Correlation matrixes of physicochemical parameters of the groundwater in the study area

	pH	EC	TDS	Ca^{2+}	Mg^{2+}	Na^+	K^+	Cl^-	HCO_3^-	SO_4^{2-}	NO_3^-	F^-	TH
(a) Pre-monsoon													
pH	1	0.13	0.14	0.11	0.13	0.11	0.21	0.11	0.10	0.20?0.20	0.28	0.14	0.12
EC		1	0.99	0.89	0.94	0.82	0.85	0.94	0.97	0.71	0.77	0.91	0.95
TDS			1	0.90	0.94	0.82	0.86	0.94	0.98	0.71	0.77	0.90	0.95
Ca^{2+}				1	0.84	0.55	0.76	0.86	0.88	0.65	0.68	0.83	0.97
Mg^{2+}					1	0.72	0.76	0.88	0.93	0.64	0.73	0.84	0.94
Na+						1	0.77	0.78	0.79	0.54	0.66	0.72	0.65
K^+							1	0.83	0.82	0.55	0.68	0.80	0.79
Cl^-								1	0.90	0.62	0.66	0.90	0.90
HCO_3^-									1	0.63	0.72	0.86	0.94
SO_4^{2-}										1	0.52	0.70	0.67
NO_3^-											1	0.68	0.73
F^-												1	0.87
TH													1
(b) Post-monsoon													
pH	1	0.22	0.23	0.24	0.14	0.24	0.34	0.25	0.19	0.18	0.15	0.10	0.21
EC		1	0.99	0.92	0.87	0.75	0.81	0.95	0.97	0.63	0.74	0.91	0.94
TDS			1	0.92	0.88	0.77	0.84	0.95	0.98	0.62	0.75	0.90	0.95
Ca^{2+}				1	0.81	0.54	0.79	0.90	0.89	0.60	0.68	0.85	0.97
Mg^{2+}					1	0.55	0.72	0.87	0.85	0.61	0.55	0.79	0.93
Na^+						1	0.63	0.72	0.73	0.40	0.60	0.65	0.57
K^+							1	0.82	0.79	0.59	0.64	0.85	0.80
Cl^-								1	0.91	0.52	0.66	0.87	0.93
HCO_3^-									1	0.54	0.71	0.87	0.92
SO_4^{2-}										1	0.41	0.58	0.64
NO_3^-											1	0.71	0.66
F^-												1	0.87
TH													1

source of Na^+. The lower molar ratio of Na^+/Cl^- (< 1.0) in many groundwater samples, probably results from ion exchange of Na^+ for Ca^{2+} and Mg^{2+} in clays (Fig. 4a). The positive correlations between Na^+-Cl^- (0.78 and 0.72), Na^+-TDS (0.82 and 0.77), and Cl-TDS (0.94 and 0.95) in the pre- and post-monsoon seasons indicate that Cl^- and part of the Na^+ are derived from anthropogenic sources (Tiwari and Singh 2014) (Table 2). The low levels of K^+ in the groundwater are a consequence of its tendency to be fixed by clay minerals and participate in the formation of secondary minerals. The plot of ($Ca^{2+} + Mg^{2+}$) versus ($HCO_3^- + SO_4^{2-}$) will be close to 1:1 line (Fig. 4b) which indicates that dissolution of calcite, dolomite, and gypsum is the dominant reaction in the area (Cerling et al. 1989; Fisher and Mulican 1997). The samples fall above the equiline indicating an excess of $Ca^{2+} + Mg^{2+}$ and the potential for the release of Ca^{2+} and Mg^{2+} by silicate weathering in both seasons. However, the plotted points fall along or below the equiline signifying the dominance of weathering and ion exchange processes (Fig. 4b). The plot of ($Ca^{2+} + Mg^{2+}$) versus HCO_3^- for the water samples shows that the majority of samples fall above the equiline and suggesting that the excess ($Ca^{2+} + Mg^{2+}$) in these water should be balanced by $SO_4^{2-} + Cl^-$ in both season (Fig. 4c). The scatter plot between HCO_3^- versus $Cl^- + SO_4^{2-}$ shows the dominance of HCO_3^- over $Cl^- + SO_4^{2-}$ at higher TDS concentrations in the study area (Fig. 4d). The plotted point on ($Ca^{2+} + Mg^{2+}$) versus total cations (TZ^+) scatter plot fall much below the equiline and the departure being more pronounced at higher concentration, reflecting an increasing contribution of Na^+ and K^+ with increasing dissolved solids (Fig. 4e). The high ($Na^+ + K^+$)/TZ^+, i.e., 0.33 and 0.29, and low ($Ca^{2+} + Mg^{2+}$)/($Na^+ + K^+$), i.e., 2.20 and 2.86 ratios during the pre- and post-monsoon seasons suggest that the chemical composition of the water is largely controlled by silicate weathering reactions with limited contribution via carbonate dissolution. The geochemical data plotted on scatter plot Ca^{2+}/Na^+ versus Mg^{2+}/Na^+ (Fig. 5) relating carbonate and silicate end members also depict the combined influence of carbonate

