MAJOR ION CHEMISTRY, SOLUTE ACQUISITION PROCESSES AND QUALITY ASSESSMENT OF MINE WATER IN DAMODAR VALLEY COALFIELDS, INDIA

ABHAY KUMAR SINGH, G. C. MONDAL, B. K. TEWARY and A. SINHA

Central Institute of Mining and Fuel Research, (Council of Scientific & Industrial Research)
Barwa Road, Dhanbad - 826 015, Jharkhand, India; E-mail: singhak@yahoo.com

ABSTRACT

An attempt has been made to carry out qualitative assessment of mine water discharges from the selected coal mining areas of Jharia, Raniganj and West Bokaro coalfields of Damodar Basin. 184 mine water samples were analyzed for pH, electrical conductivity (EC), major cations (Ca, Mg, Na, K), major anions (HCO_3, SO_4, Cl, NO_3), and heavy metals (Fe, Mn, Cu, Zn, Pb, Cr, Ni, Co, As). The hydrochemical data has been evaluated in terms of major ion chemistry, solute acquisition processes and suitability of mine water for domestic, industrial and irrigation uses. The pH of the analyzed mine waters varies from 6.8–8.5 indicating mildly acidic to alkaline nature of the water. The electrical conductivity (EC) values varied from 409 µS cm^{-1} to 2000 µS cm^{-1} for measured samples and spatial differences between the EC values reflects the wide variation in lithology, surface activities and hydrological regime prevailing in the region. The anion chemistry of the analyzed water samples shows the dominance of SO_4 and HCO_3 with minor contribution from Cl, NO_3 and F. The observed high values of sulphate in the mine water of the area may be attributed to the oxidative weathering of pyrites. On an average chloride is contributing 5-12% of the total anionic balance (TZ^-). Fluoride and nitrate have low concentrations and on average contributing <2% the total anions. The cation chemistry indicate that 40% of the samples are Mg>Ca>Na>K, while the 32% belong to Ca>Mg>Na>K and 24% of Na>Mg>Ca>K. The weathering and cation exchange processes normally control the levels of these cations. Concentrations of some heavy metals (Fe, Mn, Cr, Pb) are found to be well above the prescribed permissible levels recommended for the drinking water. The water quality assessment for drinking purposes indicate that most of the mine water having high TDS, total hardness (TH) and sulphate concentrations. This suggests that mine water of the study area is not suitable for direct use in drinking and domestic purposes and needs a proper treatment before its utilization. The assessment of water for irrigation uses show that the water is good to permissible quality and can be used for irrigation uses. However, high values of salinity, %Na, SAR, RSC and Mg-hazard at certain sites especially of Raniganj coalfield areas, restrict its suitability for agriculture uses.

1. INTRODUCTION

Surface mine development and underground mine working below piezometric level invariably changes the hydraulic gradient, thus affecting ground and surface water flow regimes vis-à-vis their quality and quantity. The presence of water in mining sites create a range of operational and stability problems and requires drainage to avoid slope stability problems and action to minimize oxidation of metallic sulfides and corrosion of mining machinery and equipment. The quality of the drainage water depends on a series of geological, hydrological and mining conditions, which vary significantly from mine to mine. Mining by its nature consumes as well as diverts water and can also pollute water resources of the area. The origin and impacts of mining on water resources arise at several stages of the mining cycle: the mining processes itself and/or at mineral processing and operational stage. It is one of the major activities causing water pollution and most of the mining areas are facing acute problems of potable water both in terms of quantity and quality. During mining operation huge quantities of water are generated and discharged in to natural drainages without any beneficial use, leaving these areas as water deficit.

Jharia and Raniganj coalfields are India's richest coal bearing areas and mining activities in this area started in the eighteenth century. Coal is exploited by both opencast as well as underground mining methods and during this process, a huge quantity of water is discharged from coal mines to the natural drainage to facilitate safe mining. By conservative estimate, BCCL (Bharat Coking Coal Ltd.) mines of the Jharia region discharge about 3,40,120 GPM (gallon per minutes) of mine water. The discharged mine water varies greatly in the concentration of contaminants present, and in some cases it may even meet the drinking water specification. Many times the discharged mine water as such is not usable and may contain unacceptable levels of heavy metals, toxic anions, organic and biological contaminants. However, by adopting a proper water management strategy, the water generated during mining operations may be harnessed and utilized for fulfilling local demand for domestic, industrial and irrigation water. However, for proper utilization and management of available water resources in mining areas, a baseline water quality data and continuous monitoring of water quality of the mining regions is a prerequisite.

In the present study, an attempt has been made to carry out an assessment of the quality of mine water discharges from the coal mining areas of Jharia, Raniganj and West Bokaro coalfields of Damodar Basin. One hundred and eighty four mine water samples were analyzed for pH, electrical conductivity (EC), major cations (Ca, Mg, Na and K), major anions (HCO_3, SO_4, Cl, NO_3), dissolved silica (H_4SiO_4) and heavy metals (Fe, Mn, Cu, Zn, Pb, Cr, Ni, Co, As). The hydrochemical data has been evaluated in terms of major ion chemistry, solute acquisition processes and suitability of mine water for domestic, industrial and irrigation uses.

