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TECHNICAL ARTICLE

Environmental Geochemistry and a Quality Assessment of Mine Water of the West Bokaro Coalfield, India

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Abstract Mine water from the West Bokaro coalfield was qualitatively assessed with respect to domestic and irrigation criteria. Thirty water samples from different mines were collected and analyzed for pH, electrical conductivity, total dissolved solids (TDS), total hardness, major cations, anions, and dissolved silica. The pH of the samples ranged from 6.6 to 8.3 in the post-monsoon season and 6.7–8.4 in the pre-monsoon season, indicating its near-neutral to slightly alkaline nature. TDS ranged from 349 to 1029 mg L^{-1} in the post-monsoon season and 499–1458 mg L^{-1} in the pre-monsoon season. The spatial differences in TDS reflect the local lithology, surface activities, and hydrology. Ca–Mg–SO_4 and Ca–Mg–HCO_3 were the dominant hydrogeochemical facies; SO_4^{2-} and HCO_3^- were the dominant anions and Ca^{2+} and Mg^{2+} were the dominant cations during both seasons. High SO_4^{2-} concentrations are attributed to oxidative weathering of pyrite and gypsum dissolution. Computed supersaturation with respect to dolomite and calcite for most samples may result from the dissolution of gypsum after the water is saturated with respect to the carbonate minerals. Despite moderate to high TDS, total hardness, and SO_4^{2-} concentrations, most of the sampled mine water was of good to permissible quality for irrigation; however, locally higher salinity and Mg restrict its suitability for irrigation at some sites.

Keywords Mine water chemistry · Irrigation water · Sodium absorption ratio · Residual sodium carbonate · Kelley index · Magnesium hazard

Introduction

Contaminated mine water is commonly discharged in India without any treatment or beneficial use. Although contaminant concentrations can vary greatly (Cravotta 2008; Mahato et al. 2014; Singh et al. 2010, 2013b), mine water can be a prospective water resource where it meets drinking water or agricultural use criteria (Cidu et al. 2007; Singh 1994). Mine water is a major water supply source in the highly populated West Bokaro coalfield area, but although water resources quality has been studied in India's Jharia, Raniganj, Singrauli, Pench, and Neyveli coalfields (Anshumali et al. 2014; Choubey 1991; Gupta 1999; Jayaprakash et al. 1999; Sarkar et al. 2007; Singh et al. 2010, 2011, 2012; Tiwary 2001), such data was not available for the West Bokaro coalfield. The present investigation was carried out to evaluate this coalfield's water quality with respect to domestic use and irrigation standards and to study its geochemistry.

The 207 km^2 West Bokaro coalfield is located in the Ramgarh district of Jharkhand, between the latitudes of 23°41′N to 23°52′N and longitudes of 85°24′E to 85°41′E (Fig. 1). It is geographically separated from the East Bokaro coalfield by the 987 m Lugu Hill. The Barkakana—Gomoh railway line passes through the eastern fringe of the coalfield and the Grand Trunk (GT) road passes along its western part. Numerous all-weather roads connect the various blocks of the coalfield with NH-33. The topography lies between 229 and 660 m above sea level, with about 61.8 % of the area between 229 and

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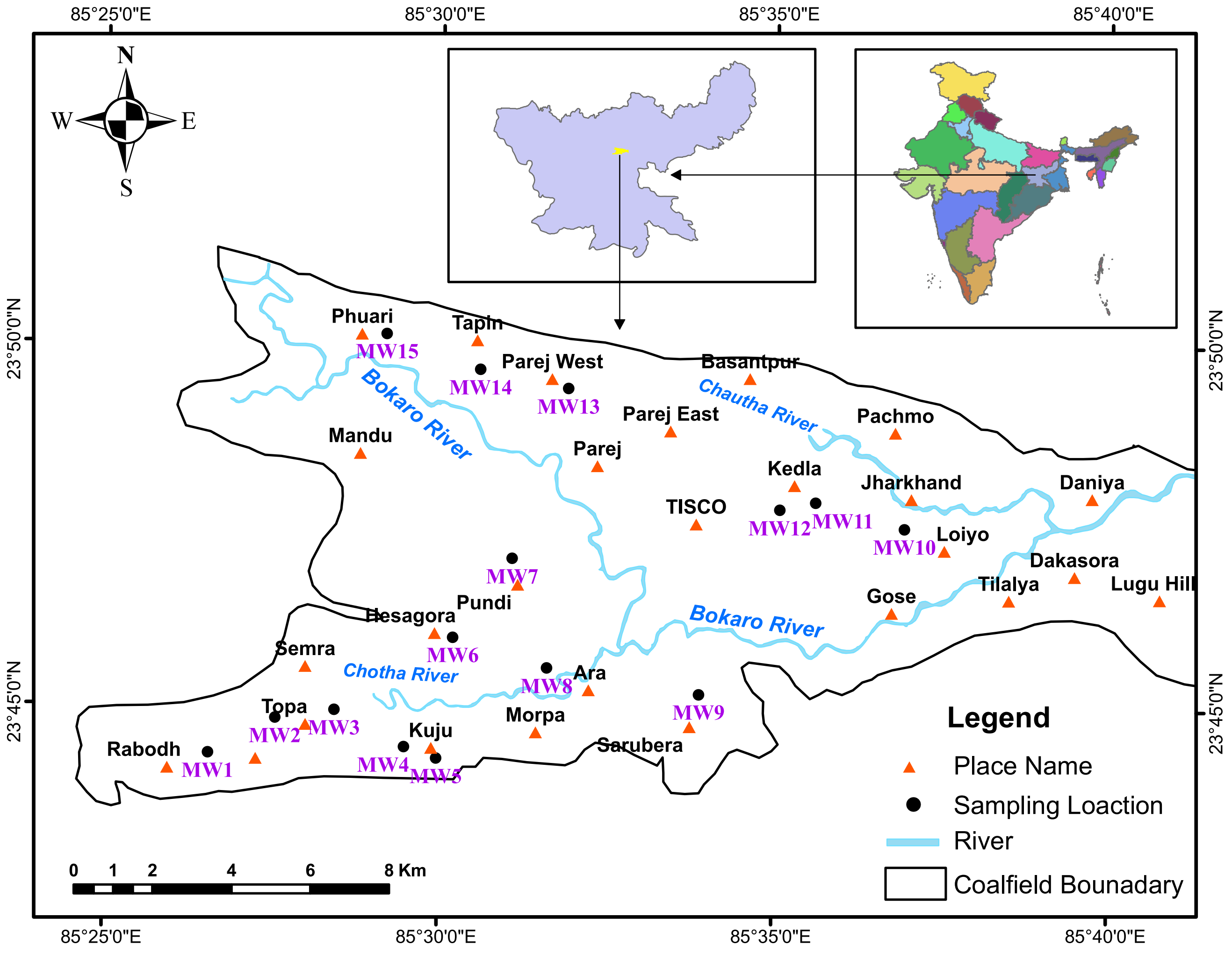