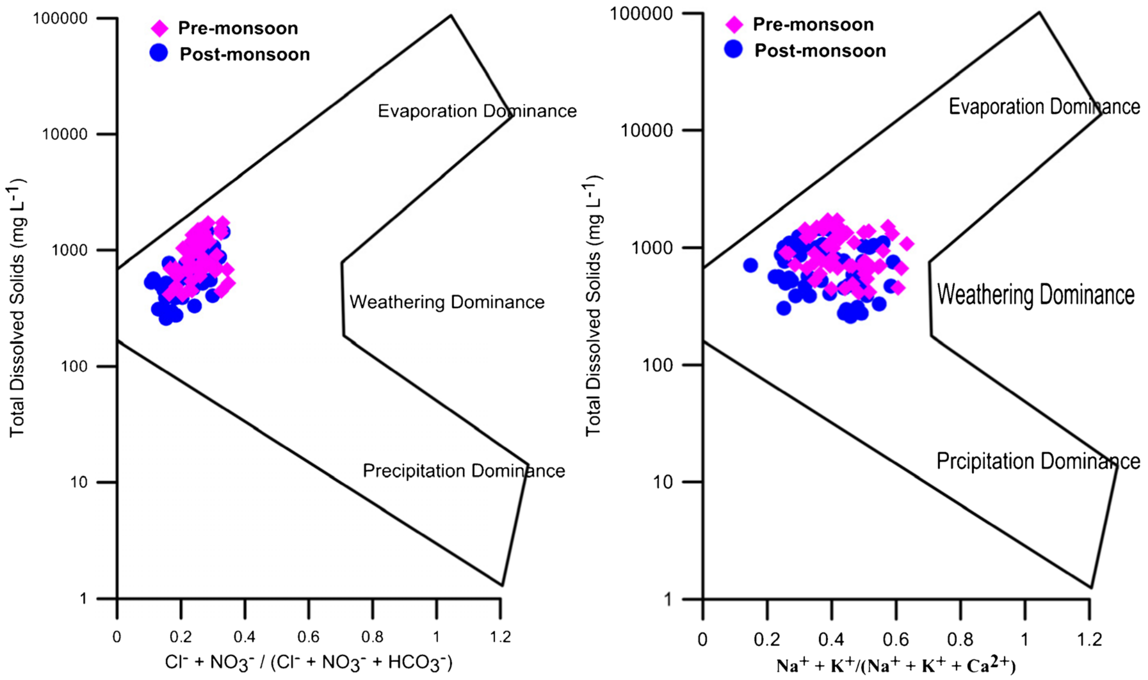


Fig. 3 Gibbs diagram for controlling factor of the groundwater quality

and silicate weathering in solute acquisition processes (Gaillardet et al. 1999). The results, as shown in Fig. 8, suggest that weathering of alumino-silicate minerals like plagioclase, mica, amphiboles, pyroxenes, etc. is the major lithogenic contributor for Na^+, K^+, Ca^{2+}, Mg^{2+}, and HCO_3^- along with minor addition of Ca^{2+}, Mg^{2+}, and HCO_3^- from dissolution of carbonates in the groundwater of the study area. Similarly, in previous work by the Mahato et al. 2016 support that the silicate weathering, carbonate weathering, and ion exchange processes controlling the chemical composition of the groundwater in the East Bokaro coalfield, Jharkhand, India.

Chloro-alkaline indices and saturation index

The chloro-alkaline indices (CAI-I and CAI-II) were used to evaluate the ion exchange process taking place during groundwater movement in the aquifer system. Chloro-indices have been calculated by using the formula given below:

$$\mathrm{CA{-}I} = \mathrm{Cl}^- - (\mathrm{Na}^+ + \mathrm{K}^+)/\mathrm{Cl}^- \quad (2)$$

$$\mathrm{CA{-}II} = \mathrm{Cl}^- - (\mathrm{Na}^+ + \mathrm{K}^+)/\mathrm{SO_4}^{2-} + \mathrm{HCO_3}^- + \mathrm{NO_3}^- \quad (3)$$

The chloro-alkaline indices (CAI-I and CAI-II) can be either positive or negative depending on whether the exchange of Na^+ and K^+ is from water with Mg^{2+} and Ca^{2+} in rock/soil or vice versa. If Na^+ and K^+ are exchanged in water with Mg^{2+} and Ca^{2+}, the value of the ratio will be positive, indicating a base-exchange phenomenon. The negative values of the ratio will indicate chloro-alkaline disequilibrium and the reaction as a cation-anion exchange reaction. During this process, the host rocks are the primary source of dissolved solids in the water.

In the present case, the chloro-alkaline index (CA-I) values ranged between − 1.19 and 0.48 meq/L with the average of − 0.18 meq/L in the pre-monsoon season and from − 1.76 to 0.72 meq/L with the average value of − 0.19 meq/L in the post-monsoon season, whereas CA-II index values ranged from − 0.37 to 0.29 meq/L (avg. − 0.06 meq/L) in the pre-monsoon season and from − 0.39 to 0.47 meq/L (avg. − 0.03 meq/L) in the post-monsoon season, respectively (Table 8). The results, as shown in Fig. 6a, b, indicate that most of the samples (approx 60.66 and 54.94% of the samples) have negative values during the pre- and post-monsoon seasons, signifying chloro-alkaline disequilibrium and the reaction as a cation-anion exchange reaction. However, the rest of samples in the pre- and post-monsoon seasons have positive values, indicating a base-exchange reaction in the study area.