2. STUDY AREA

The Damodar River basin area extends from $22^0 45'$ N to $24^0 30'$ N and $84^0 45'$ E to $88^0 00'$ E and includes 12% of the state of Jharkhand and 9% of the state of West Bengal. The catchment area of the Damodar basin is delineated by the Central Pollution Control Board as 23,170 Km^2. Though not rich in metallic minerals, the Damodar basin is regarded as the store house of Indian coal. Other than coal several other minerals are associated with the geological formations in the Damodar basin including mica, fire clay, bauxite, limestone, china clay, barite and iron stone. At least seven coalfields zone can be identified in the Gondowana trough of Damodar valley. These are (i) Jharia, (ii) Raniganj, (iii) West Bokaro, (iv) East Bokaro, (v) Ramgarh, (vi) South Karanpura and (vii) North Karanpura. Of all these coalfields, the Jharia and Raniganj have the largest concentration of workable coalmines (**Fig. 1**).

Fig. 1. Location of Jharia, Raniganj and West Bokaro coalfields

Jharia coalfield is extensively developed and is a major storehouse of much needed and scarce coking coal in India. The Jharia coalfield is situated in a sickle shaped sedimentary basin surrounded by Precambrian metamorphic rocks. The basin covers an area of about 453 sq km around Jharia town, while Dhanbad town lies just to the northeast of the metamorphic basin. The sedimentary rocks of the coalfields represent the Damuda Group of Gondwana Supergroup, an Upper Palaeozoic-Mesozoic sequence of glaciofluviatile origin. They lie unconformably over the Precambrian gneiss and schist and are pierced by igneous intrusive of Mesozoic-Tertiary age. The Gondwana sequence in the Jharia basin begins with Talchir Formation which is followed stratigraphically upwards by the Barakar, Barren Measures and Raniganj Formations. The Barakars are economically the most important member of Gondwana Group as they contain a number of thick and good quality coal seams. The formation comprises essentially felspathic sandstones of pebbly to very fine grain sizes with colors varying from white/grey to yellowish. The other lithological units are argillaceous and carbonaceous sandstones, arenaceous shale, intercalations of shale & sandstone, carbonaceous shales and coal seams. Two phases of deformation accompanied by igneous intrusion are believed to have occurred in this basin. The earlier (Lower Cretaceous) phase led to the intrusion of mica peridotite and the later (Palaeocene) one resulted in dolerite intrusion. The mica-peridotite occurs as dykes and sills all over the coalfield and has caused extensive deveolatilisation of coal seams.

The Raniganj coalfield lies in West Bengal and partly in Jharkhand states at the easternmost part of the Damodar valley coalfields (**Fig. 1**). It is the next only in importance to the Jharia coalfield. Raniganj coalfield is situated about 185 Km North-West of Kolkata. The Raniganj coalfield is the birth place of coal mining in the India and mining operation in this coalfield started in 1774. The Raniganj coalfield area covers about 1530 km^2, spreading over Burdwan, and Birbhum, Bankura and Purulia districts in West Bengal and Dhanbad district in Jharkhand. The Raniganj coalfield is a part of the Gondwana Supergroup. The Gondwana Formation here extends over an area of more than 1000 square km, occupying a roughly rectangular tract. A large part of the coalfield is occupied by Barakar and Raniganj Measures. The younger sedimentaries comprising Panchet and Supra Panchet Formation occur over a smaller area in the northern western part. The field is surrounded by Achaean rocks on all side except in the east where its boundary is not clear as it is covered over by alluvium. The Talchir formation is exposed in the north-west and northern border of the field and comprise of boulder bed at the base overlain by greenish sand stone and shales. Laterites and lateritic soils are mostly concentrated in the degradational and dissected uplands and riverine alluvial soils are found along the river stretches.

The West Bokaro coalfield covers an area of 207 km^2 in the Hazaribag district of Jharkhand. It is a major store house of medium coking coal. The West Bokaro coalfield forms a broad syncline with its axis trending E-W and exhibits a complete sequence of the lower Gondwana Formation which rest un-conformably on Archaean basement rock. The main coal bearing formations of this coalfield are the Barakar and Karharbari. Igneous intrusives in the form of mica-periodotite, lamrophyre and dolerite are reported from this coalfield.

3. MATERIALS AND METHODS

For the assessment of mine water quality of the Damodar Valley coalfields, systematic sampling was carried out during 2007-08. One hundred and eighty four representative mine water samples were collected from different mines of Jharia (97), Raniganj (51) and West Bokaro (36) coalfields. The mine water samples were collected from both underground as well as opencast mines in one liter narrow mouth pre-washed polyethylene bottles. For heavy metal analysis, 100ml samples were acidified with HNO_3 and preserved separately. Temperature, electrical conductivity (EC) and pH values were measured in the field using a 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 method was used to determine the concentration of bicarbonate (APHA 1992). Major anions (F, Cl, SO_4, NO_3) were analysed on ion chromatograph (Dionex DX-120) using anions AS12A/AG12 columns coupled to an anion self-regenerating suppressor (ASRS) in recycle mode. Major cations (Ca, Mg, Na, K) were also measured by ion chromatograph by using cation column (CS12A/CS12G) and cation self-regenerating suppressor (CSRS) in recycle mode. The analytical precision was maintained by running a known standard after every 10 samples. The overall precision (expressed as percent relative standard deviation - RSD) was below 10% for all samples. Concentration of heavy metals in acidified water samples were determined by ICP-MS (Perkin Elmer). The accuracy of the analysis was checked by analyzing the NIST 1643b water reference standard. The precision obtained in most cases was better than 5% RSD with comparable accuracy.

4. RESULTS AND DISCUSSION

Major Ion Chemistry

The general statistics of major and trace element geochemistry of mine water collected from underground and opencast mines of Jharia, Raniganj and West Bokaro Coalfields are summarized in **Table 1**.

