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Impact assessment of chromite mining on groundwater through simulation modeling study in Sukinda chromite mining area, Orissa, India

Ratnakar Dhakate*, V.S. Singh, G.K. Hodlur

National Geophysical Research Institute, Hyderabad 500007, Andhra Pradesh, India

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ABSTRACT

The pre-Cambrian chromites ore deposits in Sukinda valley, Jajpur District, Orissa, India, are well known for chromite ore deposits. The exploitation of the ore is carried out through open cast mining method since the last few decades. In the process, the overburden and ore dumps are stored on ground surface, where leaching of chromite and other toxic element takes place particularly during monsoon seasons. This leachate may cause threat to groundwater in the vicinity. An integrated approach has been adopted to evaluate possibility of pollution due to mine seepage and leachate migration on groundwater regime. The approach involves geophysical, hydrogeological, hydro-chemical and aquifer modeling studies. The investigation has the significance as many habitats surround the mining area facing groundwater problems.

1. Introduction

In the process of development, mining is one of the core industries contributing, knowingly or unknowingly, towards the deterioration of the environment in terms of air, water and land pollution [13]. To achieve sustainable development, environmental protection elements should be introduced at the planning stage of the mining project. India is endowed with a wide range of mineral reserves. In the country there are approximately 9906 mining leases spread over an area of 7453 km^2 covering 55 minerals other than fuel. Metal mining posses problems to the water environment by discharging mine water from underground and open pit mines [14,23]. Leachate water and runoff water from overburden/waste rock dumps also contaminate nearby water streams [35]. The potential impacts from leaching operations on the environment are most likely to be experienced as changes to surface and groundwater quality. The quality of the mine water depends upon various factors including physical characteristics of the ore, net acid generating potential, groundwater characteristics, back fill practice, mining practice and age of mine etc., and aquifer characteristics.

Mine water can frequently have quality problems, primarily due to the alteration of equilibrium in underground water and the formation of Acid Rock Drainage (ARD in metal mine or sulfides ores). This in turn creates a problem of dissolving heavy metals and carrying suspended particles of lithological materials and affected the surface and groundwater quality. ARD has been recognized as one of the largest environmental problem facing the metal mining sector [7,27]. ARD and associated heavy metal contamination is caused by natural oxidation taking place when minerals are exposed to air and water. Sulfide oxidizing bacteria play an important role in the formation of Acid Mine Drainage (AMD) [22,34], and these can be control by wetlands [22], while waste rock and tailings are the most significant sources of acid drainage, other mine components such as open pit surfaces, underground workings, stockpiles and concentrate stage and loading areas are also potential sources of AMD. Metal mining especially Pb-Zn mine severely contaminates groundwater quality [12]. Metal contamination due to mining and associated activities at Zawar zinc mine, Rajasthan, India also reported by [27].

In arid or semi-arid environment where surface water is limited, the most affected environmental component often affected is groundwater. The principle pathways by which leach contaminants can enter into groundwater are leakage or spills from storage ponds, leach pad liners, subsequent leaching to groundwater, storm water run-on/off uncontrolled leaching from heaps and dumps following closer [23].

Level of pollution due to chromite ore mining has also been reported to be severe [25]. Tailing dams seepage as well as effluent discharged from concentration and screening plants also plays an important role in groundwater pollution. The surrounding soil and plants are also reported to be enriched in chromium content around the chromium rich ultramafic terrains in Pakistan [21], these ultramafic soils is also helpful in oxidation of chromium [9]. Previous studies have shown that a high degree of heavy metal contamina-

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[*] Corresponding author. Tel.: +91 40 23434700; fax: +91 40 27171564.
E-mail address: dhakate_ratnakar@yahoo.com (R. Dhakate).

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tion in soil and plants has occurred in many places in the world, which could be related to the occurrence of ore deposits [14].

The Sukinda valley in Jajpur District, Orissa, is known for its deposit of chromites ore producing nearly 8% of chromite ore in India [18]. There are number of open cast mines in the area. During the process of mining the waste rock materials as well as chromite ores are dumped on ground surface. In Sukinda mining area around 7.6 million tonnes of solid waste have been generated in the form of rejected minerals, overburden material/waste rock and sub grade ore [18]. The mine seepage water is also discharged into the nearby drainage and Damasal Nala, which is often being used as source of water by adjoining villages.

Chromium exists in the environment in either the trivalent Cr(III), or hexavalent Cr(VI) form, Cr(III) is considered to be essential to mammals for the maintenance of glucose, lipid, and protein metabolism. On the other hand, Cr(VI) is known to have an adverse effect on the lungs, liver and kidneys [36]. Concentration and mobility in groundwater are directly related to the dominant valence state in which chromium occurs, which in turn is controlled by chemical and physical characteristics of the groundwater environment. Chromium in groundwater is influenced primarily by oxidation–reduction potential (Eh) and pH [17]. At constant pH, Cr(VI) species predominate in solution under high Eh (oxidizing) conditions, whereas Cr(III) species predominate under lower Eh conditions. Cr(VI) species can be readily reduced to Cr(III) in the presence of naturally occurring organic matter [5,6,34], ferrous [Fe (II)] iron [11,19,31] and sulfide [31], these constituents act as reducing agent in aquifer sediments [4]. Cr(VI) can also be reduced by *Thiobacillus ferrooxidans* [28,33], by using trimanganese tetroxide, and by manganese (III) oxide [30].

The main source of potable water in the area is groundwater, which is tapped by shallow dug wells, and deep bore wells. In order

