

Mineral-Water Interfacial Reactions and Their Effect on Elemental Mobilisation

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Received January 30, 2015; revised and accepted October 1, 2015

Abstract: Laboratory measurements of water samples from a range of environments in the Bhilai region demonstrated the ability to identify characteristic features of groundwater quality. This study focusses on geology and hydrology of the studied site to evaluate the ability to locate the source of contamination, either geological or concentration of mine drainage or industrial pollution causing adverse quality of potable water in some areas of this region. Monitoring the groundwater at periodic intervals over a two-year period provided information on the production and transport of pollutant. During analysis of the water samples concentration of redox species such as Fe^{2+} and S^{2-} were found significantly above their detection limits. Anomalous high concentration of ferrous iron Fe^{2+} (65 ppm) and sulphide S^{2-} (24 ppm) witnessed in various areas are indicative of the reducing conditions of the ground water. The majority of bore wells and hand-pump samples clustered towards the Ca-Mg-HCO_3 regime of the phase diagram. In contrast to increased concentrations of Fe^{2+} , an increased alkalinity up to 700 ppm has been observed which makes the study significant. A correlation study indicated that the iron and sulphide anomaly is primarily related to point source contamination.

Key words: Groundwater quality, sedimentary basin, ferrous, sulphide, landfills.

Introduction

Ground water is a basic resource that is often naturally or anthropogenically contaminated by microorganisms, disinfectants, inorganic and organic chemicals, and radionuclides (USEPA, 2004). The iron occurs naturally in the aquifer but levels in ground water can be increased by dissolution of ferrous borehole and handpump components. Iron-bearing groundwater is often noticeably orange in colour, causing discolouration of laundry, and has an unpleasant taste, which is apparent in drinking and food preparation (Tyrrel et al., 1998). The average crustal abundance of iron is 5% by weight. The iron content of soils is typically in the range of 0.5% to 5%, and is dependent upon the source rocks from which the soil was derived, transport

mechanisms, and overall geochemical history. Not only is iron common, but it is also reactive and readily reflects changes in surrounding Eh/pH conditions.

The Bhilai city encompasses about 1395 acres in the Durg city of Chattisgarh (Figures 1 and 2). With all the industrial activities, it is obvious that Bhilai has a high potential for environmental pollution. Yet almost no reported literature was obtained on the current status of groundwater pollution in Bhilai. To gain an insight of the groundwater contamination a systematic monitoring of the ground water in and around Bhilai was conducted. The analysis of the ground water focusses on geology and hydrology of the studied site to evaluate the ability to locate the source of contamination, either geological or concentration of mine drainage or industrial pollution causing adverse quality of potable water in some areas

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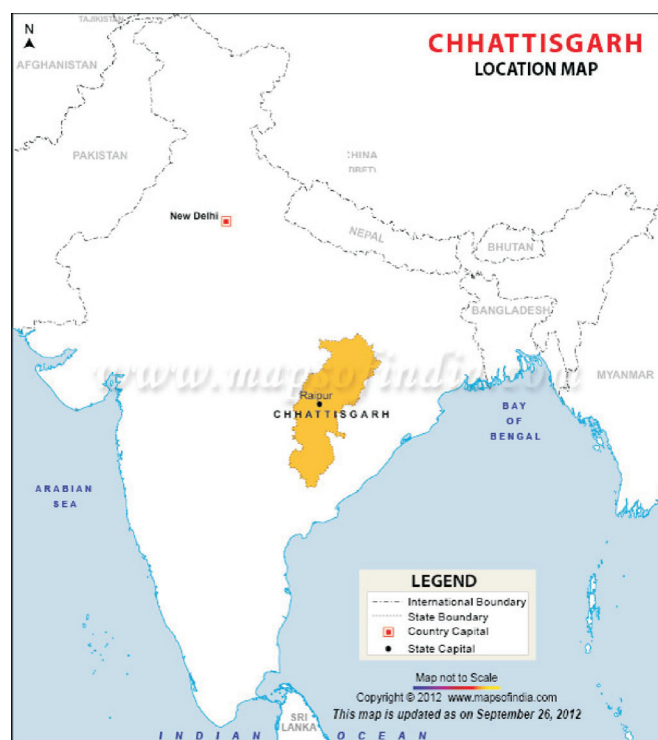


Figure 1: Map of India showing Chhattisgarh.

of this region. Under this study we have investigated the status of ground water in the rural and urban areas adjoining Bhilai Steel Plant (BSP). Bhilai steel plant area is spread over an area of 27.36 km². Bhilai is situated at 21°13'N latitude and 81°26'S longitude and has a population of 6.25 lakhs (Census - 2011.co.in). The rocks of this area belong to a complex sedimentary suite of precambrian regime (Figure 2).

Chhattisgarh is a major Proterozoic (Purana) basin (Holland, 1906) in the central part of the Indian craton and comprises a thick succession of sandstone, shale and limestone, known as the Chhattisgarh Supergroup (Naqvi and Rogers, 1987; Murti, 1987; Das et al., 1992; Datta, 1998; Das et al., 2001). Establishment of Bhilai Steel Plant and the development of large number of dependent industries brought about an industrial revolution in Chhattisgarh. The world's best quality of iron ore is found in Bailadila deposits of Dantewara district in Chhattisgarh. The other important deposits of iron ore are located in Kanker, Durg and Rajnandgaon districts (Directorate of Geology & Mining). During the processing of iron ore from the mine to the rolling mill, 10% of the iron ore used to make these billion tons of steel is thrown away as waste. Precipitation and groundwater seeping through this waste produces leachate, which is contaminated from the various organic and inorganic substances with which it comes