Fig. 1 Map of the West Bokaro coalfield, showing locations of mining areas and sampling sites

350 m, 36.6 % between 350 and 400 m, and a small area, i.e. 1.6 % above 400 m. The coalfield is drained by the Bokaro River passing through the central part of the coalfield from the west to the east. The Chautha and Chotha rivers are the main tributaries of the Bokaro River, and drain the northern hilly terrain and southern region of the coalfield, respectively.

The West Bokaro coalfield area is characterized by a tropical climate, with very hot pre-monsoon and cold post-monsoon seasons. The months of May and June (up to middle of month) are the peak of the pre-monsoon season with an average maximum temperature of 44 °C, while December and January are the coldest months. The average annual rainfall of the district is 1418 mm, and more than 85 % of the annual rainfall occurs during the four monsoon months, June to September (Mondal et al. 2009; Tiwari et al. 2015).

The coalfield forms a broad syncline with its axis trending E-W and exhibits the complete sequence of the lower Gondwana Formation, which rests unconformably on basement rocks (Mondal et al. 2009; Tiwari et al. 2015). The geology of the study area consists of the Barakar Formation, Barren Measures, Mahadeva, Metamorphics, Panchet, Raniganj, and Talchir Formations. The Barakar Formation covers most of the coalfield and consists of coarse- to fine-grained sandstone, pebbly conglomerates, gritty sandstones, grey shales, carbonaceous shales, fire clays, and coal seams.

Materials and Methods

Systematic sampling of mine water quality of the West Bokaro coalfield was carried out during November, 2012 and May, 2013. Representative water samples from the Barakar Formation were collected from the Pindra, Kuju, Topa, Hesagora, Pundi, Ara,Sarubera, Kedla, Jharkhand, Tapin, and Parej mines (Fig. 1). Thirty mine water samples (15 in the post-monsoon season, and 15 in the pre-monsoon season) were collected from both underground

(underground mine sumps and surface water discharges) and opencast (mine pits and settling ponds) mines in 1 L narrow mouth pre-washed polyethylene bottles. Electrical conductivity (EC) and pH were measured in the field using a Consort C831 portable conductivity and pH meter. In the laboratory, the water samples were filtered through 0.45 µm Millipore membrane filters to separate suspended particles. Acid titration and molybdosilicate methods were used to determine the bicarbonate (HCO_3^-) and silica (SiO_2) concentration, respectively (APHA 1998). Major anions (F^-, Cl^-, SO_4^{2-}, and NO_3^-) were analysed on a Dionex Dx-120 ion chromatograph using AS12A/AG12 columns coupled to an anion self-regenerating suppressor in recycle mode. Major cations (Ca^{2+}, Mg^{2+}, Na^+, and K^+) were measured with a Varian 680FS atomic absorption spectrophotometer in flame mode after calibrating the instrument with known standards. Three cation analysis results were averaged for each sample, and the instrument was recalibrated after every 10 samples. Percent relative standard deviation (RSD) was <10 % for the three results. Cationic and anionic charge balance (<10 %) was achieved for all samples.

Spatial distribution maps of water-quality parameters were prepared using ArcMap GIS software with the spatial analyst module and the inverse distance weighted (IDW) interpolation technique. Piper diagrams, saturation index (SI) with respect to major minerals, and statistical summaries were computed using AqQA, Grapher and SPSS software. The 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:

$$\mathrm{SI} = \log(\mathrm{IAP}/\mathrm{Ksp}) \tag{1}$$

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 dissolution of the mineral phase, if present.

Results and Discussion

The physico-chemical parameters of the analysed mine water samples, including statistical measures such as minimum, maximum, average values and standard deviation, are given in Table 1.

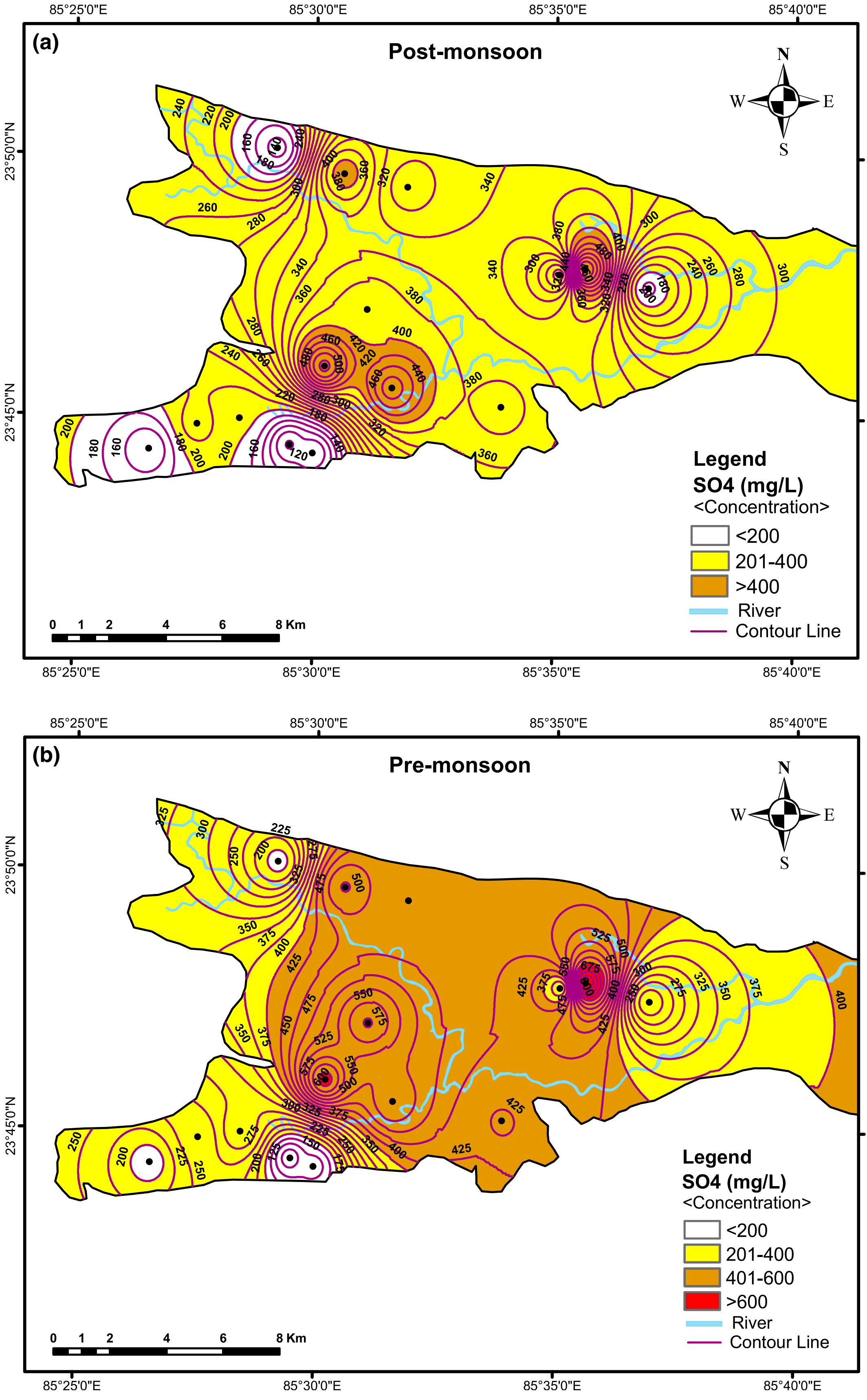
pH, EC and Total Dissolved Solids (TDS)

