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Quality Assessment of Mine Water in the Raniganj Coalfield Area, India

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Abstract In a qualitative assessment of mine water from the Raniganj coalfield, 77 mine water samples were analyzed to assess water quality and suitability for domestic, industrial, and irrigation uses. The pH of the mine water ranged from 6.5 to 8.8. Total dissolved solids (TDS) ranged from 171 to 1,626 mg L^{-1}; spatial differences between the TDS values reflect variations in lithology, activities, and prevailing hydrological regime. The anion chemistry was dominated by HCO_3^- and SO_4^{2-}. On average, Cl^- contributes 10 and 19% of the total anionic balance, respectively, in the Barakar and Raniganj Formation mine water. F^- and NO_3^- contribute <2% to the total anions. The cation chemistry is dominated by Mg^{2+} and Ca^{2+} in the mine water of the Barakar Formation and Na^+ in the Raniganj Formation mines. Much of the mine water, especially of the Barakar Formation area, has high TDS, total hardness, and SO_4 concentrations. Concentrations of some trace metals (i.e. Fe, Cr, Ni) were found to be above the levels recommended for drinking water. However, the mine water can be used for irrigation, except at some sites, especially in the Raniganj Formation area, where high salinity, sodium adsorption ratio, %Na, residual sodium carbonate, and excess Mg restrict its suitability for agricultural uses.

Keywords Hydrogeochemistry · Mine water · Raniganj coalfield · Residual sodium carbonate · Sodium adsorption ratio · Water quality

Introduction

Mining threatens the quality and quantity of surface and ground water resources in many part of the world (Allen et al. 1996; Choubey 1991; Gupta 1999; Khan et al. 2005; Singh et al. 2008; Singh 1998; Tiwary 2001). Mining, by its nature consumes, diverts, and can seriously pollute water resources. As there is no proper water management plan at most mines in India, water is often discharged without any treatment or beneficial use. There, it may pollute the natural surface drainage and other water resources, including ground water (Singh et al. 2007). Mine water can vary greatly in the concentration of contaminants present, and some mine water discharges can be a potential water resource, where the local water demands for industrial, irrigation, and even drinking and domestic uses can be fulfilled by effective utilization (Cidu et al. 2007; Singh 1994). In the present study, discharges from mines in the Raniganj coalfield were analysed and compared to water quality standards for domestic, industrial, and irrigation uses.

The Raniganj coalfield lies in the easternmost part of the Damodar Valley Coalfield and is bounded by 23°25′N to 23°50′N latitude and 86°38′E to 87°20′E longitude. It covers about 1,530 km^2 geographical area, spreading over the Burdwan, Birbhum, Bankura, and Purulia districts in West Bengal and Dhanbad district in Jharkhand. A network of roads and railway branches link the area with other part of the country (Fig. 1). The topography of the Raniganj coalfield is gently undulating and the elevation generally ranges from 65 to 75 m above sea level. The highest elevations are the Panchet (643 m) and Biharinath hills (451 m). The drainage pattern is mainly dendritic to subdentritic in nature (Srivastava and Mitra 1995) and most mines of this coalfield lies between two rivers, the Damodar

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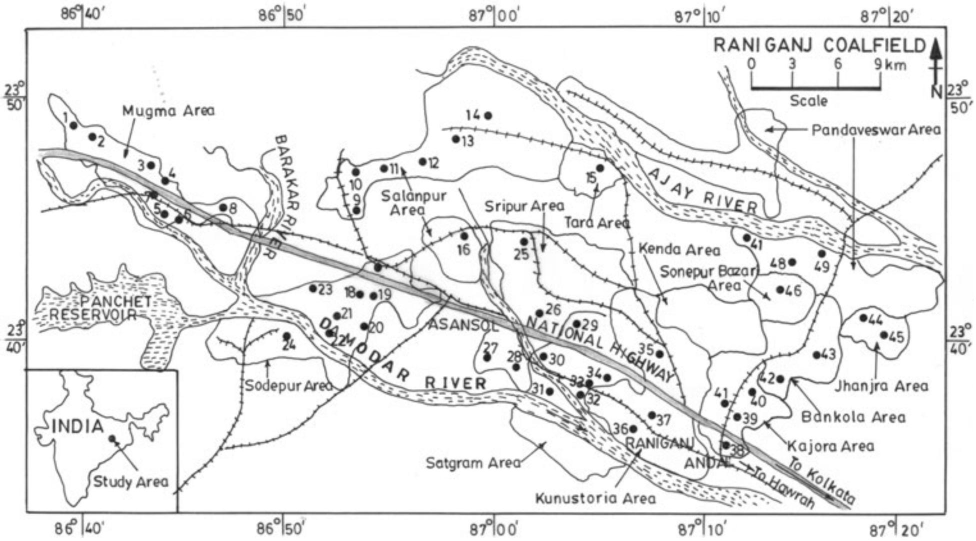

Fig. 1 Location of the Raniganj coalfield, showing sampling sites

and Ajay, which flow almost parallel to each other. The Damodar River traverses the southern part of the coalfield, flowing due east, while the Ajay River flows in the northern part. The area is a tropical region with fairly wide temperature variations. The climate of the Raniganj area is characterised by very mild winters and hot wet summers. The maximum temperature peaks at about 44°C during May–June and dips to 5–7°C in December–January. Most of the rainfall (80%) occurs during the monsoon period (June–September); the annual rainfall varies from 1,200 to 1,400 mm.

The Raniganj coalfield is the birth place of coal mining in India; mining started in this coalfield in 1774. Coal is currently being produced by underground as well as opencast mining methods by the Eastern Coalfield Ltd (ECL), a subsidiary of Coal India Ltd. In addition, a small portion of the coalfield is operated by BCCL (Bharat Coking Coal Ltd), SAIL (Steel Authority of India), and other private companies.

The Raniganj coalfield is a part of the Gondwana Supergroup, which extends here over a rectangular area greater than 1,000 km^2. A full succession of lower Gondwana and younger rocks occurs, attaining a maximum thickness of more than 3,200 m. A large part of the coalfield is occupied by coal-bearing horizons of the Barakar and Raniganj Formations. A fluvio–lacustrine coal barren sequence known as the Iron Stone Shale separates these two coal-bearing horizons. The Panchet Formation (also barren of coal) overlies the Raniganj Formation, and comprises feldspathic sandstone and red clays (Fig. 2).

The Raniganj coalfield is surrounded by Archaean rocks on all sides except in the east, where its boundary is not clear, as it is covered by alluvium. The dip of the strata is generally southerly; the oldest rocks are exposed along the northern margin, and successively younger strata outcrop towards the south. The northern margin represents the normal depositional boundary between the basal Gondwana and the basement Archaeans while the western and southern boundaries are faulted. The Talchir Formation is exposed in the northwest and northern border of the field and comprises a boulder bed overlain by greenish sandstone and shales. The Barakar Formation occupies an irregular 155 km^2 area along the northern half of the field and consists of white and buff massive sandstones and grits with occasional shale beds. It includes many workable coal seams in the Mugma, Salanpura, and Tara mining areas. The Ironstone Shales comprise about 365 m of carbonaceous shales containing nodules of clay ironstone. The Raniganj Formation outcrops along the central and southern part of the field, consisting of greyish fine sandstone, carbonaceous shales, and extensive coal seams, including the Sodepur, Sripur, Satgram, Kunustoria, Pandaveswar, Kajora, Bankola, Sonepur Bazari, and Jhanjra mining areas (Table 1).