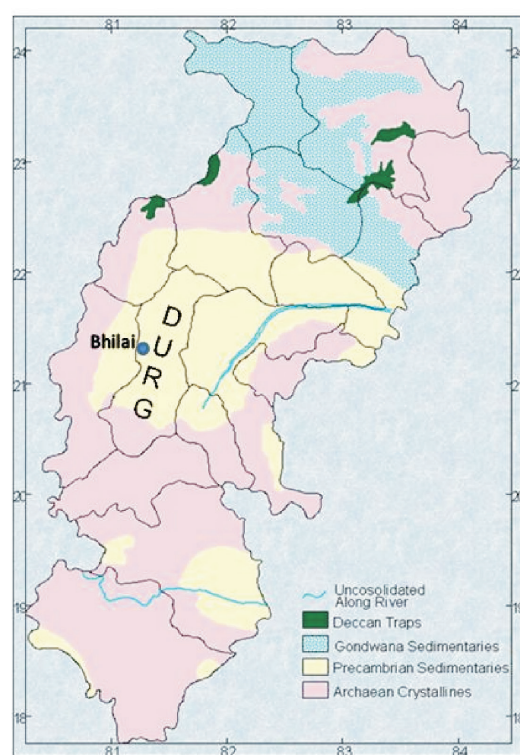


Figure 2: Geologic cross-section of Chhattisgarh (adapted from CGWB, Raipur).

in contact as it migrates through the waste. Leachate seeping from a landfill contaminates the ground water beneath the landfill, forming a plume. The normal movement of ground water causes the leachate plume to extend away from a landfill, in some cases for many hundreds of metres.

Iron enriched in bodies is considered to have been formed by either magmatic or hydrothermal processes; by far the most extensive anomalous concentrations are found in the group of sedimentary rocks. The Durg-Bhilai region is rich in mineral deposits especially iron-ore, limestone and quartzite. The ground water occurs under unconfined conditions in all lithological conditions as also in deep fractured zones of granite rocks. Due to the presence of sedimentary basin in this area the aquifers are at greatest risk from contamination.

Natural water quality problems are caused mainly by iron, manganese, hydrogen sulphide and hardness. When investigating the water quality, these parameters were used to indicate possible contamination: electrical conductivity, chloride, sulphate, iron as good indicators of contamination. Out of 16 samples analyzed from various sectors of Bhilai (Figure 3), 13 sites were found to be contaminated with iron, with a maximum concentration of 65 ppm. These contaminated sites were given frequent and close examination to understand the

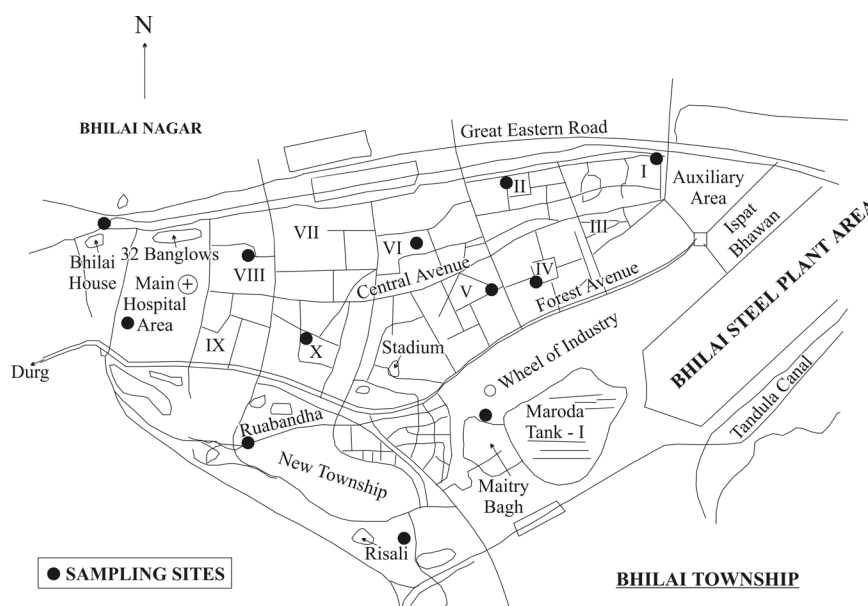


Figure 3: Map of sampling locations of Bhilai township.

geochemical operators. The study shows a substantial presence of iron and sulphide species even at neutral and near-neutral conditions where the groundwater is supposed to be in equilibrium.

Analysis Procedure

On-site analysis of pH, temperature, conductivity, total dissolved solids and oxidation-reduction potential were conducted using a portable water testing kit (Macro Scientific), which was calibrated earlier. Rest of the parameters was analyzed in the laboratory after transporting the samples to the laboratory. The results of pH, conductivity, TDS and ORP measured by using water testing kit were verified by measuring with the regular analytical equipments. The pH and ORP were determined by using pH and mV electrode (Orion, USA). TDS and conductivity were measured using conductivity meter. The analytical techniques for the determination of some other elements included the following: Flame photometer (Toshniwal) was used for the determination of Na^+ and K^+ , Ca^{2+} and Mg^{2+} were determined by titration procedure, Cl^- by Argentometric method, iron and manganese by spectrophotometric method. Turbidity method was used to determine SO_4^{2-} and NO_3^- was determined spectrophotometrically.

Reagents

Analytical reagent grade chemicals (Merck, Germany/India) were used in all tests. Deionized and double distilled water was used in all the analysis. All

references to water in the method refer to reagent water unless otherwise specified. Acid viz. HNO_3 , H_2SO_4 , HCl etc. were analysed to determine the level of impurities. Stock solutions of the elements were prepared using standard procedure (APHA, 1992).

