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Research Article

GROUNDWATER QUALITY STATUS AND HYDROCHEMICAL VULNERABILITY AROUND THE SURJAGARH OPENCAST IRON ORE MINING BELT, GADCHIROLI DISTRICT OF MAHARASHTRA (INDIA)

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Abstract
Groundwater quality in mineral-rich hard-rock regions is strongly influenced by natural water–rock interaction, terrain conditions, and land-use disturbance associated with mining activity. The present study assesses groundwater quality status and hydrochemical vulnerability around the Surjagarh opencast iron ore mining belt using hydrochemical parameters, BIS drinking-water comparison, district-background comparison, and station-wise vulnerability classification. The analysis focused on selected parameters including pH, electrical conductivity, total dissolved solids, total hardness, calcium, magnesium, chloride, sulphate, bicarbonate, sodium, iron, uranium, and total alkalinity. Results showed that groundwater in the study area is generally near-neutral to mildly alkaline, with pH ranging from 7.00 to 8.70. Electrical conductivity indicated moderate dissolved ionic load, while total hardness and magnesium emerged as the dominant groundwater-quality concerns. Total hardness exceeded the BIS acceptable limit in 77.9% of analyzed records, and magnesium exceeded the acceptable limit in 61.0% of records. Calcium and TDS showed localized exceedance, whereas chloride, sulphate, and iron remained within permissible limits. Vulnerability classification indicated that most records fall within moderate to high vulnerability classes. The study identifies hardness, magnesium, localized calcium, and TDS as principal contributors to groundwater-quality vulnerability and emphasizes the need for systematic groundwater monitoring around the Surjagarh mining belt.

Key Words: Groundwater quality; Hydrochemical vulnerability; Opencast iron ore mining; Surjagarh mining belt; BIS standards; Hard-rock aquifer

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1. INTRODUCTION

The global problem of climate change has been one of the gravest problems of our epoch, and it is almost entirely man-made and brought about by industrialization,

In mineral rich areas, groundwater is an important resource since it provides the drinking-water supply, domestic use, agriculture and the local ecological stability, especially in hard rock areas where surface-water supply can be seasonal. Groundwater quality in mining belts is influenced by natural rock–water interaction, in addition to disturbance of the land, excavations, changes in drainage, changes in slopes, and exposure of fresh mineral surfaces. These processes may impact dissolved solids, hardness, major ions, and certain trace elements and can alter the flow of water in weathered and fractured rocks. Thus, rather than assessing the presence or absence of specific contaminants, it is important to consider the hydrochemical status and vulnerability of groundwater around opencast mining areas.Groundwater systems may be affected by opencast mining in a number of ways. Surface runoff and infiltration can be altered by removal of overburden and by the excavation of benches. Disturbed slopes, exposed rock faces, haul roads and waste disposal areas can increase sediment transport and/or alter the local recharges. The effects can be more complicated in hilly and forested areas where runoff can flow rapidly down slopes and link disturbed areas with streams, shallow aquifers and village water sources. Research conducted in the Indian mining areas revealed that major ions, dissolved solids, hardness and metal concentrations in groundwater could change in the vicinity of the mining belts, depending on the geology, intensity of mining, hydrological connectivity and seasonal recharge conditions (Singh & Kamal, 2017).The chemistry of the groundwater is unique and of particular concern in the iron ore mining areas, since the chemistry of the iron-bearing formations, lateritic weathering, associated trace elements, and the disruption of the surface geology by mining may all affect the chemistry of the groundwater. The use of water quality index and heavy metal pollution index methods was shown to be helpful in explaining the quality of groundwater in and around iron ore mining landscapes in the Bailadila iron ore mining area (Jareda et al., 2018). More recent studies on groundwater affected by iron mining have also highlighted the importance of considering spatial and temporal variability of the metals and the importance of differentiating between potential anthropogenic contamination and background. (Giri et al., 2023) This type of evidence can help inform a responsible vulnerability approach, especially if there is no direct causal proof of contamination.