Materials and Methods

Systematic sampling was carried out during the months of April–May in 2008. Representative water samples were collected from different mines of the Mugma, Salanpur, Tara, Sodepur, Sripur, Satgram, Kunustoria, Pandaveswar, Sonepur-Bazari, Kajora, Bankolla, and Jhanjra mining areas (Fig. 1; Table 2). Of the 77 water samples collected, 32 were from the mines of the Barakar Formation and 45 from Raniganj Formation mines. Samples were collected from both underground (underground sumps and surface water discharges) and opencast (mine pits and settling ponds) mines in 1 L narrow-mouth pre-washed high density polyethylene bottles. Prior to each field trip,

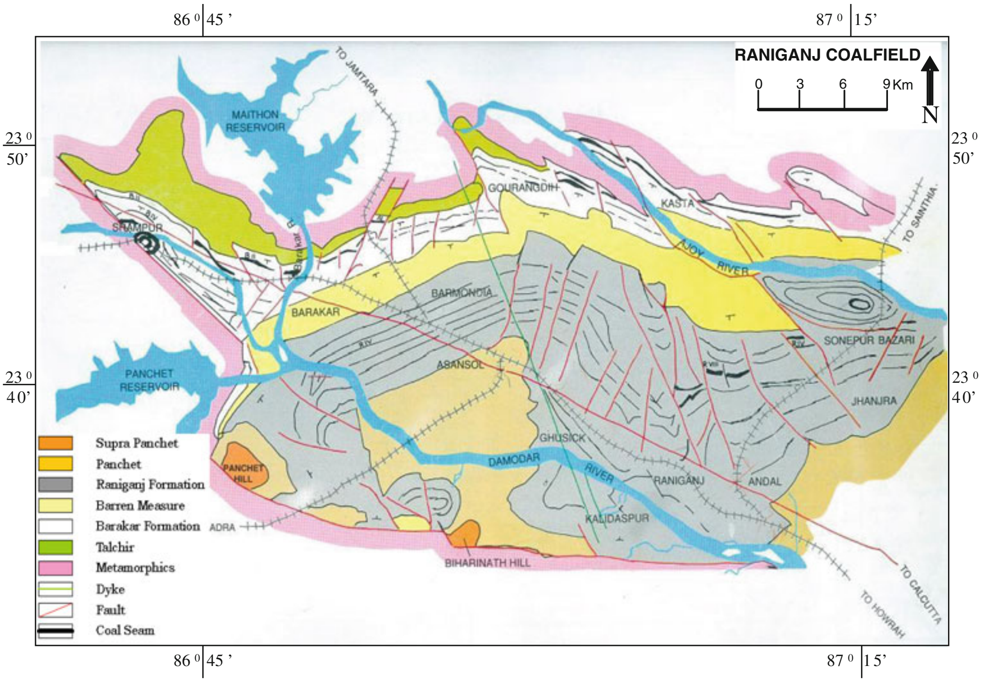

Fig. 2 Geological map of the Raniganj coalfield

Table 1 Geological formations of the Raniganj Coalfield

Geological age	Formation	Major lithology
Recent	River alluvium	Sand, clay and limestone
	Unconformity	
Jurassic to Cretaceous	Rajmahal Trap/Intratrappeans	Dolerite, mica peridotite dykes and sills
Upper Triassic	Supra Panchet	Sandstone and shales
	Unconformity	
Lower Triassic	Panchet Series	Medium- to coarse-grained feldspathic sandstone and red clays
Upper Permian	Raniganj measures	Fine- to medium-grained sandstone, sandy or micaceous shale, coal seams, siltstone, and carbonaceous shale
Middle Permian	Iron Stone Shale	Carbonaceous shales containing nodules of clays
Lower Permian	Barakar measures	Massive sandstones and grits with shale beds and coal seams
Upper Carboniferous	Talchir series	Tillites to boulder conglomerate, yellowish green sandstone, etc.
	Unconformity	
Archaean	Metamorphic rocks with igneous intrusive	Granites, granitic gneiss, hornblend schist traversed by bands and patches of amphibolite, pegmatite, and veins of quartz

polyethylene bottles were washed in the laboratory with dilute hydrochloric acid and then rinsed twice with double distilled water. Temperature, EC, and pH were measured in the field using a portable conductivity and pH meter. Before sampling, bottles were also rinsed with the sampled water. For trace metal analysis, 100 mL samples were acidified with HNO_3 and preserved separately.

In the laboratory, the water samples were filtered through 0.45 μm Millipore membrane filters to separate suspended sediment. The samples were analyzed for pH, electrical conductivity (EC), major cations (Ca^{2+}, Mg^{2+}, Na^{+}, and K^{+}), major anions (F^{-}, Cl^{-}, HCO_3^{-}, SO_4^{2-}, NO_3^{-}), dissolved silica (H_4SiO_4), and trace metals following standard analytical methods. Acid titration and molybdosilicate methods were used to determine the concentration of bicarbonate and dissolved silica, respectively (APHA.AWWA.WPCF 1995). Major anions (F^{-}, Cl^{-}, SO_4^{2-}, NO_3^{-}) were analysed on an ion chromatograph (Dionex Dx-120) using anion (AS12A/AG12) columns coupled to an anion self-regenerating suppressor (ASRS) in recycle mode. Concentration of major cations (Ca^{2+}, Mg^{2+}, Na^{+}, and K^{+}) were measured by atomic absorption (Varian, 280 FS) in flame mode. The analytical precision was maintained by running a known standard after every

Table 2 The names of the mining area and mine, the sampling site, and the nature of the sample for the Raniganj coalfield water samples

Mine area	Site	Mine name	Water type	Mine area	Site	Mine name	Water type
Mugma	1a	Chapapur U/G	U/W		20b	Patmohona U/G	P/W
	1b	Chapapur U/G	P/W		21a	Chinakuri III U/G	U/W
	2a	Badjna U/G	U/W		21b	Chinakuri III U/G	P/W
	2b	Badjna U/G	P/W		22a	Chinakuri I U/G	U/W
	3a	Khudia U/G	U/W		22b	Chinakuri I U/G	P/W
	3b	Khudia U/G	U/W		23a	Sodepur (R) U/G	U/W
	3c	Khudia U/G	P/W		23b	Sodepur (R) U/G	P/W
	3d	Khudia OCP	M/W		24a	Parbelia U/G	U/W
	3e	Khudia OCP	S/W		24b	Parbelia U/G	P/W
	4	Raja U/G	P/W	Sripur	25	Bhanora U/G	P/W
	5a	Lakhi Mata U/G	U/W		26a	Ningha U/G	U/W
	5b	Lakhi Mata U/G	P/W		26b	Ningha U/G	P/W
	6a	Mandman U/G	U/W		27	Ghusick U/G	P/W
	6b	Mandman U/G	P/W		28	Kalipahari U/G	P/W
	7a	Shyampur B U/G	U/W	Satgram	29	Satgram Project	P/W
	7b	Shyampur B U/G	P/W		30	Ratibati U/G	P/W
	8a	Rajapura OCP	M/W		31a	Tirat U/G	P/W
	8b	Rajapura OCP	S/W		31b	Tirat U/G	U/W
Salanpur	9	Debu (Old) OCP	M/W		32a	Nimcha U/G	U/W
	10a	Benjomehari OCP	M/W		32b	Nimcha U/G	P/W
	10b	Benjomehari OCP	S/W		33	Amkola U/G	P/W
	11a	Dabour U/G	U/W		34a	J.K. Nagar U/G	P/W
	11b	Dabour U/G	P/W		34b	J.K.Nagar U/G	P/W
	12a	Sangramgarh OCP	S/W	Kunustoria	35	Kunustoria U/G	P/W
	12b	Sangramgarh OCP	M/W		36	Amrit Nagar U/G	P/W
	13a	Mohanpur OCP	M/W		37	Aamadasuta U/G	P/W
	13b	Mohanpur OCP	S/W	Kajora	38	Lachhipur U/G	P/W
	13c	Mohanpur OCP	P/W		39	Khas Kajora U/G	P/W
	14a	Gourandi OCP	M/W		40	Madhusudanpur U/G	P/W
	14b	Gourandi OCP	S/W	Bankola	41	Naba Kajora U/G	P/W
Tara	15a	Tara West OCP	M/W		42	Moira U/G	P/W
	15b	Tara East OCP	M/W		43	Shyamsundapur U/G	P/W
Sodepur	16	Barmondia U/G	P/W	Jhanjra	44	Nakra Konda U/G	P/W
	17a	Dubeshwari U/G	P/W		45	Jhanjra U/G	P/W
	17b	Dubeshwari U/G	U/W	Sonepur Baz. Pandaveswar	46	Sonepur Bazari	P/W
	18	Bejdih U/G	U/W		47	Samla U/G	P/W
	19a	Methani U/G	U/W		48	Dalurband OCP	M/W
	19b	Methani U/G	P/W		49a	Pandaveswar U/G	U/W
	20a	Patmohona U/G	U/W		49b	Pandaveswar U/G	P/W

U/G = Underground mine; U/W = Underground sump water; P/W = Pump water discharges at surface; OCP = Open cast project; M/W = Mine pit water; S/W = Settling pond water

15 samples. The overall relative standard deviation (RSD) was less than 10%. Concentration of trace metals in mine water samples were determined by ICP-MS (Perkin–Elmer). The accuracy of the analysis was checked by analyzing a NIST 1643b water reference standard. The precision obtained in most cases was better than 5% RSD with comparable accuracy.

Hydrogeochemistry

The results of the geochemical analysis of water samples collected from different mining areas of Raniganj coalfield is given in Table 3. The general statistics of major ion chemistry of mine water from coal-bearing areas of the Barakar and Raniganj Formation is summarized in Table 4.