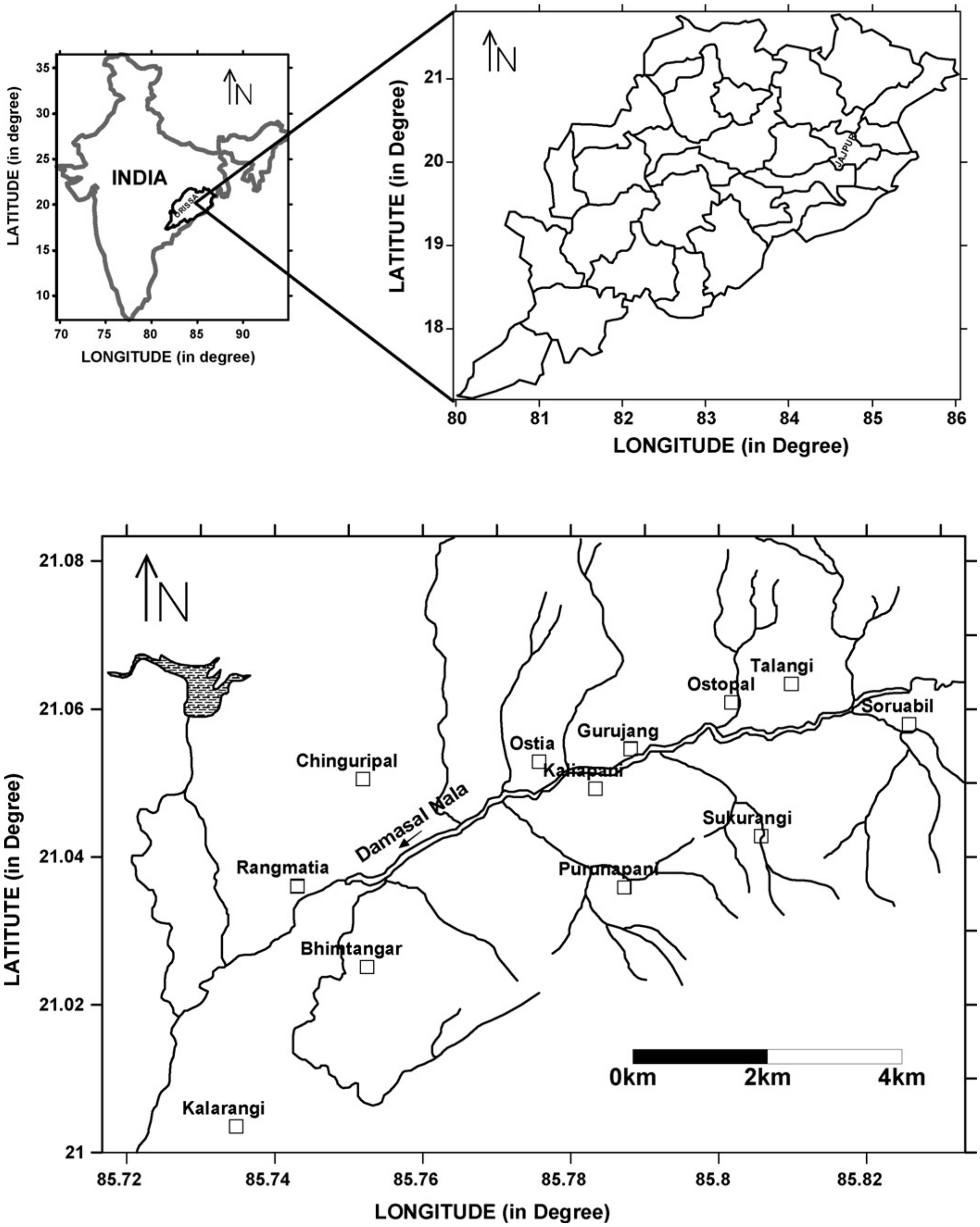

Fig. 1. Key map of the study area.

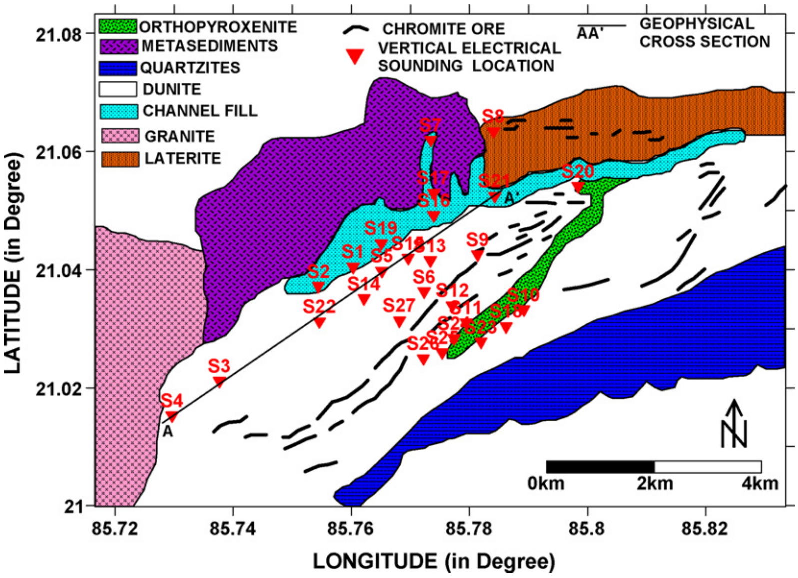

Fig. 2. Geological map of the study area showing vertical electrical sounding locations and geophysical cross section.

to protect groundwater from the contamination of chromite, it is vital to understand the hydrogeology and its characteristic parameters. Detail geophysical, hydrogeological and chemical studies have been carried out to understand the hydrogeological settings and aquifer behaviour in the mining area. Hexavalent chromium is one of the most toxic water pollutants and causes cancer of lungs, nasal cavity, paranasals sinus, cancer of the stomach and larynx [36]. Recommendations have been made to protect groundwater from the contamination of chromite and other impurities from the ore dump and mining seepages.

2. Study area

In order to study the hydrogeological settings in a typical chromite open cast mining area, an area of about 50 km^2 has been selected in the Jajpur District, Orissa, India which forms a part of Sukinda valley as shown in Fig. 1. It comprises the entire drainage of the area. Drainage in the area flows towards NW, which finally join Damasal Nala. Damasal Nala is perennial in nature as most of the mine seepage is discharged into it. In the south, the Mahagiri Hill ranges attain an altitude of 300 m above mean sea level and in the north Daitri Hill ranges have attained an altitude of 200 m above mean sea level, whereas the elevation of Damasal Nala and its surrounding occur between 100 and 180 m above mean sea level. Most of the mines are located in the central part of the area and are leased to various companies. The giant mining companies being Orissa Mines Corporation (OMC), Indian Metal and Ferro Alloy, TISCO etc.

3. Geological background

The chromite deposits forms a part of famous chromite bearing ultramafic complex of Sukinda valley. These ultramafics are highly metamorphosed and belong to pre-Cambrian age. The rocks of the area are associated with six sedimentary sequences and each is separated by an unconformity [1,3]. The Sukinda ultramafic complex is bounded in the north by the Daitari Hill range and in the south by the Mahagiri Hill ranges, which are mostly composed of quartzites. The general trend of the Daitari Hill is E–W, while that of Mahagiri Hill is NE–SW. The Sukinda valley presents a synformal fold plunging towards WSW at a low angle, 10–15° [3]. The ultramafics appear to have been intruded into the quartzites and this layered laccolithic complex is composed of alternate bands of chromite, dunite, periodotite and orthopyroxenite, repeated in a rythimic fashion. These ultramafic are extensively lateritised and limonitised. The occurrences of numberous chert bands are also found within the ultramafics, which are often completely weathered to a mass of talc–limonite. The chromite ores occur as bands within the ultramafic body at six stratigraphic levels. The thickness of chromite ore body ranging from 0.3 to 20 m and in length from 100 m to 7 km. The thickest and longest bands occur in Kaliapani–Bhimtanagar tract, whereas, in the western sectors the ores occurs as dissemination or discontinuous bands. In the east the ores are friable to lumpy in nature. The geological map of the study area is shown in Fig. 2. The stratigraphy sequence of the areas is given in Table 1.

4. Hydrology of the area

The weathered lateritised–limonite mantle, ultramafics, orthopyroxenite as well as the underlying semiweathered and fractured country rocks forms the source of groundwater in the area [8,10]. The groundwater occurrence depends on the nature and, extent of weathering characteristics of the rock formation. The groundwater in the area is generally under semi-confined to confined condition. The various hydrogeological units are as follows.

Table 1
Stratigraphy sequence in the Sukinda valley area

Age	Formations	
Recent of Pleistocene	Soil, alluvium laterite	
	Unconformity	
Precambrian	Ultramafic	Dolerite Granite Gabbro-diorite Pyroxenite Dunite Peridodite with Chrome ore
	Meta-sediments	Gritty-quartzite
	Meta-volcanics	Meta-volcanics
	Base not seen	

Table 2
Details of Vertical Electrical Resistivity Sounding (VES) layer parameters

Sl. No.	Location	Layer resistivity 'ρ' (Ω m)						Layer thickness 'h' (m)				
		ρ_1	ρ_2	ρ_3	ρ_4	ρ_5	ρ_6	h_1	h_2	h_3	h_4	h_5
1	Chirgunia (near bore well)	214	1486	129	569	81		2.1	2.3	3.4	4.4	
2	Kaliapani (near Nala)	562	2529	133	96	–		1.5	4.0	25.9	–	
3	Bhimtangar	320	1812	206	25	–		1.0	7.0	4.0	–	
4	Kalrangi	374	197	144	47	–		3.6	6.2	22.6	–	
5	Kaliapani (proposed colony site)	318	78	387	55	–		0.6	3.4	22.0	–	
6	Sukinda Mines (near C point)	456	141	51	453	–		0.9	12.2	40.7	–	
7	Chinguripal Mine	561	190	2614	301	–		0.7	1.6	11.6	–	
8	Gurjanga (near A pillar)	445	106	384	52	–		0.6	2.7	12.2	–	
9	TISCO old working	93	2226	156	51	–		0.8	5.0	21.9	–	
10	Puranapani	47	14	74	9674	–		0.8	2.4	31.3	–	
11	IMFA magazine	95	8	8816	–	–		0.9	11.6	–	–	
12	IFMA mine	567	398	6344	62	5009	501	1.3	2.5	15.0	14.7	12.0
13	IMFA office	634	2241	547	11	–		0.7	2.8	9.5	–	
14	Kaliapani (near A pillar)	232	12	10069	–	–		6.0	30.7	–	–	
15	Kaliapani	407	1610	40	–	–		1.5	10.5	–	–	
16	Kaliapani (OMC)	16	6	38	9920	–		0.9	4.3	30.4	–	
17	Ostia	544	286	2303	537	204		0.8	1.0	10.6	31.3	
18	Puranapani	181	114	12	10,060	–		1.0	6.1	20.1	–	
19	Kaliapani	10	155	649	205	–		1.5	10.2	32.6	–	
20	Kaliapani (near Huta)	364	113	42	9998	–		1.8	28.5	42.1	–	
21	Kaliapani (near nala)	336	652	126	240	–		0.8	1.8	20.2	–	
22	Kaliapani (near Chrome Nagar)	346	813	100	19	10,094		0.6	3.3	11.2	33.1	
23	Mahagiri Mines	130	314	9	10,434	–		1.0	1.8	11.1	–	
24	Mahagiri Mines	32	11	60	23	10,217		1.0	14.1	11.8	11.3	
25	ISPAT Magazine	265	27	119	–	–		0.6	5.0	–	–	
26	ISPAT Magazine	15	13	65	9996	–		1.6	1.4	58.0	–	
27	JINDAL Mine	343	115	468	52	–		0.7	1.4	4.9	–	