Descriptive hydrochemistry, standard comparison, water quality index (WQI) and statistical tools for groundwater quality interpretations of suitability and environmental risk are increasingly being used together in groundwater-quality studies in India. The use of the methods based on WQI and supported with GIS has been prevalent in both mining and non-mining groundwater such that the hydrochemical data can be simplified to make it interpretable as groundwater quality classes (Kumar & Krishna, 2021). Groundwater-quality classification has been used in similar approaches using GIS and hydrochemical data to aid in both scientific interpretation and water-resource management (Ram et al., 2021). Integrated WQI and multivariate approaches also are helpful for determining water-quality controls and for delineating groups of parameters with the strongest influence on groundwater quality degradation (Gautam et al., 2024).The Surjagarh opencast iron ore mining belt is an important area for groundwater-quality assessment because it is situated in a mineralized hard-rock area where mining activities, terrain disturbance and local groundwater dependence all exist. In general, project level environmental documents present baseline or compliance oriented data and do not make project level comparisons of groundwater in and around the mining belt to the wider district level hydrochemical conditions. This has resulted in a gap in the research: Hydrochemical analysis of groundwater around Surjagarh needs to be done independently, a comparison needs to be done between the present water quality samples and the BIS drinking water standards, and a relative vulnerability assessment needs to be done. BIS IS 10500 sets acceptable and permissible limits for various water-quality parameters in drinking water, thus serves as a suitable basis for evaluating the excess of water-quality parameters in groundwater (BIS, 2012). Based on the recent pollution assessment in the mining regions in the hydrochemical signature, pollution indices, and multivariate techniques further support the relevance of combining the standard comparison with vulnerability-oriented interpretation (Kausher et al., 2023; Naskar et al., 2025). Groundwater quality is also important for evaluating the hydrogeochemical characteristics, as these directly impact the quality of drinking water, and the potential for exposure to groundwater in rural and resource-dependent areas (Roy et al., 2023).

Thus, the present study evaluates the groundwater quality status and hydrochemical vulnerability of Surjagarh opencast iron ore mining belt.

2. MATERIALS AND METHODS

2.1 Study area

The study was conducted around the Surjagarh opencast iron ore mining belt in the Etapalli block of Gadchiroli district of Maharashtra, India. The area represents a mineral-rich hard-rock terrain where groundwater occurrence is largely controlled by weathered and fractured rock conditions. Such geological settings are important for groundwater-quality assessment because dissolved ions, hardness, alkalinity, and selected trace elements may vary according to rock-water interaction, recharge conditions, drainage movement, and local environmental disturbance.

The mining belt is linked with mechanized opencast iron ore mining. The size of the mine lease area is reported as

348.09 ha, with a fully mechanized opencast mining method, bench height of 10 m, the bench width is greater than 15 m, the individual bench slope is 80° and the overall pit slope is 45°. The depth of the mines is reported up to 480 m above mean sea level (AMSL), the water table is reported at 260 m AMSL and it is envisaged during mining activities that no intersection with the water table will occur. The following properties give the hydrogeological background information for the groundwater-quality status and hydrochemical vulnerability within the mining belt (Ministry of Environment, Forest and Climate Change [MoEFCC], 2023).

2.2 Data sources and analytical scope

Secondary hydrochemical and mine-context information were used in this study. The CGWB dataset on groundwater quality was used to obtain the groundwater-quality data and to use the hydrochemical data for descriptive statistics, comparison of groundwater with BIS and comparison with the groundwater of the district and classification as groundwater vulnerable (Central Ground Water Board [CGWB] 2025). The opencast mining method, lease area, bench configuration, pit slope, water-table position, groundwater-intersection status and mine depth was drawn from the Surjagarh Environmental Clearance document (MoEFCC, 2023) for the purpose of official mine-context information. The reference values for acceptable and permissible concentration have been taken from BIS IS 10500 drinking-water standards (BIS, 2012). The groundwater stations around the Surjagarh mining belt was considered as the analysis area while the rest of the groundwater stations in the entire Gadchiroli district were considered as the district background group. The study was not designed to demonstrate that the groundwater was directly contaminated by the mining activity, but rather to determine the groundwater-quality status, exceedance, and relative hydrochemical vulnerability of the groundwater in and around the mining belt.

2.3 Selection of groundwater-quality parameters

The analysis used parameters that were relevant to groundwater-quality status and available in usable form for the study area. The selected parameters were pH, electrical conductivity, total dissolved solids, total hardness, calcium, magnesium, chloride, sulphate, bicarbonate, sodium, iron, uranium, and total alkalinity. These parameters were chosen to cover the major hydrochemical parameters needed for the evaluation of alkalinity, mineralization, hardness, tendency towards salinization, and the major ion and certain trace element of concern. Central indicators were not employed the parameters which do not have an adequate and consistent local observation. It is noteworthy that iron and uranium were retained due to their hydrochemical relevance, but were treated with caution when the number of observations was small. Parameters having few valid samples were only retained for descriptive reporting and for tentative interpretations. In particular, there were only a few valid observations of TDS, iron and uranium in the near-belt records, and these parameters were not used to make broad site-wide conclusions.