Table 3 Major ion chemistry of water from mines of the Raniganj Coalfield Area

Site	pH	EC	TDS	F^-	Cl^-	HCO_3^-	SO_4^{2-}	NO_3^-	Si	Ca^{2+}	Mg^{2+}	Na^+	K^+	TH
1a	8.0	485	446	0.70	17.1	261	31.8	1.2	13.8	42.4	28.7	44.5	4.4	224
1b	8.1	1326	1261	0.90	27.0	326	565.7	0.6	7.6	123.6	134.7	59.4	15.6	863
2a	8.2	907	887	2.13	61.8	269	313.8	0.5	12.8	92.7	89.6	41.4	3.9	600
2b	8.2	927	904	2.21	36.9	349	262.9	3.4	7.8	80.6	109.9	41.7	9.4	653
3a	8.0	1169	1162	1.10	143.3	250	452.0	2.5	10.7	124.8	127.2	42.3	8.6	835
3b	8.1	1160	1120	1.30	110.1	238	456.2	0.8	9.7	121.0	134.4	39.8	8.9	855
3c	8.4	1131	1101	0.90	106.0	254	446.7	1.0	9.7	107.1	129.7	38.5	7.8	801
3d	8.2	888	834	1.30	27.2	284	302.2	0.5	5.6	73.9	111.4	21.4	6.8	643
3e	8.4	879	813	1.30	27.8	269	307.8	0.3	4.3	66.7	108.8	20.4	6.7	614
4	7.2	568	517	0.78	42.5	183	158.3	2.0	16.4	26.0	49.1	33.6	5.2	267
5a	8.2	879	564	0.80	10.6	154	247.4	7.7	8.1	62.9	47.2	18.8	6.0	351
5b	8.0	690	571	0.80	51.2	196	158.0	13.3	13.5	69.2	39.6	23.4	5.4	336
6a	8.0	1030	771	0.37	22.9	204	312.8	0.5	13.1	104.5	52.2	55.3	5.9	476
6b	7.9	1003	888	0.70	25.4	284	360.2	0.9	8.2	99.7	76.5	25.0	7.3	564
7a	8.1	733	592	0.80	50.8	200	155.3	13.0	13.0	73.9	46.4	30.5	8.5	375
7b	8.1	631	529	0.80	56.2	116	210.0	6.5	14.1	58.8	37.4	22.6	7.0	301
8a	8.1	766	646	0.80	28.0	181	258.2	5.7	10.1	45.1	87.3	24.1	6.0	472
8b	8.0	755	611	0.80	28.3	197	216.7	6.0	9.3	42.7	83.5	22.0	4.4	450
9	7.8	409	337	0.58	22.7	112	115.1	0.4	7.6	36.3	22.1	15.7	4.1	182
10a	7.6	982	967	0.50	13.7	89	585.9	4.4	7.5	132.9	103.6	20.5	8.6	758
10b	7.6	966	948	0.90	15.3	97	556.9	5.1	8.1	132.1	104.5	19.6	8.9	760
11a	7.9	972	948	1.20	34.5	215	415.9	0.9	12.3	121.7	96.3	42.2	7.7	700
11b	8.0	964	938	1.40	34.6	223	399.9	0.4	12.3	122.9	95.5	41.0	7.4	700
12a	8.1	940	925	0.90	26.5	234	410.7	7.0	10.6	83.6	105.5	37.1	8.8	643
12b	8.0	997	976	1.40	28.3	277	387.9	7.9	11.3	113.6	102.8	38.0	7.9	707
13a	8.0	1227	1107	1.00	18.2	315	462.6	0.9	11.7	134.8	123.9	32.4	6.5	846
13b	8.0	1034	982	0.90	20.4	289	388.9	5.0	13.5	112.8	109.9	33.3	8.4	734
13c	8.1	920	895	0.90	20.7	246	366.8	0.8	10.9	103.0	102.4	34.8	8.5	678
14a	7.9	415	341	0.52	23.4	124	100.7	5.3	6.4	37.5	21.9	16.7	5.2	184
14b	7.9	412	336	0.57	24.0	120	100.5	4.8	6.3	36.8	22.0	16.1	4.9	182
15a	7.5	1290	1016	1.75	31.2	243	512.0	2.9	18.6	83.8	73.1	56.3	11.7	510
15b	7.0	930	755	1.46	23.8	75	450.0	9.6	15.9	109.5	61.0	16.2	8.5	524
16	8.8	2000	1626	1.14	75.1	1032	17.4	7.1	10.9	16.9	12.6	450.2	2.5	94
17a	8.3	537	430	0.71	26.6	238	24.6	4.4	20.2	25.9	11.0	75.1	2.8	110
17b	8.7	1208	1057	0.84	43.8	643	72.5	13.6	15.8	11.0	10.0	244.2	2.5	69
18	7.5	1358	954	0.50	205.7	383	115.8	6.1	22.9	52.5	61.3	103.9	2.2	383
19a	8.2	1123	1087	0.69	153.8	395	209.2	7.4	16.3	24.6	102.7	167.0	10.0	484
19b	8.2	1125	1077	0.81	153.8	391	206.8	10.7	15.7	18.9	110.0	159.6	9.9	499
20a	8.5	882	807	0.84	47.9	399	135.6	3.2	13.2	37.5	29.4	136.7	4.4	215
20b	8.5	865	770	0.45	41.2	387	117.7	3.2	13.3	34.7	28.4	139.0	4.6	203
21a	8.8	1190	994	0.95	81.6	582	29.8	3.2	18.9	12.5	8.2	253.8	2.5	65
21b	8.7	1105	926	1.15	71.6	544	25.2	3.3	15.6	10.1	5.7	247.0	2.0	49
22a	8.8	1337	1176	0.61	74.9	743	10.3	9.7	21.0	16.2	3.9	303.5	3.5	57
22b	8.7	1228	1055	0.61	70.2	659	9.8	8.2	20.1	13.8	4.3	275.0	3.0	52
23a	8.5	1149	960	0.93	61.0	624	20.7	4.1	18.4	18.7	21.8	185.8	4.0	136
23b	8.3	1033	964	0.86	53.5	628	23.0	9.6	19.4	39.2	32.2	154.1	4.1	230
24a	8.2	1129	983	0.99	29.0	620	61.7	8.8	12.2	12.4	6.1	229.2	2.2	56
24b	8.3	1174	1053	0.71	30.7	662	68.2	9.3	12.5	13.4	7.1	247.0	2.3	63

Table 3 continued

Site	pH	EC	TDS	F^-	Cl^-	HCO_3^-	SO_4^{2-}	NO_3^-	Si	Ca^{2+}	Mg^{2+}	Na^+	K^+	TH
25	8.5	714	625	0.61	40.9	336	41.5	5.6	14.3	37.9	29.6	114.8	3.9	216
26a	8.5	1175	1134	0.48	67.9	757	8.5	10.7	22.6	13.0	18.7	239.5	4.1	109
26b	8.1	1190	1165	0.56	70.0	775	8.7	10.3	22.3	27.8	18.6	235.6	4.1	146
27	8.4	1519	1454	2.12	97.8	875	3.9	2.5	12.9	18.4	13.5	345.5	2.9	101
28	8.2	927	840	0.46	78.7	403	129.0	0.8	14.5	39.8	25.1	146.0	3.6	203
29	7.7	793	579	0.47	92.2	248	40.4	5.4	32.0	8.5	29.8	117.8	4.2	144
30	7.6	753	620	0.75	46.2	342	74.5	1.5	26.9	13.1	50.0	62.0	3.6	238
31a	7.5	1386	1090	1.63	71.5	650	20.6	10.4	31.6	3.3	9.6	286.0	5.6	48
31b	7.4	994	818	0.58	68.0	467	39.7	4.0	29.0	6.5	22.4	175.3	5.3	108
32a	6.5	676	513	0.65	34.6	243	94.8	2.7	30.8	17.0	29.4	55.7	4.0	163
32b	7.5	807	612	0.92	53.6	315	64.8	1.2	31.8	9.0	32.7	96.4	6.5	157
33	7.5	806	671	0.56	42.5	325	112.2	4.9	35.4	18.5	36.5	90.3	5.4	196
34a	7.8	737	600	0.91	46.3	312	59.5	2.8	34.2	15.3	46.6	78.1	4.7	230
34b	8.2	885	693	0.95	40.0	354	66.1	4.8	30.1	5.1	13.8	173.5	4.8	69
35	7.2	804	570	0.61	53.0	253	101.5	0.5	33.0	24.5	34.8	65.3	4.3	204
36	7.7	864	650	0.97	54.7	306	105.0	5.1	35.3	11.7	27.4	98.0	5.4	142
37	7.3	331	228	0.72	14.5	112	19.4	5.3	18.2	28.8	9.9	16.5	2.4	113
38	7.1	702	491	0.54	41.8	256	40.9	5.7	43.1	9.9	31.8	57.1	4.0	155
39	7.9	832	673	0.58	56.9	372	50.5	3.8	25.8	12.4	34.8	112.9	3.8	174
40	7.2	811	602	0.34	53.3	315	56.0	3.7	38.6	13.6	30.7	86.4	4.7	160
41	7.2	1026	725	0.78	78.9	152	275.0	5.7	38.1	46.1	41.9	81.7	5.4	287
42	8.2	1012	890	0.91	89.7	512	12.9	1.7	37.0	4.9	10.5	215.1	5.3	55
43	8.0	709	465	0.52	54.8	187	45.0	7.9	28.7	6.5	15.3	114.2	5.2	79
44	7.6	869	667	0.32	85.0	345	16.5	3.9	43.1	5.3	12.3	151.1	4.6	64
45	7.3	420	407	0.80	27.2	211	35.4	9.5	17.5	60.1	18.0	22.8	4.4	224
46	7.6	1282	964	0.40	110.9	310	275.9	8.2	30.6	22.8	68.1	129.9	7.5	337
47	7.9	298	264	0.33	30.5	107	24.6	3.3	44.3	19.2	9.4	22.7	2.3	87
48	7.6	270	171	0.87	18.0	83	12.3	2.9	12.1	14.9	7.0	18.9	1.4	66
49a	7.8	790	580	1.08	124.0	241	9.5	9.1	39.0	3.6	9.9	139.7	3.5	50
49b	7.9	821	646	0.73	56.8	263	109.6	5.8	40.7	10.5	11.4	143.0	4.2	73