The pH of the samples ranged from 6.6 to 8.3 in the post-monsoon season and 6.7–8.4 in the pre-monsoon season, with similar near-neutral to alkaline values at each site for the post- and pre-monsoon samples. EC ranged from 430 to 1436 µS cm^{-1} (avg. 864 µS cm^{-1}) in the post-monsoon season, and from 657 to 1625 µS cm^{-1} (avg. 1123 µS cm^{-1}) in the pre-monsoon season. TDS ranged from 349 to 1029 mg L^{-1} (avg. 643 mg L^{-1}) in the post-monsoon season and 499 to 1458 mg L^{-1} (avg. 906 mg L^{-1}) in the pre-monsoon season. Greater salinity for the pre-monsoon samples was indicated by higher EC and TDS at a given site. On the basis of TDS, the water can be classified as fresh (TDS < 1000 mg L^{-1}), brackish (>1000 mg L^{-1}), saline (>10,000 mg L^{-1}), or brine

Table 1 Summary statistics of the analytical data

Parameters	Units	Post-monsoon (n = 15)			Pre-monsoon (n = 15)		
		Range	Average	SD	Range	Average	SD
pH	–	6.6–8.3	7.7	0.4	6.7–8.4	7.7	0.4
EC	µS cm^{-1}	430–1436	864	294	657–1625	1123	286
Turbidity	NTU	0.9–14.7	4.8	3.7	0.8–15.1	4.2	3.8
HCO_3^-	mg L^{-1}	87.3–246	163	51.3	105–368	252	78
F^-	mg L^{-1}	0.3–1.6	0.9	0.4	0.8–1.96	1.4	0.4
Cl^-	mg L^{-1}	4.1–84.2	18	24.4	5.97–98.1	28.2	25.4
NO_3^-	mg L^{-1}	0.5–27.7	9.7	8.6	2.3–36.6	15.4	11.2
SO_4^{2-}	mg L^{-1}	98–545	290	152	108–701	372	186
Silica	mg L^{-1}	8.3–21	15.5	4.6	11.2–23.1	17.2	4.1
Na^+	mg L^{-1}	7.2–41.3	21	11.4	16.7–64.6	38.3	13.3
Ca^{2+}	mg L^{-1}	34–154	84	43	51.4–200	118	57
Mg^{2+}	mg L^{-1}	16–65	46	13	21.6–88.4	61.5	18.8
K^+	mg L^{-1}	5.7–18	9.0	3.0	6.7–23.4	12.3	4.8
TDS	mg L^{-1}	349–1029	643	209	499–1458	906	273
TH	mg L^{-1}	203–651	399	137	271–864	547	184

TH total hardness, *EC* electrical conductivity, *TDS* total dissolved solids, *SD* standard deviation


(a)
Post-monsoon
N
W
E
S
85°25'0"E
85°30'0"E
85°35'0"E
85°40'0"E
23°50'0"N
23°45'0"N
Legend
SO4 (mg/L)
<Concentration>
<200
201-400
>400
River
Contour Line
0 1 2 4 6 8 Km
120
140
160
180
200
220
240
260
280
300
320
340
360
380
400
420
440
460
480
500
(b)
Pre-monsoon
N
W
E
S
85°25'0"E
85°30'0"E
85°35'0"E
85°40'0"E
23°50'0"N
23°45'0"N
Legend
SO4 (mg/L)
<Concentration>
<200
201-400
401-600
>600
River
Contour Line
0 1 2 4 6 8 Km
125
150
175
200
225
250
275
300
325
350
375
400
425
450
475
500
525
550
575
600
625
675

◀**Fig. 2** **a** and **b** Concentration contour map of sulphate showing spatial variation in the post-monsoon and pre-monsoon seasons

(100,000 mg L^{-1}) (Freeze and Cherry 1979). Thus, 87 % of the mine water samples in the post-monsoon and 67 % in the pre-monsoon seasons were fresh water; the rest were brackish.

Major Ion Chemistry

Sulphate, bicarbonate, Ca^{2+}, and Mg^{2+} were the dominant dissolved ions in the West Bokaro coalfield mine water, constituting 45.2, 25.4, 13.1, and 7.1 % of the TDS in the post-monsoon and 41.4, 28, 13.1, and 6.8 in the pre-monsoon seasons, respectively, along with lesser contributions from Na^+ (3.3 and 4.3 %) and Cl^- (2.8 and 3.1 %) in the post- and pre-monsoon seasons. Potassium, nitrate, and fluoride together contributed very little (3 %) towards the TDS solute load during both seasons.