2.4Data cleaning and preparation

Groundwater-quality data were pre-screened for analysis. All blanks, non-numeric entries and invalid observations were coded as missing data. Only valid observations were used to calculate the parameters. Units were kept as in the data set: pH as unitless, EC as µS/cm, major chemical parameters as mg/L. TDS values where corresponding EC values showed the presence of dissolved ions were treated as invalid and "zero" values were ignored. Any entries with TDS of 0 were excluded from descriptive statistics and exceedance calculations for TDS. This adjustment was made to ensure consistency of hydrochemistry and to prevent underestimation of dissolved-solids concentration. This correction was applied before descriptive statistics, BIS exceedance analysis, and Mann–Whitney U comparison. The groundwater records were divided into two analytical groups which include near-Surjagarh mining belt group and Gadchiroli district background group. The near-belt group was applied to the characterization of groundwater quality in the vicinity of the mining belt whereas the wider district group was applied to determine if the near-belt groundwater exhibited a distinct hydrochemical pattern.

2.5 Descriptive hydrochemical analysis

Descriptive statistics were calculated for each selected groundwater-quality parameter in the near-Surjagarh belt. The statistics included minimum, maximum, mean, median, and standard deviation. Median values were emphasized in interpretation because groundwater-quality data are often non-normally distributed and may be affected by extreme values.

The descriptive analysis was used to identify the general groundwater-quality status of the mining belt. pH was used to assess acidity or alkalinity; EC and TDS were used to indicate dissolved ionic load; total hardness, calcium, and magnesium were used to evaluate hardness-related mineralization; chloride and sulphate were used to examine salinity-related tendencies; and iron and uranium were used as selected trace-element indicators where valid data were available.

2.6 BIS drinking-water exceedance analysis

Groundwater-quality parameters were compared with BIS IS 10500 drinking-water standards. For each parameter with a BIS limit, the number and percentage of samples exceeding the acceptable limit were calculated. Where a permissible limit was available, exceedance above the permissible limit was also calculated (BIS, 2012). For parameters with no relaxation under BIS, values beyond the acceptable range were treated as exceedances requiring concern.

The exceedance percentage was calculated as:

$$\text{Exceedance percentage} = \frac{\text{Number of samples exceeding the BIS limit}}{\text{Total valid samples for that parameter}} \times 100$$

This analysis was used to identify the main contributors to groundwater-quality stress around the Surjagarh mining belt

2.7 Near-belt versus wider district comparison

To find out if there was any marked hydrochemical pattern around the Surjagarh mining belt, some parameters of near-belt group were compared with the background parameters of the entire Gadchiroli district. The comparison was done on the basis of mean, median, median difference and statistical significance. The Mean–Whitney U test was employed due to the fact that groundwater-quality parameters are frequently not normally distributed and sample sizes vary by parameter. P-values < 0.05 were considered statistically significant. This comparison was only applied to determine the hydrochemical contrast of near-belt and wider district groundwater groups and not as a direct causal link from mining.

2.8 Hydrochemical vulnerability classification

A hydrochemical Vulnerability Classification was derived from the exceedance patterns of BIS. The evaluation of each groundwater record was based on the number and severity of exceedances in the parameters. Parameters scoring 0 were considered within the acceptable limits, parameters scoring 1 were considered outside the acceptable limits and parameters scoring 2 were considered outside the permissible limits. If there was no BIS relaxation, values outside the acceptable range were considered as permissible-level exceedance. Each record's total score was then normalised to the maximum possible score that the record could achieve for the number of valid parameters available in that record, to allow records with different numbers of valid parameters to be compared. Records were ranked as Low, Moderate, High and Very High Vulnerability classes using the normalized score. The mean vulnerability score was determined at each station as the average of all the valid groundwater records available at each station.

2.9 Station-wise vulnerability assessment

Mean vulnerability score of each groundwater station was calculated to assess vulnerability at each station. A dominant vulnerability class was then assigned to each station according to the dominant vulnerability at each station in the groundwater records. Station-wise vulnerability was compared with distance of the station from Surjagarh mine co-ordinate to see whether there is any spatial tendency of the vulnerability throughout the mining belt. This analysis was performed to help delineate areas of relatively high groundwater-quality concern and to support the station-wise vulnerability results. There was a cautious interpretation of distance, as local geology, recharge, drainage pathways and groundwater-flow conditions may also be important factors influencing hydrochemical vulnerability.