4.1. Laterite–limonite–chert

These are the altered product of ultramafics. These are the most extensive and potential aquifers and occur in the eastern part of the area [8,10]. The groundwater in this zone occurred in the upper part of aquifer (up to a depth of 25 m) under the phreatic condition, whereas the deeper aquifer occurs (at depths below 25 m) under confined condition. The seasonal fluctuation of water level in this formation ranges from 1.67 to 4.88 m.

4.2. Laterite-weathered and fractured ultramafics associated with limonite and chert

This formation occupies the central and west central parts and covers almost the entire mining region in the Sukinda valley. The formation lies below a thin and discontinuous capping of the soil and lateritic mantle, which persists up to 20 m. The extent of weathering in this formation is comparatively less than the laterite–limonite–chert formation. The groundwater occurs in this formation under phreatic condition up to a depth of 20–25 m bgl [8,10]. The deeper aquifer in this formation is constituted by the weathered–semiweathered and fractured ultramafics and generally remains in hydraulic continuity with top aquifer and groundwater generally exists in these deeper horizons near to water table conditions.

Table 3
Resistivity ranges of various litho-units

Lithology	Resistivity ranges (Ω m)
Clay	<10
Sandy clay/clayey sand clay and kankar (aquifer)	10–25
Weathered dunite/peridotite/metabasalt (aquifer)	>25–160
Hard and massive bed rock	>160

4.3. Colluvial and channel fill deposits

The formations are generally mixture of boulders, gravels, pebbles, granules etc., highly cemented with ferruginous and siliceous matrix and have restricted occurrences in the foot hill of Mahagiri and Daitri Hill ranges region and along the course of Damasal Nala. The maximum thickness of these formations if around 12–15 m [8,10]. The average seasonal fluctuation of water level in this formation is around 4 m.

Table 4
Details of well inventory in Sukinda Mines area

Sl. No.	Location	Total depth (m)	Electrical conductivity of water (μΩ))
1	Chirgunia	36.57	150
2	Bhimtangar	45	290
3	Bhimtangar	7.62	100
4	Kalrangi	10.66	150
5	Kaliapani	73.15	490
6	Chinguripal	92.96	110
7	Gurujanga	53.34	50
8	TISCO market	76.20	360
9	Kaliapani near temple	76.20	260
10	Puranapani	25	400
11	Kaliapani near school	60.96	250
12	Chirgunia	25	150
13	Kaliapani IMFA campus	54.86	200
14	Kaliapani IMFA Campus	54.86	200
15	Kulipasi	20	250
16	Kaliapani near temple	20	180
17	Kaliapani near Hanuman temple	36.57	240
18	Kaliapani near majdoor Union Office	24.38	200
19	Kaliapani Opp. IMFA dump site	20	100
20	Kaliapani	12.40	210
21	Kaliapani near Matarani Temple	45.72	160
22	Tata Mines near Gupta Huting	30	200

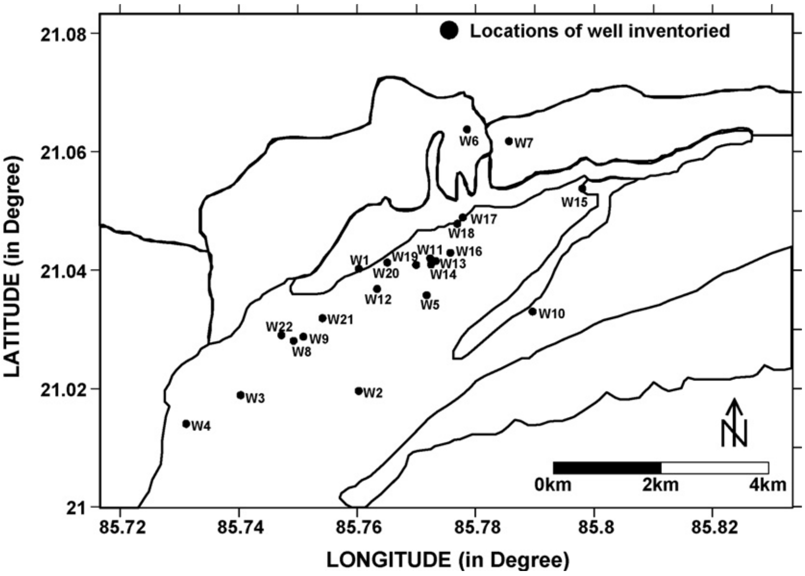

Fig. 3. Map showing well inventoried location.

4.4. *Other hydrogeological units including orthopyroxenites*

This group of formations includes orthopyroxenites occurring in the central part around Purnapani village. These formations except the orthopyroxenites are comparatively less weathered and maximum thickness of weathering is up to 15 m bgl [8,10]. Whereas orthopyroxenites from low ridge like exposures and the extend of weathering is maximum up to a depth of 10 m.

5. Methods

To assess the impact of mining on groundwater regime, various methods used like geophysical investigations, hydrogeological investigations, groundwater quality and modeling, are briefly described in the text to follow.

5.1. *Geophysical investigations*

In order to assess the aquifer regime in this region a detailed geophysical and hydrogeological investigation were carried out. Twenty-seven (27) Vertical Electrical Soundings (VESs) in Schlumberger configuration with maximum half current electrode separation of 100 m were carried out to conceptualize the aquifer geometry [29]. The Schlumberger configuration array uses four collinear point electrodes, measures the potential gradient at the mid-point by keeping the measuring electrodes close to each other. Four electrodes were placed along a straight line symmetrically over centre point ‘O’. Current (*I*) was sent through the outer current electrodes *A*, *B* and the potential is measured across inner potential electrodes *M* and *N*. The separation between the potential electrodes was kept small when compared to the current electrodes separation such for any data observed, ($MN \leq 1/5$ AB).

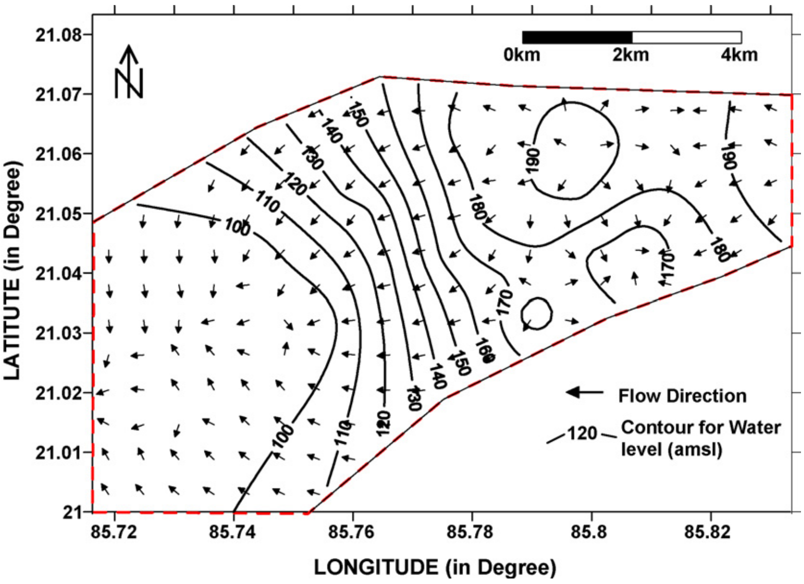

Fig. 4. Groundwater flow map.