Table 1. Statistical parameters of major and trace metal concentration in mine water of Jharia, Raniganj and West Bokaro Coalfields of Damodar basin and comparison of parameters with prescribed limits of WHO (1997) and BIS (1991) for drinking uses

Parameters	**Jharia Coalfield (n = 97)**				**Raniganj Coalfield (n = 51)**				**West Bokaro Coalfield (n = 36)**				**WHO (1997)**	**BIS (IS-10500)**	
	Min.	**Max.**	**Avg.**	**Std.Dev.**	**Min.**	**Max.**	**Avg.**	**Std.Dev.**	**Min.**	**Max.**	**Avg.**	**Std.Dev.**		**Highest desirable**	**Maximum permissible**
pH	6.20	8.60	7.67	0.53	7.50	9.10	8.21	0.37	4.27	8.43	7.63	0.75	7.0-9.5	6.5-8.5	No relaxation
EC (μS cm^{-1})	559	1653	1073	245	409	2000	991	292	276	1598	799	343			
TDS (mg l^{-1})	459	1568	948	243	336	1861	895	289	220	1502	695	338	1200	500	2000
F^- (mg l^{-1})	0.15	3.0	0.77	0.47	0.37	2.31	0.91	0.42	0.36	1.62	0.96	0.35	1.5	1.0	1.5
Cl^- (mg l^{-1})	1.3	260	50.4	41.6	10.6	206	54.2	42.2	2.4	38.8	12.1	8.7	250	250	1000
NO_3^- (mg l^{-1})	0.00	114.3	13.2	23.3	0.3	13.6	5.0	3.9	0.1	48.5	6.2	9.0	50	10	45
HCO_3^- (mg l^{-1})	33.3	732	301.3	173	89.2	1232	373.1	240.9	13.4	505	174.4	102.2	-	200	600
SO_4^{2-} (mg l^{-1})	18.0	806	343	193	0.3	586	213	176	4.2	950	331.3	260.9	250	200	400
Ca^{2+} (mg l^{-1})	20.4	182.1	94	35	6.9	134.8	60.7	42.1	29.2	250	93.5	53.8	-	75	200
Mg^{2+} (mg l^{-1})	4.8	157	74.6	36.1	2.6	134.7	59.9	44.9	8.9	119.9	49.4	29.6	-	30	100
Na^+ (mg l^{-1})	14.0	226	44.7	35.2	15.7	505	109.2	112.1	4.1	68.9	20.7	13.0	200	-	-
K^+ (mg l^{-1})	1.6	33.2	8.1	4.6	2.0	15.6	5.8	2.8	2.3	13.2	6.7	2.9	-	-	-
TH (mg l^{-1})	112	960	542	177	28	863	398	277	109	1118	437	244	500	300	600
Fe (μg l^{-1})	143	854	423	147	71.6	972.7	329	226	69.3	1682	652	385	300	300	1000
Mn (μg l^{-1})	4.5	1200	136	260	4.04	356	39.4	70.0	23.3	9920	1431	3196	500	100	300
Cu (μg l^{-1})	4.6	819	32.3	114.4	6.71	51.9	18.75	11.47	13.0	287	46.0	70.2	2000	50	1500
Zn (μg l^{-1})	12.8	1294	106.1	224	17.4	201.7	60.0	52.5	48.8	918	194	233	4000	5000	15000
Ni (μg l^{-1})	5.6	84.0	17.6	12.7	6.5	110.2	45.6	32.2	61.4	621	154	166	20	-	-
As (μg l^{-1})	0.2	48.3	3.4	8.0	0.75	128.7	10.06	24.5	2.88	33.4	7.21	7.84	10	50	No relaxation
Co (μg l^{-1})	0.1	20.1	1.2	2.8	0.09	6.2	0.95	1.15	1.0	382	34.1	101	-	-	-
Cr (μg l^{-1})	4.7	14.7	8.1	2.8	5.20	83.4	44.6	30.9	60.5	178	81.2	28.8	50	50	No relaxation
Pb (μg l^{-1})	6.1	35.9	14.9	6.9	10.2	61.1	22.6	10.92	25.6	47.6	34.3	6.6	10	50	No relaxation
SAR (epm)	0.3	7.7	1.0	1.1	0.3	41.6	4.9	8.0	0.1	1.5	0.5	0.3	-	-	-
%Na (epm)	6.3	77.8	17.3	12.6	6.6	97.5	38.4	32.7	4.5	38.7	13.0	8.4	-	-	-
RSC (epm)	-5.8	9.5	-0.5	3.0	-6.2	19.9	2.1	6.0	-9.1	2.4	1.5	2.9	-	-	-
MH (%)	7.8	81.4	54.8	16.0	28.4	90.6	57.5	12.2	28.8	63.1	45.3	9.4	-	-	-

EC = Electrical Conductivity, TDS = Total Dissolved Solids, SAR = Sodium Adsorption Ratio, RSC = Residual Sodium Carbonate, MH = Magnesium Hazard

In general, pH of water samples is slightly acidic to alkaline in nature and the mean value of pH for the mine water of Damodar valley coalfield is 7.81. The pH of the analysed samples varies from a low of 6.17 in mine water of West Bokaro to 8.43 again found in the mine water of West Bokaro coalfield. The electrical conductivity (EC) values varied from 559 µS cm^{-1} to 1653 µS cm^{-1} for Jharia mine water, 409 µS to 2000 µS cm^{-1} in Raniganj and 276 µS cm^{-1} to 1598 µS cm^{-1} in West Bokaro mine water samples with average value of 1073 µS cm^{-1}, 991 µS cm^{-1} and 799 µS cm^{-1} respectively. The total dissolved solids (TDS), which is sum of the dissolved ionic concentration varies between 459-1568 mg l^{-1} (Avg. 948 mg l^{-1}) in Jharia mine water to 336-1861 mg l^{-1} (Avg. 895) in Raniganj and 220-1502 mg l^{-1} (Avg. 695 mg l^{-1}) in West Bokaro mine water. The mean value of the TDS for entire study area is 878 mg l^{-1}. The large variations in the EC, TDS and ionic concentrations in the mine water resource of the area may be attributed to lithological variation, geochemical processes and hydrological condition of the mines.