3. RESULTS

3.1 Hydrochemical composition of groundwater

The groundwater around the Surjagarh opencast iron ore mining belt was predominantly near neutral to very slightly alkaline and pH ranged between 7.00 to 8.70 with a median value of 7.80. The electrical conductivity did not exhibit a high degree of variation (190 to 1782 µS/cm) with a median of 819.50 µS/cm which suggested a variable amount of dissolved ionic load in the groundwater samples.

Table 1 shows that descriptive statistics indicate that salinity parameters related to hardness were more dominant than chloride or sulphate related indicators. The levels of total hardness recorded from 65-583 mg/L as $CaCO_3$ with a median value of 300 mg/L, which is above the BIS acceptable limit of 200 mg/L, but not exceeding the permissible limit of 600 mg/L.

Magnesium (Mg) ranged from 4.00 to 120.35 mg/L, with a median concentration of 34.05 mg/L which is slightly higher than the acceptable limit of 30 mg/L as prescribed by BIS. Calcium was elevated in a few samples, and chloride and sulphate were not elevated and were within the BIS limits.

Table 1. Descriptive statistics of selected groundwater-quality parameters around the Surjagarh mining belt

Parameter	n	Minimum	Maximum	Mean	Median	SD	BIS acceptable limit	BIS permissible limit
pH	77	7.00	8.70	7.83	7.80	0.43	6.5–8.5	No relaxation
EC (µS/cm)	84	190.00	1782.00	811.15	819.50	292.09	—	—
TDS (mg/L)	4	484.00	1158.00	711.75	602.50	307.31	500	2000
Total hardness (mg/L as $CaCO_3$)	77	65.00	583.00	299.74	300.00	108.22	200	600
Calcium (mg/L)	75	18.00	140.00	60.53	56.00	29.47	75	200
Magnesium (mg/L)	77	4.00	120.35	36.90	34.05	19.39	30	100
Chloride (mg/L)	75	4.00	138.26	66.56	63.28	32.00	250	1000
Sulphate (mg/L)	74	0.00	200.00	41.54	37.50	35.07	200	400
Bicarbonate (mg/L)	75	36.61	519.00	248.98	244.00	115.40	—	—
Sodium (mg/L)	73	3.00	115.00	43.90	40.00	26.91	—	—
Iron (mg/L)	3	0.00	0.05	0.02	0.00	0.03	0.3	No relaxation
Uranium (mg/L)	2	0.49	2.04	1.27	1.27	1.10	0.03	0.03
Total alkalinity (mg/L as $CaCO_3$)	9	104.90	245.08	158.41	154.92	42.39	—	—

The interpretation of TDS, iron, and uranium was kept cautious because these parameters had fewer valid near-belt observations than the major-ion and hardness parameters. As shown in Table 1, the groundwater-quality profile is mainly characterized by moderate mineralization, elevated hardness, magnesium enrichment, and localized calcium and TDS elevation. Chloride, sulphate, and iron did not show corresponding enrichment in the analyzed records.

3.2 BIS drinking-water exceedance pattern

The BIS exceedance pattern suggests that the overall hardness of the groundwater was major groundwater-quality issue in the Surjagarh mining belt. Table 2 shows that 60 out of the 77 hardness records were above the BIS acceptable limit which constitute 77.9% of the analysed samples. But all the hardness values were below the permissible limit of BIS. The second most common exceedance parameter was magnesium (47 of 77 records exceeded the acceptable limit). There were 19 of 75 records with a calcium value above the acceptable limit, and 3 of 4 valid records that had TDS levels above the acceptable limit. Chloride, Sulphate and iron were found within the BIS limits. In Figure 1 the exceedance pattern is shown on a parameter-by-parameter basis.

Table 2. BIS exceedance pattern of groundwater-quality parameters around the Surjagarh mining belt

Parameter	Samples analyzed	Above acceptable limit, n	Above acceptable limit, %	Above permissible limit, n	Above permissible limit, %	Result interpretation
pH	77	5	6.5	5	6.5	Mild alkalinity exceedance in limited samples
TDS	4	3	75.0	0	0.0	Acceptable-limit exceedance only
Total hardness	77	60	77.9	0	0.0	Dominant hydrochemical stress indicator
Calcium	75	19	25.3	0	0.0	Localized acceptable-limit exceedance

Magnesium	77	47	61.0	1	1.3	Frequent acceptable-limit exceedance
Chloride	75	0	0.0	0	0.0	Within BIS limits
Sulphate	74	0	0.0	0	0.0	Within BIS limits
Iron	3	0	0.0	0	0.0	Within BIS limit

The uranium exceedance result should be treated as a limited-record signal because it was based on only two valid observations.

