Contamination, Sources, and Environmental Hazards of Groundwater in Bemetara District, Chhattisgarh, Central India

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Abstract: The groundwater of the the Bemetara district of Chhattisgarh in central India over a large area is hard in nature due to its high mineral content. An elevated concentration of Na^+, Mg^{2+}, Ca^{2+}, and SO_4^{2-} in the groundwater has been observed, falling within the ranges ($n = 16$) 30–437, 43–341, 169–660, and 254–2,330 $mg\,L^{-1}$ with a mean value of 107 ± 93, 117 ± 69, 387 ± 171, and $1{,}059 \pm 595$ $mg\,L^{-1}$, respectively. The temporal and spatial variations in the groundwater concentration of species, i.e., SO_4^{2-}, Cl^-, NO_3^-, Na^+, K^+, Mg^{2+}, Ca^{2+}, Al, and Fe, during the period 2010–2016 are described. The sources of the contaminants and quality of the groundwater are discussed. The environmental hazards of the contaminated water, i.e., land degradation, rusting of buildings and pipes, physiological drought, and ill health of aquatics, birds, and animals, in the Bemetara area are discussed.

Author keywords: Groundwater quality; Gypsum; Mineralization; Environmental hazard.

Introduction

Sulfates occur naturally in numerous minerals, including gypsum ($CaSO_4 \cdot 2H_2O$), epsomite ($MgSO_4 \cdot 7H_2O$), and barite ($BaSO_4$), and their dissolved minerals contribute to the mineral content of many drinking waters (Greenwood and Earnshaw 1984). Sulfur is important for humans because it is part of the amino acid methionine, which is an absolute dietary requirement. The permissible limit of SO_4^{2-} in water is 150 $mg\,L^{-1}$. Sulfates can contribute to an undesirable taste in water, and intake of sulfate-contaminated drinking water has effects on human health, for example, neurological effects and behavioral changes, disturbance of blood circulation, heart damage, effects on eyes and eyesight, reproductive failure, damage to the immune system, stomach and gastrointestinal disorders, damage to liver and kidney function, hearing defects, disturbance of the hormonal metabolism, dermatological effects, and suffocation and lung embolism (Backer 2008; Burgess et al. 2010). Sulfate solution in contact with concrete can cause chemical changes to the cement, which can lead to significant microstructural effects, resulting in a weakening of the cement binder (Atasoy and Yesilnacar 2010; Lorente et al. 2011; Pradhan 2014). Naturally occurring sulfate-contaminated water has been reported in some regions of the world (Seller and Canter 1980; MDH 2008; Horst et al. 2011; Mubarak et al. 2015; Han et al. 2016; Stanton et al. 2017). Similarly, groundwater containing high concentrations of Cl^-, Na, Mg, and Ca in other locations of the world has been observed (Kukillaya et al. 2004; Hajalilou and Khaleghi 2009; van Weert et al. 2009; Yamakanamardi et al. 2011; Razowska-Jaworek 2014; Bhandary et al. 2018).

In the Bemetara district of central India, there is a high incidence of gastrointestinal disorders in humans and livestock, together with serious impacts on wet and bush land ecosystems and a marked corrosion of materials (e.g., houses, pipelines, buildings, roads, water supply systems), all attributable to water pollution. Nonetheless, a detailed investigation of the mineral contamination of water in this region has not been reported to date. In this work, the contamination variations, sources, and toxicity of groundwater from this region of central India are discussed.

Materials and Methods

Study Area

The Bemetara district in the Indian state of Chhattisgarh (21.70° N 81.53° E) was selected for the proposed investigation owing to the high salt content in the water (Fig. 1). The district consists of four blocks, Bemetara, Nawagarh, Saja, and Berla. The area is occupied by mesoproterozoic sedimentary hard rocks over approximately 2.8×10^3 km^2, with a population of around 1 million

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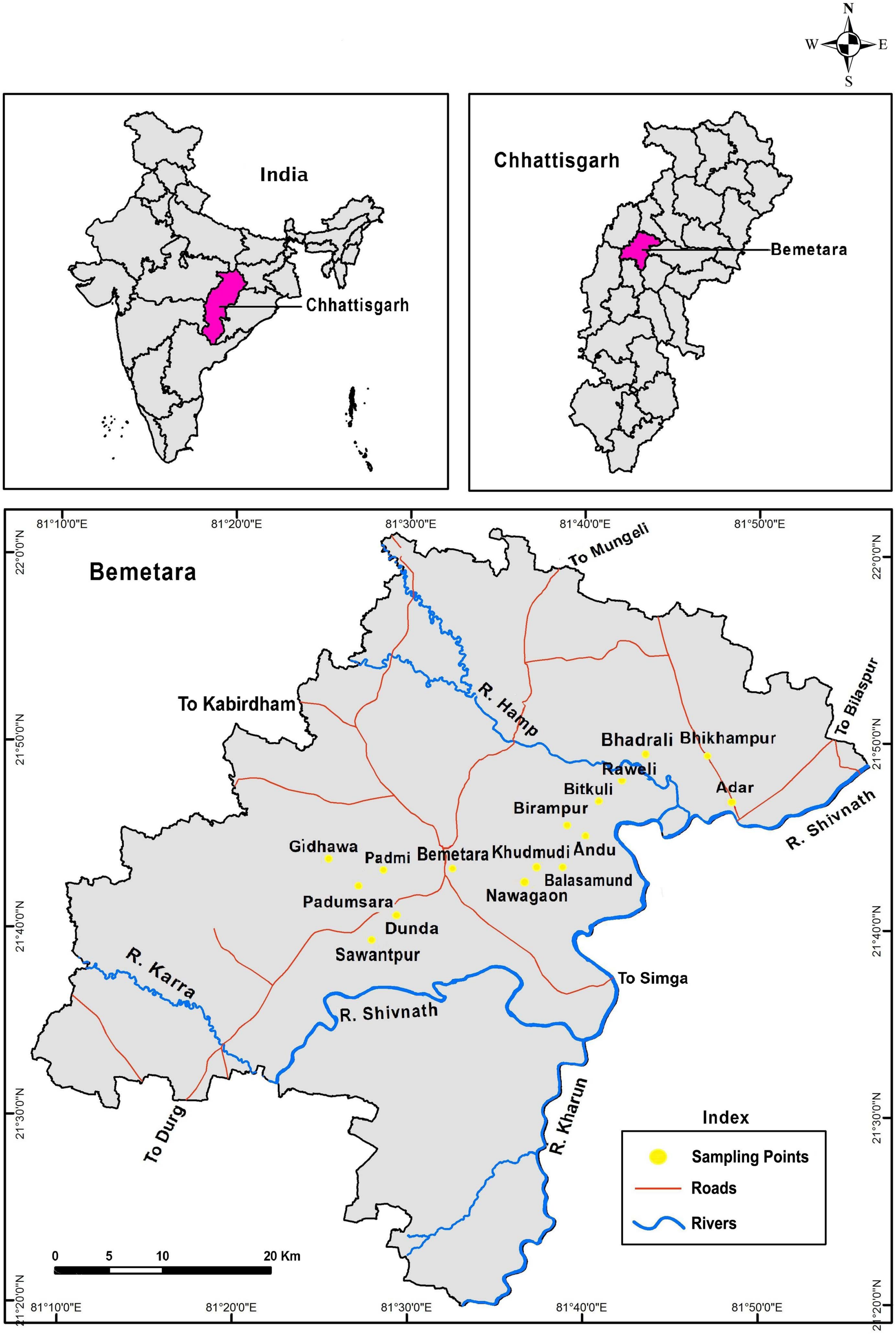


Fig. 1. Sampling locations in Bemetara area, Durg, Chhattisgarh, India.

inhabitants. The water quality, plant biodiversity, and food grain yields in this area have been negatively affected due to the precipitation of minerals in the water.