The cation chemistry is dominated by magnesium and calcium in the mine water of the Jharia and West Bokaro coalmines and sodium and magnesium in the mine waters of Raniganj coalmining areas. The cation chemistry indicate that 40% of the samples are Mg>Ca>Na>K, while the 32% belong to Ca>Mg>Na>K and 24% of Na>Mg>Ca>K (**Fig. 2a**) Weathering of rock forming minerals and cation exchange processes normally control the levels of these cations. High concentration of Ca and Mg in the waters are attributed to the weathering of crystalline dolomitic limestones and Ca-Mg silicates (amphiboles, pyroxenes, olivine, biotite). The dolomitic limestones usually occur as isolated bands and lenticles of varying dimensions in the study area, while the basic rocks occur as Archean lavas and basic intrusive at some places (Ghosh 1983). Concentration of potassium is low and least dominant cation in the mine waters of Damodar valley coalfields. The sodium and potassium in the aquatic system is derived from the atmospheric deposition, evaporite dissolution and silicate weathering. The weathering of Na and K silicate minerals like albite, anorthite, orthoclase and microcline may be the possible source of the Na and K in the present study area. In addition, dissolution of Na/K salts developed in the drainage basin due to cycling wetting and drying phase during high and low flow regime of Damodar River may also contributed some amount of Na and K.

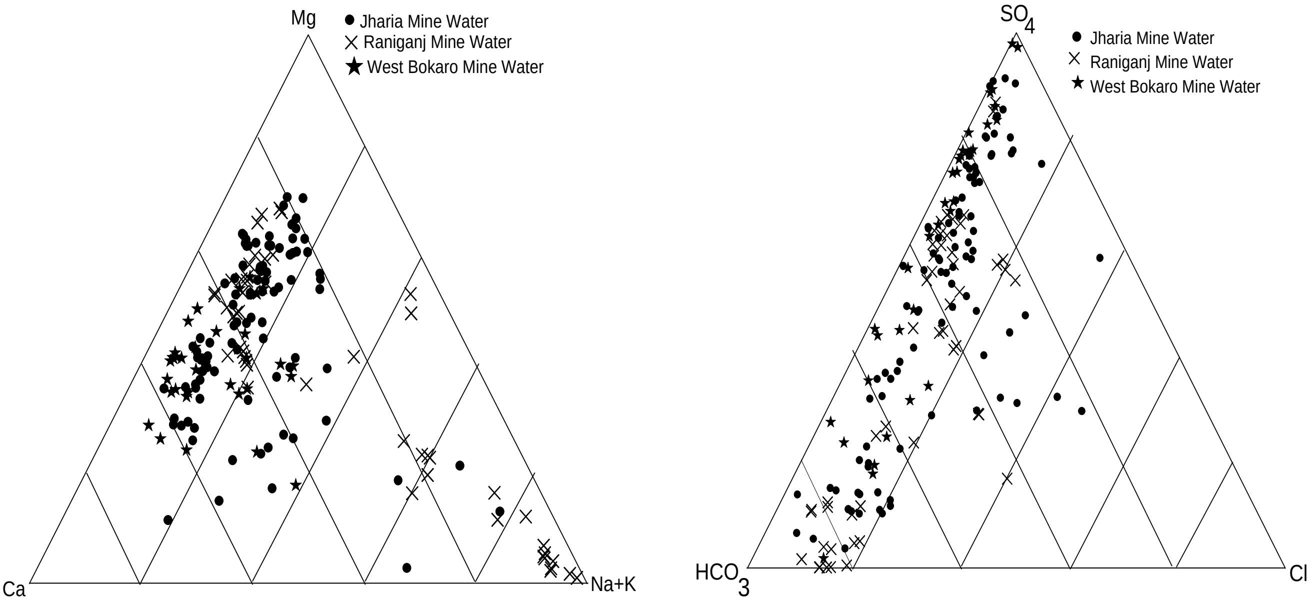

Fig. 2. (a) Cations and (b) Anions triangular diagrams

The anion chemistry shows that HCO_3 and SO_4 are the dominant anions in the mine water of Domodar valley coalfields with minor contribution from Cl (**Fig. 2b**). In the samples of mine water, concentration of bicarbonate varies from a minimum of 33 mg l^{-1} to a maximum value of 732 mg l^{-1} in Jharia (Avg. 301 mg l^{-1}). Its concentration ranges between 89 to 1232 mg l^{-1} (Avg. 373 mg l^{-1}) in the Raniganj area and 13 to 505 mg l^{-1} in the West Bokaro coalmines. Bicarbonate contributes on an average 37%, 50% and 34% to the total anions (TZ^-) in the Jharia, Raniganj and West Bokaro mine waters respectively. Bicarbonates are derived mainly from the soil zone CO_2 and dissolution of carbonates and reaction of silicates with carbonic acid. The soil zone in the subsurface environment contains elevated CO_2 pressure (produced as result of decay of organic matter and root respiration), which in turn combines with rainwater to form bicarbonate by the following reactions:

$$CO_2 + H_2O = H_2CO_3$$
$$H_2CO_3 = H^+ + HCO_3^-$$

Bicarbonate may also be derived from the dissolution of carbonates and/or silicate minerals by the carbonic acid from the reactions:

$CaCO_3 + H_2CO_3 = Ca^{2+} + 2HCO_3^-$
Limestone
$CaMg(CO_3)_3 + 2H_2CO_3 = Ca^{2+} + Mg^{2+} + 4HCO_3^-$
Dolomite
$2NaAlSi_3O_8 + 2H_2CO_3 + 9H_2O = Al_2Si_2O_5(OH)_4 + 2Na^+ + 4H_4SiO_4 + 2HO_3^-$
Albite Kaolinite

Sulphate is the dominant anion in a numbers of mine water samples, especially of Jharia and West Bokaro coalfields. Concentration of sulphate varies from 18 to 806 mg l^{-1} in Jharia with average value of 343 mg l^{-1} and contributing about 50% (4-90%) towards the total anionic balance in equivalent unit. In Raniganj mine water, it follows the HCO_3 abundance and contributing 37% to the total anions. SO_4 constitute 59% of the total anionic balance and its concentration varies 4.2 to 950 mg l^{-1} (average 331 mg l^{-1}) in West Bokaro mine water. On a global basis, one third of the SO_4 in aquatic systems derived from rock weathering, about 60% from fossil fuel combustion and minor amounts from volcanism (5%) and cycling salts (2%). Rock weathering sources include two major forms of sulphur in sedimentary rocks, pyrite i.e-FeS_2 and gypsum i.e.-$CaSO_4$ (Berner and Berner, 1987). Pyrite (FeS_2) occurs as a secondary mineral in the Gondwana coals and associated sediments of the area. The observed high values of sulphate in the mine waters of the study area may be attributed to the oxidative weathering of pyrites by the reaction sequence (Lowson and others 1993):

$2FeS_2 + 7O_2 + 2H_2O = 2Fe_2^+ + 4SO_4^{2-} + 4H^+$
Pyrite

$4Fe^{2+} + O_2 + 4H^+ = 4Fe^{3+} + 2H_2O$

$FeS_2 + 14Fe^{3+} + 8H_2O = 15Fe^{2+} + 2SO_4^{2-} + 16H^+$

where the first step represents the initiation reaction and the other two steps represent propagation reactions. High concentration of sulphate in ground and mine water from mining belt of Jharia region is also reported by other workers (Choubey 1991; Tiwary 2001, Singh et al., 2008).

The chloride concentration in the analysed samples varies between 1.3 to 260 mg l^{-1} in Jharia, 11 to 206 mg l^{-1} in Raniganj and 2.4 to 39 mg l^{-1} in West Bokaro mine water with mean concentration of 50, 54 and 12 mg l^{-1} respectively. Chloride constitutes 11%, 12% and 5% of the total anions (TZ^-) respectively in Jharia, Raniganj and West Bokaro coalmining areas. Many minerals may contain small amount of chloride as an impurity. Chloride is present in lower concentrations in common rock types than any of the other major constituents of natural water. It is assumed that bulk of the chloride in groundwater derived primarily from halite, sea spray, brines and hot springs. Abnormal concentration of chloride in the study site may result from anthropogenic sources including agricultural runoff, domestic and industrial wastes and leaching of saline residues in the soil (Appelo and Postma 1993). Concentration of fluoride and nitrate is found to be low in most of the samples and only a few samples, exceeds the 1.5 mg l^{-1} and 45 mg l^{-1} limits for drinking uses. Fluoride ions have dual significance in water supply. High concentration of fluorides (F^-) causes dental flurosis (disfigurement of the teeth). The formation of fluoride complex may be important in solublizing beryllium, aluminium, tin and iron in natural water and are also contribute to aquatic fluoride. The fluoride in waters may be derived from the weathering of rocks and phosphatic fertilizers used in agriculture. Fluoride occurs naturally as fluorspar (fluorite), rock phosphate, triphite, phosphorite and other minerals. Among the factors which control the concentration of fluoride are the climate of the area and the presence of accessory minerals in the rock mineral assemblage through which the groundwater is circulating. The fluoride is usually derived from the weathering of fluoride bearing rock forming minerals like muscovite, biotite, fluorite and fluoro-apatite but the low concentration of fluoride in the study area indicates limited lithogenic input of this ion into the water. There are three major sources of nitrogen in the water - biological fixation, precipitation, and the application of fertilizers. Human activities have also influenced the nitrogen load considerably. However, in the present case, the observed higher concentration of dissolved nitrate in some mine water samples may be related to past exploitation processes such as the use of explosives and wood in the mining workings.

Heavy Metal Distribution

Table 1 show the concentration range of heavy/trace metals analyzed in the acidified mine water samples collected from some selected sites in the Jharia, Raniganj and West Bokaro coalfields. In the water samples studied, Fe, Zn and Mn are the most dominant metals. In Jharia coal mine water, concentration of Fe ranged from a minimum of 143 $\mu g\ l^{-1}$ to a maximum of 845 $\mu g\ l^{-1}$, Mn from 4.5 to 1200 $\mu g\ l^{-1}$ and Zn from 12.8-1294 $\mu g\ l^{-1}$. Concentration of Fe, Mn, Cu and Cr also exceed the WHO (1997) and BIS (1991) limits in a number of mine water samples of Raniganj and West Bokaro coalfields. Concentration of Zn, Co, Ni, Cd, and As are found well within the threshold values except in a few samples. The presence of higher concentration of heavy metals in discharged mine water may cause contamination of other water resources in the area which would expose the population to the health hazards like hypertension, cancer and gastrointestinal disorder.