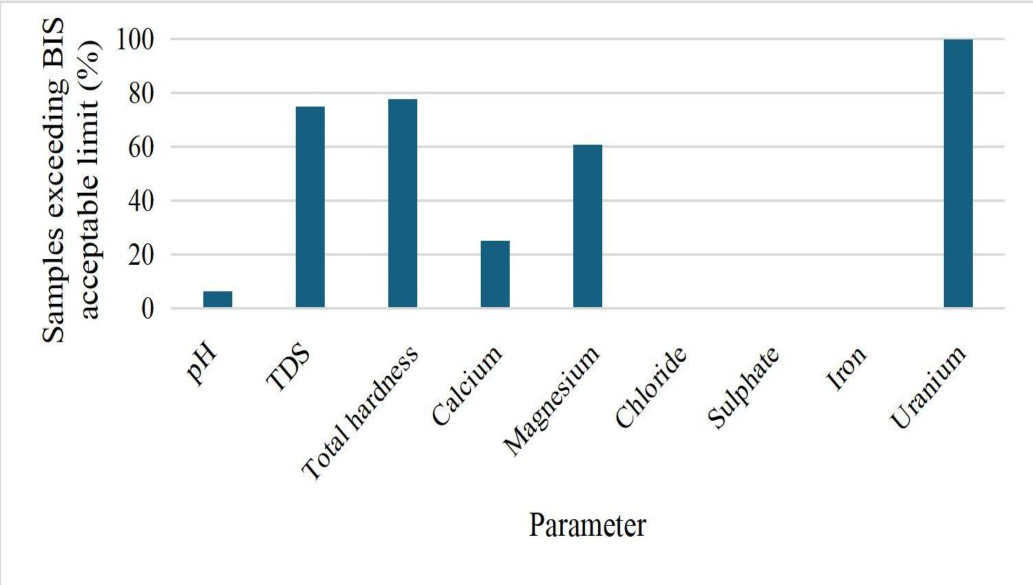

Figure 1. Parameter-wise BIS acceptable-limit exceedance in groundwater around the Surjagarh mining belt

Note: Uranium exceedance is based on limited valid records.

The exceedance pattern in Table 2 and Figure 1 shows that groundwater vulnerability is primarily associated with hardness, magnesium, TDS, and calcium. The absence of chloride, sulphate, and iron exceedance indicates that the observed hydrochemical stress is not dominated by chloride-sulphate salinity or iron enrichment.

3.3Comparison with wider Gadchiroli groundwater background

To find out whether the groundwater samples around the Surjargarh mining belt had formed a distinct hydrochemical pattern, the groundwater of the Surjargarh mining belt has been compared with that of the groundwater of the broader Gadchiroli district. Results from the comparison are given in Table 3.

The median pH in both groups was identical at 7.80. Median EC was slightly lower around the mining belt (819.50 µS/cm) than in the wider district background (851.00 µS/cm). Median total hardness was also slightly lower around the mining belt (300 mg/L) than in the wider Gadchiroli background (315 mg/L). After excluding invalid zero-TDS records, median TDS was 602.50 mg/L in the near-belt group and 562.00 mg/L in the wider district group, but this difference was not statistically significant. Calcium, magnesium, sulphate, bicarbonate, sodium, iron, and alkalinity showed broadly similar values between the two groups.

Table 3. Comparison of groundwater quality around the Surjagarh mining belt and wider Gadchiroli district

Parameter	Near-belt n	Near-belt median	Near-belt mean	Wider district n	Wider district median	Wider district mean	Median difference	p-value
pH	77	7.80	7.83	597	7.80	7.82	0.00	0.9035
EC	84	819.50	811.15	643	851.00	990.07	-31.50	0.1234

(µS/cm)								
TDS (mg/L)	4	602.50	711.75	82	562.00	658.16	40.50	0.5183
Total hardness	77	300.00	299.74	577	315.00	359.67	-15.00	0.1542
Calcium	75	56.00	60.53	577	56.00	65.67	0.00	0.7723
Magnesium	77	34.05	36.90	589	35.00	46.97	-0.95	0.4577
Chloride	75	63.28	66.56	576	71.96	108.52	-8.69	0.0132
Sulphate	74	37.50	41.54	572	35.00	60.02	2.50	0.3520
Bicarbonat e	75	244.00	248.98	585	226.00	255.12	18.00	0.6945
Sodium	73	40.00	43.90	557	37.00	45.88	3.00	0.3765
Iron	3	0.00	0.02	45	0.00	0.10	0.00	0.6952
Total alkalinity	9	154.92	158.41	119	170.00	196.84	-15.08	0.5171

Note: pH is unitless, iron and major ions are expressed in mg/L.