Result Analysis

pH Variation

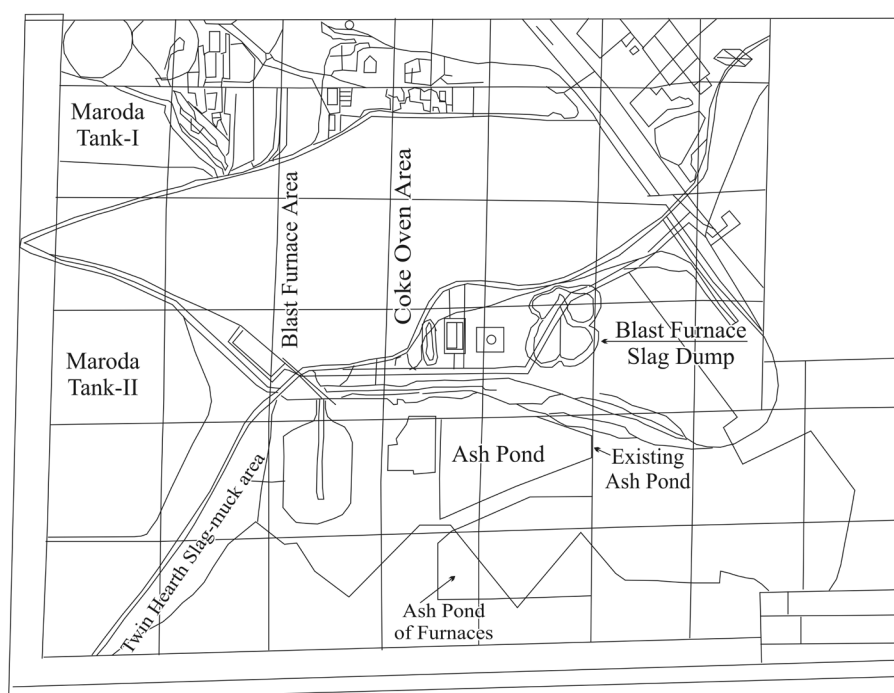
The pH in almost every location varied in the range of 6.59 to 7.6 and the lower pH was measured at the industrial zone i.e. near the vicinity of the Bhilai Steel Plant area (Table 1). This lowering pH towards the plant area is hypothesized to the probable dumping of solid/liquid wastes that may be acidic in nature. The basis for this hypothesis lies in fact that the Bhilai Steel Plant is having a sulphuric acid plant (DC-DC Technology). This plant produces 140 tons sulphuric acid per annum. This acid is used for recovery of ammonia from the bye-product plant of coke-ovens as shown in Figure 4. Similarly one more source of acidic waste could be the pickling/etching process generally carried out in steel plants. All such sources may generate a huge amount of acidic waste which is frequently dumped in the landfill. These landfill are appearing to be prima-facie responsible for the appearance of iron and sulphide in ground water of Bhilai.

The decrease in the pH of the ground water in the vicinity of the industry may be due to continuous seepage of these acids from landfills. As we proceed downwards the slope of the area, in the midway i.e.

Table 1: Synoptic sampling at various locations in the industrial zone (2004-2006)

Locations	pH	Cond	Fe ³⁺	Fe ²⁺	Mn ²⁺	Na ⁺	K ⁺	S ²⁻	SO ₄ ²⁻	Cl ⁻	NO ₃ ⁻	Hard	Ca ²⁺	Mg ²⁺	Alk	ORP	TDS
Sect I	6.59	0.47	7.8	3.2	ND	10.1	0.0	16	10	40	0.54	200	88	9.6	412	272	235
Sect II	6.9	0.52	1.5	0.75	ND	30.8	9.9	20	29	60	0.85	160	56	14.4	362	264	257
Sect III	7.05	0.57	0.87	1.52	ND	27.2	2.5	16	16	70	0.42	200	64	14.4	340	256	292
Sect IV	6.84	0.53	0.55	0.29	ND	32.6	3.9	16	19	60	0.41	240	88	14.4	325	218	268
Sect V	6.9	0.43	0.96	0.90	ND	54	3.6	20	16	40	0.28	200	64	14.4	300	215	218
Sect VI	7.6	0.51	0.22	0.97	ND	60.3	3.4	28	16	40	0.11	200	56	24	300	211	259

Cond: Conductivity, Hard: Hardness, Alk: Alkalinity (Conc. in ppm)

**Figure 4: Landfill and waste disposal site in the premises of Bhilai Steel Plant.**

the central zone, still the iron is surprisingly high, with neutral pH (7.01 - 8.36) as shown in, probably because H⁺ ions are neutralized by the alkalinity of the receiving water without the removal of the accompanying metal ion (Table 2). The pH of the boundary zone varied from 6.79 to 7.48 which indicated the dilution of the acidic water with the alkaline aquifer of the region (Table 3).

The principal aqueous constituents that are subjected to pH effects are the metals, which generally exist in their oxidized forms in aqueous solution containing measurable quantities of dissolved oxygen. The majority of these compounds exist as a polyvalent cation and related complexes. The carbonate system plays a major role in determining the pH and buffering capacity of precipitation.

The pH values of groundwater generally varied from 6.7 to 8.3 indicating moderately alkaline to slightly

neutral in nature. Ground waters with pH value above 10 are exceptional and may reflect contamination by strong base such as NaOH and Ca(OH)₂ (Langmuir, 1997). The range of desirable limit of pH of water prescribed for drinking purpose by ISI (ISI, 1983) (Piper, 1944) and WHO (WHO, 1984) is 6.5–8.5 while that of EEC (Lloyd et al., 1985) is 6.5-9.0.

At the studied locations the variation in pH values were within a narrow range (6.7-8.3). The pH of analysed groundwater samples were within the limits prescribed by ISI, WHO and EEC. This relatively consistent pH range indicates that the ground water is probably from aquifers of a single formation. The slight alkaline nature of ground water at some places may be due to the presence of fine aquifer sediments mixed with clay and mud.