Anion chemistry was dominated by SO_4^{2-} and HCO_3^-, with secondary contributions from Cl^-. The HCO_3^- concentration ranged from 87.3 to 246 mg L^{-1} (avg. 163 mg L^{-1}), constituting 34 % of the total anion equivalents (TZ^-) during the post-monsoon season. However, during the pre-monsoon season, HCO_3^- ranged from 105 to 368 mg L^{-1} (avg. 252 mg L^{-1}), constituting 37.7 % of the TZ^-. HCO_3^- was the dominant anion at the Kuju, Hesagara, Jharkhand, Kedla, and Parej mines. The soil zone contains elevated CO_2 pressure, produced by organic matter decay and root respiration (Appelo and Postma 1996; Singh et al. 2013a). The bicarbonates are mainly derived from this soil zone and dissolution of carbonates and silicates by carbonic acid.

Sulphate ranged from 98 to 545 mg L^{-1} (avg. 290 mg L^{-1}) in the post-monsoon season and 108–701 mg L^{-1} (372 mg L^{-1}) in the pre-monsoon season, contributing an average of 60 and 55.6 % of the TZ^- in the post- and pre-monsoon seasons, respectively. Sulphate was higher at the Hesagara, Pundi, Ara, Sarubera, Kedla, Parej, and Tapin mines and lower at the Pindra, Topa, and Jharkhand mines (Fig. 2). Sulphate in mine water is commonly derived from the oxidative weathering of sulphide minerals, such as pyrite (FeS_2); however, gypsum ($CaSO_4 \cdot 2H_2O$) and anhydrite ($CaSO_4$) can also be a sulphate source (Han et al. 2013; Singh et al. 2011).

Chloride ranged from 4.1 to 84.2 mg L^{-1} (avg. 18 mg L^{-1}) in the post-monsoon season and from 5.97 to 98.1 mg L^{-1} (avg. 28.2 mg L^{-1}) in the pre-monsoon season, contributing an average of 3.7 and 4.2 % of the TZ^- during the post- and pre-monsoon seasons, respectively. NO_3^- ranged from 0.5 to 27.7 mg L^{-1} (avg. 9.7 mg L^{-1}), contributing about 2.0 % TZ^- in the post-monsoon season, and from 2.3 to 36.6 mg L^{-1} (avg.15.4 mg L^{-1}), contributing about 2.3 % of the TZ^- in the pre-monsoon season. Thus, NO_3^- and Cl^- contributes lightly more to the TZ^- during the pre-monsoon season. 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). Additionally, biological nitrogen fixation and the use of explosives in mining areas are possible nitrate sources in mine water (Singh et al. 2012). Concentrations of F^- in the mine water samples ranged from 0.3 to 1.6 mg L^{-1} (avg. 0.9 mg L^{-1}) in the post-monsoon and 0.8–1.96 mg L^{-1} (avg. 1.4 mg L^{-1}) in the pre-monsoon seasons. In general, F^-concentrations were found to be low, accounting for <1.0 % of the total anionic charge.

On average, alkaline earths ($Ca^{2+} + Mg^{2+}$) account for 82 and 78 % of the total cation equivalent concentrations (TZ^+) and dominate over the alkalis ($Na^+ + K^+$) in the post- and pre-monsoon seasons, respectively. The Ca^{2+} concentration ranged from 34 to 154 mg L^{-1} in the post-monsoon season and 51.4–200 mg L^{-1} in the pre-monsoon season, with average values of 84 and 118 mg L^{-1}, accounting for 53 and 51 % of the TZ^+ in the post- and pre-monsoon seasons, respectively. The Ca^{2+} concentrations were higher in water from the Hesagara, Pundi, Ara, Sarubera, Kedla, Parej, and Tapin mines (Supplemental Fig. 1). Weathering and dissolution of calcium carbonate (limestone and dolomite), calcium sulfate (gypsum, anhydrite), and calc-silicate minerals (amphiboles, pyroxenes, anorthite) are the most common calcium sources. Mg^{2+} ranged from 16 to 65 mg L^{-1}(avg. 46 mg L^{-1}) in the post-monsoon season and 21.6–88.4 mg L^{-1}(avg. 61.5 mg L^{-1}) in the pre-monsoon season, accounting for 29 and 27 % of the TZ^+ in the post- and pre-monsoon seasons, respectively. The Mg^{2+} concentrations were higher in the Pindra, Topa, Hesagara, Ara, Sarubera, Jharkhnad, Kedla, and Tapin mines.

Concentrations of Na^+ and K^+ ranged from 7.2 to 41.3 and 5.7 to 18 mg L^{-1} in the post-monsoon season and 16.7–64.6 and 6.7–23.4 mg L^{-1} in the pre-monsoon season, respectively. Sodium (13 and 17 %) and potassium (5 and 5 %) together contribute an average of about 18 and 22 % of the TZ^+ in the post- and pre-monsoon seasons, 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; Kumar et al. 2006; Singh et al. 2012). 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).

Hydrochemical Relations and Water Type

The trilinear plots and corresponding diamond-shaped Piper (1944) diagram reveal that the mine water is primarily Ca–Mg–SO_4 and secondarily Ca–Mg–HCO_3 during both seasons (Supplemental Fig. 2). Most of the mine water plots in the Ca^{2+} and Mg^{2+} dominant zone in the cation facies, the $SO_4{}^{2-}$ zone in the anion facies, and in zones 1, 3, 4, 6, and 9 in the Piper diagram (Supplemental Fig. 2). All of the mine water plots in zone 1, which indicates dominance of alkaline earths ($Ca^{2+} + Mg^{2+}$) over alkalis ($Na^{+} + K^{+}$). In majority of the post- and pre-monsoon samples, respectively, strong acids ($SO_4{}^{2-}$ + Cl^{-}) exceed weak acids ($HCO_3{}^{-}$) and plot in zone 4. In the remaining samples, weak acids exceed strong acids and plot in zone 3. Considering the predominance of strong acids, 73 and 60 % of the post- and pre-monsoon samples, respectively, lie in zone 6, indicating that non-carbonate hardness exceeds 50 %. 27 and 40 % of the post- and pre-monsoon samples, respectively, plot in zone 9, with no dominant cation–anion, and should be referred to as Ca–Mg–SO_4–Cl–HCO_3 water.