The saturation index (SI) is defined as the logarithm of the ratio of ion activity product (IAP) to the mineral equilibrium constant (Ksp) at a given temperature (Freeze and Cherry 1979; Stumm and Morgan 1981) and is expressed as:

$$\mathrm{SI} = \log\,(\mathrm{IAP}/\mathrm{Ksp}) \quad (4)$$

A positive SI indicates that the water is supersaturated with respect to the particular mineral phase and therefore incapable of dissolving the mineral; the mineral phase may precipitate. A negative SI indicates undersaturation and potential for

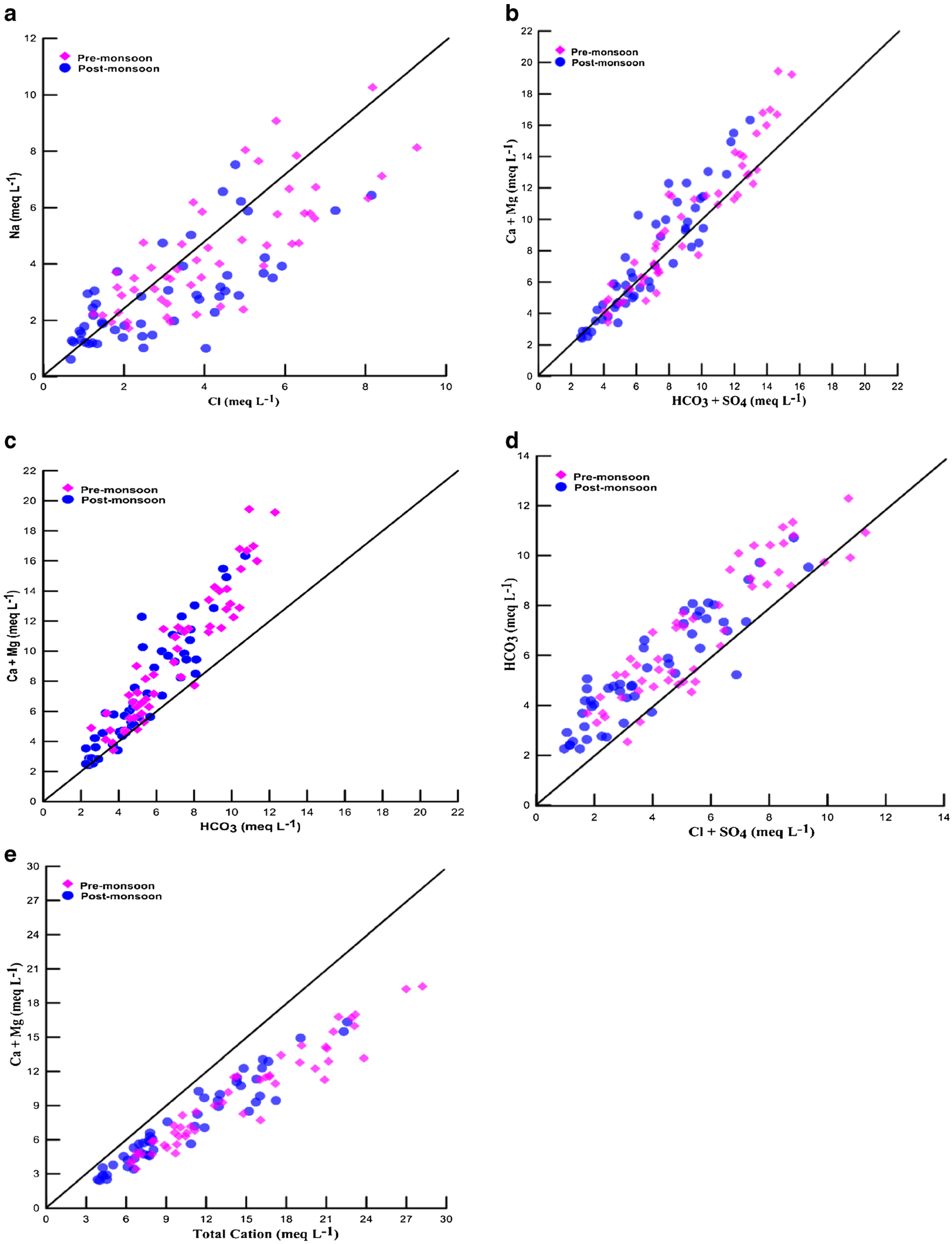
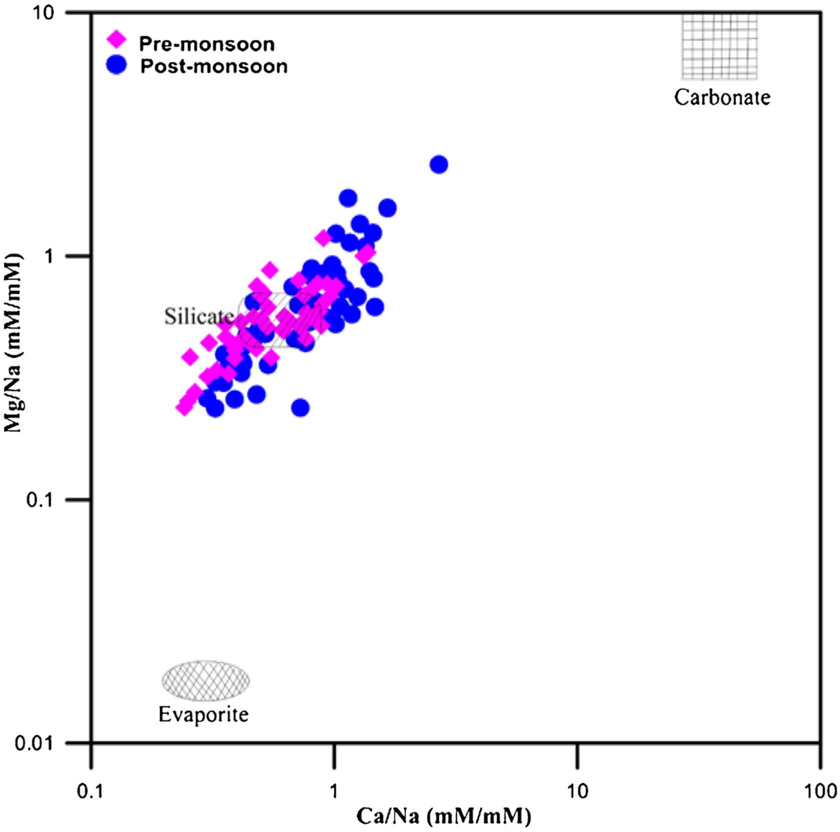