Table 2: Regular monitoring of a contaminated borewell (Sec X) in the central zone (2004-2006)

	<i>pH</i>	<i>Cond</i>	<i>Fe</i> ³⁺	<i>Fe</i> ²⁺	<i>Mn</i> ²⁺	<i>Na</i> ⁺	<i>K</i> ⁺	<i>S</i> ²⁻	<i>SO</i> ₄ ²⁻	<i>Cl</i> ⁻	<i>NO</i> ₃ ⁻	<i>Hard</i>	<i>Ca</i> ²⁺	<i>Mg</i> ²⁺	<i>Alk</i>	<i>ORP</i>	<i>TDS</i>
Nov	7.10	0.53	0.02	0.08	ND	15.9	8.0	1.2	12	ND	0.26	240	59	30	230	136	396
Dec	7.45	0.49	3.25	65	ND	9.9	5.0	24	2.0	20	0.078	120	60	19.2	300	155	246
Jan	8.12	0.48	0.12	0.33	ND	15.3	6.0	4.8	8.0	ND	0.03	200	24	33.6	700	141	243.5
Feb	7.21	0.52	0.04	0.2	ND	15.9	7.0	16	20	8.6	0.18	210	56	35	246	124	210
Mar	7.65	0.42	0.08	0.28	ND	16.2	7.0	16	24	12.9	0.24	250	61	20.9	261	118	263
Apr	7.84	0.55	0.11	0.34	ND	16.8	8.0	6.2	35	20.4	0.36	264	98	51	291	109	271.5
May	8.36	0.79	0.13	0.49	ND	19.7	9.0	12	26	25.6	0.55	274	112	86.4	335	112	384.2
Jun	7.35	0.80	0.37	0.55	ND	10.2	1.0	17.92	5.0	12.4	0.15	220	160	28.6	780	153	401.5
Jul	7.01	0.62	0.02	0.24	ND	25.5	7.0	0.0	10.0	20	0.06	192	112	19.2	431.2	73	310
Aug	7.52	0.57	0.24	1.63	ND	17.3	6.0	24	5.0	20	0.42	140	24	67.2	500	161	285
Sep	7.31	0.46	0.09	1.35	ND	10.9	5.0	16	5.0	15	0.22	119	63	29.8	446	132	246
Oct	7.15	0.42	0.25	20	ND	10.7	0.0	16	5.0	20	0.22	140	50	14.4	500	159	212

Table 3: Synoptic sampling at various locations in the boundary zone (2004-2006)

<i>Locations</i>	<i>pH</i>	<i>Con</i>	<i>Fe</i> ³⁺	<i>Fe</i> ²⁺	<i>Mn</i> ²⁺	<i>Na</i> ⁺	<i>K</i> ⁺	<i>S</i> ²⁻	<i>SO</i> ₄	<i>Cl</i> ⁻	<i>NO</i> ₃ ⁻	<i>Hard</i>	<i>Ca</i> ²⁺	<i>Mg</i> ²⁺	<i>Alk</i>	<i>ORP</i>	<i>TDS</i>
Sec VII	7.47	0.47	0.88	0.56	ND	22.8	8.0	0.0	10	40	0.18	200	50	14.4	350	151	234
Sec VIII	7.05	0.52	1.12	1.22	ND	19.2	7.0	2.4	20	40	0.35	240	50	4.8	500	160	260
Sec IX	6.84	0.52	2.25	0.25	ND	11.8	3.0	0.0	3.0	10	0.09	316	72	19.2	1500	159	259
Bank colony	7.25	0.51	1.0	0.36	ND	12.9	8.0	0.0	19	20	0.39	260	64	26.3	600	253	309
Hospital area	7.48	0.55	1.0	0.24	ND	14.2	8.0	1.2	20	20	0.14	260	62	24.2	600	214	214
Maroda Tank	7.54	0.60	0.89	0.17	ND	9.4	6.8	12	20	30	0.05	280	53	23.4	730	234	359
Maroda	7.31	0.34	0.26	0.37	ND	112	3.6	1.2	25	40	0.08	300	56	9.6	275	199	176
Risali	7.09	0.48	0.59	0.29	ND	10	3.0	6.0	9.0	20	0.06	310	49	14.2	349	176	228
Ruabandha	7.16	0.51	0.61	0.3	ND	7.8	2.9	6.0	10	10	0.03	300	57	20	647	164	268

Sulphide Contamination

During Iron making, molten iron is produced in the blast furnace by reacting iron ore, coke and limestone. The silica of the ore reacts with limestone to produce slag. This slag may contain other impurities of the ore such as sulphur from the fuels. The most frequently reported chemical by TRI (Toxic release inventory) system adopted in the United States from iron steel facility is sulphuric acid. In view of the above the levels of sulphate detected at the studied location in the range of 2-35 mgL⁻¹ and sulphide in the range of 1.2-28 mgL⁻¹ may not be surprising. Maximum concentration of S²⁻ (16-28 mgL⁻¹) was observed in the industrial region indicating the reducing environment of the aquifer. Further, the mobilisation of soluble salts of iron, calcium and magnesium may be enhanced in such situations. The sulphide ion is a relatively strong base and exists in many aquifers as a result of anaerobic biochemical processes. There are a large number of species of

sulphate-reducing bacteria and their distribution is ubiquitous. Generally, sulphate reducing bacteria do not grow well at pH values below 5.5 and prefer higher levels of alkalinity, with 6.6 being optimal (Govind et al., 1999).

Iron Contamination

The concentration of iron in ground water collected from various bore wells is shown in Tables 1-3. An increased iron concentrations 7.8 mgL⁻¹ near the industrial vicinity and 65 mgL⁻¹ in the midway of the slope (central zone) towards the discharge area was obtained. A higher concentration of this element makes the ground water unusable without prior treatment. The present recommended limit for iron in water, 0.3 mgL⁻¹ (ICMR, 1975) is based on taste and appearance rather than on any detrimental health effect. When the level of iron in water exceeds the 0.3 mgL⁻¹ limit, the red, brown, or yellow staining of laundry, glassware, dishes

and household fixtures such as bathtubs and sinks occurs has been witnessed in most of the residences of central zone area procuring bore well facility. The water is having a metallic taste and an offensive odour. Water system piping and fixtures are becoming restricted or clogged.