Unit: mg L^{-1} except pH, EC (µS cm^{-1})

TDS total dissolved solids, *TH* total hardness

Figure 3 shows the percent contribution of individual ions towards the total cationic and anionic mass balance.

Temperature, pH, EC, and TDS

The mine water temperatures measured during field collection ranged from 24.9 to 27.2°C, with an average value of 25.9°C. The pH of the water samples varied from 6.5 to 8.8; the average pH was 8.0. The electrical conductivity (EC) values ranged from 270 to 2,000 µS cm^{-1}, with an average value of 923 µS cm^{-1} for measured samples. The total dissolved solids (TDS), which is the sum of the dissolved ionic concentrations, ranged between 171 and 1,626 mg L^{-1} (avg. 795 mg L^{-1}). The TDS and EC values in the water samples from surface and underground mines were generally in agreement, except at a few sites (Table 3). However, wide spatial variations were observed in the EC and TDS concentrations in different areas of the Raniganj coalfield. In general, the TDS values were low for the Kunustoria, Pandaveswar, and Jhanjra areas, and high in the Mugma, Salanpur, Sodepur, Sripur, and Sonepur Bazari mining areas (Fig. 4a). This spatial variation in TDS values may be attributed to variations in lithology, hydrological processes, and prevailing mining.

Major Anion Chemistry

The anion chemistry of the analyzed water samples shows HCO_3^- and SO_4^{2-} to be the dominant anions at both underground and opencast mines. The HCO_3^- concentration

Table 4 Measured parameters in the Barakar and Raniganj formation mine water

Parameters	Barakar formation mine water ($n = 32$)				Raniganj formation mine water ($n = 45$)			
	Min.	Max.	Avg.	Std. Dev.	Min.	Max.	Avg.	Std. Dev.
pH	7.0	8.4	8.0	0.3	6.5	8.8	8.0	0.5
EC	409	1326	887	243	270	2000	949	324
TDS	336	1261	803	251	171	1626	790	301
F^-	0.37	2.21	1.01	0.43	0.32	2.12	0.76	0.32
Cl^-	10.6	143.3	37.8	29.3	14.5	205.7	65.7	36.8
HCO_3^-	75.0	349.0	214.8	72.1	83.0	1032.0	420.8	213.7
SO_4^{2-}	31.8	585.9	327.2	146.3	3.9	275.9	67.4	65.8
NO_3^-	0.3	13.3	3.8	3.6	0.5	13.6	5.7	3.1
H_4SiO_4	4.3	18.6	10.7	3.3	10.9	44.3	25.2	10.0
Ca^{2+}	26.0	134.8	86.8	33.2	3.3	60.1	19.3	13.1
Mg^{2+}	21.9	134.7	82.4	35.4	3.9	110.0	26.2	22.6
Na^+	15.7	59.4	32.0	12.2	16.5	450.2	153.5	92.0
K^+	3.9	15.6	7.3	2.3	1.4	10.0	4.2	1.7
TH	182	863	556	213	47	499	156	107

Units: mg L^{-1}, except EC ($\mu S\ cm^{-1}$)

TH total hardness, *TDS* total dissolved solids

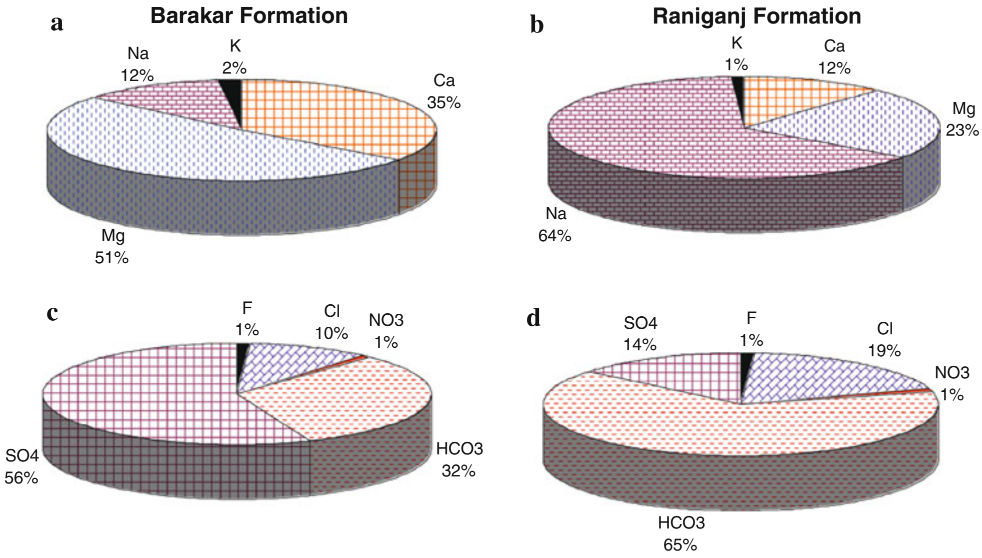

Fig. 3 Contribution of individual ions towards the total (**a**, **b**) cationic and (**c**, **d**) anionic mass balance in the Barakar and Raniganj Formation mine water samples

ranged from 75 to 1,032 mg L^{-1}; the average HCO_3^- concentration was 336 mg L^{-1}. HCO_3^- was the dominant anion in the Sodepur, Sripur, Satgram, Kunustoria, Pandaveswar, Kojora, and Jhanjra mining areas, whereas in the Mugma, Salanpur, and Tara mining areas, sulphate was the dominant anion (Fig. 4b). In equivalent units, HCO_3^- is contributing 32 and 65% to the total anionic balance in the Barakar and Ranginaj Formation mines, respectively (Fig. 3c, d).

The SO_4^{2-} concentrations ranged from 3.9 to 586 mg L^{-1} (avg. 174 mg L^{-1}) and accounted for 32% of the total anions in the mine water of the Raniganj coalfield. The average concentration of SO_4^{2-} is much higher in the mine water of the Barakar Formation area (327.2 mg L^{-1}), than at the mines of the Raniganj Formation (67.4 mg L^{-1}) (Table 4). SO_4^{2-} constituted 56 and 14% of the total anions in mine water of the Barakar and Raniganj Formation areas, respectively (Fig. 3c, d). Spatial variation of SO_4^{2-} concentrations showed relatively higher values for the Chapapur, Khudia, Bonjemehari, Dabour, Sangramgarh, Mohanpur, and Tara mines (Fig. 4c). Sulphate is usually derived from the oxidative weathering of sulphide bearing minerals like pyrite (FeS_2), or dissolution of gypsum ($CaSO_4{\cdot}2H_2O$) or anhydrite ($CaSO_4$). Pyrite (FeS_2) occurs as a secondary mineral in the Gondwana coals and associated sediments.