Fig. 4 Scatter plot between a Na^+ versus Cl^-, b $Ca^{2+} + Mg^{2+}$ versus $HCO_3^- + SO_4^{2-}$, c $Ca^{2+} + Mg^{2+}$ versus HCO_3^-, d HCO_3^- versus $SO_4^{2-} + Cl^-$, e $Ca^{2+} + Mg^{2+}$ versus total cations (TZ^+)

Fig. 5 Plot of Ma^{2+}/Na^+ versus Ca^{2+}/Na^+ relating carbonate and silicate end members (mM)



dissolution of the mineral phase, if present. The plot of saturation indices of calcite (SI_c) versus dolomite (SI_d) demonstrates that 91 and 82% of the water samples in the pre- and post-monsoon seasons are supersaturated with respect to dolomite and calcite. The SI_d values are higher than the SI_c values (Fig. 7). This supersaturation could lead to the precipitation of Ca and/or Ca-Mg carbonate under suitable physico-chemical conditions. This explains the presence of calcareous nodules, which contain a mixture of calcite and/or dolomite in the study area (Singh et al. 2008). About 9 and 18% of the water samples have negative SI indices and are undersaturated with respect to both calcite and dolomite in the pre- and post-monsoon seasons, respectively. Samples plotting in this field come from an environment where calcite and dolomite are depleted or where Ca and Mg exist in other forms would also probably fall in this field.

Suitability of groundwater for irrigation purposes

Electrical conductivity (EC), salinity, sodium absorption ratio (SAR), residual sodium carbonate (RSC), percent sodium (Na %), Kelly's ratio (KR), magnesium hazard (MH), and permeability index (PI) were analyzed to delineate the suitability of groundwater for irrigation purposes which shows in the Table 8. Groundwater suitability for irrigation purpose depends on the dissolved ion component and soil drainage is also one of the important factors for plant growth with water quality. Well-drained soil with highly saline water will be good for crop production but in poorly drained areas, the groundwater is not fulfilled even with good water quality (Todd 1980; Richards 1954).

Sodium absorption ratio

The U.S. Salinity Laboratory (1954) proposed a diagram for studying the suitability of groundwater for irrigation purposes based electrical conductivity and sodium adsorption ratio. High salt concentration (EC) in water leads to the formation of saline soil, while a high sodium concentration leads to the development of an alkaline soil. The sodium or alkali hazard expressed in terms of SAR and estimated by the formula:

$$\begin{aligned}&\mathrm{SAR} = \mathrm{Na}/[(\mathrm{Ca}+\mathrm{Mg})/2]^{0.5}\\&\text{concentration in meg/L}\end{aligned} \tag{5}$$

In the US salinity diagram, irrigation water is classified as low (EC = < 250 µS cm^{-1}), medium (EC = 250–750 µS cm^{-1}), high (EC = 750–2250 µS cm^{-1}), and very high (EC = 2250–5000 µS cm^{-1}), salinity classes (USSL 1954). On the basis of SAR value, water is classified into low (SAR < 6), medium (SAR 6–12), high (SAR 12–18), and very high (SAR.18) alkali waters (Fig. 8). The SAR values in the study area ranged from 0.97 to 4.08 meq/L with the average value of