Mechanisms Controlling Mine Water Chemistry

Weathering of carbonate, silicate, and sulphide minerals and dissolution of evaporites are the major lithogenic sources of the dissolved ions. Gibb's diagrams representing the ratios of $Na^{+} + K^{+}/(Na^{+} + K^{+} + Ca^{2+})$ and $Cl^{-} + NO_3{}^{-}/(Cl^{-} + NO_3{}^{-} + HCO_3{}^{-})$ as a function of TDS, are widely employed to assess the functional sources of dissolved chemical constituents, like precipitation, rock weathering, and evaporation (Gibb's 1970). The plot of relevant major ion data on Gibbs's diagram (Supplemental Fig. 3) suggests rock weathering as the major driving force controlling the mine water chemistry. The plot of $Ca^{2+} + Mg^{2+}$ versus $HCO_3{}^{-} + SO_4{}^{2-}$ is close to the 1:1 line during both seasons (Supplemental Fig. 4a), which indicates that dissolution of calcite, dolomite, and gypsum may be the dominant reactions, but the coupling of pyrite oxidation with carbonate neutralization can also produce the observed 1:1 ratio (Han et al. 2013):

$$\begin{aligned} &FeS_2 + 2CaCO_3 + 3.75O_2 + 1.5H_2O \\ &\quad = Fe(OH)_3 + 2SO_4^{2-} + 2Ca^{2+} + 2CO_2 \end{aligned} \tag{2}$$

$$\begin{aligned} &FeS_2 + 4CaCO_3 + 3.75O_2 + 3.5H_2O \\ &\quad = Fe(OH)_3 + 2SO_4^{2-} + 4Ca^{2+} + 4HCO_3^{-} \end{aligned} \tag{3}$$

Note that the equivalents ratio is the same for reactions 1 and 2 since each mole of $SO_4{}^{2-}$ or Ca^{2+} has 2 equivalents, and that of $HCO_3{}^{-}$ has 1 equivalent.

The linear plot of $Ca^{2+} + Mg^{2+}$ versus $HCO_3{}^{-}$ + $SO_4{}^{2-}$ shows the dominance of carbonate, sulfate, or sulfide mineral weathering (Supplemental Fig. 4a). However, most 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 (e.g. $CaMgSiO_6 + 4H^{+} = Ca^{2+} + Mg^{2+} + 2SiO_2 + 2H_2O$) or possibly by reverse ion exchange (e.g. Cerling et al. 1989; Fisher and Mullican 1997; Rajmohan and Elango 2004). The plot of $Ca^{2+} + Mg^{2+}$ versus total cations (TZ^{+}) shows that plotted points approach the 1:1 equiline with a small offset (intercept) that may be explained by the Na^{+} and K^{+} (Supplemental Fig. 4b). The scatter plot between $HCO_3{}^{-}$ versus $Cl^{-} + SO_4{}^{2-}$ shows the dominance of $Cl^{-} + SO_4{}^{2-}$ over $HCO_3{}^{-}$ at higher TDS concentrations (Supplemental Fig. 4c).

Saturation Index (SI)

The plot of saturation indices of calcite (SI_c) versus dolomite (SI_d) demonstrate that 80 and 87 % of the mine water samples are supersaturated with respect to dolomite and calcite. The SI_d values are higher than the SI_c values (Supplemental Fig. 5). This supersaturation may be due to gypsum dissolution by water already saturated with respect to the carbonate minerals. Such 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 20 and 13 % of the water samples had negative SI indices and were undersaturated with respect to both calcite and dolomite in the post- and pre-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 for Drinking and Livestock Use

The physico-chemical parameters of the mine water were compared with the standard guideline values recommended by the World Health Organisation (WHO 1997) and Bureau of Indian Standards (BIS 2003) for drinking and public health. Table 2 shows that most of the area's mine water is not suitable for drinking and domestic purposes and requires suitable treatment before utilization, possibly including disinfection to remove pathogens, which were not evaluated in this assessment. TDS, total hardness (TH), and $SO_4{}^{2-}$ are the major objectionable parameters. The TDS exceed the desirable limit of 500 mg L^{-1} in 60 and 53 % of the samples and the maximum permissible limit of 1000 mg L^{-1} in 13 and 40 % in the post- and pre-monsoon seasons, respectively. The consumption of highly turbid water may cause a health risk as excessive suspended

Table 2 Mine water samples of the study area exceeding the desirable limits prescribed by World Health Organisation (WHO 1997) and Bureau of Indian Standards (BIS 2003) for drinking purposes

Water quality parameters	WHO (1997)		BIS (2003) (IS: 10500)		Number of samples exceeding desirable limits Post-Monsoon/ Pre-monsoon	Percentage of samples exceeding desirable limits Post-monsoon/ Pre-monsoon
	Maximum permissible limits	Maximum desirable	Maximum permissible limits	Maximum desirable		
pH	6.5–9.2	7.0–8.5	6.5–9.2	8.5–8.5	0/0	0/0
EC	1500	750	–	–	10/14	67/93
Turbidity	–	<5.0	–	<5.0	6/4	40/27
HCO_3^-	600	200	600	200	5/10	33/67
F^-	1.5	0.6–0.9	1.5	1.0	5/12	33/80
Cl^-	600	250	1000	250	0/0	0/0
NO_3^-	50	–	100	45	0/0	0/0
SO_4^{2-}	600	200	400	200	10/11	67/73
Na^+	200	50	–	–	0/3	0/20
Ca^{2+}	200	75	200	75	7/9	47/60
Mg^{2+}	150	30	100	30	13/14	87/93
K^+	200	100	–	–	0/0	0/0
TDS	1500	500	2000	500	11/14	73/93
TH	500	100	600	300	10/14	67/93