Sample Collection

The sampling network for water collection is shown in Fig. 1. Groundwater samples were collected in duplicate from 16 locations (cities and villages) using the method of Nielsen and Nielsen (2006). Polyethylene bottles were used for water collection, after rinsing three times with the water to be sampled prior to collection. Samples sent to the laboratory were stored at −4°C. For seasonal variation studies, water was collected in three seasons: monsoon (September), postmonsoon (January), and premonsoon (May) in 2009–2010. For the temporal variation investigation, water was collected in the postmonsoon season (January) from 2011 to 2016. Physical parameters [viz., pH, temperature (T), electrical conductivity (EC), dissolved oxygen (DO), and oxidation-reduction potential (ORP)] were measured on the spot immediately after water sampling.

Analyses

Total dissolved solids (TDS) were determined by evaporation of the water samples, previously filtered through a glass fiber filter, and by drying until a constant weight was achieved (APHA 2005). Total hardness (TH) and total alkalinity (TA) were determined using titration methods (Nollet Leo and De Gelder Leen 2007). Ions (viz., Cl^-, NO_3^-, SO_4^{2-}, Na^+, K^+, Mg^{2+}, and Ca^{2+}) were analyzed by ion chromatography using a Dionex DX1100 (Sunnyvale, California) apparatus equipped with anion and cation separation columns and a conductivity detector. Metals, i.e., Al and Fe, were analyzed with a GBC atomic absorption spectrometer (AAS).

Water Indices

To assess water quality, various indices, viz., sodium adsorption ratio (SAR), sodium hazard (SH), magnesium hazard (MH), permeability index (PI), Kelly's ratio (KR), and water quality index (WQI), were calculated, according to the following equations:

$$\mathrm{SAR} = \frac{\mathrm{Na^+}}{\sqrt{\frac{\mathrm{Ca^{2+}+Mg^{2+}}}{2}}} \quad (1)$$

$$\mathrm{SH} = \frac{\mathrm{Na^+ + K^+}}{\mathrm{Na^+ + K^+ + Mg^{2+} + Ca^{2+}}} \cdot 100 \quad (2)$$

$$\mathrm{MH} = \frac{\mathrm{Mg^{2+}}}{\mathrm{Ca^{2+} + Mg^{2+}}} \cdot 100 \quad (3)$$

$$\mathrm{PI} = \frac{\mathrm{Na^+} + \sqrt{\mathrm{HCO_3^-}}}{\mathrm{Ca^{2+} + Mg^{2+} + Na^+}} \cdot 100 \quad (4)$$

$$\mathrm{KR} = \frac{\mathrm{Na^+}}{\mathrm{Mg^{2+} + Ca^{2+}}} \quad (5)$$

where concentrations are expressed in $\mathrm{meq\,L^{-1}}$.

The WQI was evaluated using a weighed arithmetic method with 10 parameters (pH, DO, EC, hardness, alkalinity, Mg^{2+}, Ca^{2+}, Cl^-, NO_3^-, and SO_4^{2-}), using the following expression (BIS 2009; WHO 2011):

$$\mathrm{WQI} = \frac{\sum \mathrm{q_n} \cdot \mathrm{W_n}}{\sum \mathrm{W_n}}$$

where $q_n = (V_n - V_{io})/(S_n - V_{io}) \cdot 100$ is the quality rating of the nth parameter; and V_n, S_n, V_{io}, and W_n are the estimated value, standard permissible value, ideal value of pure water, and unit weight of nth parameter, respectively. V_{io} is 0 for all parameters, except for pH and dissolved oxygen (in which it is 7.0 and 14.6 $\mathrm{mg\,L^{-1}}$, respectively).

Statistical Analysis

Aqachem software (Waterloo Hydrogeologic) was used for the preparation of piper diagrams. Multivariate statistical models—factor analysis (FA) and hierarchical cluster analysis (HCA)—were used for the source apportionment of ions and metals, in agreement with Shrestha and Kazama (2007) and Hajalilou and Khaleghi (2009), using STATISTICA version 7.1 software (Dell, Statsoft).

Results and Discussion

Characteristics of Water

The physical characteristics of the tube wells and groundwater in the postmonsoon period, January 2010, are presented in Table 1. The newest was 10 years old, while the oldest was 20. Depths ranged from 46 to 91 m. A slight variation in temperature (T) was observed, with values ranging from 24.1°C to 28.1°C. The pH values of the groundwater samples were in the 7.3–7.8 range, with a mean value of 7.6 ± 0.1, so all groundwater samples were within the prescribed desirable range (6.5–9.2) for drinking water (BIS 2009; WHO 2011).

Very high values of EC and TDS were observed and ranged from 892 to 3,930 $\mu\mathrm{S\,cm^{-1}}$ and from 1,205 to 5,362 $\mathrm{mg\,L^{-1}}$, respectively. The highest EC and TDS values corresponded to a tube well in Location 12, the closest (approximately 20 km) to Shivnath River. The EC value was well correlated ($r = 0.98$) with the TDS of the water. The mean EC and TDS values ($1{,}997 \pm 405$ $\mu\mathrm{S\,cm^{-1}}$ and $2{,}677 \pm 582$ $\mathrm{mg\,L^{-1}}$, respectively) in the groundwater samples were well above the allowed limits of 300 $\mu\mathrm{S\,cm^{-1}}$ and 500 $\mathrm{mg\,L^{-1}}$, respectively (BIS 2009; WHO 2011). According to the salinity classification by Davis and De Wiest (1966), the water of the area under study would fall under the moderately saline category.

The DO and ORP values ranged from 4.9 to 6.3 $\mathrm{mg\,L^{-1}}$ and from 135 to 240 mV, respectively. The ORP values were at least three times lower than the recommended value of 650 mV. The DO and ORP values showed moderate negative correlations with the tube well depth and TDS ($r = -0.82$ and $r = -0.92$, respectively).

Total alkalinity (TA) is mainly derived from the dissolution of carbonate minerals and from CO_2 present in the atmosphere and in soil above the water table. The TA values for the groundwater samples ranged from 425 to 1,417 $\mathrm{mg\,L^{-1}}$ as $CaCO_3$. The highest TA value, observed at Location 4, may be due to cattle waste contamination with carbonate and bicarbonate ions. All TA values were found to be several-fold higher than the recommended value (120 $\mathrm{mg\,L^{-1}}$) (BIS 2009; WHO 2011).

Total hardness (TH) index values, which relate to Mg^{2+} and Ca^{2+} concentrations, varied from 393 to 1,500 $\mathrm{mg\,L^{-1}}$, expressed as $CaCO_3$. The highest TH value of the water was observed at Location 1, which may be tentatively ascribed to the extraction of large amounts of water for irrigation purposes. TH showed a fair correlation ($r = 0.60$) with TA, perhaps due to buffering of Mg^{2+} and Ca^{2+}. The water from all tube wells can be regarded as extremely hard (>180 $\mathrm{mg\,L^{-1}}$ $CaCO_3$), according to Doneen (1964).