Water Quality Assessment

The data obtained by chemical analyses were evaluated in terms of its suitability for drinking and general domestic use, livestock use and irrigation use.

(i) Suitability for drinking and general domestic uses

To assess the suitability for drinking and public health purposes, the hydrochemical parameters of the mine water of the study area are compared with the prescribed specification of WHO (1993) and the Indian standard for drinking water (BIS, 1991). **Table 1** show that the values of TDS and EC exceed the permissible limit in most of the mine water samples, indicating higher concentrations of dissolved ions. The total hardness (TH) of the analysed mine water samples varies between 112 to 960 mg l^{-1} (Avg. 542 mg l^{-1}) in Jharia, 28 to 863 mg l^{-1} (Avg. 398 mg l^{-1}) in Raniganj and 109 to 1118 mg l^{-1} (Avg. 437 mg l^{-1}) in West Bokaro indicating hard to very hard types of water. Hardness of the water is a property attributable to the presence of alkaline earths i.e. Ca and Mg (Brown et al., 1970). The data indicate that 35% of Jharia, 33% of Raniganj and 30% of West Bokaro mine water have TH values higher than 600 mg l^{-1}, which is the maximum permissible limit as per IS-10500 (BIS 1991). Hardness has no known adverse effect on health but it can prevent formation of lather with soap and increases the boiling point of water. High TH may cause the encrustation on water supply distribution systems. There is some evidence that drinking extremely hard water might lead to an increased incidence of Urolithiasis (Bokiana, 1965). Concentrations of sulphate are found to be higher that the permissible limits of 400 mg l^{-1} in a 43%, 18% and 33% of the samples respectively of Jharia, Raniganj and West Bokaro coalfields, restricting its direct uses for drinking purposes. High sulphate concentration with excess of Mg may cause a laxative effect on the human system. It may also contribute to the corrosion of metals in the distribution system, particularly in waters having low alkalinity. Nitrate exhibits undesirable effects when present in water for potable supply. Concentration of nitrates exceeds the desirable limits in about 10% of the analysed samples. High concentration of nitrate levels can cause methaemoglobinaemia in infants and gastric carcinomas (Comly 1945, Gilli and others 1984)

(ii) For used for livestock

Irrigation canal, ponds, river and reservoir water may serve as water supplies for livestock. The data in Ayers and Wescot (1985) and Shuval et al. (1986) indicates that water salinity <1500 mg l^{-1} and Mg <250 mg l^{-1} is suitable for drinking by most livestock. The mine water of the present areas meets these standards and suitable for livestock drinking purpose with a few exceptions where TDS exceeds the 1500 mg l^{-1} limit.

(iii) Suitability for irrigation uses

The important characteristics or properties of water to be considered for irrigation use are electrical conductivity, salinity, percent sodium, sodium adsorption ratio, residual sodium carbonate and magnesium hazard.

(a) Electrical conductivity (EC) and sodium percentage (Na %)

Electrical conductivity (EC) and sodium concentration are very important in classifying irrigation water. Water used for irrigation always contains measurable quantities of dissolved substances, which in general are called salts. They include relatively small but important amounts of dissolved solids originating from the weathering of rocks and soils and from dissolution of lime, gypsum and other salt sources as water flows over or percolates through them. The salts present in the water, besides affecting the growth of plants directly, also affects soil structure, permeability and aeration, which indirectly affects plant growth. The sodium percentage (Na %) in the water samples of mine water is calculated by the equation :

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

The sodium percentage (Na %) in the study area ranges between 6.3-77.8% (Avg. 17.3%) in Jharia, 6.6 to 98% (Avg. 38%) in Raniganj and 4.5-38.4% (Avg. 13%) in West Bokaro coal mine waters. The high %Na causes deflocculation and impairment of the tilth and permeability of soils (Karanth 1987). As per the Indian Standard (BIS 1991), a maximum sodium percentage of 60% is recommended for irrigation water. The plot of electrical conductivity and sodium percent on the Wilcox (1955) diagram shows that mine water of Jharia and West Bokaro coalfields are excellent to good and good to permissible quality and can be used for irrigation purposes. High sodium percentage in mine waters of Raniganj coalmines places it in the doubtful to unsuitable category and restricts its direct use for irrigation purposes (**Fig. 3**).

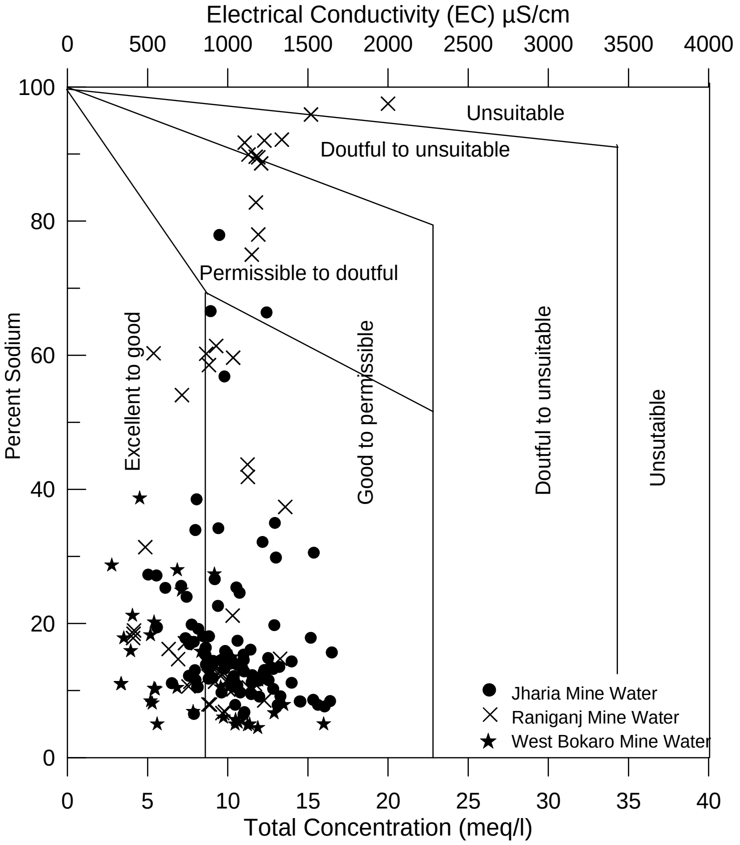

Fig. 3. Wilcox diagram relating electrical conductivity (EC) and sodium percent (%Na)