Unit: Concentration in mg L^{-1}, except EC (μS cm^{-1}), Turbidity (NTU) and pH

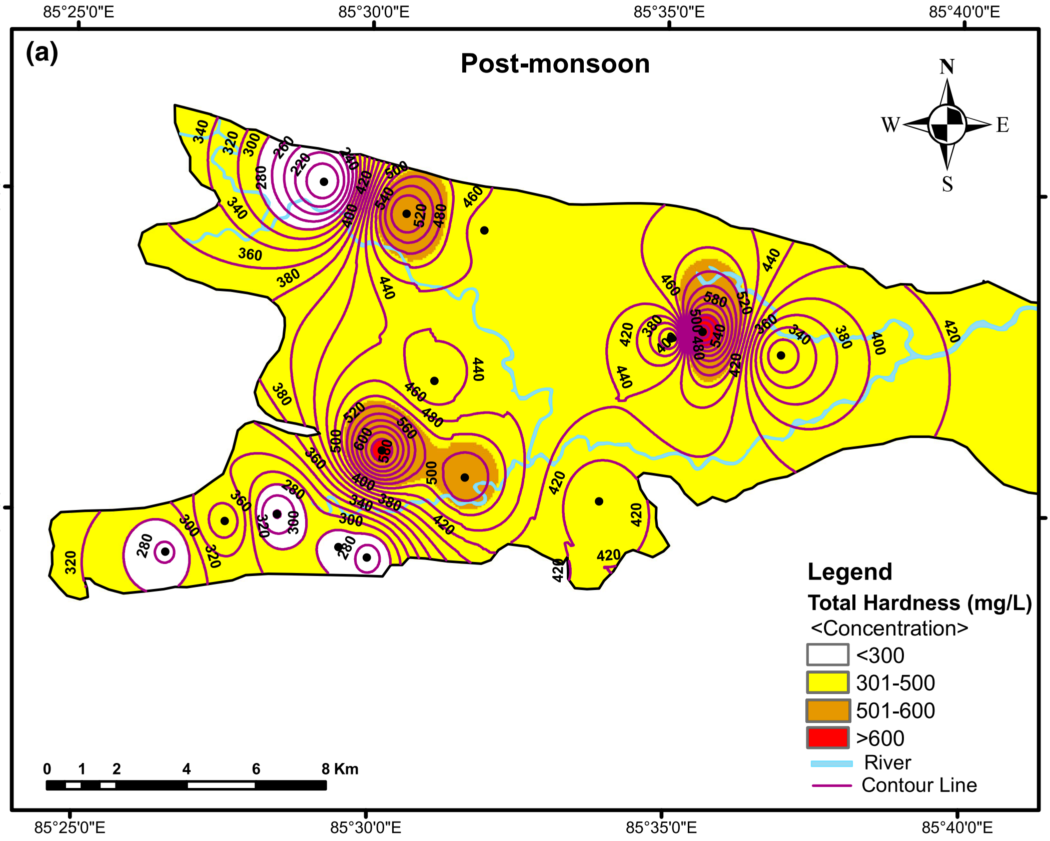
solids can protect pathogenic microorganisms from disinfectants and stimulate the growth of bacteria during storage (Singh et al. 2013a; Tiwari and Singh 2014). The turbidity, from 0.9 to 14.7 and 0.8 to 15.1 NTU, exceeds the recommended value of 5 NTU in 43 and 27 % of the mine water samples in the post- and pre-monsoon seasons, respectively. The TH of the analysed mine water ranged between 203 and 651 mg L^{-1} (avg. 399 mg L^{-1}) in the post-monsoon season and 271 and 864 mg L^{-1} (avg. 547 mg L^{-1}) in the pre-monsoon season, respectively, indicating hard to very hard water. The analytical data indicate that 33 and 7 % of the samples are hard and that the remaining 67 and 97 % exceed the desired 300 mg L^{-1} limit for drinking water during the post- and pre-monsoon seasons, respectively (Fig. 3). The high hardness may cause encrustations on water supply distribution systems. There is also suggestive evidence that long-term consumption of extremely hard water might lead to an increased incidence of urolithiasis (kidney stones), anencephaly, prenatal mortality, some types of cancer, and cardio-vascular disorders (Agrawal and Jagetia 1997; Durvey et al. 1991).

Among the cations, Ca^{2+} and Mg^{2+} exceed the respective desirable limits of 75 and 30 mg L^{-1} in most of the mine water samples. However, the concentrations are within the respective maximum permissible limit of 200 and 100 mg L^{-1} (BIS 2003). The recommended limit for Na^+ in drinking water is 200 mg L^{-1} (WHO1997); Na^+ concentrations were less than that during both seasons.

Sulphate concentrations in 27 and 47 % of the water samples exceeded the maximum permissible limit of 400 mg L^{-1} in the post- and pre-monsoon seasons, respectively, restricting direct use for drinking and domestic purposes. Higher sulphate concentrations are associated with respiratory disorders (Subba Rao 1993). Water with 200–400 mg L^{-1} SO_4^{2-} has a bitter taste and concentrations of 1000 mg L^{-1} or more can have a laxative effect.

Fluoride is an essential element for maintaining normal development of teeth and bones, but fluoride concentrations >1.5 mg L^{-1} may result in dental fluorosis and >3.0 mg L^{-1} can cause skeletal fluorosis (Nawlakhe and Bulusu 1989). Concentrations of F^- exceed the permissible limit of 1.5 mg L^{-1} in about 13 and 47 % of the mine water samples in the post- and pre-monsoon seasons, respectively. Concentrations of NO_3^- and Cl^- were within the respective permissible limits of 45 and 250 mg L^{-1} in all of the mine water during both seasons.

Livestock water should be of high quality to prevent diseased livestock, salt imbalance, or poisoning. Most of the water quality limits for livestock are the same as for human drinking water, although the total permissible levels of total suspended solids and salinity are higher. Mine water discharges serve as drinking water sources for livestock at many places. Ayers and Wascot (1985), Shuval et al. (1986) reported that water with a salinity <1500 mg L^{-1} and $Mg < 250$ mg L^{-1} is suitable for drinking by most livestock. All of the tested discharged mine water met these standards.