The only parameter for which a statistically significant difference is observed is chloride, but the near belt median is lower than the wide belt median of the district. Therefore, the near-belt groundwater does not exhibit a distinctively higher chloride, sulphate, iron or hardness signature compared to the general district groundwater background.

3.4Hydrochemical vulnerability classification

The results of hydrochemical vulnerability classification revealed that majority of the groundwater records in the mining belt of Surjagarh have been classified under moderate and high vulnerability class. As can be seen in Table 4, the class with moderate vulnerability was the most abundant vulnerability class with 48.8% of the records. 22.6% was deemed high vulnerability and 17.9% was deemed low vulnerability. The distribution of vulnerability classes is shown in Figure 2.

Table 4. Hydrochemical vulnerability classification of groundwater around the Surjagarh mining belt

Vulnerability class	Samples	Percentage
Low	15	17.9
Moderate	41	48.8
High	19	22.6
Very high	2	2.4
Not classified	7	8.3

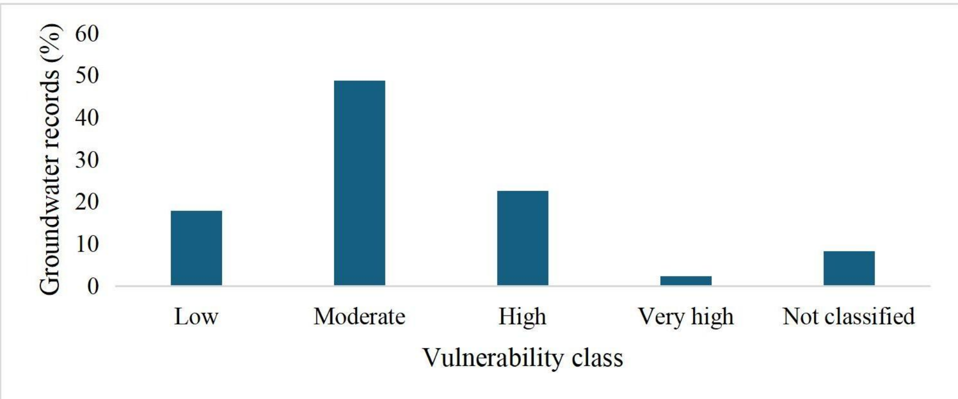

Figure 2. Hydrochemical vulnerability classification of groundwater around the Surjagarh mining belt

Table 4 and Figure 2 suggest that vulnerability to groundwater contamination is not insignificant, but is primarily grouped in the moderate to high range. Very high vulnerability was only present for 2.4% of the records, and was heavily affected by few observations of uranium. The vulnerability pattern is thus more likely to be considered a hydrochemical stress pattern based upon hardness and mineralization than a high level of widespread contamination.

3.5Station-wise hydrochemical vulnerability pattern

Clear spatial variations in hydrochemical vulnerability were observed in a station-wise analysis. The station-wise vulnerability scores are presented in Table 5, and their relationship with distance from the Surjagarh mine coordinate is shown in Figure 3.

Hedri had the highest mean vulnerability score, and was found to be primarily high vulnerability. The majority of areas were classified as moderate vulnerability – mostly Etapalli, Elchil, Medpalli, Tadgaon, Pirimili and Todsa Tola.

Table 5. Station-wise hydrochemical vulnerability around the Surjagarh mining belt

Station	Distance from mine coordinate (km)	Mean vulnerability score	Dominant vulnerability class
Hedri	3.01	0.278	High
Todsa Tola	12.02	0.083	Moderate
Etapalli	15.03	0.220	Moderate
Tadgaon	24.90	0.131	Moderate
Elchil	25.51	0.195	Moderate
Pirimili	26.50	0.101	Moderate
Medpalli	27.79	0.190	Moderate