(b) Alkali and Salinity Hazard (SAR)

The salinity or total concentration of soluble salts in irrigation water can be expressed for the purpose of classification of irrigation water as low (EC = <250 µS cm^{-1}), medium (250-750 µS cm^{-1}), high (750-2250 µS cm^{-1}) and very high (2250-5000 µS cm^{-1}). While high salinity (high EC) in water leads to formation of saline soil, a high sodium concentration leads to development of an alkaline soil (Richards, 1954). Excessive solutes in irrigation water are a common problem in semiarid areas where water loss through evaporation is maximal. Salinity problems encountered in irrigated agriculture are most likely to arise where drainage is poor which allows the water table to rise close to the rooting zone of plants causing the accumulation of sodium salts in the soil solution through capillary rise following surface evaporation of water. The sodium or alkali hazard in irrigation water is determined by the absolute and relative concentration of cations and is expressed in terms of sodium adsorption ratio (SAR) and it can be estimated by the formula:

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

There is a significant relationship between SAR values of irrigation water and the extent to which sodium is adsorbed by the soils. If water used for irrigation is high in sodium and low in calcium, the cation-exchange complex may become saturated with sodium. This can destroy the soil structure owing to dispersion of the clay particles. The calculated value of SAR in the study area ranges from 0.3-7.7 in the Jharia, 0.3-28.5 in Raniganj and 0.1 -1.5 in the West Bokaro mine waters. The plot of data on the US salinity diagram, in which the EC is taken as salinity hazard and SAR as alkalinity hazard, shows that water samples fall in the category C2S1, C3S1, C3S2, and C3S3, indicating medium to high salinity and low to high alkali water (**Fig. 4**). High salinity water cannot be used on soils with restricted drainage and it requires special management for salinity control and plants with good salt tolerance should be selected for such area. Low sodium water (S1) can be used for irrigation on almost all soils with little danger of the development of harmful levels of exchangeable sodium. Medium sodium water (S2) will present an appreciable sodium hazard in fine textured soils having high cation exchange capacity. This water can be used on coarse textured or organic soils with good permeability. High sodium water (S3) may produce harmful levels of exchangeable sodium in most soils and will require special soil management including good drainage, high leaching and organic matter additions.

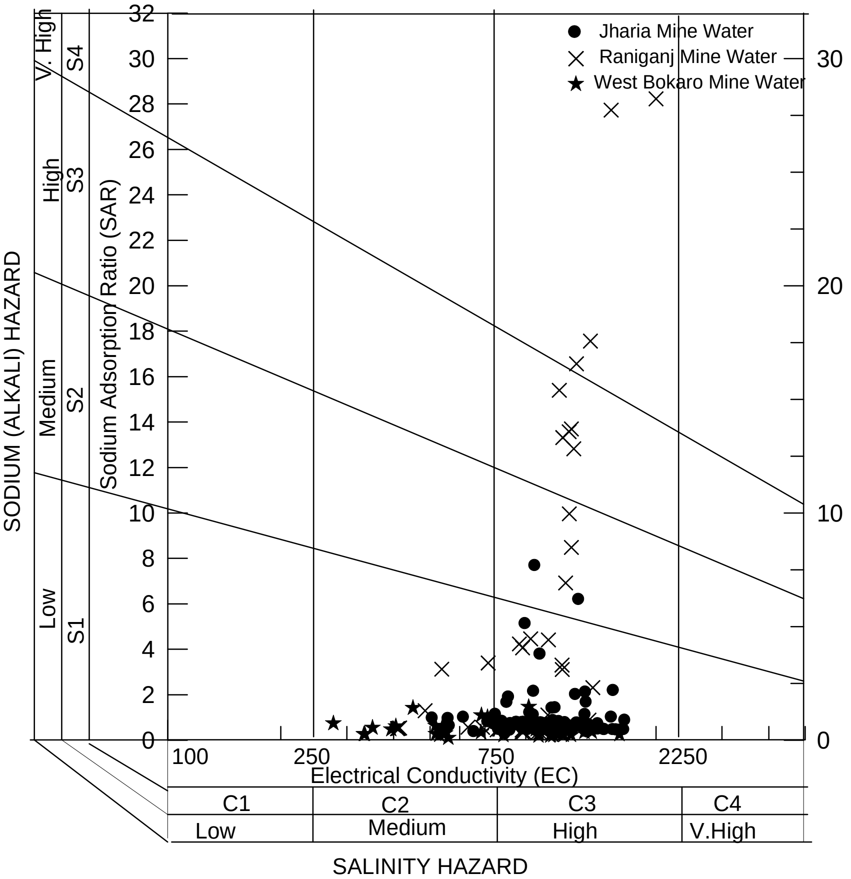

Fig. 4. The plot of data on the US salinity diagram (After Richards 1954)

(c) Residual Sodium Carbonate (RSC)