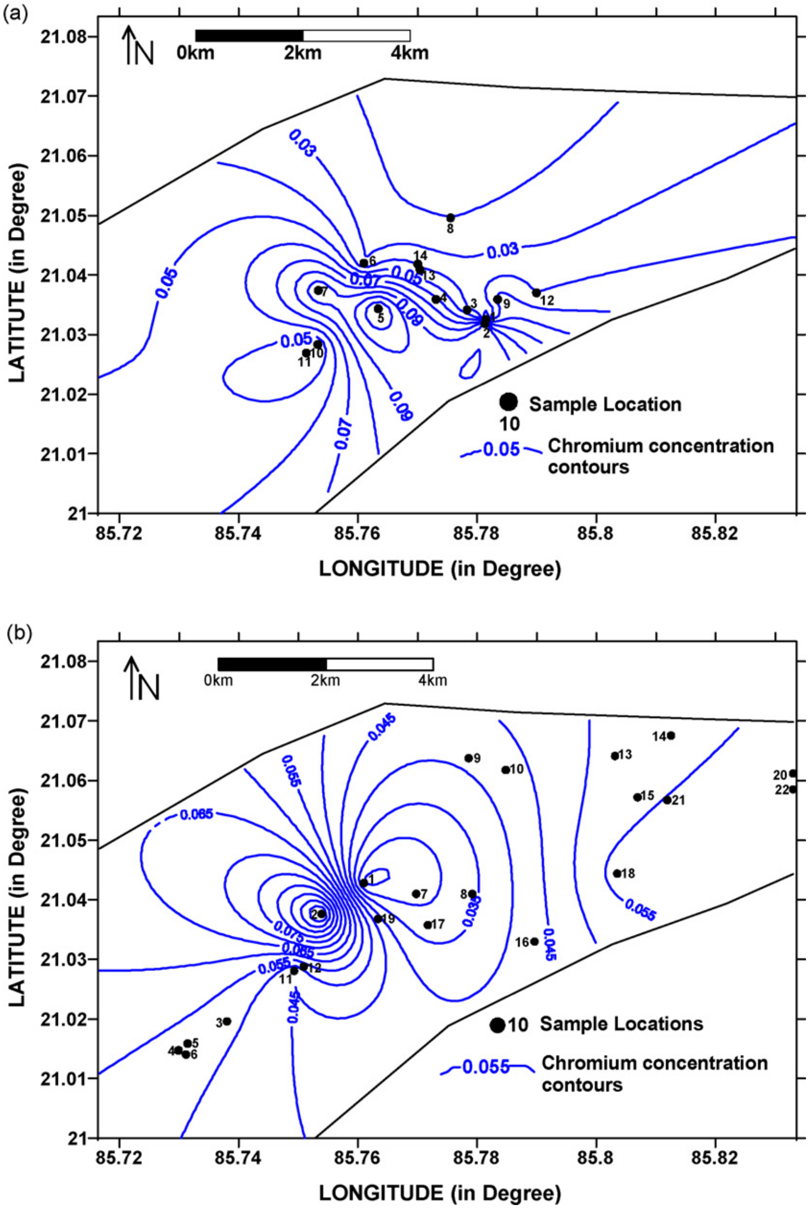

Fig. 5. (a and b) Sample location showing contour pattern for chromium concentration for post-monsoon (October–November, 2001) and pre-monsoon (April, 2002) period.

The configuration or geometric factor for the Schlumberger array is given by

$$G = \frac{\pi}{2}\frac{(AB/2)^2 - (MN/2)^2}{(MN/2)}$$

where *AB* is the distance between current electrodes, *MN* is the distance between potential electrodes, and the apparent resistivity is obtained with the formula

$$\rho_a = G\left(\frac{\Delta V}{I}\right)$$

where $(\Delta V/I)$ is the potential difference between potential electrodes due to the flow of current (I) between the two current electrodes.

Table 5
Summary of pumping test

Sl No.	Well No.	Pumping period (min)	Drawdown (m)	Recovery time (min)	Discharge (m^3/day)	Transmissivity (m^2/day)	Storativity
1	5	60	1.998	471	6.2–8.9	4	0.007
2	10	100	0.616	70	25.27	80	0.0001
3	14	100	3.195	119	27.87	16	0.00004
4	16	60	0.646	70	19.8–35.2	60	0.04
5	20[a]	90	0.86	1158	37.78	0.25	0.0005

[a] Dug well.

Table 6
Chemical analysis of water samples in an around Sukinda Chromite Mine for post-monsoon (October–November, 2001) and pre-monsoon (April, 2002) period

Sample code	Parameters											
	pH	TDS (mg/l)	BOD (mg/l)	COD (mg/l)	DO (mg/l)	TSS (mg/l)	F (mg/l)	SO_4 (mg/l)	Cl (mg/l)	Cu (mg/l)	Fe (mg/l)	Cr(VI) (mg/l)
(a)												
W1[b]	7.6	419	0.2	42	7.0	46	0.4	26	11.1	0.016	0.39	0.025
W2S[b]	7.3	386	0.4	53	7.2	63	0.2	19	13.5	1.8	0.41	0.38
W3[b]	7.2	421	0.1	63	7.4	47	0.1	21	14.2	0.167	0.54	0.018
W4[b]	6.1	309	0.3	21	8.0	21	0.5	34	15.3	0.036	0.29	0.115
W5[b]	7.2	215	0.2	85	6.9	19	0.2	23	9.8	0.078	0.21	0.421
W6[c]	6.8	185	0.1	42	7.1	15	0.3	34	6.8	0.048	0.35	0.049
W7[c]	6.8	219	0.3	21	7.4	12	0.2	41	5.9	0.03	0.31	0.046
W8[c]	7.4	310	0.1	290	6.5	23	0.1	11.9	10.8	0.23	0.29	0.083
W9[b]	7.0	419	0.1	53	4.0	29	0.2	45.1	18.5	0.23	0.28	0.012
W10[d]	7.0	507	0.2	42	6.9	12	0.2	27.4	12.1	0.045	0.18	0.009
W11[d]	7.5	422	0.3	63	7.1	14	0.3	25.1	13.4	0.02	0.21	0.009
W12[d]	7.5	305	0.1	–	4.8	64	0.1	18.5	14.1	0.026	0.24	0.043
W13[d]	7.5	232	0.2	10	3.9	32	0.2	29.4	9.6	0.035	0.27	0.032
W14[d]	7.0	386	0.4	–	4.6	15	0.4	35.2	4.8	0.183	0.34	0.019

Sample code	Parameters					
	pH	TSS (mg/l)	TDS (mg/l)	Alkalinity (mg/l)	Hardness (mg/l)	Cr(VI) (mg/l)	Electrical Conductivity of water (μΩ)
(b)							
W1[d]	7.30	35	288			0.032	190
W2[d]	7.60	23	150	137	150	0.023	210
W3[d]	6.52	15	111	110	130	0.104	200
W4[b]	7.49	13	167	68	50	0.043	50
W5[b]	7.59	14	363	140	170	Nil	190
W6[b]	7.20	9	30	40	70	Nil	50
W7[b]	7.06	26	233	72	80	0.057	270
W8[b]	6.58	29	309	–	–	Nil	490
W9[b]	7.18	13	105	86	110	0.043	340
W10[c]	7.0	29	191	196	210	0.052	290
W11[c]	6.62	12	54	72	80	Nil	100
W12[c]	6.09	4	35	81	90	Nil	70
W13[c]	7.38	21	116	135	150	Nil	150
W14[c]	6.87	13	71	49	90	Nil	100
W15[c]	7.46	29	152	121	150	Nil	250
W16[c]	6.28	28	140	60	90	0.450	110
W17[c]	7.41	13	218	41	50	Nil	360
W18[c]	6.50	21	187	170	195	Nil	260
W19[c]	5.67	26	61	125	140	Nil	50
W20[c]	5.88	29	99	59	70	Nil	140
W21[c]	6.74	24	369	84	80	Nil	400
W22[c]	6.53	34	328	125	130	Nil	370
W23[c]	5.96	12	162	185	200	Nil	150
W24[c]	5.47	15	123	92	100	Nil	190
W25[c]	5.86	28	320	105	120	0.013	320

Total Suspended Solids (TSSs), Total Dissolved Solids (TDSs), and Cr^{+6} (hexavalent chromium).