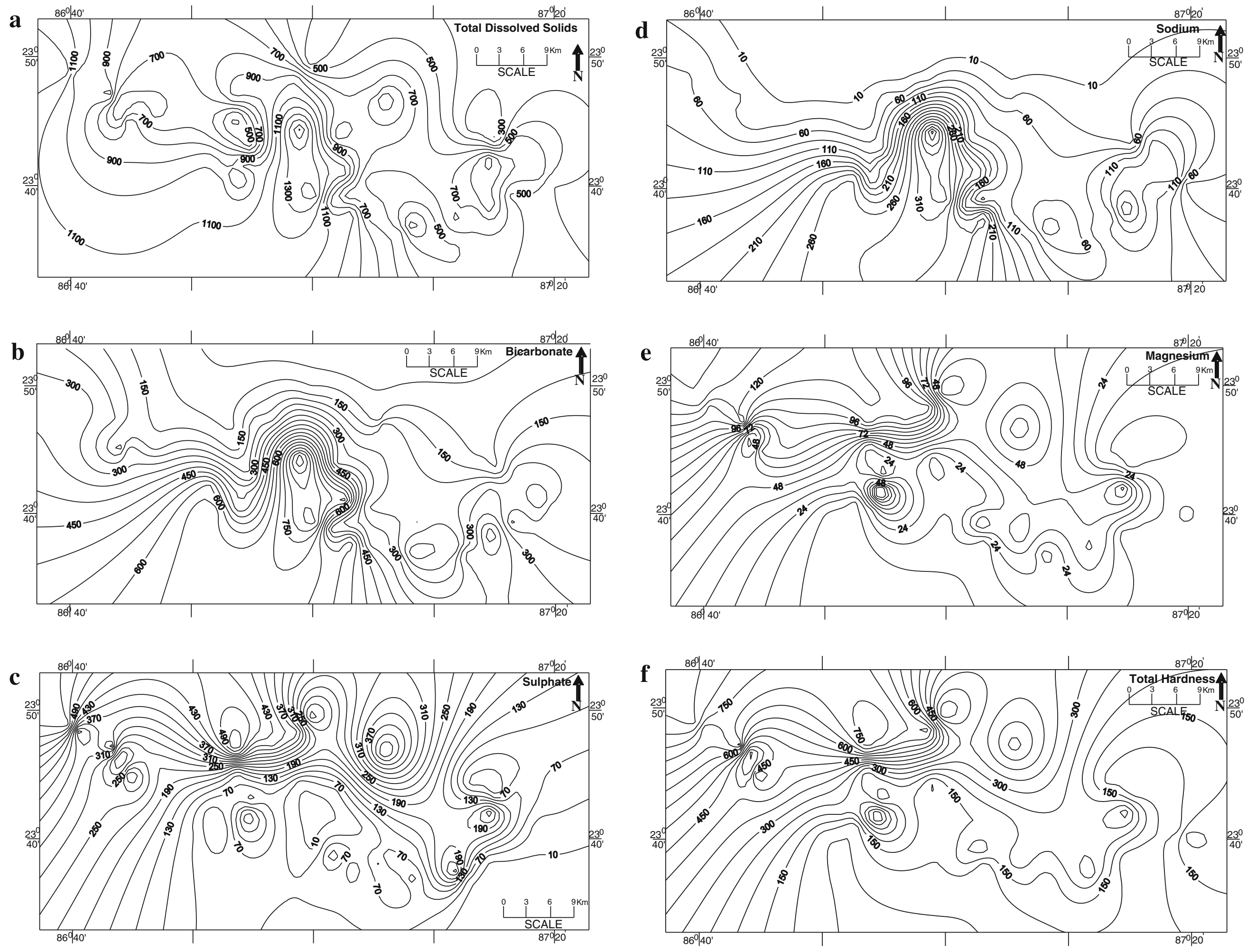

Fig. 4 Concentration contour map of **a** TDS, **b** HCO_3^-, **c** SO_4^{2-}, **d** Na^+, **e** Mg^{2+}, and **f** TH, showing spatial variation

Chloride concentrations in the analyzed mine water samples ranged from 10.6 to 205.7 mg L^{-1}, with an average value of 54.5 mg L^{-1}. On average, Cl^- is contributing 10 and 19% of the total anionic balance, respectively, in Barakar and Raniganj Formation mine waters (Fig. 3c, d). The Cl^- concentrations were relatively higher at the Sodepur, Mugma, and Pandaveswar area mines. The large lateral variation in the Cl^- concentrations and the high observed concentrations in some mine water indicate local recharge, and is attributed to contamination by untreated industrial and mine waste effluents.

Fluoride concentrations in the analyzed mine water sample ranged from 0.32 to 2.21 mg L^{-1} (avg. 0.86 mg L^{-1}), accounting for <1.0% of the total anionic balance (Fig. 3c, d). A relatively higher F^- concentration was observed in the Badjana, Khudia, Sangramgarh, Dabour, Ghusick, Tirat, and Tara mine waters. Higher F^- values in these samples may be due to the weathering of fluoride-bearing minerals like biotite, muscovite, fluorite, and apatite, which occur as accessory minerals in the granites, granitic gneisses, and intrusive rocks of the area.

The NO_3^- concentration ranged from 0.3 to 13.6 mg L^{-1} and the average concentration value was 4.9 mg L^{-1}, contributing about 1% of the total anionic balance. The chief sources of nitrate are biological fixation, atmospheric precipitation, fertilizers, and industrial sewage (Appelo and Postma 1993).

Major Cation Chemistry

The cationic chemistry of the mine water of Raniganj coalfield is dominated by magnesium and sodium, in the Barakar Formation and Raniganj Formation mines, respectively (Table 4). Concentrations of Na^+ ranged from 15.7 to 450 mg L^{-1} with an average concentration of 103.7 mg L^{-1}. On average, Na^+ accounts for 42% (5.2–92%) of the total cations (TZ^+). The spatial variation of Na^+ concentration was higher in the Sodepur, Sripur, and

Satgram mining areas and lower in the mine water of the Mugma and Salanur areas (Fig. 4d). Na^+ exceeded the concentrations of Ca^{2+} and Mg^{2+} in the Raniganj Formation mine waters, contributing 64% of the total cationic mass balance, compared to 12% in the Barakar Formation mine waters (Fig. 3a, b). Na^+ in the aquatic system is mainly derived from atmospheric deposition, evaporite dissolution, and silicate weathering (Berner and Berner 1987). Relatively higher concentration of Na^+, HCO_3^-, dissolved silica, and high Na^+/Cl^- and Na^++K^+/TZ^+ ratios, especially in the mine water of Ranignaj Formation area, likely indicate weathering of Na and K silicate minerals like albite, anorthite, and orthoclase.

Magnesium is a common constituent of natural water. In the analyzed mine water samples, Mg^{2+} constitutes 35% of the total cationic balance and its concentration ranged from 3.9 to 134.7 mg L^{-1} (avg. 49.3 mg L^{-1}). Spatial variation of Mg^{2+} concentrations was higher for the mine water of the Mugma and Salanpur mining areas (Fig. 4e). In Barakar Formation mine waters, Mg^{2+} constituted 51% of the total cations; its concentration ranged between 21.9 and 134.7 mg L^{-1} (Fig. 3a, b). The presence of Ca^{2+} and Mg^{2+} make the water hard.

The concentration of Ca^{2+} in the mine waters of the Raniganj area ranged from 3.3 to 134.8 mg L^{-1}, with an average of 46.7 mg L^{-1}. Calcium accounted for 21% of the total cations in the Ranignaj coal mine waters; the contribution of Ca^{2+} was relatively higher (35%) for mine water of the Barakar Formation than the Raniganj Formation (12%) (Fig. 3a, b).

Trace Element Chemistry

Table 5 shows the concentration of 16 trace metals analysed in the 27 mine water samples collected from selected mines of the Raniganj coalfield. With only a few exceptions, Zn, Cu, Cd, As, Se, Sb, Be, and Co concentrations did not exceed the desirable limits for drinking water.