(a)
Post-monsoon
N
W
E
S
85°25'0"E
85°30'0"E
85°35'0"E
85°40'0"E
23°50'0"N
23°45'0"N
340
320
300
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360
380
420
460
480
500
520
540
560
580
600
440
400
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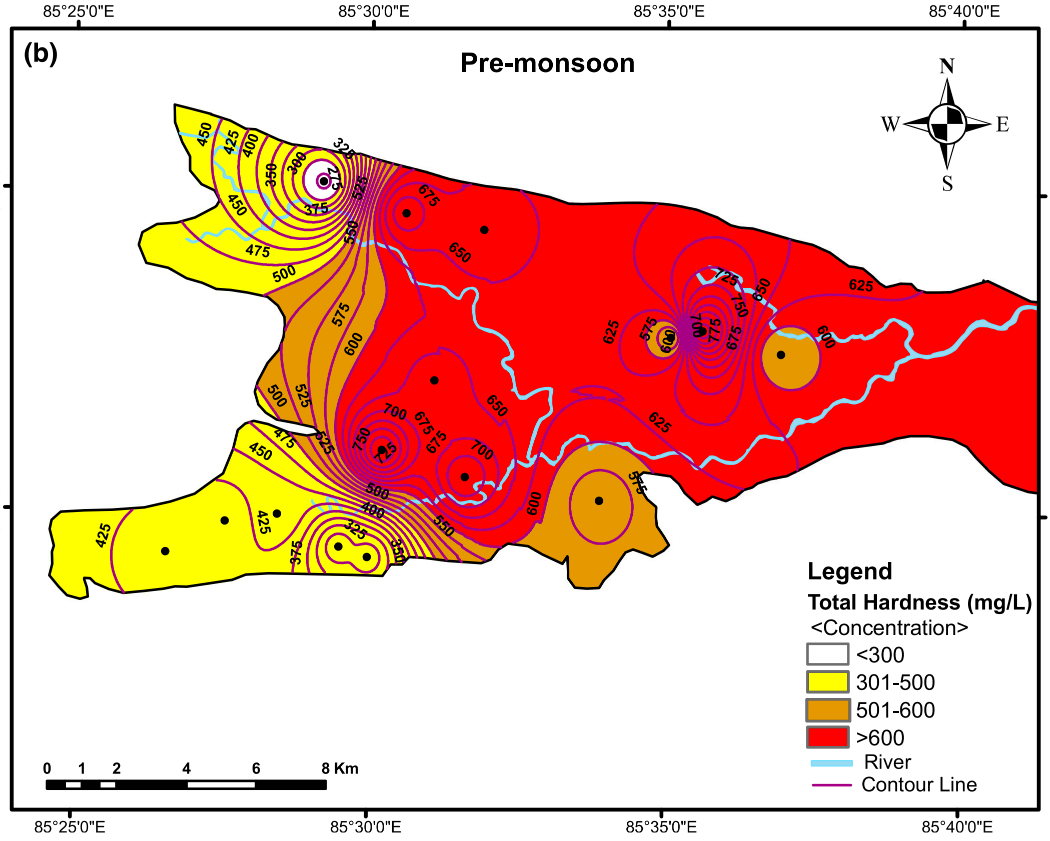
<Concentration>
<300
301-500
501-600
>600
River
Contour Line
0 1 2 4 6 8 Km


(b)
Pre-monsoon
N
W
E
S
85°25'0"E
85°30'0"E
85°35'0"E
85°40'0"E
23°50'0"N
23°45'0"N
450
425
400
375
350
325
475
500
525
550
575
600
625
650
675
700
725
750
775
Legend
Total Hardness (mg/L)
<Concentration>
<300
301-500
501-600
>600
River
Contour Line
0 1 2 4 6 8 Km

◀**Fig. 3** **a** and **b** Concentration contour map of total hardness showing spatial variation in the post-monsoon and pre-monsoon seasons

Table 3 Parameters indicating suitability of water for irrigation (after Shainberg and Oster 1976; Todd 1980), including percent sodium (%Na), sodium absorption ratio (SAR), residual sodium carbonate (RSC), permeability index (PI), Kelley index (KI) and magnesium hazard (MH)

SAR = $\mathrm{Na}/[(\mathrm{Ca} + \mathrm{Mg})/2]^{0.5}$ (i)

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

RSC = $(\mathrm{CO_3} + \mathrm{HCO_3}) - (\mathrm{Ca} + \mathrm{Mg})$ (iii)

PI = $(\mathrm{Na} + \sqrt{\mathrm{HCO_3}})/(\mathrm{Ca} + \mathrm{Mg} + \mathrm{Na}) \times 100$ (iv)

KI = $\mathrm{Na}/(\mathrm{Ca} + \mathrm{Mg})$ (v)

MH = $\mathrm{Mg}/(\mathrm{Ca} + \mathrm{Mg}) \times 100$ (vi)

All concentrations are in meq L^{-1}

Salinity, sodicity, toxicity, and related parameters are generally considered when evaluating the suitability of water for irrigation (Shainberg and Oster 1976; Todd 1980). Specific parameters indicating suitability of water for irrigation (Table 3) are based on the effects of dissolved major ions on plant growth and soil properties. High salt concentrations (high EC) in water can lead to the formation of saline soil, while high Na concentrations can lead to the development of an alkaline soil. The Na or alkali hazard in the use of water for irrigation is determined by the absolute and relative concentration of cations and is expressed in terms of the sodium absorption ratio (SAR). The calculated SAR value in the study area ranges from 0.2 to 1.1 (avg. 0.48) in the post-monsoon season and 0.4–1.3 (avg. 0.7) in the pre-monsoon season. Plotting the data on the U.S. salinity diagram (USSL 1954), in which the EC defines the salinity hazard and the SAR the alkalinity hazard shows that 33 and 7 % of the samples in the post- and pre-monsoon seasons, respectively, are classified as C2S1, indicating good to permissible water quality for irrigation (Supplemental Fig. 6). About 67 % of the post-monsoon and 93 % of the pre-monsoon samples are classified as C3S1, indicating that the water is highly saline, though low in alkalinity. Highly saline water (C3) cannot be used directly on soils without special salinity control measures, though this water can be used to irrigate salt-tolerant and semi-tolerant crops under favourable drainage conditions.

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; Tiwari et al. 2013). The Indian Standard (BIS 2003) recommends a maximum of 60 Na% for irrigation water. The Na% in the study area ranged from 6.9 to 27 % (avg. 13 %) in the post-monsoon season and from 8.6 to 29 % (avg. 16.3 %) in the pre-monsoon season. A plot of the analytical data on the Wilcox (1955) diagram, which relates EC to Na%, indicates that the mine water may be used for irrigation without any hazard (Fig. 4).