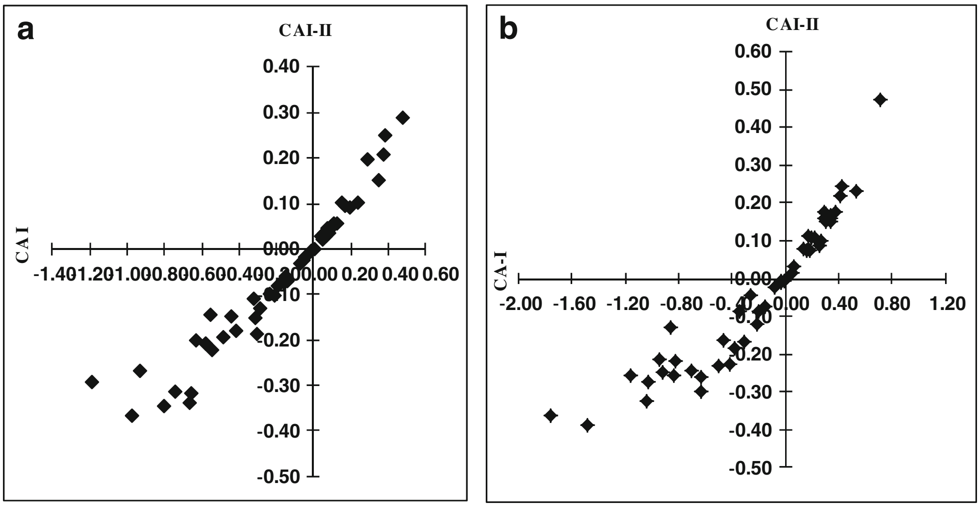


Fig. 6 Plot of CAI-I against CAI-II for the pre-monsoon season (**a**) and post-monsoon season (**b**) of the study area

2.03 in the pre-monsoon season and from 0.45 to 3.46 meq/L with the average value of 1.50 meq/L in the post-monsoon season, respectively (Table 8). According to USSL (1954) diagram, 19.60 and 47.05% of the samples in the study area during the pre- and post-monsoon seasons are fall in the zone of C2S1 indicating medium-salinity and low-sodium hazards water, such type of water can be suitable for irrigation purposes with little danger of development of exchangeable sodium and salinity. However, about 80.38 and 52.94% in the pre- and post-monsoon seasons of the groundwater samples are falls in the zone of C3S1 category, indicating high salinity and low-sodium hazards (Fig. 8). High saline water cannot be used on soils with the low drained area without any proper management and salt-tolerant plants/crops should be selected for high-saline regions (Todd 1980; Hem 1985; Karanth 1987; Singh et al. 2012b).

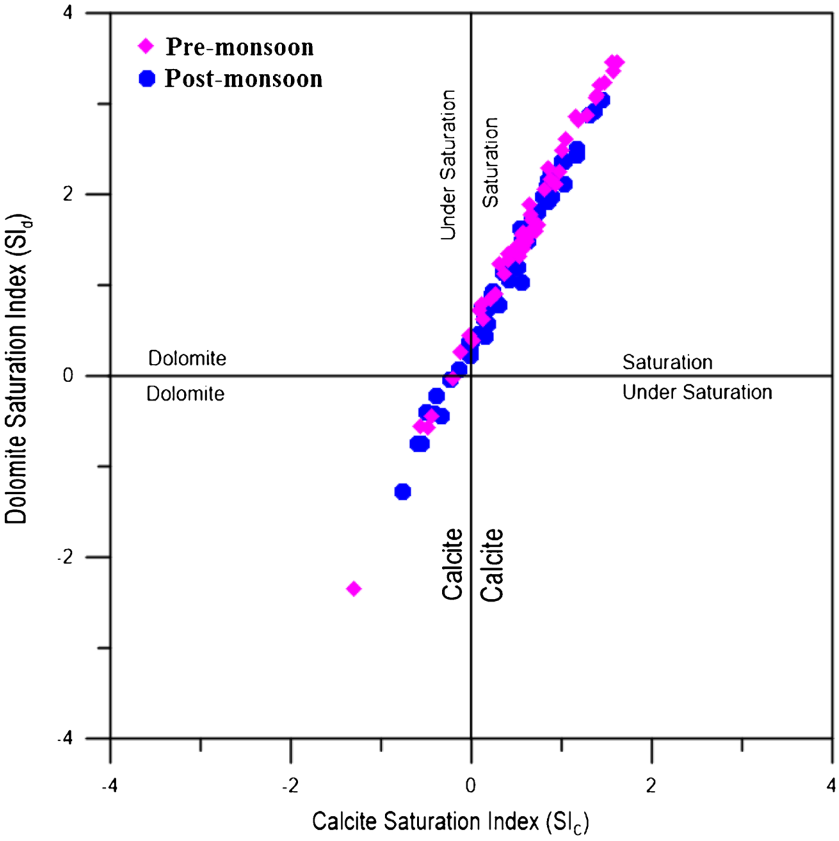


Fig. 7 Relationship between calcite (SI_c) and dolomite (SI_d) saturation indices