Table 5 Trace element chemistry of the Raniganj coalfield area mine water

Site	B	V	Cr	Mn	Fe	Ni	Co	Cu	Zn	As	Se	Mo	Ag	Cd	Ba	Pb
1	144	9.2	75.3	139.8	487	60.7	6.16	41.7	201.7	8.1	4.7	22.1	3.4	5.4	370	37.5
2	61	5.5	63.2	51.8	571	95.0	1.48	14.2	183.2	3.1	2.1	4.5	1.0	0.7	113	28.1
3a	69	6.8	71.0	77.8	973	65.2	1.43	14.9	115.4	3.9	2.1	5.0	0.7	0.3	79	23.6
3c	53	5.1	82.4	36.9	570	62.3	1.02	51.9	64.6	12.7	1.8	3.4	1.1	0.5	55	61.1
5	56	5.5	66.0	20.9	406	47.1	1.12	9.5	189.3	3.5	3.1	3.7	1.1	0.9	82	26.7
6	106	7.0	45.1	24.8	774	110.2	1.78	31.3	66.7	6.8	2.8	12.6	1.0	0.6	199	–
7	55	4.5	83.6	22.9	430	62.0	1.10	11.2	34.7	5.3	1.4	4.1	0.6	0.4	81	24.2
11	61	4.6	61.7	20.3	486	65.6	0.96	17.8	36.1	6.3	1.3	2.9	0.6	0.5	51	29.5
17	76	10.7	62.4	17.4	248	52.2	0.80	22.4	47.5	10.1	2.9	8.9	0.8	0.3	237	18.7
18	113	6.7	69.8	356.1	515	64.3	1.43	12.3	38.9	3.5	1.3	2.6	0.6	0.5	208	25.8
19	74	6.6	70.0	22.0	360	56.1	0.93	24.4	61.1	33.7	1.1	5.5	2.0	0.6	202	26.5
20	89	6.5	58.2	11.8	312	74.3	0.78	28.1	43.7	5.3	1.3	7.5	0.6	0.4	189	25.0
21	88	7.8	69.0	20.0	259	43.1	0.85	21.5	58.2	6.1	1.6	6.8	0.6	0.3	197	20.2
22	78	5.7	63.0	53.4	329	60.2	1.00	32.1	84.7	14.4	2.2	8.7	2.5	0.6	604	31.2
23	77	4.8	67.0	18.6	286	59.0	0.81	34.3	44.2	7.4	1.8	9.2	1.6	0.3	586	33.8
24	75	7.3	66.2	17.3	258	48.8	0.68	18.9	61.2	5.4	1.2	4.1	0.5	0.2	120	21.1
26	73	3.4	70.2	69.1	349	108.9	0.96	18.2	55.3	4.7	1.2	4.7	0.7	0.6	958	27.4
29	29	3.1	5.8	4.0	80	9.9	0.12	9.1	19.3	1.1	1.0	5.4	0.2	0.1	156	11.9
32	34	3.1	6.0	8.2	71	7.7	0.16	8.6	25.2	0.8	1.6	8.3	0.3	0.1	34	15.0
33	54	2.7	6.7	35.1	79	8.6	0.48	13.8	38.8	1.8	0.9	9.4	0.6	0.1	104	20.0
35	31	1.6	5.5	4.2	128	7.3	0.13	6.7	17.4	1.1	2.0	4.9	0.2	0.1	96	10.4
38	37	2.7	5.7	4.0	72	7.1	0.16	10.1	19.0	0.9	0.3	3.7	0.2	0.1	108	10.6
42	74	3.9	5.2	4.2	210	11.2	0.31	7.6	20.9	1.1	0.7	3.9	0.2	0.1	44	16.8
43	62	7.2	5.7	4.7	75	7.5	0.11	9.1	20.2	1.0	0.2	4.0	0.2	0.1	84	11.1
45	108	7.8	8.7	9.7	367	22.6	0.77	19.2	27.4	4.3	2.2	11.0	0.6	0.1	413	13.4
46	24	2.2	6.1	4.2	114	8.5	0.11	8.5	28.1	0.8	2.5	4.4	0.1	0.1	15	10.7
49	65	2.3	5.7	4.2	74	6.5	0.09	9.1	19.0	2.5	1.2	4.2	0.2	0.1	123	10.2

Unit: µg L^{-1}

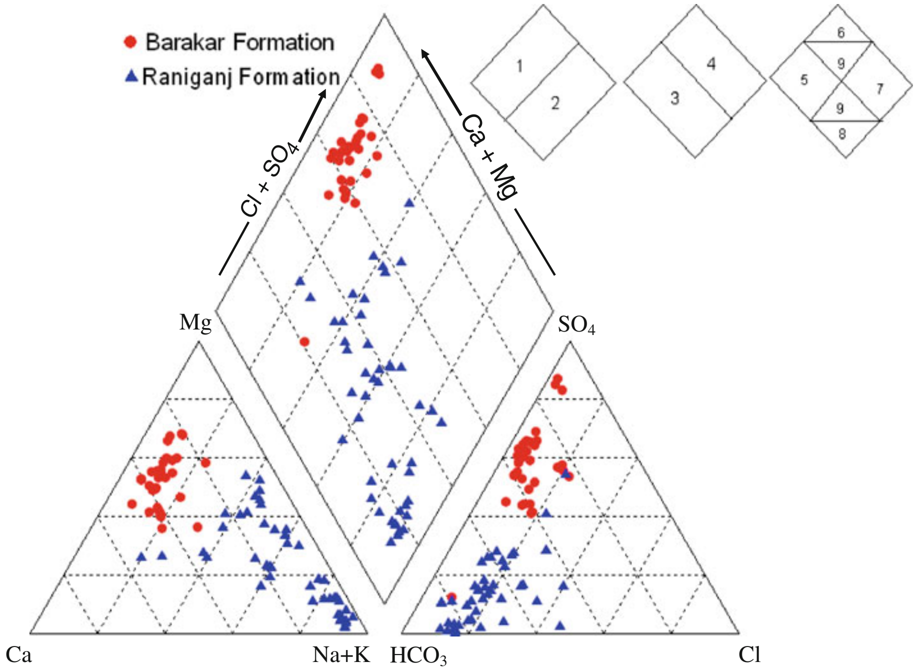

Fig. 5 Piper's trilinear diagram, showing the relationship between dissolved ions and hydrochemical facies

However, at many sites, concentrations of Fe, Mn, Cr, and Ni were above the desirable limit of the WHO (1997) and Indian drinking water standard (BIS 1991). The amount of Fe ranged from 71 to 973 μg L^{-1}, exceeding the desirable limit of 300 μg L^{-1} in 13 mine water samples; however, it was below the maximum permissible limit of 1,000 μg L^{-1} (BIS 1991). Manganese exceeded the permissible limit of 300 μg L^{-1} in only one sample. The amount of Pb detected was in the range of 10.2–61.2 μg L^{-1}, below the Indian permissible limits of 50 μg L^{-1}, except in one sample. The amount of highly toxic metals, like Cd, As, and Se, were also found to be well within the proscribed limits. Boron concentrations ranged from 24 to 144 μg L^{-1} (avg. 69 μg L^{-1}), below the drinking water desirable limit of 1,000 μg L^{-1}. Thus, the concentrations of most metals in the mine water in the study area were well below the desirable/permissible levels recommended for the drinking water by the Bureau of Indian Standard (BIS 1991) and World Health Organisation (WHO 1997. The water that contained higher concentrations of some metals (i.e. Fe, Cr, Ni) would require treatment before domestic and irrigation use.

Geochemical Classification and Hydrogeochemical Facies

The evolution of water composition and chemical relationship between dissolved ions can also be evaluated by plotting the data on a Piper (1944) trilinear diagram. The plotted mine water of the Mugma, Salalnpur, and Tara mining areas of the Barakar Formation fall in regions 1, 4, 6, and 9, signifying the dominance of alkaline earths (Ca+Mg) over the alkalies (Na+K), strong acids (SO_4^{2-}+Cl^-) over weak acids (HCO_3^-), and non-carbonate hardness. About 21% of the Barakar mine water samples show intermediate (mixed) chemical character; their plotted points fall in the middle portion (region 9) of the diamond shaped field (Fig. 5).

The Raniganj Formation mine water shows more varied chemical character. Most of the Raniganj Formation samples fall in region 2, indicating the dominance of alkalies (Na+K) over alkaline earth (Ca+Mg). In 33% of the samples, alkaline earth exceeds alkalies and plotted points fall in region 1. In 90% of the Raniganj Formation area samples, weak acids exceed strong acids and plotted points fall in region 3. About 20% of the samples have carbonate hardness (secondary alkalinity) that exceeds 50%, and 33% of the samples have carbonate alkali (primary alkalinity) that exceeds 50%; the plotted points fall in regions 5 and 8, respectively. The rest of the samples (44%) of the Raniganj Formation area have an intermediate (mixed) chemical character (region 9).

The facies mapping approach applied to the present study shows that Ca–Mg-SO_4, Na-HCO_3, and Ca–Mg-HCO_3 are the dominant hydrochemical facies; an appreciable percentage of the mine water has a mixed hydrochemical character (Back 1961). Most of the mine water of the Barakar Formation area occurs as Ca–Mg–SO_4 hydrochemical facies, while the Raniganj Formation area shows the dominance of Ca–Mg-HCO_3 and Na-HCO_3.

Water Quality Assessment

Data obtained by geochemical analyses were evaluated in the terms of suitability for drinking, irrigation, livestock, and industrial uses.