Iron bacteria are nuisance organisms often associated with soluble iron in water. Because they cause a slime buildup they are objectionable. Calcium is an essential nutrient for these bacteria, which is surplus in this area. The presence of iron bacteria is indicated by a gelatinous slime on the inside wall of the toilet flush tank and gelatinous “rusty slugs” being discharged at the tap which is a common problem encountered in many localities during our sampling period.

Redox Conditions of Groundwater

The reaction of iron in weathering process depends on the Eh-pH system of the environment and on the oxidation states of the compounds. Low pH and redox potential level favour the ferrous form; high pH and redox level creates a stable environment for ferric iron. Table 3 indicates lower redox conditions of the groundwater samples and thus, a high concentration of Fe^{2+} form of iron. Mn^{2+} concentration did not exceed 0.05 mgL^{-1} in any of the water samples. SO_4^{2-} levels in the samples were in the permissible level of drinking water (ICMR, 1975). Higher concentrations of S^{2-} i.e. up to 28 mgL^{-1} were detected in the samples which indicated the reducing conditions of the ground water. Citizens consuming this ground water with increased iron and sulphide levels reported an unpleasant odour and taste, caused corrosion to plumbing and settling of darken particles on the bottom of their collecting vessels.

Hydrochemical Facies

The chemical composition of groundwater samples of a contaminated site in the central region and from all the sampled location of the steel city, Bhilai (borehole and handpump samples) is shown through the phase diagrams (Figures 5, 6 and 7). Major cations and anions such as Na^+ , K^+ , Ca^{2+} , Mg^{2+} , HCO_3^- , CO_3^{2-} , SO_4^{2-} and Cl^- as shown in Table 4 were plotted in hydro-chemical trilinear diagram. The phase diagram clearly explains the dominations of the anions, $\text{CO}_3^{2-} + \text{HCO}_3^-$ and cations, $\text{Ca} + \text{Mg}$ in the studied area. This pattern underlines that the water samples are enriched with calcium and bicarbonate types and, from this it is evident that these ions play a major role in deciding the form of alkalinity in the ground water of the

sedimentary basin. The hydrochemical facies of the trilinear plot reveals the ground water of the steel city

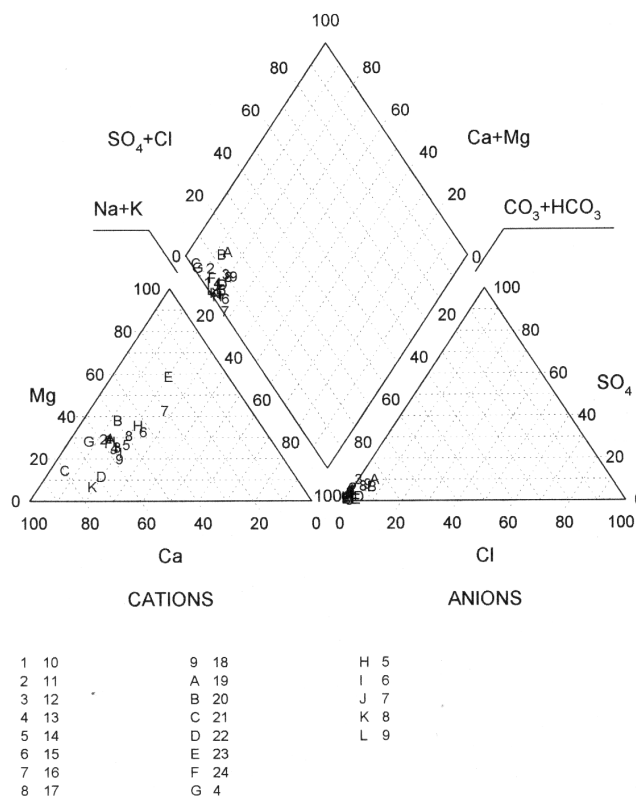


Figure 5: Trilinear diagram of a contaminated site in the central region for 2004-2006.

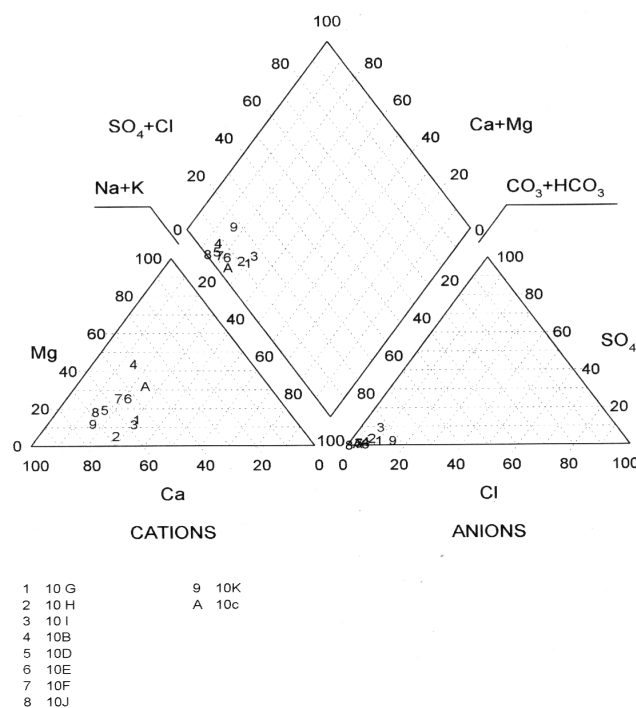
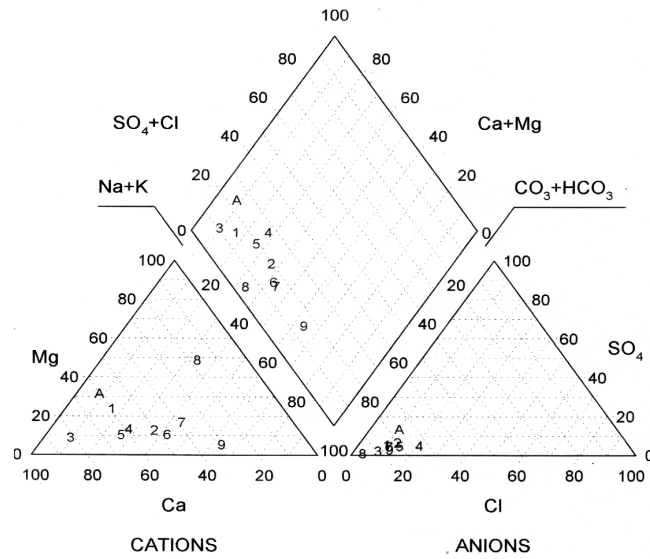


Figure 6: Trilinear diagram of locations around central region for 2004-2006.