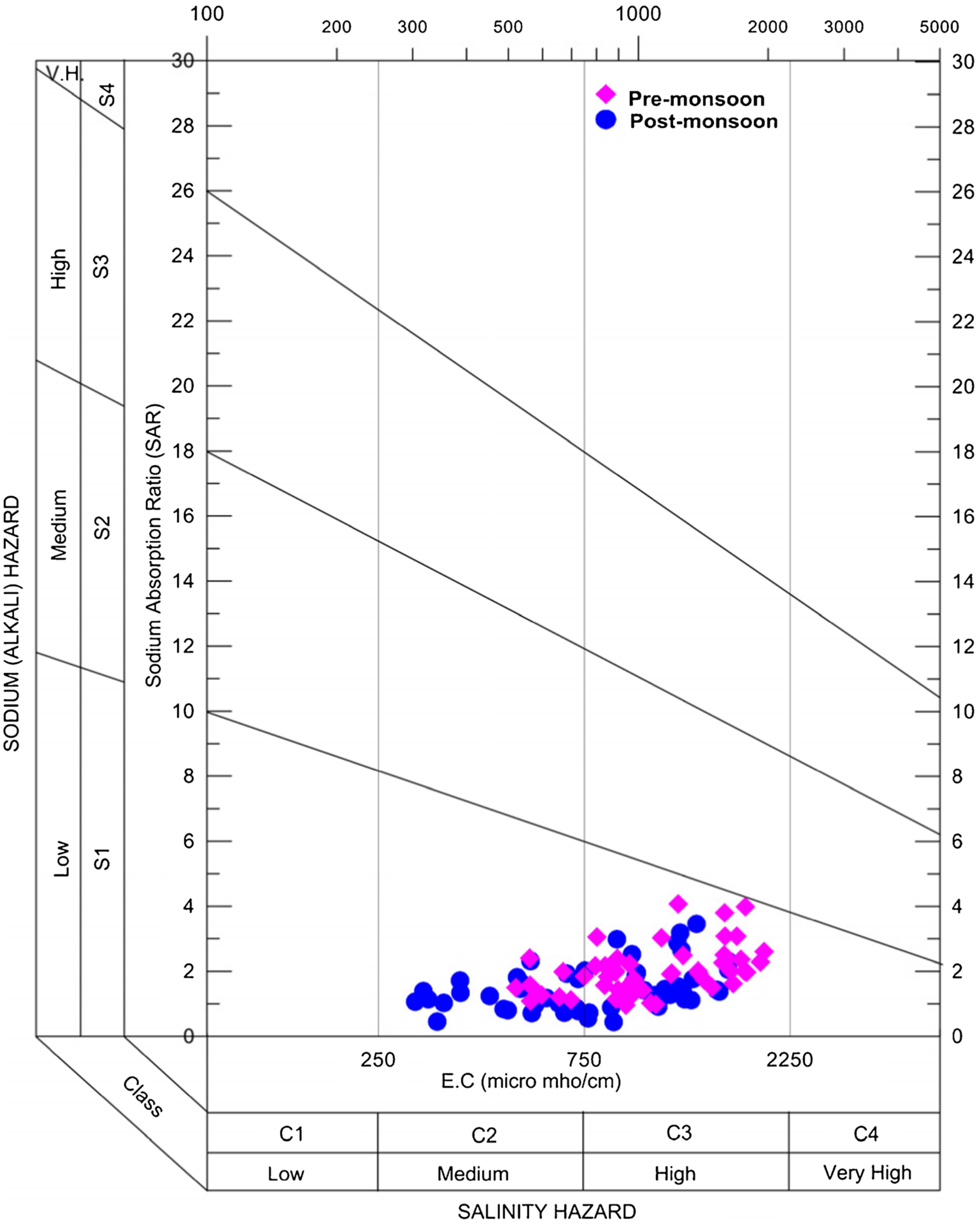


Fig. 8 Classification of the groundwater based on USSL diagram

Table 8 Statistical summary of the groundwater samples for irrigation purpose of the study area

	Pre-monsoon season				Post-monsoon season			
Parameters	Min.	Max.	Mean	SD	Min.	Max.	Mean	SD
CA-I	− 1.19	0.48	− 0.18	0.38	− 1.76	0.72	− 0.19	0.56
CA-II	− 0.37	0.29	− 0.06	0.16	− 0.39	0.47	− 0.03	0.19
MH	36.89	61.68	48.99	6.51	24.76	60.31	44.79	7.42
PI	35.38	76.89	51.99	10.07	29.32	79.58	53.62	12.89
KI	0.21	1.04	0.49	0.19	0.10	0.89	0.42	0.20
RSC	− 8.53	0.28	− 2.74	2.05	− 7.06	0.53	− 1.99	1.89
Na%	18.46	51.82	33.8	7.90	10.01	48.00	29.17	9.61
SAR	0.97	4.08	2.03	0.74	0.45	3.46	1.50	0.71