The chemical characteristics of the groundwater samples collected in the postmonsoon season are presented in Table 2.

Table 1. Physical characteristics of tube well and groundwater, January 2010

Serial Number	Location	Age (years)	Depth (m)	T (°C)	pH	DO ($mg\,L^{-1}$)	ORP (mV)	EC ($\mu S\,cm^{-1}$)	TDS ($mg\,L^{-1}$)	TA ($mg\,L^{-1}$)	TH ($mg\,L^{-1}$)
1	Padumsara	20	61	25.3	7.5	5.2	139	2,990	4,100	1,413	1,500
2	Bhadrali	15	61	25.4	7.5	5.3	187	1,880	2,393	788	833
3	Padmi	15	76	26.8	7.5	5.2	181	2,100	2,806	935	1,000
4	Gidhwa	5	91	27.8	7.7	5.0	145	2,650	3,958	1,417	1,440
5	Duda	20	61	25.6	7.8	5.4	205	1,560	1,911	717	645
6	Bhikhanpur	15	61	25.8	7.6	5.8	238	1,235	1,537	747	448
7	Bemetara	10	91	28.1	7.6	5.1	198	1,580	2,423	425	940
8	Nawagaon	20	46	24.6	7.5	6.3	215	2,100	3,223	435	1,193
9	Raweli	20	46	24.7	7.4	5.9	238	931	1,373	595	470
10	Khurmuri	20	46	24.6	7.6	5.8	240	892	1,205	795	393
11	Balsamund	15	61	24.7	7.6	5.3	210	1,920	2,079	570	830
12	Andu	12	61	24.6	7.7	5.9	135	3,930	5,362	1,352	1,480
13	Sawantpur	15	61	24.5	7.3	5.7	221	1,250	1,513	760	490
14	Birampur	20	61	24.4	7.6	5.6	154	2,780	3,813	737	1,485
15	Adar	20	46	24.1	7.8	6.2	214	1,530	1,841	657	580
16	Bitkuli	3.0	91	28.1	7.8	4.9	161	2,620	3,301	1,217	1,093
	Minimum	3.0	46	24.1	7.3	4.9	135	892	1,205	425	293
	Maximum	20	91	28.1	7.8	6.3	240	3,930	5,362	1,417	1,500
	Mean	15	64	25.6	7.6	5.5	193	1,997	2,677	848	926
	Standard deviation, ±	5	16	1.4	0.1	0.4	36	827	1,188	329	404

Extremely high SO_4^{2-} concentrations were detected, with values ranging from 254 to 2,330 $mg\,L^{-1}$, well above the permissible limit of 150 $mg\,L^{-1}$ (BIS 2009; WHO 2011). SO_4^{2-} content showed a moderate/high correlation with Mg^{2+} and Ca^{2+} contents ($r = 0.86$ and $r = 0.90$, respectively), suggesting that it may come from the dissolution of gypsum.

Chloride in groundwater may originate from different sources, which include the dissolution of halite and related minerals. Chloride concentrations in the groundwater samples ranged from 7.0 to 76 $mg\,L^{-1}$, much lower than the recommended limit of 250 $mg\,L^{-1}$ (BIS 2009; WHO 2011).

Sodium concentration varied from 30 to 437 $mg\,L^{-1}$. Such an extremely high concentration of Na^+ (much higher than the 180 $mg\,L^{-1}$ limit for drinking water) was observed in Location 12, which, as noted earlier, lies closer to the river. It is worth noting that high Na^+ concentrations (beyond 20 $mg\,L^{-1}$) in water is associated with various health hazards (e.g., hypertension, heart diseases, kidney problems). The Na^+/Cl^- ratios ranged from 1.3 to 48. Since Na^+ concentrations exceed Cl^- concentrations in all samples under consideration, a geogenic origin may be presumed. Potassium concentrations were very low in the samples under study, in the 2.1–10.4 $mg\,L^{-1}$ range. The Na^+/K^+ ratio ranged from 10 to 190. Magnesium and Ca^{2+} concentrations ranged from 43 to 341 $mg\,L^{-1}$ and from 169 to 660 $mg\,L^{-1}$, beyond the permissible limits of 30 and 75 $mg\,L^{-1}$, respectively. The highest Mg^{2+} and Ca^{2+} concentrations were again observed from the water

Table 2. Chemical characteristics of the groundwater, January 2010–2016 ($mg\,L^{-1}$)

Year	Serial Number	Cl^-	NO_3^-	SO_4^{2-}	HCO_3^-	NH_4^+	Na^+	K^+	Mg^{2+}	Ca^{2+}	Al	Fe
2010	1	13	3.6	1,610	848	1.2	133	6.7	139	660	1.69	0.74
	2	36	11.2	924	473	1.9	91	5.3	96	354	1.38	0.45
	3	23	4.7	1,109	561	1.8	94	4.8	108	430	1.57	0.32
	4	46	5.6	1,489	850	1.4	120	5.2	169	610	1.66	0.34
	5	7.0	18.4	696	430	2.6	74	5.7	98	259	1.28	0.43
	6	29	4.3	427	448	1.8	116	6.1	64	183	1.13	0.45
	7	48	12.2	1,153	255	1.2	41	3.6	96	407	1.25	0.62
	8	65	4.7	1,621	261	1.6	85	3.2	129	513	1.34	0.73
	9	40	4.4	438	357	1.1	48	2.5	50	202	1.17	0.38
	10	27	5.5	254	477	1.8	30	5.2	43	169	1.09	0.37
	11	76	17.3	736	342	4.0	98	3.2	111	343	1.31	0.42
	12	14	6.8	2,330	811	2.9	437	4.0	341	519	1.71	0.90
	13	73	4.9	385	456	2.6	66	2.5	68	201	1.19	0.37
	14	42	1.2	1,808	442	2.1	89	3.5	130	657	1.74	0.83
	15	32	3.9	700	394	2.4	76	2.1	89	233	1.27	0.42
	16	23	4.2	1,265	730	2.9	120	10.4	134	459	1.61	0.54
	Minimum	7	1.2	254	255	1.1	30	2.1	43	169	1.09	0.32
	Maximum	76	18.4	2,330	850	4.0	437	10.4	341	660	1.74	0.9
	Mean	37	7	1,059	508	2.1	107	4.6	117	387	1.40	0.52
	Standard deviation, ±	21	5	595	197	0.8	93	2.1	69	171	0.23	0.19

Table 2. (*Continued.*)