[b] Mine water samples.

[c] Damasal Nala water samples.

[d] Groundwater samples.

A curve is plotted on a double logarithmic graph sheet using the recorded field data. Half current electrode separations are plotted on the *X*-axis and the corresponding resistively values are plotted on the *Y*-axis. The shape of the sounding curve varies depending upon the pattern of apparent resistivity values observed for various electrode separations. The sounding curve is useful for quantitative interpretation of the electrical resistivity data. The qualitative interpretation of the subsurface layer resistivity distribution can be observed from the shape of the curve. The vertical electrical sounding data was interpreted by using three and four-layered master [24]. The interpreted data was refined by using software packages [20]. The field sounding curve is first interpreted and a subsurface geophysical model of resistivities and their respective thicknesses is estimated. This is fed to the software package along with raw field data, namely the half current electrode separation and the corresponding apparent resistivity. The soft ware first superimposes the field curve on another curve which it draws by inverting the manually interpreted model. This is called the computed curve. Further, the software iterated the model values superimpose the plots of the field and the computed curves, till there is a perfect match between the two. The final iterated model is the most realistic interpretation of the sounding curve. A brief summary of the interpreted results of geophysical investigation is given in Table 2. The location of Vertical Electrical Sounding along with geology is shown in Fig. 2. The characteristic resistivities of various litho-units are shown in Table 3.

5.2. *Hydrogeological investigation*

Well inventory of 22 wells (few dug wells as well as bore wells) have been carried out in and around the mining area [29]. The static water levels are recorded in these bore well/dug well. The location of boreholes and dug wells is shown in Fig. 3. Total depth and the electrical conductivity measured of all the wells

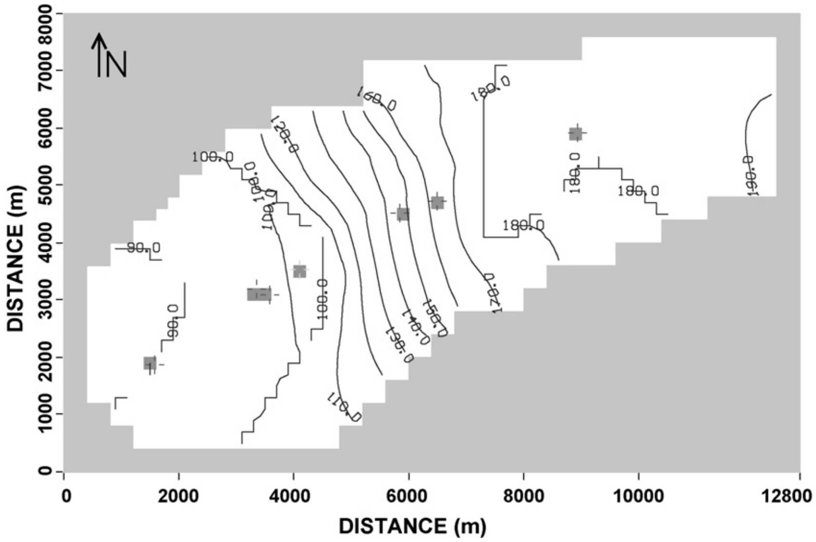

Fig. 6. Steady-state condition obtained for October–November 2001 water level by using MODFLOW.

are shown in Table 4. The groundwater flow direction is shown in Fig. 4. Pumping tests were carried out on five wells to know the hydraulic properties such as transmissivity and storativity of the aquifer [32]. A brief summary of pumping test is given in Table 5.

5.3. Groundwater quality

5.3.1. Methodology and method

Geochemical investigations were carried out in Sukinda chromite valley area, Orissa, shown in Fig. 5(a and b) for the year October–November 2001 and April 2002. Water samples were collected from different locations covering mine effluents and groundwater samples from different hand pumps, bore wells and dug wells including shallow and deep hand pumps, with in situ measurement of pH and electrical conductivity (EC). The surface water and groundwater samples were collected in pre-acid washed polythene bottles and preserved for further analysis. Preservation and analysis of sample was done in the laboratory by following standard methods [15]. Heavy metal analysis was carried out by using Atomic Absorption Spectometer, Model GBC 902 and Spectrophotometer, Model Spectronic 20D in laboratory.

The water samples for post-monsoon (October–November, 2001) and pre-monsoon (April, 2002) period were collected from the dug wells, tube wells, mine seepage and from Damasal Nala for analysed to study the quality of water with special reference to concentration of Cr(VI). The analysis results are shown in Table 6(a and b).

5.4. Impact of mining on groundwater quality

In order to understand the movement of pollutant and seepages from the mine in the groundwater regime in the basin an attempt has been made to construct a mathematical model using software Visual MODFLOW for Windows version 2.61 [16]. Integrated study using electrical resistivity, water-well inventory data and also keeping in view the geological information of the basin. Essentially,

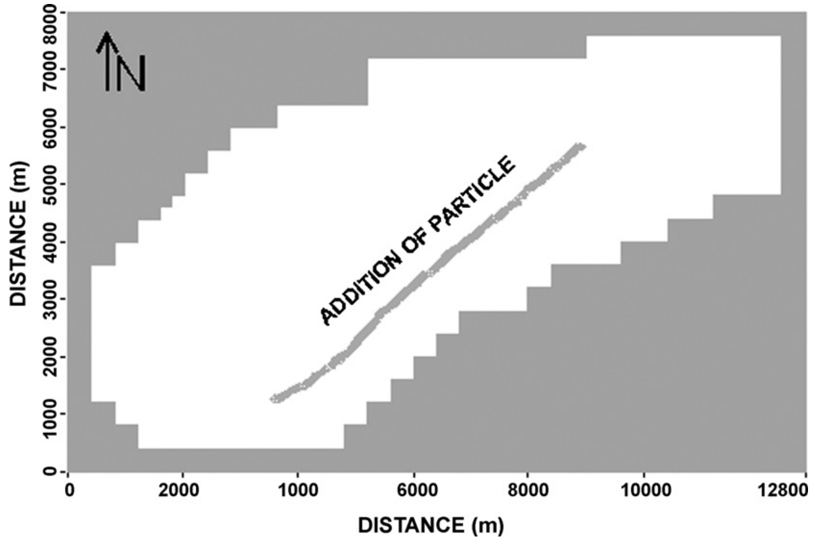

Fig. 7. Addition of particle in the study area.

mathematical modeling of a system implies obtaining solutions to one or more partial differential equations describing groundwater regime. In the present case, it was assumed that the groundwater system is a two-dimensional one wherein the Dupuit-Forchheimer condition is valid. The partial differential equation describing two-dimensional groundwater flows may be written in a homogeneous aquifer as

$$\frac{\partial}{\partial y}\left(\frac{T_x \partial h}{\partial y)}\right)+\frac{\partial}{\partial y}\left(\frac{T_y \partial h}{\partial y}\right)=\frac{S \partial h}{\partial t \pm W} \quad (1)$$

where T_x, T_y = the transmissivity values along x and y directions respectively, h = the hydraulic head, S = storativity, W = the groundwater volume flux per unit area (+ve for outflow and −ve for inflow), x and y = the Cartesian co-ordinates.