Unit concentrations are in meq/L

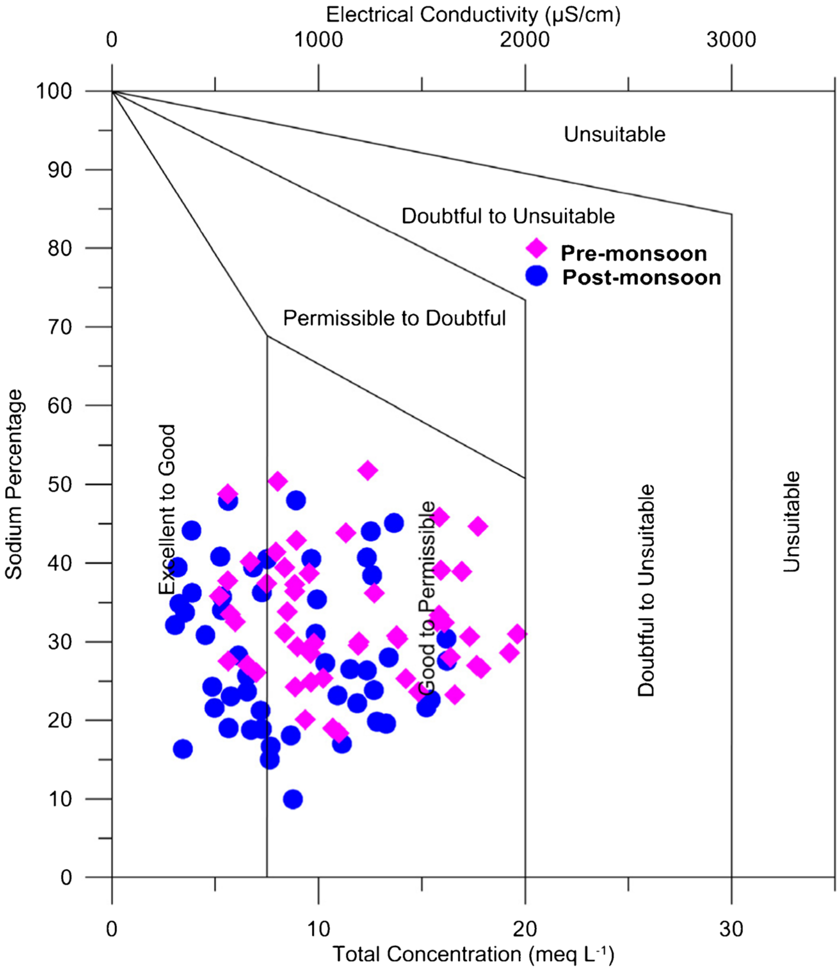


Fig. 9 Sodium percentage plot for water quality classification (Wilcox diagram 1955)

Percent sodium

The sodium concentration is usually expressed in terms of sodium percent which is generally used for evaluating the suitability of water for irrigation purposes because sodium reacts with soil to reduce its permeability (Wilcox 1955). High Na content can promote the exchange of Na ions in water for Ca and Mg in the soil, which causes the soil to deflocculate and can decrease soil permeability (Singh et al. 2008). Na% is classified into five classes for irrigation uses: excellent (< 20%), good (20–40%), permissible (40–60%), doubtful (60–80%), and unsuitable (> 80%) and it can be estimated by the formula:

$$\mathrm{Na\%} = \mathrm{Na} + \mathrm{K}/(\mathrm{Ca} + \mathrm{Mg} + \mathrm{Na} + \mathrm{K}) \times 100 \quad (6)$$

concentration in meq/L.

In the study area, percent sodium (Na %) in the groundwater samples ranged from 18.46 to 51.82% with the average value of 33.8% in the pre-monsoon season. However, Na% during the post-monsoon season ranged from 10.01 to 48% with the average value of 29.17%, respectively (Table 8). A plot of the analytical data on the Wilcox (1955) diagram, which relates EC to Na%, indicates that the groundwater water may be used for irrigation without any hazard (Fig. 9).

Residual sodium carbonate

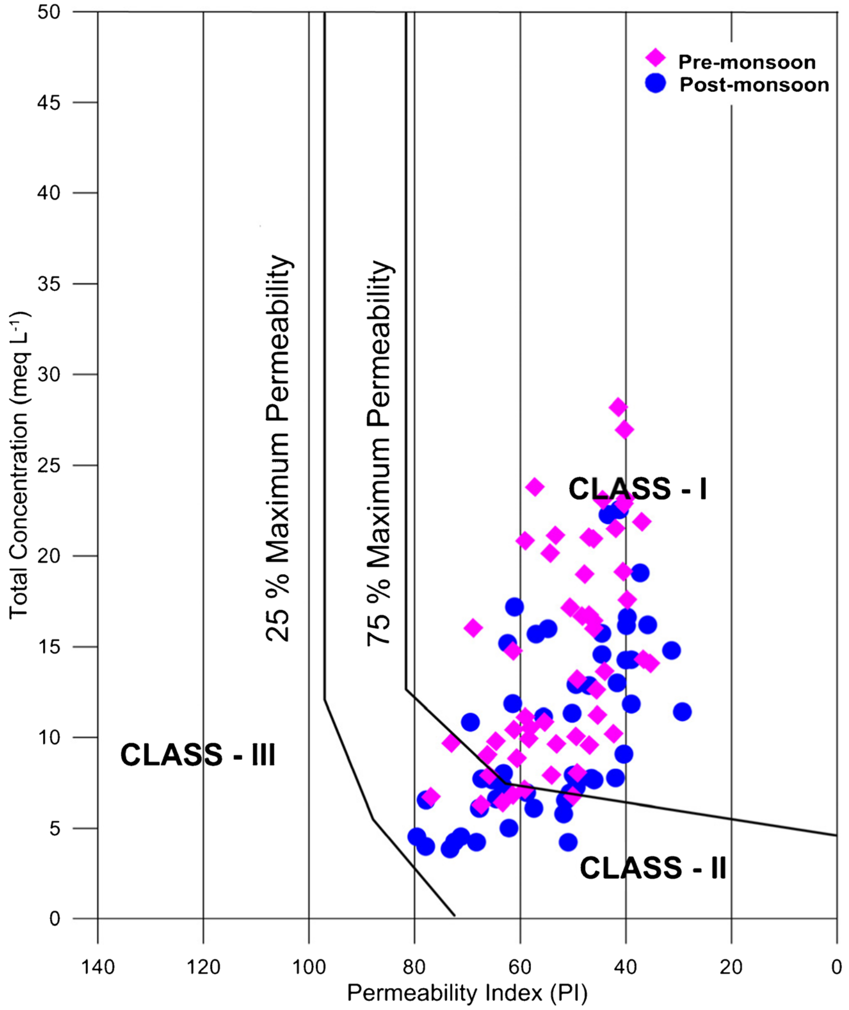
The high concentration of carbonates ($HCO_3^- + CO_3^-$) in excess of alkaline earths ($Ca^{2+} + Mg^{2+}$) is termed as the RSC that affect the suitability of groundwater for agricultural purposes because there may be a chance of high content of sodium ions due to complete precipitation of Ca^{2+} and Mg^{2+} ions (Ragunath 1987; Eaton 1950) and the residual sodium carbonate (RSC) has been calculated by using formula:

$$\mathrm{RSC} = (\mathrm{CO}_3 + \mathrm{HCO}_3) - (\mathrm{Ca} + \mathrm{Mg}) \quad (7)$$

concentration in meg/L

Richards (1954) classified irrigation water into three types on the basis of RSC values, if RSC values < 1.25 meq/L

Fig. 10 Rating of irrigation water on the basis of PI (Doneen 1964)



(good), it lies between 1.25 and 2.50 meq/L (doubtful), and a value > 2.5 meq/L (unsuitable). In the present study, RSC values in the pre- and post- monsoon seasons ranged from − 8.53 to 0.28 meq/L (mean − 2.74 meq/L) and from − 7.06 to 0.53 meq/L ((mean − 1.99 meq/L), respectively (Table 8). In the study area, the groundwater samples have RSC value < 1.25 meq/L in both seasons that indicates all water samples are suitable for irrigation purposes without any hazards.

Magnesium hazard and Kelly's ratio

The magnesium hazard and Kelley index are also used to classify water for irrigation. The MH and KI can be determined by the formula:

$$MH = Mg/(Ca + Mg) \times 100 \quad (8)$$

$$KI = Na/(Ca + Mg) \quad (9)$$

concentration in meq/L.

Szabolcs and Darab (1964) proposed a magnesium hazard (MH) value for irrigation water; above 50 meq/L magnesium ratio is recommended for unsafe and unsuitable for agricultural activity. From the analytical data, the MH values ranged from 36.89 to 61.68 meq/L and 24.76 to 60.31 meq/L with the mean value of 48.99 meq/L and 44.79 meq/L during the pre- and post-monsoon seasons, respectively (Table 8). Based on the above criteria, approximately 23.52% of the samples in the pre-monsoon season and 43.13% of the samples in the post-monsoon season are not suitable for agricultural purposes.

Water with a KI > 1.0 contains excessive Na (Kelley 1946; Paliwal 1967). The Bokaro district groundwater had KI values from 0.21–1.04 meq/L with the mean value of 0.49 meq/L in the pre-monsoon season and from 0.10–0.89 meq/L with the mean value of 0.42 meq/L during the post-monsoon season, respectively (Table 8). In both seasons, the groundwater samples of the study area are safe for irrigation purposes based on the KI value.

Permeability index

Permeability index (PI) is another parameter for assessing the suitability of water for irrigation uses. Doneen (1964) classified irrigation waters based on the permeability index (PI). PI can be determined by the formula:

$$PI = \left(Na + \sqrt{}HCO_3\right)/(Ca + Mg + Na) \times 100 \qquad (10)$$

concentration in meq/L.

Soil permeability is affected by long-term use of water rich in Na^+, Ca^{2+}, Mg^{2+}, and HCO_3. Doneen (1964) classified irrigation water in three PI classes. Class-I and class-II water types are suitable for irrigation with 75% or more of maximum permeability, while class-III type of water, with 25% of maximum permeability, is unsuitable for irrigation. The PI values ranged from 35.38 to 76.89% (mean 51.99%) in the pre-monsoon season and from 29.32 to 79.58 (mean 53.62%) in the post-monsoon seasons, respectively (Table 8). On this basis of PI classes, the water of the study area is also suitable for irrigation uses without any problem (Fig. 10).

Conclusions

The groundwater of the Bokaro district is slightly acidic to slightly alkaline nature and its chemistry is dominated by Ca^{2+} and Na^+ in the cationic concentration and HCO_3^- and Cl^- in the anionic abundances during the pre- and post-monsoon seasons, respectively. Ca-Mg-HCO_3 and Ca-Mg-Cl are the dominant hydrogeochemical facies in the Bokaro district groundwater during both seasons, respectively. Most of the groundwater samples (91 and 82%) in the pre- and post-monsoon seasons are supersaturated with respect to dolomite and calcite, signifying the presence of calcareous nodules in the sub-surface soil profile of the area. The results of the present study are suggested that the chemical composition of the groundwater is mainly controlled by the rock weathering phenomena, ion exchange processes with minor contributions from anthropogenic activities of the study area.

The concentrations of TDS, hardness, Ca^{2+}, Na^+, and Cl^- are above the drinking water desirable limit established by the WHO (2006) and BIS (2012) in the groundwater of the study area during both seasons, respectively. Furthermore, the concentrations of the physico-chemical parameters in the water samples are all higher in the pre-monsoon season than the post-monsoon season, respectively. Most of the groundwater samples of the Bokaro district are good to permissible quality for irrigation uses during both seasons, respectively. However, high salinity and MR values at some locations restrict the suitability for irrigation uses. These findings indicate that the groundwater of the study area is required suitable water treatment and special management plan before using for domestic and irrigation purposes.

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