Year	Serial Number	Cl^-	NO_3^-	SO_4^{2-}	HCO_3^-	NH_4^+	Na^+	K^+	Mg^{2+}	Ca^{2+}	Al	Fe
2011	1	86	18	2,034	510	6.4	156	6.1	164	718	1.42	0.46
	2	30	14	896	606	3.2	42	4.4	104	156	1.26	0.56
	3	142	26	1,015	334	2.5	118	6.5	122	520	1.40	0.78
	4	49	7.2	1,240	512	2.4	146	4.3	132	252	1.34	0.36
	5	32	1.8	1,108	488	1.9	86	12	128	274	1.47	0.62
	6	28	9.2	450	448	6.8	68	5.6	24	267	1.34	0.56
	7	108	22	852	488	1.4	44	8.4	65	180	1.42	0.72
	8	70	3.2	450	856	2.8	112	6.2	162	316	1.34	0.68
	9	38	2.6	315	642	4.2	64	6.7	46	88	1.44	0.76
	10	74	12	1,835	340	5.6	78	15	86	622	1.40	0.52
	11	88	0.94	625	376	2.4	72	7.8	142	412	1.46	0.68
	12	46	0.85	2,940	590	9.2	522	7.4	412	714	1.55	0.52
	13	76	18	556	620	3.3	70	12	96	146	1.38	0.64
	14	52	0.54	1,912	302	7.4	126	13	158	716	1.45	0.68
	15	60	0.78	1,735	352	6.5	109	10	134	508	1.35	0.66
	16	38	4.7	1,320	460	2.4	132	5.5	156	252	1.36	0.42
	Minimum	28	0.5	315	302.0	1.4	42	4.3	24	88	1.30	0.36
	Maximum	142	26.0	2,940	856.0	9.2	522	15.0	412	718	1.60	0.78
	Mean	64	8.9	1,205	495.3	4.3	122	8.2	133	384	1.40	0.60
	Standard deviation, ±	32	8.5	723	144.9	2.4	112	3.3	85	220	0.10	0.12
2012	1	98	22	2,802	578	5.6	112	7.2	110	918	1.24	0.42
	2	28	12	1,044	642	4.2	82	5.1	120	170	1.58	0.39
	3	158	37	708	320	3.6	144	5.4	96	234	1.66	1.04
	4	58	6.20	1,516	576	3.8	162	3.2	180	345	1.46	0.41
	5	42	2.12	1,256	552	2.2	92	10	152	280	1.88	0.72
	6	38	12.12	430	488	4.6	98	3.6	42	340	1.18	0.32
	7	118	24.4	512	476	2.1	22	5.1	120	204	2.02	1.02
	8	76	4.8	466	930	4.5	52	5.2	44	208	1.26	0.72
	9	36	3.2	244	714	2.3	56	3.4	76	108	2.14	0.88
	10	90	10.50	2,352	328	4.4	58	12	115	814	1.12	0.64
	11	64	1.12	1,030	422	2.7	130	5.1	48	525	1.46	0.43
	12	60	1.24	3,918	624	8.8	224	6.2	332	892	2.05	0.42
	13	85	25	690	772	4.6	94	8.2	116	180	1.48	0.67
	14	58	0.54	2,260	262	6.7	90	10	245	996	2.04	0.81
	15	52	1.12	1,980	334	5.4	102	7.3	167	602	0.96	0.66
	16	42	5.02	1,378	504	1.9	124	3.2	188	260	1.60	0.38
	Minimum	28	0.54	244	262	1.9	22	3.2	42	108	0.96	0.32
	Maximum	158	37	3,918	930	8.8	224	12.4	332	996	2.14	1.04
	Mean	69	11	1,412	533	4.2	103	6.3	134	442	1.57	0.62
	Standard deviation, ±	34	11	1,017	181	1.9	49	2.7	77	305	0.37	0.23
2013	1	92	26	2,952	622	8.6	136	8.1	132	1,008	2.35	0.42
	2	36	10	1,123	736	3.2	96	4.2	140	216	2.49	0.44
	3	160	36	767	364	4.2	136	4.2	120	272	2.01	0.95
	4	78	7.30	1,836	602	5.5	176	4.4	226	400	1.75	0.49
	5	36	0.36	1,368	622	3.6	102	8.2	170	320	2.54	0.97
	6	43	10	572	508	3.4	120	4.4	38	392	1.63	0.48
	7	128	33	648	508	3.4	48	4.1	106	248	2.57	1.17
	8	85	5.15	547	1,057	3.6	78	4.4	68	296	1.88	0.80
	9	43	3.61	328	789	2.6	72	4.4	98	152	2.61	1.08
	10	107	11	2,311	364	6.2	76	16	142	904	1.70	0.58
	11	57	0.05	1,188	488	3.6	122	4.1	58	608	1.90	0.54
	12	53	0.84	4,716	675	10.2	260	8.2	396	968	1.97	0.54
	13	78	27	785	830	3.4	126	12	142	224	2.15	0.82
	14	46	0.30	2,549	291	8.2	124	12	280	1,064	1.57	0.92
	15	46	0.79	2,246	384	6.2	124	8.2	192	664	1.31	0.72
	16	50	4.87	1,476	622	3.2	146	4.4	200	312	2.06	0.59
	Minimum	36	0.05	328	291	2.6	48	4.1	38	152	1.31	0.42
	Maximum	160	36.1	4,716	1,057	10.2	260	16	396	1,064	2.61	1.17
	Mean	71	11.03	1,588	591	4.9	121	7.0	157	503	2.03	0.72
	Standard deviation, ±	36	12.34	1,153	201	2.3	49	3.7	90	318	0.39	0.24

Table 2. (*Continued*.)