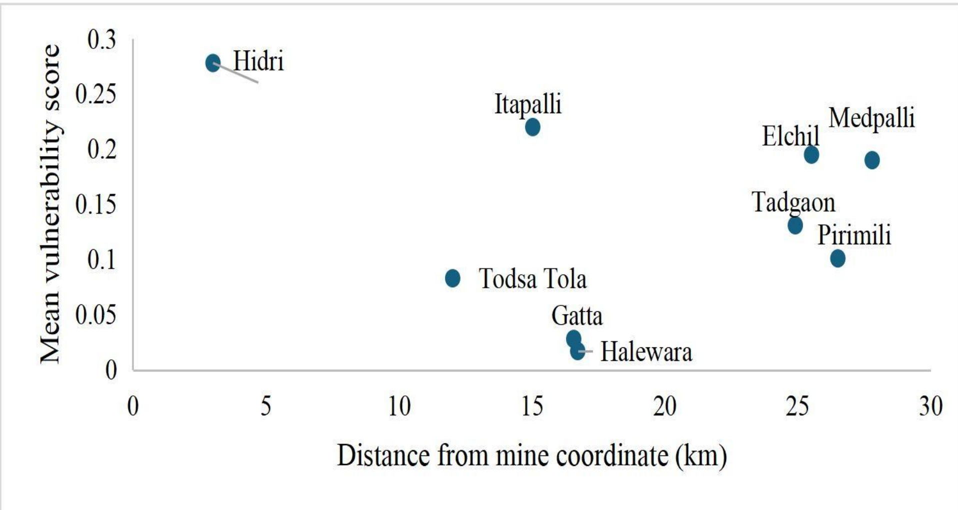

Figure 3. Station-wise hydrochemical vulnerability score by distance from the Surjagarh mine coordinate

As shown in Table 5 and Figure 3, vulnerability did not decline in a simple linear manner with distance. The nearest station was Hidri with the highest mean vulnerability score, but there were others further away that were still in the moderate range. This suggests that the hydrochemical conditions at a certain region in and around Surjagarh belt might also be a factor rather than the distance and could also play an important role in the groundwater vulnerability. In general, the findings of the present work indicate that the main factors affecting the vulnerability of groundwater quality in the Surjagarh opencast iron ore mining belt are total hardness, magnesium, localized calcium and exceedance of TDS. There was no significant exceedance noted for chloride, sulphate or iron in the records available.

4.DISCUSSION

Groundwater-quality data around the Surjagarh opencast iron ore mining belt reveal a hydrochemical profile dominated by moderate mineralization and hardness-related stress, rather than a clear salinity- or iron-dominated pattern. The near neutral to mildly alkaline pH indicates that there are no acidic conditions that are present in the groundwater system. This is because the strong acidic character of the mine drainage is often correlated with the increased mobilization of metals; however, there is no such acidic hydrochemical environment recorded in the available Surjagarh records. Rather the issues are with the combined hardness, the magnesium content, the localized rise in the calcium content, and the small amount of TDS overage. This process is typical in hard rock aquifers in which hardness and the mineral composition of the water may be greatly affected by weathering, variations in recharge, residence time, and mineral dissolution. Groundwater chemistry has been observed to influence with the land-use setting and recharge of monsoons and interactions with the water and the rocks, particularly in cases where the water-rock interaction is dominated by fractured and weathered rock, in hard-rock aquifer studies (Rajmohan et al., 2025).

The high percentage of the total hardness and magnesium exceedance suggests that mineralization is the major concern for groundwater vulnerability in the Surjagarh belt and not wide spread contamination of toxic elements. The total hardness was found to be more than BIS limit in 77.9% of the records analysed and magnesium more in 61.0% of the records analysed. Excess of calcium was more localized and the concentration of chloride and sulphate did not exceed the BIS limits. This indicates that carbonate or silicate weathering, interaction with mafic minerals and local hard rock geochemistry could be significant factors affecting groundwater chemistry. Natural geochemical controls may coincide with surface disturbance, slope cutting, exposed rock surfaces and changed recharge pathways in mining areas. Hence the observed hydrochemical stress is seen to be a groundwater quality vulnerability indicator in the hard rock mineralized environment.

A careful reading and interpretation of the other background information, such as the comparison between near-belt groundwater and the broader background of the Gadchiroli district, further reinforces the need for caution. The pH, EC, TDS, hardness, calcium, magnesium, sulphate, bicarbonate, sodium, iron, and alkalinity were not significantly different between the near-belt and district-background groups for most of these parameters. The only parameter found to be statistically significant was the chloride parameter, but the median value of the chloride parameter was lower in the near-belt group. This finding suggests that there is no clearly defined cluster of groundwater contamination enriched in chloride, sulphate, iron or hardness in the vicinity of the Surjagarh belt compared to the background ground of the district. In hydrogeology, groundwater chemistry will be relevant for comparison as it is influenced by the local mining activity as well as the regional lithological background. A multivariate and hydrochemical study has also highlighted the need to differentiate the impacts of mining from natural hydrogeochemical evolution prior to assigning a water quality change to mining activity (Li et al., 2022).