Drinking and General Domestic Uses

The proscribed limits of WHO (1997) and Indian drinking water standards (BIS 1991) were used to assess suitability for drinking and public health purposes. Most of the mine water of the study area is not suitable for direct use in drinking and domestic purposes (Table 6). TDS, total hardness (TH), and SO_4 are the major objectionable parameters. Carrol (1962) proposed four classes of water: fresh (<1,000 mg L^{-1}), brackish (1,000–10,000 mg L^{-1}), saline (10,000–100,000 mg L^{-1}), and brine (>100,000 mg L^{-1}) based on total dissolved solids. By this criteria, 78% of the analyzed mine water samples are fresh and 22% are brackish. However, according to WHO (1997) guidelines, the TDS exceeds the desirable limit of 500 mg L^{-1} in 92%, and the maximum permissible limit of 1,000 mg L^{-1} in about 22% of the mine water samples.

Water can be classified as soft (<75 mg L^{-1}), moderately hard (75–150 mg L^{-1}), hard (150–300 mg L^{-1}), and very hard (>300 mg L^{-1}) (Sawyer and McCarty (1967). The TH of the analyzed mine water samples ranged from 48 to 863 mg L^{-1} (avg. 320 mg L^{-1}), soft to very hard. The data indicate that 40% of the mine water samples have TH values higher than 300 mg L^{-1}, which is the desirable limit, and 22% exceed the maximum permissible limit of 600 mg L^{-1} (BIS 1991). The spatial variation shows

Table 6 Geochemical parameters in the mine water compared to WHO (1997) and Indian standards (IS-10500) for drinking water

Parameters	Range	Mean	WHO (1997)		BIS (1991) IS:10500	
			Maximum desirable	Highest permissible	Maximum desirable	Highest permissible
Major ions (mg L^{-1})						
pH	6.5–8.8	8.0	7.0–8.5	6.5–9.2	6.5–8.5	8.5–9.2
EC (μS cm^{-1})	270–2,000	923	750	1,500	–	–
TDS	171–1,626	795	500	1,500	500	2,000
HCO_3^-	75–1,032	336.3	200	600	200	600
SO_4^{2-}	3.9–585.9	174.0	200	600	200	400
Cl^-	10.6–205.7	54.2	250	600	250	1,000
NO_3^-	0.3–13.6	4.9	–	50	45	100
F^-	0.32–2.21	0.86	0.6–0.9	1.5	1.0	1.5
Ca^{2+}	3.3–134.8	47.0	75	200	75	200
Mg^{2+}	3.9–134.7	49.3	30	150	30	100
Na^+	15.7–450.2	103.7	50	200	–	–
K^+	1.4–15.6	5.5	100	200	–	–
TH	48–863	320	100	500	300	600
Trace metals (μg L^{-1})						
B	24–144	69	300		1,000	5,000
Cr	5.2–83.6	44.6	50		50	No relaxation
Mn	4.0–356	39.4	500		100	300
Fe	71–973	329	300		300	1,000
Ni	6.5–110.2	45.6	20		–	–
Co	0.09–6.2	0.95	–		–	–
Cu	6.7–51.9	18.7	2,000		50	1,500
Zn	17.4–201.7	60.1	4,000		5,000	15,000
As	0.8–33.7	5.8	10		50	No relaxation
Se	0.2–4.7	1.7	10		10	No relaxation
Cd	0.1–5.4	0.5	3.0		10	No relaxation
Pb	10.2–61.1	22.7	10		50	No relaxation
Ba	15–958	204	300			
Ag	0.1–3.4	0.8	–			

higher TH values for the water of the Barakar Formation mines (avg. 556 mg L^{-1}) than the Raniganj Formation (avg. 156 mg L^{-1}) mines (Fig. 4f). High TH may cause precipitation of calcium carbonate and encrustation on water supply distribution systems. There is suggestive evidence that long term consumption of extremely hard water might lead to an increased incidence of urolithiasis, anecephaly, parental mortality, some types of cancer, and cardio-vascular disorders (Agrawal and Jagetia 1997; Durvey et al. 1991).

The recommended limit for Na in drinking water is 200 mg L^{-1}. Concentrations of Na were less than this in all the water samples from the Barakar Formation area. However, the proscribed limit was exceeded in 12 samples collected from the Raniganj Formation area.

Sulphate concentrations in 14% of the water samples exceeded the maximum permissible limit of 400 mg L^{-1}, restricting direct use for drinking and domestic use. Most of the water collected from the mines of the Barakar Formation area had high SO_4^{2-} and Mg^{2+} content. Water with about 200–400 mg L^{-1} SO_4^{2-} has a bitter taste, and a concentration of 1,000 mg L^{-1} or more can cause intestinal disorder. Sulphate causes odour and corrosion of sewers because it gets converted to hydrogen sulphide. It may also cause corrosion of metals in the distribution system, particularly in water with low alkalinity.

In many mine water samples, the concentrations of some trace metals (Cr, Fe, Ni) were above the level recommended for drinking water by the Indian Standard Institution (BIS 1991). Concentrations of other metals were generally well within the threshold values.

Irrigation Uses

Water for irrigation should satisfy the needs of soil and plants of the area for normal growth and crop production. Electrical conductivity and Na^+ play a vital role. High salt content in irrigation water causes an increase in soil solution osmotic pressure. The salts, besides affecting the growth of the plants directly, also affect the soil structure, permeability, and aeration, which indirectly affect plant growth. Salinity problems in irrigated agriculture are most likely to arise where drainage is poor, which allows the water table to rise close to the root zone of plants, causing Na salts to accumulate in the soil solution through capillary rise following surface evaporation. The total soluble salt concentration in irrigation water can be classified as low (EC = 250 µS cm^{-1}), medium (EC = 250–750 µS cm^{-1}), high (EC = 250–750 µS cm^{-1}), and very high (EC = 2,250–5,000 µS cm^{-1}) (Richards 1954). The suitability of water for irrigation can be assessed by means of many determinants, such as sodium absorption ratio (SAR), percent sodium (Na%), residual sodium carbonate (RSC), and permeability index (PI). These parameters were estimated for mine water of the Raniganj coalfield area.

Sodium Adsorption Ratio

A high Na concentration changes soil properties and reduces soil permeability, which leads to development of an alkaline soil. The Na or alkali hazard is determined by the absolute and relative concentration of cations and is expressed in terms of the SAR, which is determined by the formula:

$$\mathrm{SAR} = \mathrm{Na}/\sqrt{\mathrm{Ca}} + \mathrm{Mg}/2$$

Irrigation waters are classified into four alkali categories (S1–S4) on the basis of SAR: low (0–10), medium (10–18), high (18–26), and very high (>26) (Richards 1954). The calculated SAR in the study area ranges from 0.3 to 20.2 meq L^{-1} (average value 4.2 meq L^{-1}). Plotted on a US salinity diagram, in which the EC represents the salinity hazard and SAR the alkalinity hazard, most of the water samples are C2S1 and C3S1, indicating medium to high salinity and low Na (Fig. 6). Low salinity and low Na water can be used for irrigation on almost all soils, with little danger of developing harmful levels of exchangeable Na. High salinity water (C3) cannot be used on soils with restricted drainage. About 12% of the mine water samples falls in the zone of C3S2, i.e. high salinity and medium alkali. Medium alkali water will present a problem in fine textured soils having a high cation exchange capacity, especially under low leaching conditions. This water can be used on coarse textured or organic soils with good permeability. About 16% of the samples, especially samples collected from the Sodepur area, had high salinity and high to very high Na (C3S3 and C3S4). High alkali water can produce harmful levels of exchangeable Na in soils and will require special soil management—good drainage, high leaching, and organic matter addition. Application of gypsum or other amendments may make the use of these waters feasible.