Year	Serial Number	Cl^-	NO_3^-	SO_4^{2-}	HCO_3^-	NH_4^+	Na^+	K^+	Mg^{2+}	Ca^{2+}	Al	Fe
2014	1	104	29	3,160	700	9.3	163	9.5	155	1,142	2.72	0.68
	2	43	12.1	1,318	843	3.8	115	4.7	164	258	2.80	0.60
	3	181	42	900	422	4.9	160	6.3	141	352	2.42	0.95
	4	88	8.8	2,103	694	6.0	190	4.9	268	465	2.10	0.77
	5	47	0.4	1,605	712	4.9	122	9.2	194	367	2.84	0.97
	6	56	12.1	771	585	5.0	144	4.9	45	442	1.98	0.72
	7	143	37	760	588	4.8	58	4.6	124	290	2.83	1.05
	8	96	6.2	755	1,200	4.6	94	5.2	80	365	2.19	0.86
	9	55	5.2	672	903	3.0	86	5.3	115	240	2.65	0.93
	10	121	13.3	2,710	490	6.8	91	18	167	1,020	2.20	0.70
	11	64	2	1,394	571	4.0	146	5.2	68	686	2.09	0.68
	12	60	1	5,491	776	11.1	280	9.2	448	1,080	2.78	0.88
	13	88	30	966	950	4.0	151	13.7	167	273	2.42	0.82
	14	52	0.4	2,860	375	9.0	140	15.8	300	1,200	2.14	0.91
	15	54	1	2,540	460	6.8	149	9.2	225	749	1.92	0.65
	16	60	5.9	1,627	719	4.1	155	4.9	230	363	2.34	0.66
	Minimum	43	0.4	672	375	3.0	58	4.6	45	240	1.92	0.60
	Maximum	181	42	5,491	1,200	11.1	280	18	448	1,200	2.84	1.05
	Mean	82	12.9	1,852	687	5.8	140	8.2	181	581	2.40	0.80
	Standard deviation, ±	39	13.8	1,278	217	2.3	51	4.3	100	347	0.33	0.14
2015	1	98	28	3,110	655	8.8	151	9.0	145	1,075	2.60	0.70
	2	40	11.1	1,241	795	3.6	107	4.5	154	243	2.90	0.60
	3	166	38	848	390	4.6	151	6.0	132	312	2.12	1.00
	4	83	8.1	1,980	650	5.7	180	4.7	250	425	1.85	0.70
	5	40	0.4	1,512	672	4.6	113	8.7	181	340	2.72	1.00
	6	53	11.1	632	552	4.7	133	4.7	42	416	1.72	0.60
	7	136	36	716	555	4.5	53	4.4	116	263	2.71	1.10
	8	92	5.7	604	1,130	4.3	87	4.7	75	344	2.10	0.80
	9	52	4	362	852	2.8	80	5.0	108	198	2.75	1.00
	10	113	12.2	2,580	450	6.4	84	17.1	156	960	1.90	0.60
	11	63	1	1,313	539	3.8	135	4.4	64	646	2.00	0.60
	12	57	0.9	5,170	732	10.5	270	8.7	430	1,034	2.08	0.80
	13	83	30	910	896	3.8	140	13.0	156	257	2.27	0.80
	14	49	0.3	2,770	340	8.5	130	15.0	295	1,135	1.66	1.00
	15	51	0.9	2,410	415	6.4	138	8.7	211	705	1.60	0.70
	16	56	5.4	1,532	678	3.8	150	4.7	215	342	2.20	0.60
	Minimum	40	0.3	362	340	2.8	53	4.4	42	198	1.60	0.60
	Maximum	166	38	5,170	1,130	10.5	270	17.1	430	1,135	2.90	1.10
	Mean	77	12	1,731	644	5.4	131	7.7	171	543	2.20	0.80
	Standard deviation, ±	36	13	1,249	208	2.2	50	4.1	96	333	0.40	0.20
2016	1	110	31	3,190	749	9.8	169	9.9	163	1,210	2.80	0.83
	2	45	12.9	1,406	890	4.0	122	4.9	173	279	3.10	0.86
	3	194	45	960	452	5.1	170	6.6	149	380	2.49	0.93
	4	98	9.5	2,244	743	6.3	201	5.2	282	502	2.16	0.82
	5	45	0.5	1,713	762	5.1	130	9.6	204	396	2.93	0.95
	6	54	12.9	823	626	5.2	152	5.2	47	477	2.04	0.92
	7	158	38	811	629	5.0	61	4.8	131	313	3.12	1.00
	8	102	6.7	806	1,250	4.8	99	5.4	84	395	2.26	0.89
	9	54	5.6	913	966	3.5	91	5.5	121	259	2.73	0.90
	10	130	14.2	2,992	524	7.1	97	19	176	1,070	2.27	0.88
	11	71	2.1	1,488	611	4.2	155	5.4	88	741	2.16	0.93
	12	66	1.1	5,580	830	11.7	295	9.6	473	1,140	2.90	0.90
	13	94	31	1,120	1,005	4.2	160	15	176	295	2.49	0.82
	14	58	0.4	2,960	401	9.5	149	17	317	1,230	2.20	0.96
	15	58	1.0	2,679	492	7.1	158	10	238	780	1.98	0.86
	16	63	6.3	1,720	769	4.3	167	5.2	243	392	2.41	0.87
	Minimum	45	0.4	806	401	3.5	61	4.8	47	259	2.00	0.80
	Maximum	194	45	5,580	1,250	11.7	295	19.0	473	1,230	3.10	1.00
	Mean	88	14	1,963	731	6.1	149	8.6	192	616	2.50	0.90
	Standard deviation, ±	43	15	1,283	225	2.4	53	4.6	104	358	0.40	0.10

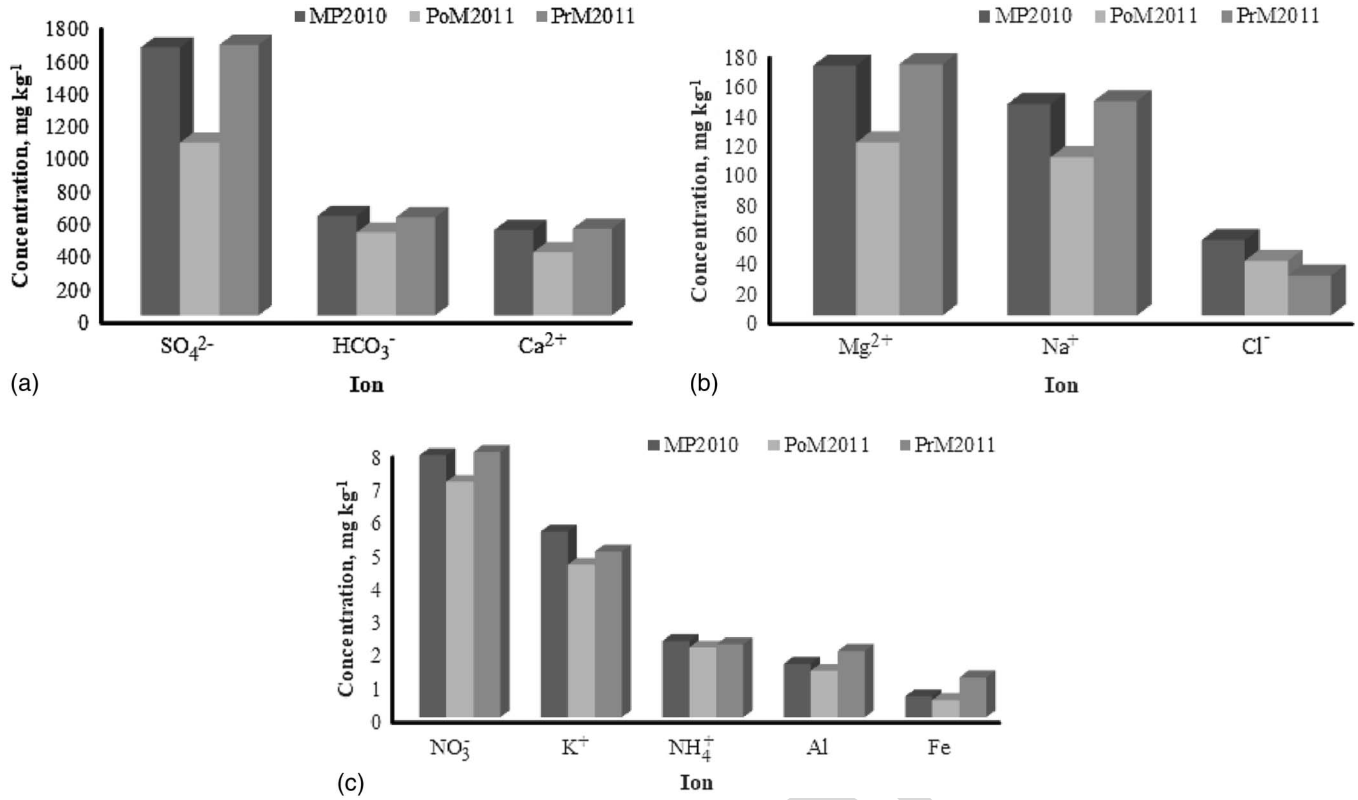


Fig. 2. Seasonal variations in concentrations of chemical species during monsoon, premonsoon, and postmonsoon periods: (a) SO_4^{2-}, HCO_3^-, and Ca^{2+}; (b) Mg^{2+}, Na^+, and Cl^-; and (c) NO_3^-, K^+, NH_4^+, Al, and Fe.