Usually, it is difficult to find exact solution of Eq. (1) and one has to resort to numerical techniques for obtaining their approximate solutions. In the present study, finite difference method was used to solve the above equation. The size of each grid is considered as 200 m × 200 m. The partial differential equation is then replaced by a set of simultaneous algebraic equations valid at different node points. Thereafter, using standard methods of matrix inversion these equations are solved for the water level. Computer software, Visual MODFLOW for Windows version 2.61 [16], was used for this work.

A physical framework of the basin has been prepared and the aquifer characteristics like permeability, recharge, storativity etc., have been assigned, as inputs parameters to prepare model of the study area. The boundary conditions as observed in the field have also been assigned in the form of Damasal Nala. The various inputs to the model have been assigned from the data obtained from integrated hydrogeological, geochemical and geophysical investigation. These inputs are number of layers and its thickness, hydraulic conductivity, storativity, total porosity, recharge to top layer and Damasal Nala elevation and its conductance are assigned to model before calibration. Two layers have been assigned to model with thickness 0–25 m for first layer and 25–60 m for second layer. Similarly hydraulic conductivity for first layer has been assigned to various geological units as per observed from pumping test results, for granite it is 20 m/day, for dunite 2 m/day, for orthopryxonites 5 m/day, for colluvial and channel fills 10 m/day, for metasediments 1 m/day, for quartzites 3 m/day and for laterite 10 m/day. For second layer it is divided into four zones as 0.1 m/day, 0.006 m/day, 0.005 m/day and 0.002 m/day. Similarly the storativity is assigned for first layer and second layer is 0.005 and total

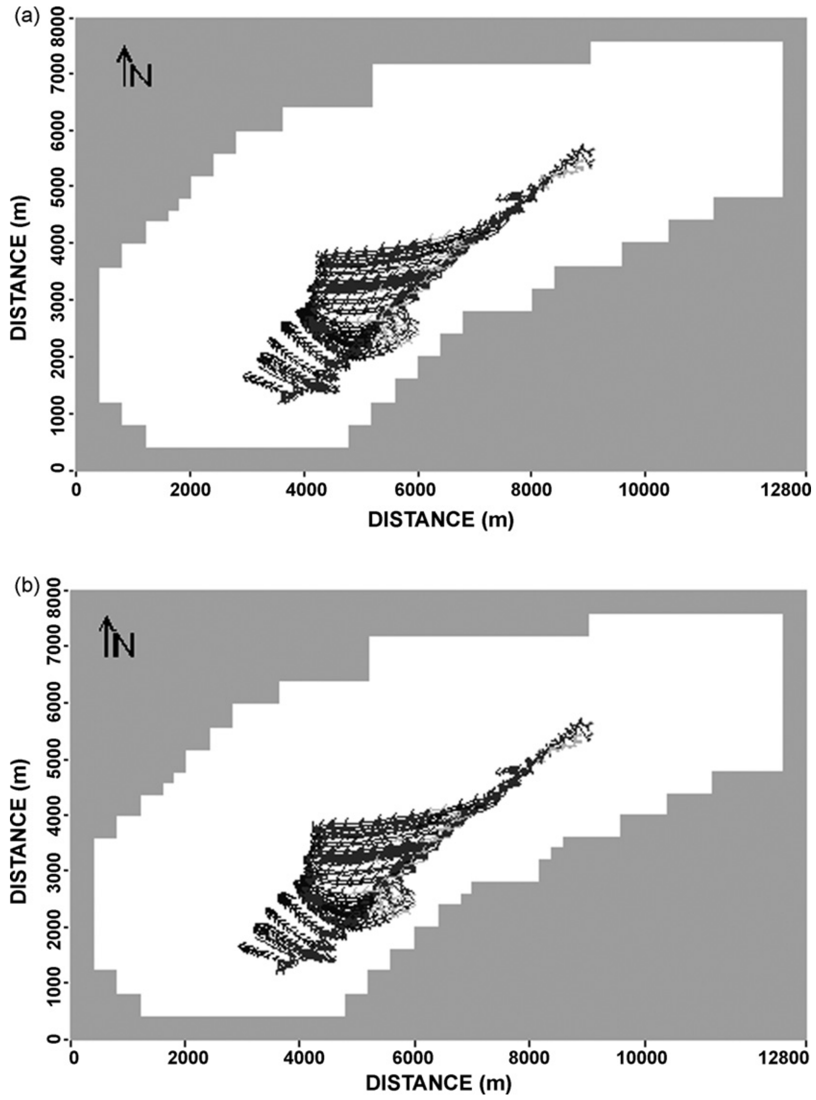

Fig. 8. (a and b) Map for particle movement for steady-state condition in 1st and 2nd Layer.

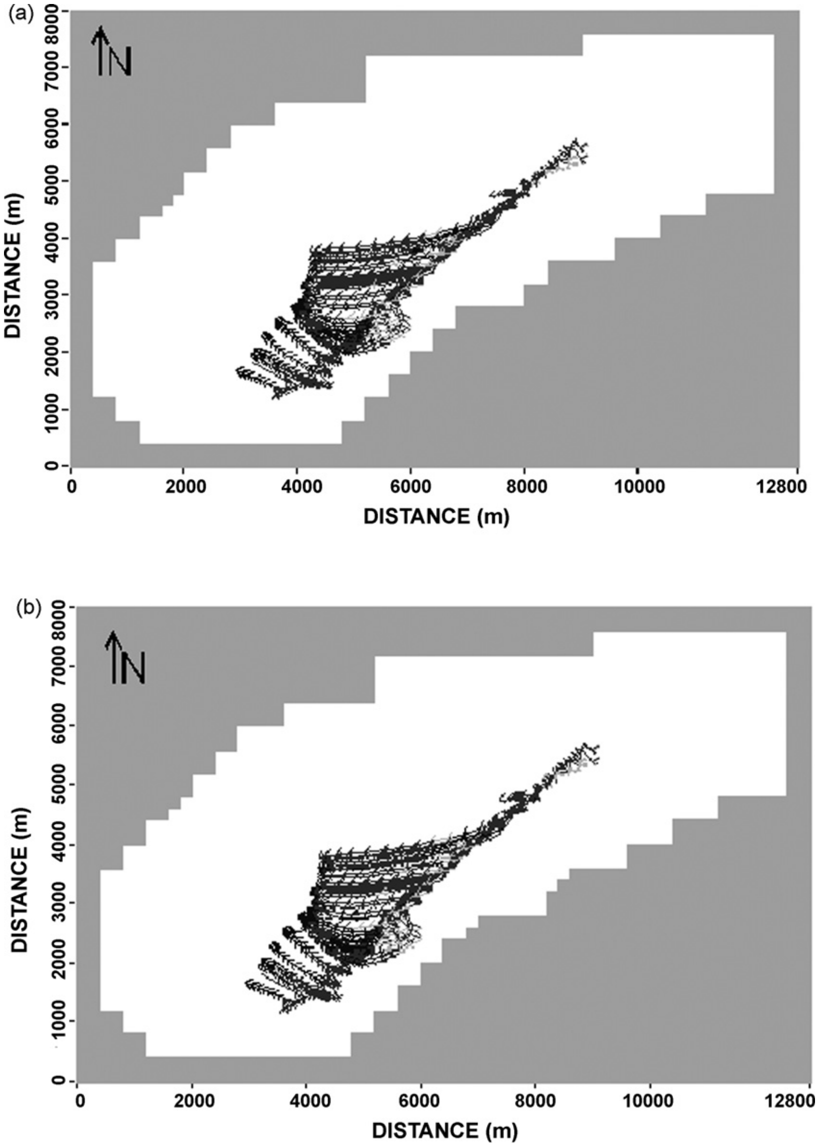

Fig. 9. (a and b) Map for particle movement for 20 years in 1st and 2nd layer.