When the sum of carbonates and bicarbonates is in excess of calcium and magnesium, precipitation Ca and Mg may occur (Raghunath 1987). To quantify the effects of carbonate and bicarbonate, residual sodium carbonate (RSC) has been computed by the equation:

$$RSC = (CO_3 + HCO_3) - (Ca + Mg) \text{ in meq/l}$$

A high value of RSC in water value leads to an increase in the adsorption of sodium on soil (Eaton 1950). Irrigation waters having RSC values greater than 5 meq l^{-1} have been considered harmful to the growth of plants, while waters with RSC values above 2.5 meq l^{-1} are not considered suitable for irrigation purpose. In most of the analysed water samples, RSC values are found below 5.0 meq l^{-1} and suitable to marginally suitable for irrigation. However, about 10% of the analysed mine water samples, especially collected from the Raniganj coalmining areas having RSC values higher than the 5.0 meq l^{-1} limit. This indicates that these waters are marginally suitable to unsuitable for irrigation uses.

(d) Magnesium Hazard (MH)

Szabolcs and Darab (1964) have proposed a Magnesium Hazard (MH) for irrigation water given by:

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

Waters with MH >50 are considered to be harmful and unsuitable for irrigation use. In the analysed waters, 65% of the mine water samples have MH >50 indicating that mine water discharges from these mines should not be used for irrigation uses without treatment.

5. CONCLUSIONS

The mine water of the Damodar Valley coalfields is mildly acidic to alkaline in nature. The chemistry of the mine water is dominated by Mg-Ca-SO_4-HCO_3, Na-Mg-HCO_3-SO_4 and Ca-Mg-SO_4-HCO_3 hydrochemical facies in the Jharia, Raniganj and West Bokaro coalfields respectively. Weathering of rock forming minerals and anthropogenic contribution from mining related activities are the major controlling factors for water chemistry. The quality assessment shows high values of EC, TDS, TH, SO_4, Fe, Mn, Cu and Cr in a number of samples which make them unsafe for drinking purposes as such. These waters can be used for domestic uses after proper treatment and disinfection. The assessment of water quality for irrigation use shows that mine water of Jharia and West Bokaro coalfields are excellent to good and good to permissible quality and can be used for irrigation without any hazard with few exceptions. However, high values of salinity and alkali hazard, Mg-hazard and %Na at many sites especially samples collected from Raniganj coal mining areas restrict the suitability of water in this area for agriculture and demands suitable water management and treatment.

6. REFERENCES

APHA.AWWA.WPCF (1992) Standard methods for the examination of water and waste water, 16th edition. Washington D.C., APHA

Appelo, C.A.J. and Postma, D. (1993) Geochemistry, groundwater and pollution. AA Balkema Publ. USA

Ayers, R.S. and Wascot, D.W. (1985) Water quality for irrigation. FAO Irrigation and Drainage Paper No. 20, Rev.1, FAO, Rome.

Berner, E.K.and Berner, R.A. (1987) The global water cycle: geochemistry and environment. Prentice-Hall, Englewood Cliffs.

BIS (1991) Indian Standards Institution - Indian standard specification for drinking water IS: 10500.

Bokiana (1965) In guidelines for drinking water quality, WHO, 1984

Brown, E., Snougsted, M.W. and Fisgmen, M.J. (1970) In techniques of water resources investigations of US Geological Survey. Book 5, US Govt. Printing Office, Washington DC.

Choubey, V.D. (1991) Hydrological and environmental impact of coal mining, Jharia coalfield, India. Environ. Geol. 17, 185-194

Comly, H.H. (1945) Cyanosis in infants cased by nitrates in well water. J. Am. Mwd. Assoc. 129, 112-114

Eaton, F.M. (1950) Significance of carbonates in irrigation waters. Soil. Sci. 39, 123-133.

Gilli, G., Corrao, G. and Favilli S.A. (1984) Concentration of nitrates in drinking water and incidence of gastric carcinomas: First descriptive study of the Piemonate Region, Italy. Sci. Total. Environ. 34, 35-37

Karanth, K.R. (1989) Ground water assessment development and management. Tata McGraw Hill Publ., New Delhi

Lowson, R.T., Reedy, B.J. and Beattie, J. K. (1993) The chemistry of acid mine drainage. Chem. Aust. 60, 389-391

Raghunath, H.M. (1987) Ground Water. Wiley Eastern Ltd. Delhi, India

Richards, L.A.. (1954) Diagnosis and improvement of saline and alkali soils, U.S. Dept. Agri. Hand Book, No. 60

Shuval, H.I., Adin, A., Fiatal, B., Raawitz, E. and Yekuterl, P. (1986) Wastewater irrigation in developing countries. Health Effects and Technological Solutions. World Bank Technical Paper, 52. Washington DC.

Singh, A.K., Mondal, G.C., Kumar, S., Singh, T.B., Tewary, B.K. and Sinha, A. (2008) Major ion chemistry, weathering processes and water quality assessment in upper catchment of Damodar River basin, India. Environ. Geol. 54, 745-758.

Szabolcs, I. and Darab, C. (1964) The influence of irrigation water of high sodium carbonate content of soils. In. Proc. 8th Intern. Congress of Isss, Trans, II:803-812.

Tiwary, R.K. (2001) Environmental impact of coal mining on water regime and its management. Water. Air. Soil. Pollu. 132, 185-199

WHO (1997) Guidelines for drinking-water quality, V.1, Recommendations, World Health Organisation, Geneva, WHO, pp1-4.

Wilcox, L.V. (1955) Classification and use of irrigation waters, USDA. Circular. 969, Washington, D.C., USA