Percent Sodium (%Na)

Percent Na is widely used for evaluating the suitability of water quality for irrigation (Wilcox 1955). High Na irrigation water causes exchange of Na in water for Ca and Mg in soil, reduces permeability, and eventually results in soil with poor internal drainage. Hence, air and water circulation is restricted during wet conditions and such soils are usually hard when dry (Collins and Jenkins 1996; Saleh et al. 1999). The Indian Standard (BIS 1991) recommends a maximum %Na of 60% for irrigation water, where %Na is calculated by:

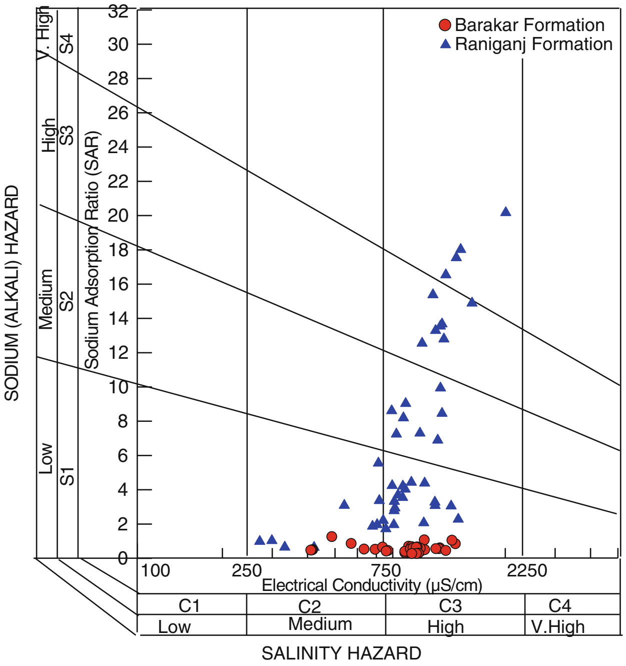

Fig. 6 US salinity diagram for classification of irrigation waters (after Richards 1954)

$$\%Na = Na + K/(Ca + Mg + Na + K) \times 100$$

all concentrations in meq L^{-1}

The %Na in the study area ranged from 6.6 to 92.9%, averaging 43.6%. Plotting the data on a Wilcox diagram shows that most of the plotted points (68%) fall in the excellent to good and good to permissible zones, indicating that the water can be used for irrigation. However, %Na values in about 25% of the samples, mostly in the Raniganj Formation area, exceed 60%, which makes these mine waters unsuitable for irrigation (Fig. 7).

Residual Sodium Carbonate (RSC)

The quantity of bicarbonate and carbonate in excess of alkaline earths (Ca^{2+}+Mg^{2+}) also influence the suitability of water for irrigation purposes. When the sum of CO_3^{2-} and HCO_3^- exceeds the sum of Ca^{2+} and Mg^{2+}, Ca^{2+} and Mg^{2+} may precipitate as a carbonate (Karanth 1989). The effects of carbonate and bicarbonate and suitability of water for irrigation can be assessed by computing the RSC values:

$$RSC = \left(CO_3^{2-} + HCO_3^{-}\right) - -\left(Ca^{2+} + Mg^{2+}\right)$$

all concentrations in meq L^{-1}

A high RSC value in water leads to an increase in the adsorption of Na on soil (Eaton 1950). Irrigation waters having RSC values greater than 5 meq L^{-1} are considered harmful to the growth of plants, while waters with RSC values above 2.5 meq L^{-1} are not considered suitable for irrigation. In most of the analysed water samples, RSC values were below 5.0 meq L^{-1} and suitable to marginally suitable for irrigation. However, about 25% of the analysed mine water samples, especially those collected from the Raniganj Formation mining areas, had RSC values higher than the 5.0 meq L^{-1} limit. These waters are marginally suitable to unsuitable for irrigation.

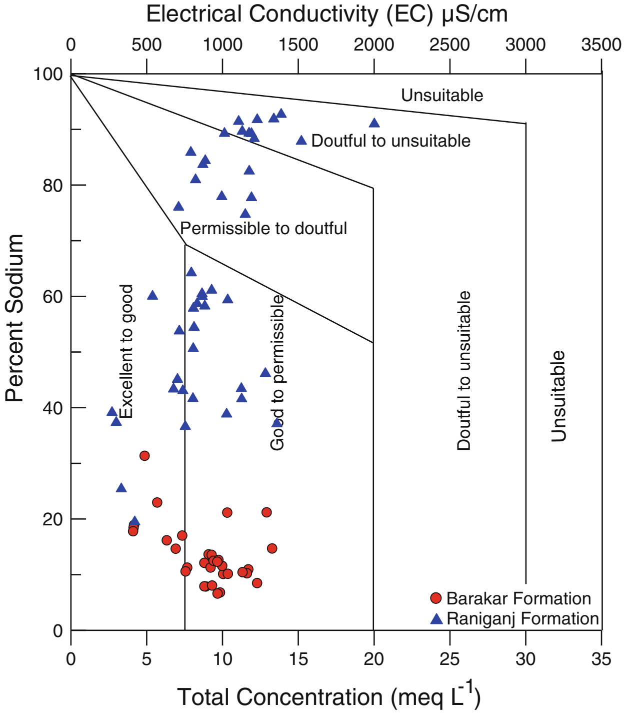

Fig. 7 Plot of sodium percent vs. electrical conductivity (after Wilcox 1955)

Permeability Index (PI)

Soil permeability is affected by long term use of water rich in Na^+, Ca^{2+}, Mg^{2+}, and HCO_3^-. The PI is also used to assess of suitability of water for irrigation and is defined as:

$$\text{Permeability index (PI)} = \frac{Na + \sqrt{HCO_3}}{Ca + Mg + Na} \times 100$$

all concentrations in meq L^{-1}

Doneen (1964) classified irrigation waters 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 types of water, with 25% of maximum permeability, are unsuitable for irrigation. Plotting our data on Doneen's chart indicates that 56% of the water samples fall in Class-I and 16% in Class-II, implying that the water is good for irrigation uses (Domenico and Schwartz 1990). However, 27% of the mine water samples belong to Class-III, the unsuitable category (Fig. 8).

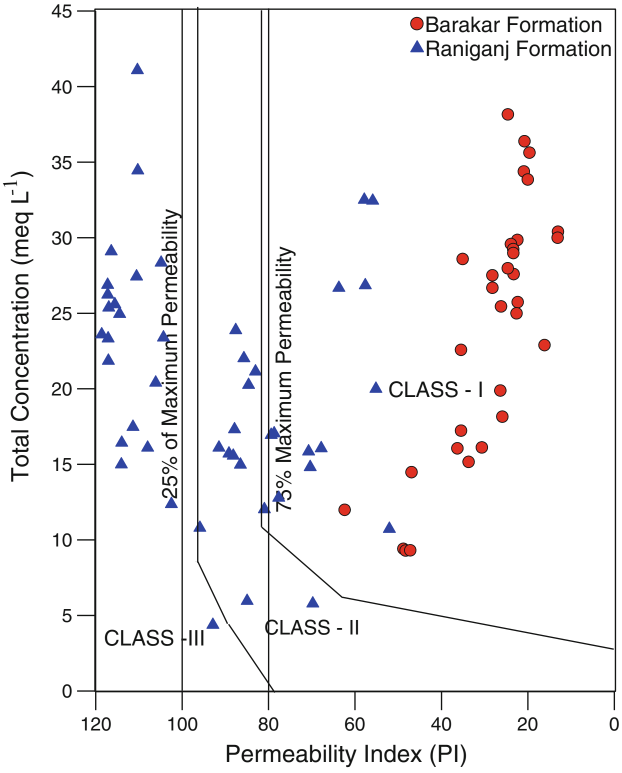

Fig. 8 Classification of irrigation water based on the permeability index (after Doneen 1964)

Magnesium Ratio

Szabolcs and Darab (1964) discussed how excessive Mg affects the quality of soil, resulting in poor agricultural returns. A Mg ratio (the concentrations of Mg over Ca+Mg) >50% is considered unsuitable for irrigation. The Mg ratio in the mine water samples ranged between 28.4 and 90.6, with an average value of 62.9. Using this criterion, most (78%) of the Raniganj Formation mine water is unsuitable for irrigation.

Industrial Uses

The water quality requirement for industries varies considerably between areas, kind of industries, and processes. The high TDS, TH, and SO_4^{2-} concentrations in most of the mine water samples of the area make the water unsafe for textiles, paper, and allied industries. Food industries such as dairying, brewing, and carbonated beverage canning must comply with drinking water standards, with disinfection and treatment before use.

Livestock Uses

Water for livestock should be of high quality to prevent livestock diseases, salt imbalance, or poisoning by toxic constituents. Most livestock water quality standards are the same as for human drinking water, though the total suspended solids and salinity can be higher. Ayers and Wascot (1985) and Shuval et al. (1986) indicate that water with a salinity <1,500 mg L^{-1} and Mg <250 mg L^{-1} is suitable for drinking by most livestock. Most of the mine water meets these standards and can be used for livestock after preliminary treatment and filtration.

Conclusions

The mine water of the Raniganj coalfields is mildly acidic to alkaline. Ca–Mg-SO_4 and Na-HCO_3^- are the dominant hydrochemical facies respectively in the Barakar and Raniganj Formation mine waters. The quality assessment shows relatively high values of EC, TDS, TH, SO_4^{2-}, Fe, Mn, and Cr in a number of mine water samples, which would make them unsafe for drinking purposes. Domestic use would require treatment and disinfection. Most of the mine water can be used for irrigation without any hazard; however, high values of salinity and alkali hazard (SAR), RSC, Mg, and %Na at many sites, especially in the Raniganj Formation areas, restrict their use for irrigation. Suitable water treatment and a soil management plan are needed for their use for this purpose in such areas.

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