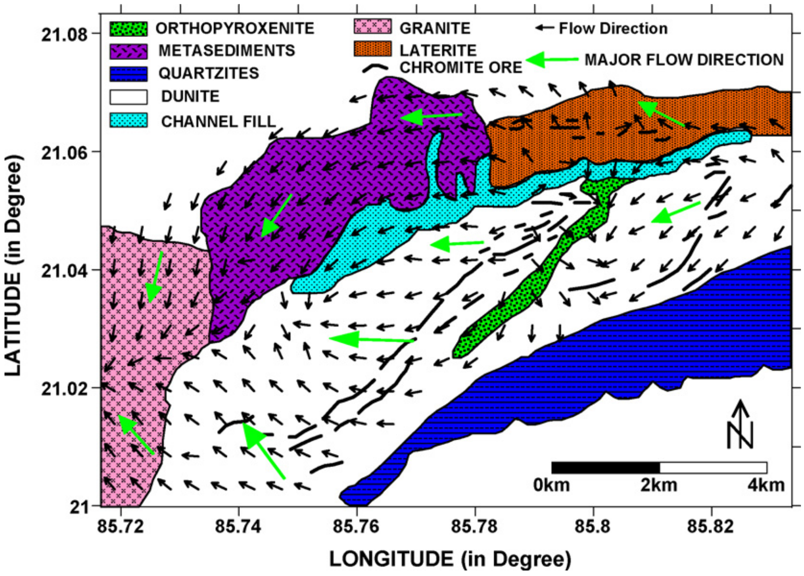

Fig. 10. Groundwater flow direction in different stratigraphic (Geologic) unit.

porosity is assigned for first layer is 0.20 and for second layer is 0.22. The recharge has been assigned to top layer in five zones, along the hill fringes it is 60 mm/year, along west side it is again 60 mm/year and along east side it is 100 mm/year and in centre region it is assigned as 200 mm/year. Similarly the top and bottom elevation of Damasal Nala has also been assigned from 186 m at upstream side and 86 m at downstream side and its conductance is assigned as 50 m/day. The model was then calibrated against the observed water level (April, 2002). The model was then used as a tool to visualize effect of mine leakage on the groundwater regime.

In the first instant the model is calibrated adjusting the parameters within the small ranges of values and then the model has been run for a steady-state condition using Visual MODFLOW for Windows version 2.61 [16]. The steady-state condition obtained is shown in Fig. 6. The result is found close to observed water level (April, 2002).

5.4.1. Particle pathlines

Concept of particle tracking is used to trace movement/migration of contaminants from the source. The method is based on the assumption that each directional velocity component varies linearly within a grid cell in its own co-ordinate direction. This assumption allows an analytical expression to be obtained describing the flow path within a grid cell. Given the initial position of a particle anywhere in a cell, the co-ordinates of any other point along its pathline within the cell, and the time of travel between them, can be computed. The principle behind particle tracking is simple; the fluid flow is seeded with particles, the locations of which is tracked through time. Depending on the nature of the particle, the fluid and the flow, the particle may follow the individual fluid elements, or they may have a relative velocity due to their buoyancy, their inertia or both. Particle tracking may thus be used both as a technique for measuring the fluid velocity if the particles are sufficiently small to follow the fluid elements. In the other extreme, multiphase and a sedimenting flows may be investigated.

The computer program MODPATH was developed by the USGS [26] to calculate two and three-dimensional particle tracking from steady-state flow simulation-using MODFLOW. MODPATH uses a semi-analytical particle-tracking scheme and can be used to compute pathlines and the position of particles at specified points in time. The pathlines accounts for the advective transport only.

To know the particle movement in the present model with initial conditions imported from MODFLOW calibration, a particle is added in a form of line shown in Fig. 7, where actually the chromite seams are present, which are considered to be the highest concentration of chromite in water and from this point only all the particles move into the aquifer system. The model then tracks the movement of the particles added. The model is run along with MODFLOW option for a transient condition for 50 years.

MODPATH has been employed to compute particle pathlines in the study area to trace the movement of contaminants for steady-state condition and for 20 years respectively, for 1st and 2nd layers shown in Figs. 8(a and b) and 9(a and b). The computed pathlines for steady-state condition, and 20 years indicate a predominant direction of contaminant migration from mining towards the Damasal Nala and towards Kaliapani, Chirgunia and Bhimtanagar Villages. The advective transport makes the contaminants to migrate about 1–2 km during last 20 years with an average groundwater velocity of 1.4 m/day for 1st layer and 0.0064 m/day for 2nd layer.

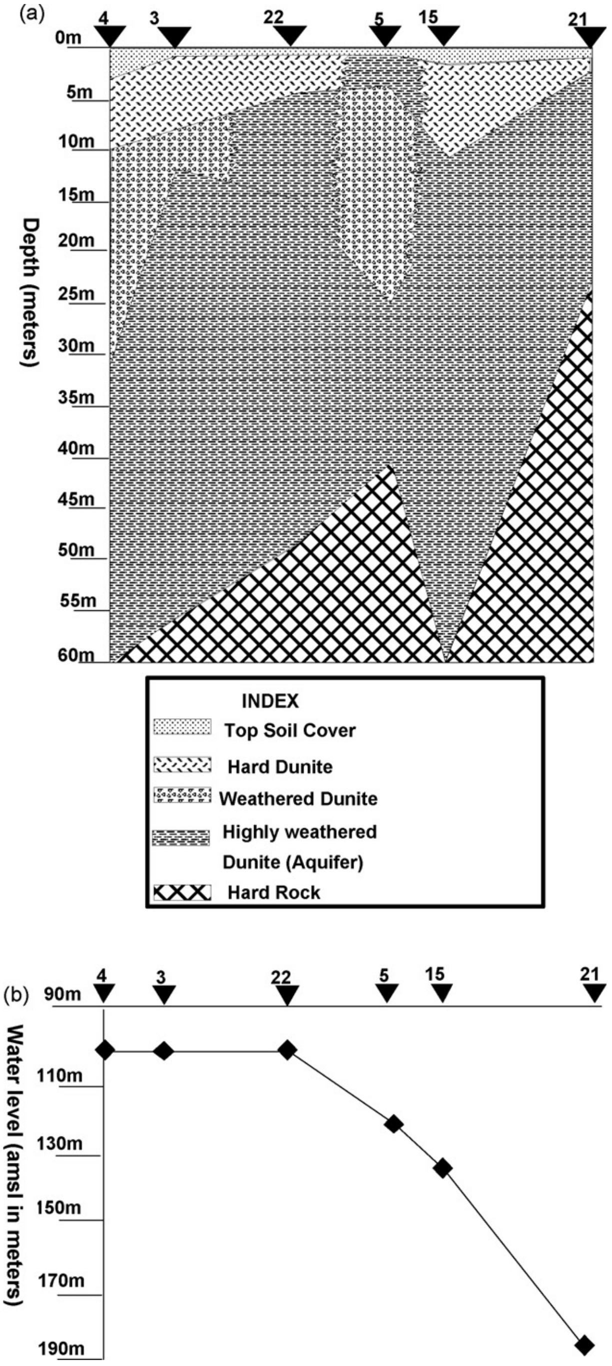

Fig. 11. (a) Geophysical cross section showing different lithology obtained from interpreted Vertical Electrical Soundings. (b) Water level graph above mean sea level (amsl) drawn along the geophysical cross section.

6. Results and discussion

The interpreted Vertical Electrical Sounding (VES) result shows maximum of 3–6 layers. Eighteen VES points shows 4 layers curves, four VES points show 5 layer curves, four VES point show 3 layer curves, while only one VES point shows 6 layer curve. The resistivities of the first layer varies from 10 to 562 Ω m and its thickness varies from 0.6 to 6 m, while the resistivity of the second layer varies from 6 to 2529 Ω m and its thickness varies from 1 to 30.7 m; whereas the aquifer resistivity shows variation from 25 to 156 Ω m and thickness 2.4–58 m, the depth of aquifer varies from 4 to 26 m below ground level. There are two aquifers in the subsurface in the area. One at a depth of about 25 m below ground level in unconfined condition and another at a depth of 25–60 m below ground level in confined condition [29]. Along the Damasal Nala and near Mahagiri Hills, the depth of aquifer is shallow below the ground level, whereas in the central part of the area the depth of aquifer is deeper.