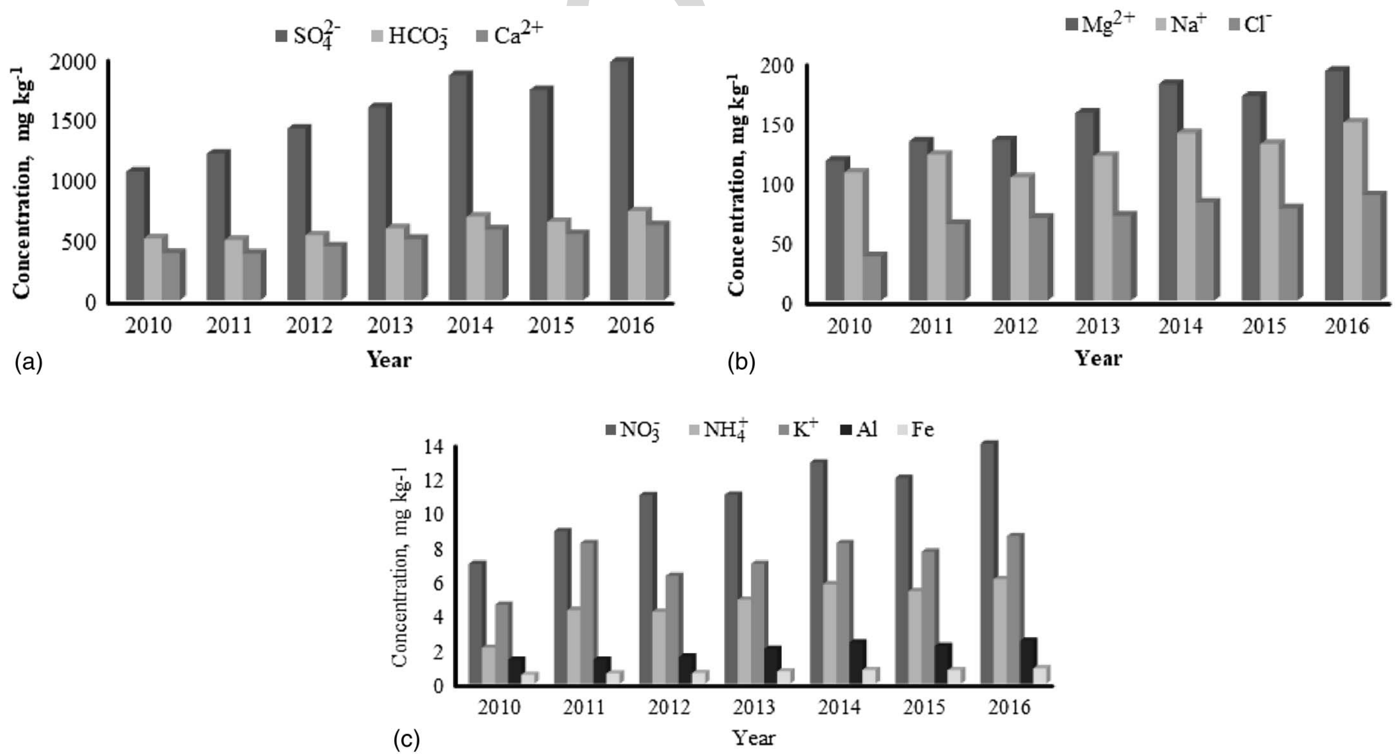


Fig. 3. Temporal variations in concentration of chemical species during postmonsoon period, 2010–2016: (a) SO_4^{2-}, HCO_3^-, and Ca^{2+}; (b) Mg^{2+}, Na^+, and Cl^-; and (c) NO_3^-, K^+, NH_4^+, Al, and Fe.

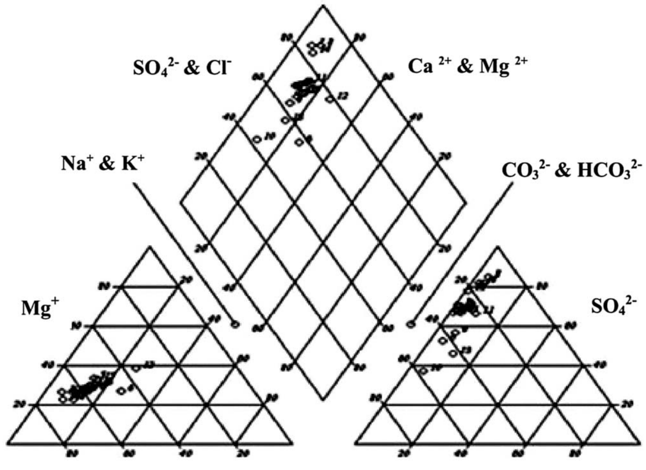


Fig. 4. Piper diagrams of groundwater in postmonsoon period, 2010.

samples from the tube well in Location 12. Nitrate concentration ranged from 1.2 to 18 $mg\,L^{-1}$, below the limit of 45 $mg\,L^{-1}$ (BIS 2009; WHO 2011).

Aluminum and iron are the most abundant metallic elements of the Earth's outer crust, so their presence in the groundwater samples originate from a variety of mineral sources. Al and Fe concentrations ranged respectively from 1.1 to 1.7 $mg\,L^{-1}$ and from 0.32 to 0.90 $mg\,L^{-1}$, exceeding the recommended limits of 0.03 and 0.3 $mg\,L^{-1}$ for all tube wells (BIS 2009; WHO 2011).

The $\Sigma anion/\Sigma cation$ ratio, expressed in terms of equivalent concentrations, was found to vary between 0.89 and 1.27, with a mean value of 1.02 ± 0.04. SO_4^{2-} was the dominating species, moderately/well correlated with Na^+, Mg^{2+}, Ca^{2+}, Al, and Fe (with r values in the 0.68–0.91 range). On average, across the 16 tube wells, ions in the water (in terms of equivalent concentration) appeared in the following decreasing order: $SO_4^{2-} > Ca^{2+} > HCO_3^- > Mg^{2+} > Na^+ > Cl^- > NO_3^- > K^+ > NH_4^+$.

Seasonal and Temporal Variations

The seasonal variations in the concentration of the ions are depicted in Fig. 2. The concentration of all the ions (except NH_4^+ and NO_3^-) was found to decrease during the monsoon period due to high rainfall (approximately 100 cm), while their concentrations (except for NH_4^+, NO_3^-, and Cl^-) notably increased in the premonsoon period owing to an increase in water temperature (approximately 26°C–30°C) and reduction of water levels (approximately 20–40 m). An increase in the concentration of ions was also observed over a 7-year period, from 2010 to 2016 (Fig. 3), tentatively ascribed to a gradual increase in the extraction of groundwater for domestic and agricultural purposes.

Water Classification

The groundwater samples were classified into two types: $Ca{-}Mg{-}SO_4{-}HCO_3$ and $Ca{-}Mg{-}Na{-}SO_4{-}HCO_3$ in accordance with the piper diagrams (Fig. 4). The dominant type, $Ca{-}Mg{-}SO_4{-}HCO_3$, showed effects of gypsum and dolomite mineral dissolution. Enrichment in Na^+ indicated dissolution of sodium-containing minerals in the aquifer.