- 1 bh1
2 bh10
3 bh2
4 bh3
5 bh4
6 bh5
7 bh6
8 bh7
9 bh8
A bh9

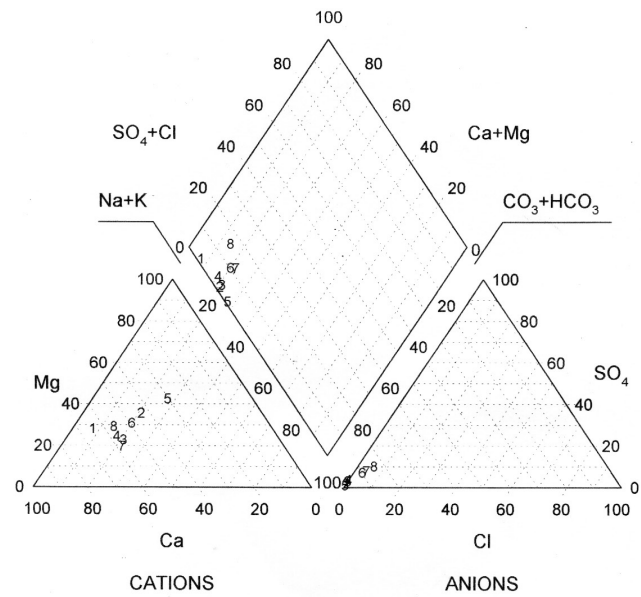
Figure 7: Composite trilinear diagram of all sampled location at Bhilai for 2004-2006.

to be a limestone aquifer system type. All the samples were mostly $\text{Ca-HCO}_3 + \text{CO}_3$ type with Ca and Mg increasing along the flow direction.

A study of the seasonal variation in the ground water of a contaminated site of the central zone has been attempted for the years 2004-2006 through the plots (Figures 8, 9 and 10). The hydrochemical facies of the premonsoon and post-monsoon plots show a more concentrated form of cations and anions. The probable reason may be water extraction during periods of drought. On such occasions, stagnant groundwater

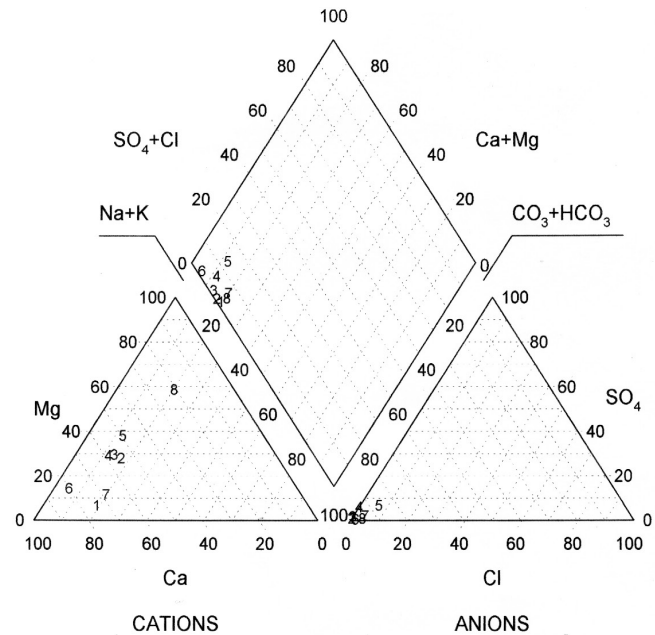
Table 4: Summary statistics of major ions, limestone aquifer (concentrations in ppm)

Major ions	Industrial zone			Central zone			Boundary zone		
	Min.	Max.	Avg.	Min.	Max.	Avg.	Min.	Max.	Avg.
Ca^{2+}	20	130	75	24	160	92	49	88	68.5
Mg^{2+}	0	67.2	33.6	19	86.4	52.7	4.8	33.6	19.2
Na^+	10	60.3	35.15	10.2	25.5	17.8	6.2	100	59.5
K^+	0	9	4.5	1	9	5	0	8	4
HCO_3^-	140	250	195	120	316	218	200	350	275
CO_3^{2-}	20	60	40	16	50	33	50	80	65
SO_4^{2-}	4	29	16.5	5	35	20	3	100	51.5
Cl^-	0	70	35	0	25.6	12.8	10	90	50



- 1 1
2 2
3 3
4 4
5 5
6 6
7 7
8 8

Figure 8: Hydrochemical facies of pre-monsoon season in central zone.



- 1 1A
2 2A
3 3A
4 4A
5 5A
6 6A
7 7A
8 8A

Figure 9: Hydrochemical facies of monsoon season in central zone.