The aquifer thickness varies from 2.4 to 70 m. The gradient of aquifer thickness is more towards the northwest direction comparing to the other parts of the area. The groundwater flow in various stratigraphic (Geologic) units is shown in Fig. 10. The majority of groundwater flow in laterite unit is along northwest direction, in metasediments unit it is in west and southwest direction, in dunite unit it is again showing west and southwest direction, whereas in granite unit it is in south and southwest direction. A direction of geophysical cross section is shown in Fig. 2. This cross section, drawn by using the interpreted layer parameters of vertical electrical soundings number 4, 3, 22, 5, 15 and 21 is shown in Fig. 11(a). A water table graph by using Fig. 4 is also drawn along with this geophysical cross section shown in Fig. 11(b). The water table graph and geophysical cross section agree well with each other i.e. if the aquifer thickness is more, the water table is shallow and if the aquifer thickness is less the water table is deep.

The well-water study indicates that in the of wells whose depth ranges from 7 to 93 m, the static water level measured during April 2002 varies from 2.3 to 20.7 m below ground level. It can be seen that the shallowest water level is near the Damasal Nala and the deepest water level is in the mining areas and it follows the general trend of the topographic elevation. The flow of groundwater is towards westward direction. In the northern part, the flow is towards Damasal Nala, whereas in the northwestern part, the Damasal Nala water seems to flow in the aquifer towards the village Chirgunia as shown in Fig. 4. The pumping test results show wide range of transmissivity, which varies from 0.25 to 80 m^2/day. For shallow aquifer up to a depth of 25 m below ground it is found to be 0.25 m^2/day and for deeper aquifer up to a depth of 25–60 m below ground it is 4–80 m^2/day. The variation of transmissivity in deeper aquifer is due to the degree of weathering and fracturing.

The pH ranges from 6.1 to 7.6 for post-monsoon period and 5.47–7.60 for pre-monsoon period. The pH regime of water samples shows acidic to midly alkaline nature. Total dissolved solids (TDSs) in the water samples are low and range from 30 to 369 mg/l for post-monsoon period and 185–507 mg/l for pre-monsoon period. In general the groundwater was found potable with most of the constituents within the permissible limit for drinking water except for very slight high concentration of Cr(VI) found in a few samples of mine seepage and Damasal Nala.

The concentration of chromium Cr(VI) observed in the surface and subsurface waters is shown in Table 6(a and b). The contour pattern for Cr(VI) concentration for post-monsoon and pre-monsoon is shown in Fig. 5(a and b) along with sample locations. The concentration of Cr(VI) exceeding the permissible limits was detected from few samples of groundwater, surface water and mine water and mine seepage. The Cr(VI) content was high near the ore bodies and it decreased with distance away from ore body. In groundwater samples, the Cr(VI) concentration varied from 0.009 to 0.043 mg/l for post-monsoon period and 0.032–0.452 mg/l for pre-monsoon period. The Cr(VI) concentration for surface water and mine water from quarry seepages ranges from 0.012 to 0.421 mg/l for post-monsoon period and 0.043–0.057 mg/l for pre-monsoon period.

The surface/mine water samples show high Cr(VI) concentration for post-monsoon period, this is due to the migration of pollutant from waste rock dump during the rainy season. Whereas, the Damasal Nala samples shows 0.046 mg/l in upstream side and 0.083 mg/l in downstream of Damasal Nala during the post-monsoon period and 0.023 mg/l in upstream side and 0.104 mg/l in downstream side of Damasal Nala during the pre-monsoon period. The high Cr(VI) concentration in Damasal Nala in down stream side is due to the mine discharge water into the stream and migration of leachate from waste-rock material in rainy season. A high Cr(VI) concentration of 0.450 mg/l was found in groundwater at one location only during the pre-monsoon period, while in remaining part it was quite below normal values, as the top soil cover of low permeability nature would not allow the leachate to migrate down.

The concentration of Total Suspended Solids (TSSs) which plays an important role in the drinking water chemistry is on higher side and it is varies from 4 to 34 mg/l during post-monsoon period and 12–64 mg/l during pre-monsoon period; whereas the permissible limits of TSS in potable water is only 10 mg/l [2]. The high concentration of TDS may be due to the insolubility of trace element in water. The TDS is comparatively more towards the S–E direction of mining area and this is further more extended towards Purnapani village. However, the samples collected from Kaliapani and South Kaliapani, which are the main villages of this area, have also shown their enrichment of Total Suspended Solids. The high concentration

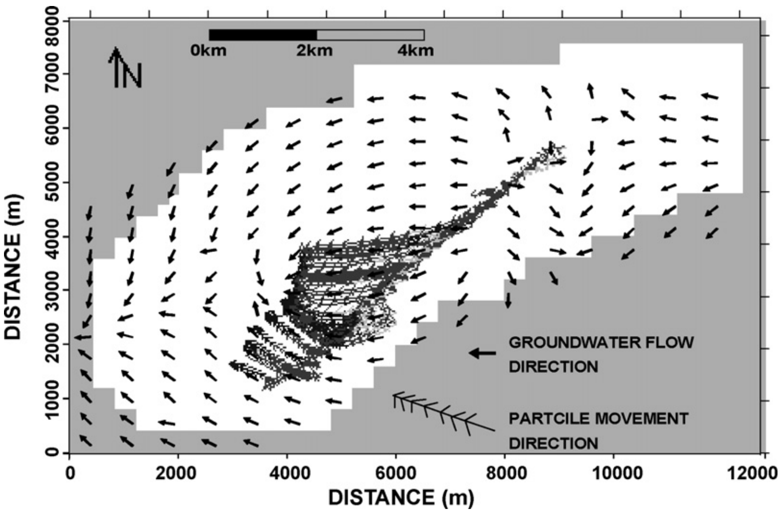

Fig. 12. Groundwater flow direction and particle movement/migration.

of Total Suspended Solid is more than the permissible limits and [2] are not allowing this for potable use.

The modeling study also suggests that the seepage from the mining area is not so pronounced that it will affect the groundwater system. From Figs. 8(a and b) and 9(a and b) it is found that the pollutant from mine will not move beyond 1–2 km from its source position for even 20 years. However the quality of water from mine seepage and from downstream side of Damasal Nala is on higher side for Cr(VI) concentration. Cr(VI) and Cr(III) both occur in natural water and in subsurface soils in oxidation state. It is less toxic and less mobile in the reduced Cr(III) state under oxidized condition and neutral to alkaline pH, chromium exists mainly as chromate [11]. A common practice to remove Cr(VI) from groundwater is to reduce chromate to Cr(III) by in situ chemical reduction [17]. By comparing Figs. 5(a and b), 8(a and b) and 9(a and b) it is found that the Cr(VI) concentration is high, where the of particle is showing predominant movement/migration in area. Fig. 12 shows the particle movement/migration and groundwater flow direction, they agree well with each other i.e. the particle movement/migration is more or less similar with that of the groundwater flow. Therefore, particle pathlines study is helpful in identifying the *t* contaminant zones and also the mine seepages areas. Further monitoring of groundwater quality will facilitate promoting remedial for avoiding any further pollution.

7. Conclusion

The application of resistivity surveys is useful in delineating the aquifer geometry and subsurface lithology. The interpreted layer parameters have very well corroborated with the geological evidence obtained by drill holes and from bore wells. The resistivity of the aquifer in the area ranges from 15 to 150 Ω m. The pH and TDS of samples collected are within the permissible limits while that the concentration is on higher side for drinking water purposes. The samples collected form mine seepage and Damasal Nala shows high concentration of Cr(VI), as most of the mine seepage is diverted to Damasal Nala. The seepage of water from different mines should not be allowed to spread over the cultivated or open area, it should be appropriately treated to reduce the Cr(VI) to Cr(III) and then may be discharged into the Damasal Nala or may be utilized for industrial or other needs to avoid any future pollution in the area. Such a study will be helpful in identifying the contamination movement and migration direction from the mining area. It will help in identifying the contaminant zones where further development and management of groundwater resources monitoring, study of groundwater quality will be helpful in reducing the Cr(VI) concentration in groundwater, to make it useful for drinking purposes.

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