The dendrograms generated by cluster analysis also presented two groups of water samples in the studied area (Fig. 5). The two clusters described the underlying process that led to spatial variations. Cluster 1 ($n = 10$), with two subgroups, contained

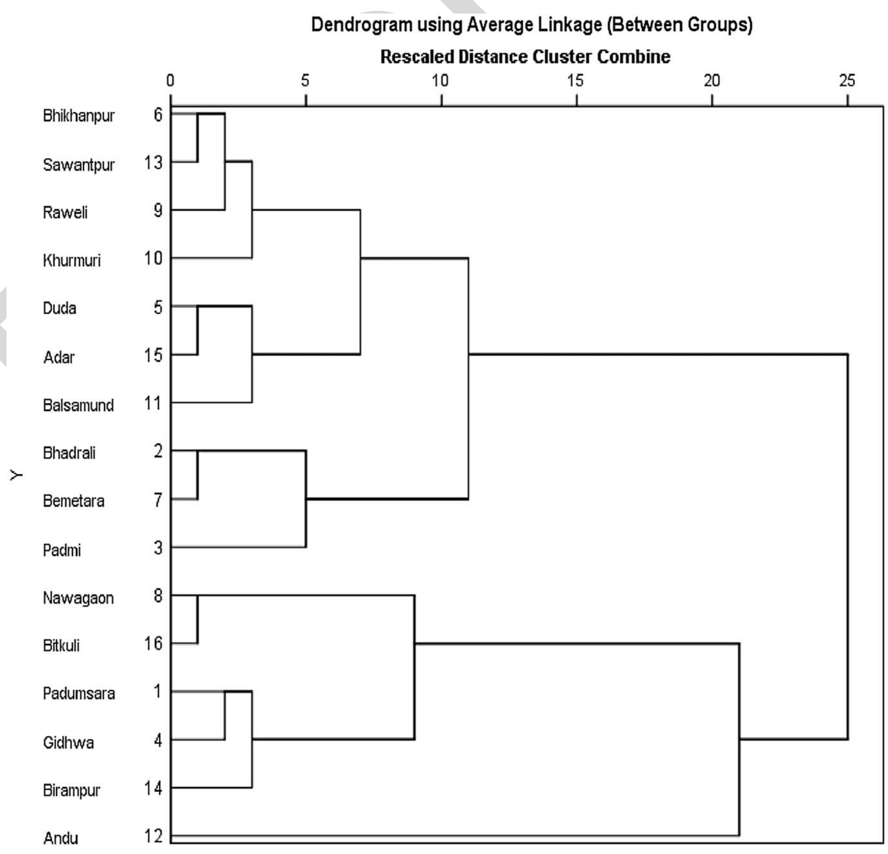


Fig. 5. Dendrogram of groundwater samples in postmonsoon period, 2010.

groundwater samples 6, 13, 9–10, 5, 15, 11, 2, 7, and 3, while Cluster 2 ($n = 6$) contained groundwater samples 8, 16, 1, 14, and 12. Parameters such as EC, TDS, SO_4^{2-}, HCO_3^-, Na^+, Mg^{2+}, Ca^{2+}, Al, and Fe were the discriminating species. The mean values of EC, TDS, SO_4^{2-}, HCO_3^-, Na^+, Mg^{2+}, Ca^{2+}, Al, and Fe were at least 1.8 times higher in the water from locations belonging to the Cluster 2 group.

Water Quality Assessment

The values of TDS, TH, TA, SO_4^{2-}, Mg^{2+}, Ca^{2+}, Al, and Fe of the groundwater samples under study were higher than the recommended values of 500, 300, 120, 150, 30, 75, 0.03, and 0.3 mg L^{-1}, respectively, and the EC value was also very high. The WQI value of the water samples ranged from 187 to 806, with a mean value of 406 ± 82, clearly indicating that the groundwater of the Bemetara area would be unsuitable for drinking.

The SAR, KR, SH, MH, and PI values of the groundwater of the studied area were in the following ranges: 0.7–5.1, 6–35, 4.2%–14.0%, 25%–52%, and 13%–39%, with mean values of $1.7\% \pm 1.0\%$, 16 ± 8, $8.3\% \pm 3.2\%$, $33\% \pm 7\%$, and $23\% \pm 7\%$, respectively (Table 3). Generally, water with MH < 50%, SAR < 10, and KR < 1 is considered suitable for irrigation (WHO 2011; Richard 1954; Kelley 1940; Wilcox 1955). Further, the SH value of the water from all tube wells was <20%, which indicates that the water would be suitable for irrigation purposes (Wilcox 1955). However, the PI value in the water of 63% of the tube wells was <25%, indicating that it would not be adequate for irrigation (Doneen 1964). In short, the groundwater of the Bemetara area may be used for the irrigation of sulfate-insensitive plants.

Source Analysis

Factor analysis was applied to the data set obtained from the groundwater samples from the 16 selected locations in the post-monsoon period. The correlation matrix of variables was generated, factors were extracted by principal components analysis, and a normalized Varimax rotation was applied (Table 4). Four factors accounted for 83.04% of the total variance. Factor 1 had high loading values for EC, TDS, SO_4^{2-}, Na^+, Mg^{2+}, Ca^{2+}, Al, and Fe variables, explained 47.22% of the total variance, and would represent the mineralization of groundwater. Factor 2 was strongly correlated with the physical parameter depth and negatively correlated with variable age. It accounted for 15.22% of total variance

Table 3. Water quality indices of groundwater during January 2010

Serial Number	WQI	SAR	KR	SH	PI	MH
1	594	1.8	13	14	19	26
2	376	1.6	16	7.8	23	31
3	422	1.5	13	9.2	21	29
4	548	1.6	12	14	18	31
5	325	1.4	15	7	24	39
6	251	2.6	34	7.3	39	37
7	331	0.7	6	4.2	13	28
8	429	1.2	10	4.3	14	30
9	193	1.1	15	5.9	27	29
10	187	0.8	11	7.8	31	30
11	385	1.7	16	5.6	22	35
12	806	5.1	35	13	31	52
13	249	1.5	19	7.5	30	36
14	554	1.2	9	7.2	14	25
15	314	1.5	17	6.5	26	39
16	524	1.8	15	12	22	33

Table 4. Factor loading matrix and total variance explained during January 2010

Variable	I	II	III	IV
Depth	0.14	**0.94**	0.02	0.09
Age	−0.17	**−0.90**	−0.17	−0.08
pH	0.09	0.20	0.42	0.62
EC	**0.96**	0.21	0.02	0.16
TDS	**0.96**	0.22	0.02	0.17
Cl^-	−0.16	0.12	0.13	**−0.94**
NO_3^-	−0.21	0.07	**0.76**	−0.03
SO_4^{2-}	**0.96**	0.14	−0.11	0.01
HCO_3^-	0.54	0.38	−0.20	0.51
NH_4^+	0.14	0.02	**0.84**	−0.03
Na^+	**0.80**	−0.08	0.28	0.25
K^+	0.04	0.54	−0.09	0.67
Mg^{2+}	**0.91**	0.08	0.24	0.15
Ca^{2+}	**0.81**	0.32	−0.30	−0.06
Al	**0.84**	0.33	−0.18	0.17
Fe	**0.82**	−0.23	−0.09	−0.03
Eigenvalue	6.71	2.57	1.84	2.16
Total variance (%)	47.22	15.22	11.20	9.40
Cumulative value (%)	47.22	62.44	73.64	83.04

Note: Significant loading value (>0.70) in bold, at $p < 0.05$.