The vulnerability classification serves as a good overview of the severity of groundwater quality stress relative to the study area. Almost half of the near-belt groundwater records were considered moderate vulnerability and approximately one-fifth were considered high vulnerability. This means that groundwater-quality stress is present, but is not present throughout the mining belt. The very high vulnerability class was limited and was heavily affected by the few observations of uranium, and should not be interpreted as a site-wide condition. The results of the station wise also indicated that there was no linear decrease of vulnerability as a function of distance from the mine coordinate. The mean vulnerability score for Hidri, the closest station, was the highest but several more distant stations were still in the moderate category. The spatial pattern indicates that hydrochemical and hydrogeological conditions in the surficial environment are likely controlling factors, and not only the proximity of the mine. Groundwater quality in other mining basins has been found to vary in space and interpretation must be made at the station level, not on a distance basis

(Alexander et al., 2017). It is also significant that there is no indication of strong chloride and sulphate exceedance. Sulphate enrichment can be used to help identify the contribution from oxidation of sulphide-bearing minerals, mine drainage or leaching from exposed mine surfaces in many groundwater systems affected by mining. In the current study, there was no statistically significant enrichment in sulphate in the near-belt group and did not exceed the BIS limits. Levels of chloride also did not exceed drinking water standards and were below the general district median. So there's not much of a mine drainage-type salinity signal in the records available. Opencast mining may have indirect effects on groundwater systems, however, through altering drainage pathways, surface drainage, recharge zones and exposing new rock faces. Studies on drainage of mines on a large scale have demonstrated that mining can influence the hydrochemical evolution of groundwater even if the chemical reaction does not manifest as a prevailing parameter, due to changes in flow field, water–rock interaction, and aquifer connectivity (Luo et al., 2022).

The outcomes indicate vulnerability to hydrochemistry in a mineralised hard rock environment where the use of opencast mining could interact with regional geology. However, the similarity of near-belt and wider district groundwater suggests that the observed pattern is likely more a geographic than mining influence. The detailed groundwater-flow information, aquifer connectivity, mine-water chemistry and repeated monitoring are necessary for open-pit mine hydrochemical studies to identify the source (Liu et al., 2021). This is pertinent here since the monitoring data available for the present analysis are not the result of purpose-designed upgradient–downgradient field sampling.

The study is overall an independent hydrochemical evaluation of the groundwater in the Surjagarh opencast iron ore mining belt and the most dominant vulnerability indicators are T.H., Mg, localized Ca, TDS. The results suggest increased monitoring of the groundwater in and around the mining belt, with a primary focus on stations that experience repeated hardness, magnesium, calcium, or TDS stress. Continuous monitoring is recommended to include seasonal sampling, close to a mine location, upgradient and downgradient sampling, trace-metal analysis, and the use of groundwater-flow and drainage information. This monitoring would help to establish if the observed vulnerability is a natural factor, a factor caused by mining, or a factor caused by both natural and anthropogenic controls.

5.CONCLUSION

The present study evaluated the hydrochemical vulnerability of groundwater around Surjagarh opencast iron ore mining belt based on hydrochemical characterization, comparison with drinking water BIS standards, district background and station-wise hydrochemical vulnerability. Overall, the groundwater was near-neutral to slightly alkaline, moderately mineralized, and characterized by a dominant hardness-related signature. The most common parameters found to be in excess of the BIS acceptable limit were total hardness and magnesium with some localized exceedance seen for calcium and TDS. The groundwater quality data available show that chloride, sulphate, and iron are all within the acceptable limits and do not appear to be a major concern in the available data; hardness and mineralization appear to be the major concerns. When compared with the groundwater parameters of other water of the Gadchiroli districts, vulnerability class is high found only in Hedari which is very close to the surjagarh opencast mine whereas moderate vulnerability class recorded in remaining samples. The vulnerability classification showed that a significant percentage of groundwater records were in moderate and high vulnerability classes, however. Additionally, results were observed to be station-wise, some with higher vulnerability scores compared to others. The results indicate that continued monitoring of groundwater quality is needed around the mining belt, particularly in stations where groundwater stresses (repeated hardness, magnesium, calcium, or TDS) were observed.

The study provides a focused hydrochemical assessment of groundwater around the Surjagarh opencast iron ore mining belt and identifies the main parameters contributing to groundwater-quality vulnerability. Future sampling should consist of seasonal sampling, upgradient and downgradient wells, full analysis of all trace metals, observation of groundwater levels, and an assessment of the mine drainage. This activity will help in strengthening long-term protection of ground water and enable good environment management in Surjagarh mining area.

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