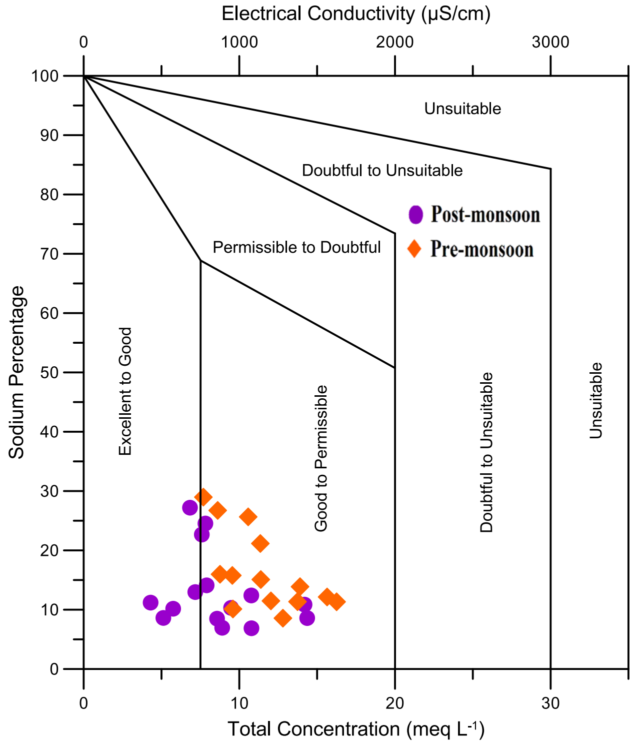


Fig. 4 Wilcox (1955) diagram for classification of mine water based on EC and Na%

The quantity of $\mathrm{HCO_3}^-$ and $\mathrm{CO_3}^-$ in excess of alkaline earths ($\mathrm{Ca}^{2+} + \mathrm{Mg}^{2+}$), expressed as residual sodium carbonate (RSC) also influences the suitability of water for irrigation (Eaton 1950; Richards 1954). Excess $\mathrm{HCO_3}^-$ and $\mathrm{CO_3}^-$ in irrigation water favours precipitation of Ca^{2+} and Mg^{2+} carbonates (consistent with positive saturation indices for calcite and dolomite, Supplemental Fig. 5) in the soil, which increases the proportion of Na ions remaining in solution (Karanth 1989). The mine water RSC values were all below 2.5 meq $\mathrm{L}^{-1}$and, on that basis at least, is suitable for irrigation.

Soil permeability is affected by long-term use of irrigation water rich in Na^+, Ca^{2+}, Mg^{2+}, and $\mathrm{HCO_3}^-$. Doneen (1964) classified irrigation water using three permeability index (PI) classes, and on this basis, the water is also good for irrigation (Fig. 5).

The Kelley index (KI) and magnesium ratio (MR) are also used to classify water for irrigation. Water with a KI > 1.0 contains excessive Na (Kelley 1946; Paliwal 1967). The West Bokaro mine water had KI values from 0.05 to 0.34 (avg. 0.13) in the post-monsoon season and 0.08–0.37 (avg. 0.17) in the pre-monsoon season, respectively, and thus is suitable for irrigation based on the KI

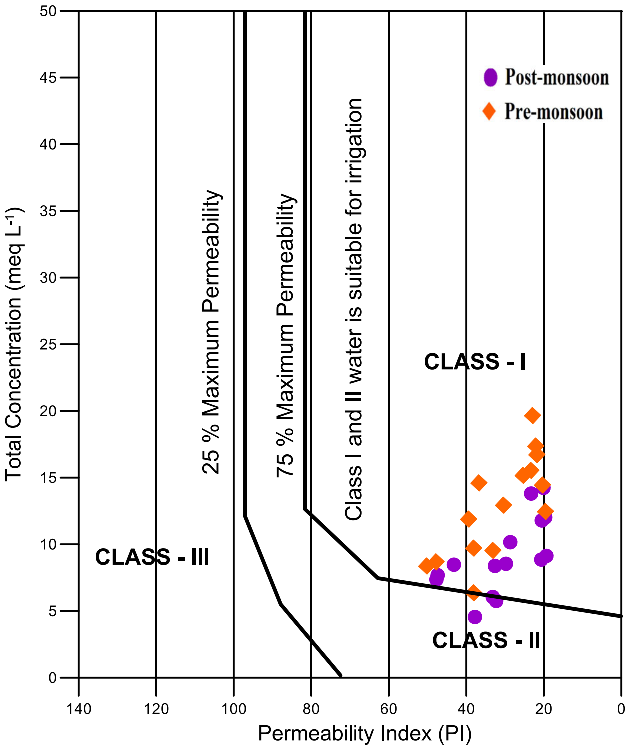


Fig. 5 Classification of irrigation water based on the permeability index (after Doneen 1964)

value. However, the MR, which reflects the concentrations of Mg compared to Ca + Mg, yielded a different result. A MR > 50 % is considered unsuitable for irrigation because excess Mg affects soil quality, resulting in poor agricultural returns (Sreedevi 2004; Szabolcs and Darab 1964). The mine water samples had MR values from 32 to 68 % (avg. 49 %) in the post-monsoon season and 33 to 68 % (avg. 48 %) in the pre-monsoon season. Since 33 % of the mine water had MR values >50 %, much of the area's mine water in both seasons is actually unsuitable for irrigation.

Conclusion

The mine water of the West Bokaro coalfield is near neutral to slightly alkaline. Ca–Mg–SO_4 and Ca–Mg–HCO_3 are the dominant hydrogeochemical facies in the West Bokaro mine water in both the post-monsoon and pre-monsoon seasons. In most of the mine water samples, concentrations of alkaline earths (Ca^{2+} + Mg^{2+}) exceed alkali cations (Na^{+} + K^{+}), and strong acids (SO_4^{2-} + Cl^{-}) dominate over weak acid (HCO_3^{-}). Dissolution of carbonate, sulphate, sulphide, and silicate minerals, as well as ion exchange processes are the major processes controlling mine water chemistry. Most of the mine water samples were supersaturated with respect to dolomite and calcite, consistent with continued dissolution of gypsum after the water achieved saturation with carbonate minerals and precipitated calcareous nodules (kankar) in the sub-surface soil.

All of the tested mine water can safely be used for livestock. However, high concentrations of EC, TDS, SO_4^{2-}, and TH in most of the mine water samples make it unsuitable for drinking without suitable water treatment. The quality of most of the mine water is good to permissible for irrigation. However, high salinity and MR values at some sites indicate that these waters should not be used for irrigation without special management.

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