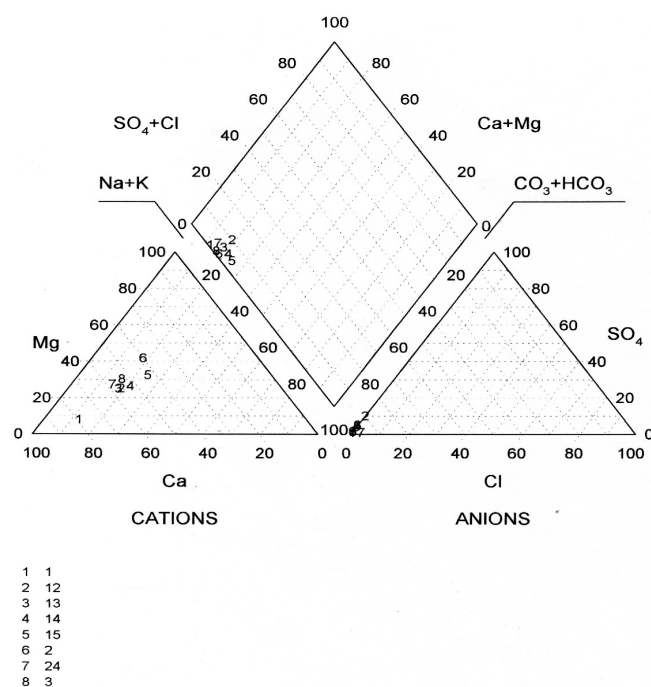


Figure 10: Hydrochemical facies of post-monsoon season in central zone.

may be pumped to the surface; this is water that has lain deep in the earth for a long time, with the result that iron levels are high but oxygen levels are very low or non-existent. During the monsoon periods the concentration of Ca+Mg tends to decrease, due to the increase in solubility of calcium and magnesium

minerals during rainfall. During the post-monsoon seasons various minerals are in a concentrated form because of the percolation of the minerals from the surface to the ground water along with the rainwater.

Correlation Analysis

Correlation analysis of the results explains the source of contamination and the probable effect of groundwater movement at the selected location e.g. Fe³⁺ and Fe²⁺ have shown a positive and significant correlation (0.45 and 0.49) with the sulphide ions in the sample of the central zone i.e. Table 6 whereas, the samples which have been collected from the locations near the industrial area i.e. Table 5 does not show any positive correlation between the iron species and sulphur species. The samples collected from the locations farthest from the industrial areas i.e. boundary zone, as shown in Table 7 showed a residual positive correlation between Fe²⁺ and S²⁻. These correlations are explainable based on the topographical features of the Bhilai city and probable hydrological patterns. The topography of Bhilai shows the area at the centre of the city in a slight depression and it receives maximum run off from the industrial site. The decrease in correlation farthest away from the industrial area testifies the dilution effect. It is also apparent that a proper mixing of the contaminant and ground water is taking place as we go away from the industrial area.

Table 5: Correlation analysis of the industrial zone

	pH	Cond	Fe ³⁺	Fe ²⁺	Na ⁺	K ⁺	S ²⁻	SO ₄	Cl ⁻	NO ₃ ⁻	Hard	Ca ²⁺	Mg ²⁺	Alk	ORP	TDS
pH	1.00															
Cond	0.21	1.00														
Fe ³⁺	-0.51	-0.29	1.00													
Fe ²⁺	-0.59	-0.29	0.88	1.00												
Na ⁺	0.22	-0.29	-0.24	-0.25	1.00											
K ⁺	0.01	-0.12	-0.24	-0.07	0.17	1.00										
S ²⁻	0.21	-0.15	0.01	-0.29	0.34	-0.45	1.00									
SO ₄	-0.23	0.37	-0.17	-0.07	0.21	0.56	-0.36	1.00								
Cl ⁻	-0.48	0.20	0.17	0.19	0.34	-0.04	0.31	0.42	1.00							
NO ₃ ⁻	-0.58	0.34	0.24	0.28	-0.20	0.39	-0.24	0.77	0.52	1.00						
Hard	-0.18	0.24	-0.17	-0.18	0.06	-0.26	-0.07	0.42	0.21	0.24	1.00					
Ca ²⁺	-0.25	0.11	0.17	0.29	0.00	0.28	-0.58	0.60	0.08	0.49	0.61	1.00				
Mg ²⁺	0.47	0.16	-0.20	-0.27	-0.23	-0.03	-0.10	0.01	-0.46	-0.27	-0.01	-0.13	1.00			
Alk	0.23	0.12	0.00	-0.26	-0.40	-0.53	0.56	-0.38	-0.17	-0.11	0.13	-0.25	0.21	1.00		
ORP	-0.61	0.32	0.42	0.42	0.11	-0.08	0.06	0.54	0.82	0.74	0.26	0.29	-0.48	-0.20	1.00	
TDS	0.12	0.60	-0.31	-0.14	-0.38	0.15	-0.57	0.07	-0.24	0.01	-0.20	-0.11	0.10	-0.38	-0.07	1.00

Cond: Conductivity, Hard: Hardness, Alk: Alkalinity (Conc. in ppm)