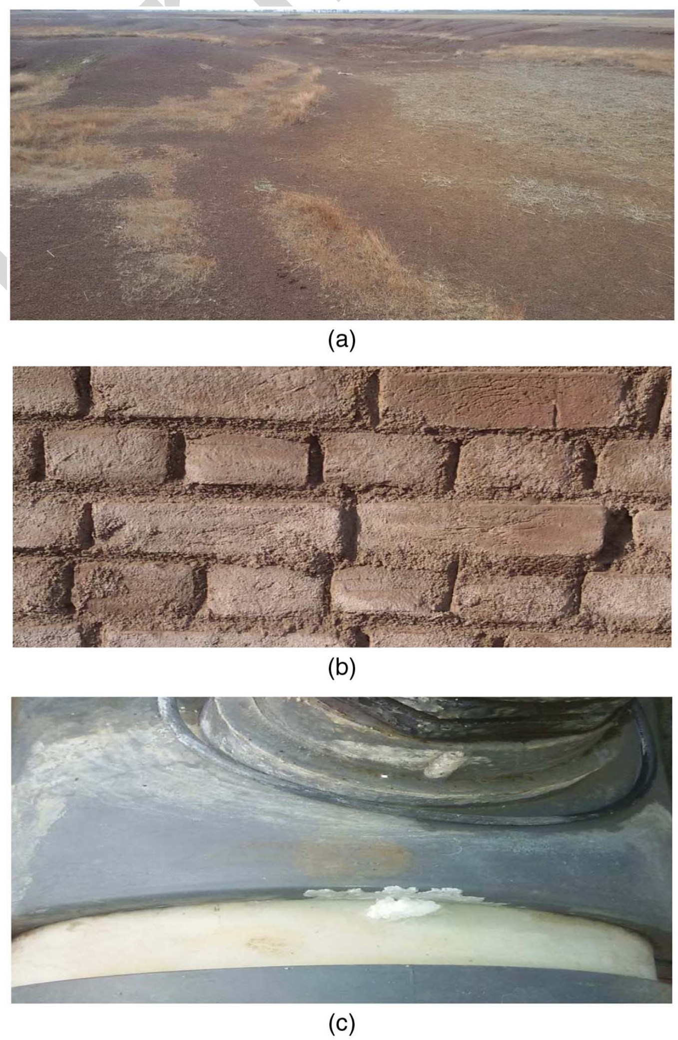


Fig. 6. Environmental hazards: (a) bare and scalded land; (b) white patches in building bricks; and (c) rusting of water supply pipes. (Images by Suryakant Chakradhari.)

(a)

(b)

Fig. 7. Chlorosis of leaves: (a) pigeon pea (Cajanus cajan); and (b) mango leaves. (Images by Suryakant Chakradhari.)

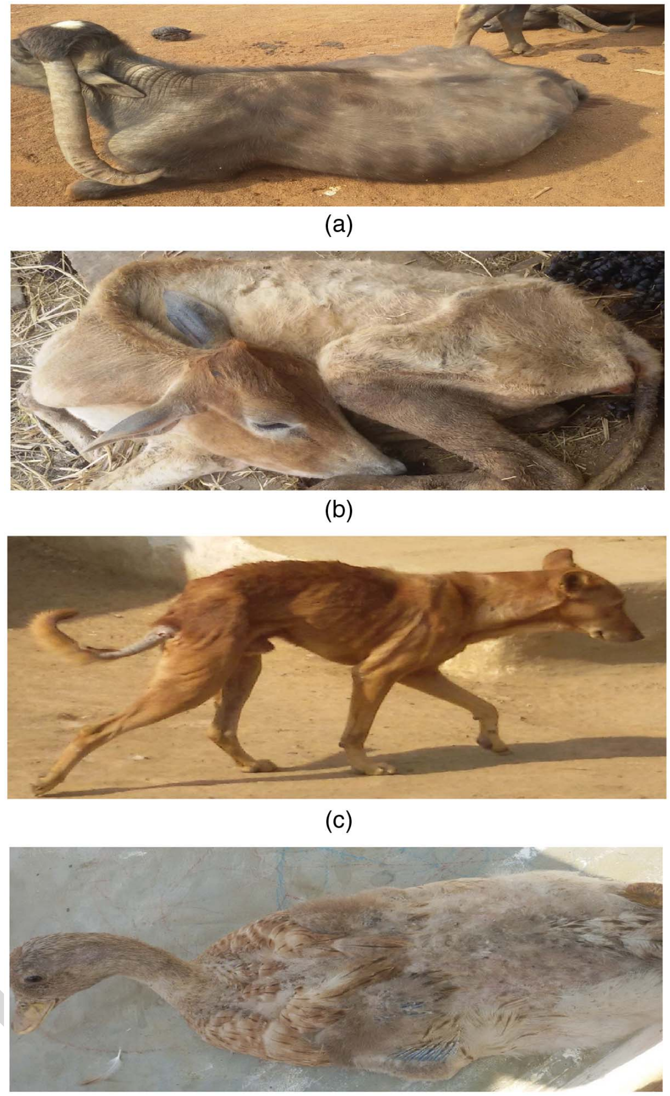
and may be ascribed to the influence of deep groundwater on the water chemical composition. Factor 3 was related to NO_3^- and NH_4^+ and accounted for 11.20% of total variance. It may represent the impact of agricultural practices (fertilization). Factor 4 accounted for 9.40% of total variance and was associated with Cl^-, tentatively representing the impact of irrigation flow return on groundwater quality.

Environmental Hazards

Environmental hazards associated with the use of groundwater in gypsum-contaminated areas include, for example, scalding of land; the appearance of a white crust on the soil surface; negative impacts on crop health; a decline in grass, shrubs, and trees; and the corrosion of sewer pipes and buildings (Ayers and Westcot 1985; Dunlop et al. 2005; UNEP 2008).

Gypsum deposition on soil surface due to irrigation increases osmotic pressure, resulting in physiological drought, with negative impacts on plant growth and yield. The surface soil in many locations in the area of study were bared and scalded, as shown in Fig. 6(a). Gypsum also attacks zinc and iron (steel) in combination with moisture. A white salt crust on brickwork and rusting of pipes due to the deposition of gypsum salt were also observed [Figs. 6(b and c)].

Symptoms on crops (e.g., chlorosis in leaves or browning of roots) are evident for sensitive plants such as barley, cucumber, *lemons, lettuce, mango*, pumpkin, sunflower, pomegranate, pigeon pea, potatoes, rice, soybean, and watermelon (Fig. 7). In contrast, higher yields are obtained for sulfate-tolerant plants (e.g., beans,



(a)

(b)

(c)

(d)

Fig. 8. Adverse health hazard in animals and aquatics: (a) buffalo; (b) cow; (c) dog; and (d) duck. (Images by Suryakant Chakradhari.)

cabbage, carrot, cauliflower, mustard, garlic, ginger, green beans, lentils, onion, peanuts, pineapple, radish, and spinach).

Regarding negative impacts on animal health, severe chronic diarrhea and, in some cases, death, are frequent in the area due to the high levels of sulfate in the drinking water. Examples for several domestic animals are shown in Fig. 8.

Conclusions

Groundwater in the Bemetara area of central India is very hard due to its high salt content. Physicochemical characteristics of water were monitored both on a seasonal basis and over a 7-year period, and the concentrations of Ca^{2+} (169–660 $mg\,L^{-1}$), Mg^{2+} (43–341 $mg\,L^{-1}$), SO_4^{2-} (254–2,330 $mg\,L^{-1}$), Al (1.1–1.7 $mg\,L^{-1}$), and Fe (0.32–0.90 $mg\,L^{-1}$) were much higher than the recommended values. Very high Na^+ concentrations (up to 437 $mg\,L^{-1}$) were also detected in particular locations. Concentrations were found to increase in the premonsoon season and over time, due to the gradual increase in the extraction of groundwater for domestic and agricultural purposes. Based on the calculated water quality indices, the groundwater may be deemed suitable for irrigation in some cases, but would be clearly unsuitable for drinking purposes. Negative impacts on animals, crops, and materials were observed. Avoiding overirrigation and plantation of high-sulfate-tolerant plants are suggested as the most promising approaches for sustainable agricultural development in this region.

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