Table 6: Correlation analysis of the central zone

	<i>pH</i>	<i>Cond</i>	<i>Fe</i> ³⁺	<i>Fe</i> ²⁺	<i>Na</i> ⁺	<i>K</i> ⁺	<i>S</i> ²⁻	<i>SO</i> ₄	<i>Cl</i>	<i>NO</i> ₃	<i>Hard</i>	<i>Ca</i>	<i>Mg</i>	<i>Alk</i>	<i>ORP</i>	<i>TDS</i>
<i>pH</i>	1.0															
<i>Cond</i>	0.2	1.0														
<i>Fe</i> ³⁺	0.0	-0.1	1.0													
<i>Fe</i> ²⁺	0.0	-0.2	0.9	1.0												
<i>Na</i> ⁺	0.3	0.5	-0.3	-0.3	1.0											
<i>K</i> ⁺	0.3	0.3	-0.3	-0.2	0.6	1.0										
<i>S</i> ²⁻	0.2	0.0	0.45	0.49	-0.1	-0.3	1.0									
<i>SO</i> ₄	0.3	0.1	-0.3	-0.3	0.3	0.2	0.0	1.0								
<i>Cl</i>	0.3	0.0	0.2	0.4	0.2	-0.1	0.7	0.1	1.0							
<i>NO</i> ₃	0.1	0.1	-0.3	-0.2	0.1	0.4	-0.2	-0.1	-0.1	1.0						
<i>Hard</i>	0.2	0.4	-0.4	-0.5	0.3	0.4	-0.6	0.3	-0.6	0.5	1.0					
<i>Ca</i> ²⁺	0.2	0.6	-0.1	-0.1	0.4	0.1	0.0	0.0	0.2	0.2	0.4	1.0				
<i>Mg</i> ²⁺	0.5	0.4	-0.2	-0.2	0.4	0.5	0.1	0.2	0.3	0.6	0.3	0.3	1.0			
<i>Alk</i>	0.2	0.3	0.0	-0.1	0.0	-0.4	0.2	-0.4	0.0	-0.1	-0.2	0.2	-0.1	1.0		
<i>ORP</i>	-0.1	0.2	0.3	0.2	-0.2	-0.1	0.2	-0.5	-0.2	0.1	0.0	0.0	0.0	0.3	1.0	
<i>TDS</i>	0.1	0.8	-0.1	-0.3	0.5	0.4	-0.1	0.1	0.0	0.1	0.4	0.6	0.3	0.1	0.2	1.0

Table 7: Correlation analysis of the boundary zone

	<i>pH</i>	<i>Cond</i>	<i>Fe</i> ³⁺	<i>Fe</i> ²⁺	<i>Na</i> ⁺	<i>K</i> ⁺	<i>S</i> ²⁻	<i>SO</i> ₄	<i>Cl</i>	<i>NO</i> ₃	<i>Hard</i>	<i>Ca</i>	<i>Mg</i>	<i>Alk</i>	<i>ORP</i>	<i>TDS</i>
<i>pH</i>	1.00															
<i>Cond</i>	-0.01	1.00														
<i>Fe</i> ³⁺	-0.62	0.24	1.00													
<i>Fe</i> ²⁺	-0.57	0.19	0.34	1.00												
<i>Na</i> ⁺	0.12	-0.60	-0.21	-0.16	1.00											
<i>K</i> ⁺	0.57	-0.06	0.05	-0.07	-0.13	1.00										
<i>S</i> ²⁻	-0.02	0.01	-0.13	0.36	0.11	0.09	1.00									
<i>SO</i> ₄	0.07	0.73	-0.14	0.03	-0.03	-0.34	0.25	1.00								
<i>Cl</i>	-0.15	0.57	0.39	0.47	0.04	0.03	0.42	0.56	1.00							
<i>NO</i> ₃	-0.38	0.17	0.63	0.71	-0.13	0.41	0.30	-0.09	0.61	1.00						
<i>Hard</i>	0.09	0.34	0.04	-0.46	0.01	-0.34	-0.79	0.34	-0.02	-0.39	1.00					
<i>Ca</i> ²⁺	-0.40	0.37	0.80	0.46	-0.16	0.10	-0.21	0.01	0.48	0.67	0.16	1.00				
<i>Mg</i> ²⁺	0.40	0.68	-0.07	-0.25	-0.44	0.11	-0.34	0.47	0.07	-0.16	0.53	0.29	1.00			
<i>Alk</i>	-0.22	0.19	0.56	-0.22	-0.36	-0.05	-0.59	-0.19	-0.32	-0.13	0.39	0.41	0.34	1.00		
<i>ORP</i>	0.56	0.23	-0.42	-0.14	0.02	0.30	-0.23	0.32	-0.09	-0.13	0.29	-0.04	0.65	-0.02	1.00	
<i>TDS</i>	0.03	0.89	0.19	0.16	-0.54	-0.01	-0.03	0.63	0.50	0.18	0.32	0.30	0.67	0.21	0.38	1.00

Conclusion

Analysis of the hydrochemical survey data from the steel city has revealed that the ground water was in the neutral range (pH 6.59–7.6). Among major cations almost all of the hand pumps and borewells are

dominated by Ca²⁺ and Mg²⁺ ions. Bicarbonate is by far the most dominant anion and in large number of wells forms maximum percentage of the TDS. Quality of the ground water in this region is delineated using the phase diagrams. Ca–Mg–HCO₃ forms the major water types. Most of the aquifer tapping this region represents the

Ca-Mg-HCO₃ water type in the Bhilai region as these are associated with limestone terrain.

Significant concentrations of iron and sulphide have been witnessed by most of the boreholes. Approximately 50% of the boreholes have iron concentration exceeding the WHO maximum acceptable limit of 0.3 mgL⁻¹ for drinking water and thus poses the risk of major aesthetic quality problems. An anthropogenic contamination with increased iron concentration was identified in aquifers of the central zone corresponding to local pollution inputs. The presence of a major and integrated iron and steel plant in the nearby area could be causing this contamination by activities such as landfill dumping of the acidic slag containing appreciable amounts of iron etc. Seepage from the waste dump of the nearby industry contaminates the local ground water which is shown by the increased concentration of iron and sulphide. This was verified by observing the ORP values which indicated a reduced state of the environment. Highly reducing conditions make the iron to be present in reduced state i.e. Fe²⁺. Since this region is basically under the limestone belt, this would react with infiltrating water to raise its pH. This would mean that the geology of the area is having buffering capacity. Additionally or alternatively, the sediments could contain organic carbon. This stimulates the activity of sulphate-reducing bacteria and thus counters acidic drainage from the iron and steel plants.

Unless iron is removed through the use of aerators or iron removal plants, it poses significant water quality problems for domestic purposes in Bhilai city. Sources of iron in the ground water include oxidation of pyrite and arsenopyrite, the reductive dissolution of hematite and goethite and, to a limited extent, magnetite in the presence of organic matter. Almost every water sample from the boreholes and hand pumps have sulfide concentrations in excess of the ADSTR guideline limit of 0.0005 to 0.3 mgL⁻¹ (ATSDR, 2004).

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