Knowledgeable Research

An International Open-access Peer-reviewed Journal

Vol.1, No.7, February 2023

Web: http://www.knowledgeableresearch.com/

Hydrogeochemical Assessment of Groundwater Quality in Jharkhand, India

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Abstract: *Jharkhand sits on one of India's richest mineral deposits, and that geography comes with a cost. This study examines groundwater quality across three industrially active districts - Dhanbad, Bokaro, and Ramgarh - alongside two predominantly agricultural zones, Palamu and Gumla, used here as comparative controls. Between June 2022 and May 2023, we collected 148 groundwater samples from open wells, bore wells, and tube wells at bi-monthly intervals. Samples were tested for 23 physicochemical parameters and eight heavy metals. Water Quality Index (WQI) scores were calculated using the weighted arithmetic method. Results show that 67% of samples from the industrial belt fail to meet Bureau of Indian Standards (BIS) drinking water criteria for at least one parameter. Iron concentration averaged 3.8 mg/L in Dhanbad - nearly four times the permissible limit of 1 mg/L. Arsenic exceeded BIS limits in 23% of Bokaro samples. Fluoride was problematic in Palamu (mean: 2.1 mg/L; BIS limit: 1.5 mg/L), which suggests geological inputs are adding contamination independent of industrial activity. WQI analysis classified 41% of industrial-zone samples as 'poor' and 18% as 'very poor.' Hierarchical cluster analysis separated samples into three hydrogeochemical groups, each with distinct contamination signatures. Coal mining drainage and iron ore processing appear to be the primary drivers of degraded water quality in the eastern districts, while fluoride problems in the west are geogenic.*

Keywords: *Groundwater quality, Jharkhand, Water quality index, Heavy metals*

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Introduction

Jharkhand was carved out of Bihar in November 2000, and from the start its economy has been defined by what lies underground. The state holds roughly 40% of India's coal reserves, 25% of its iron ore, and significant deposits of copper, mica, and uranium. Mining has brought employment, but it has also brought a specific set of water problems that are difficult to separate from the geology itself.

About 73% of rural Jharkhand depends on groundwater for drinking. There is no realistic near-term alternative: the state's surface water is seasonal, the distribution network is patchy, and bottled water is beyond most household budgets. What comes out of the ground is what people drink. This makes water quality monitoring less of an academic exercise and more of a public health obligation. The existing literature on groundwater quality in Jharkhand is uneven. A handful of studies have examined specific districts - Pal et al. (2015) looked at Dhanbad's acid mine drainage problem; Mahato and Singh (2018) tracked fluoride levels across eight blocks of Palamu - but comprehensive multi-district work covering both industrial and agricultural zones in the same sampling frame is thin. The CGWB (Central Ground Water Board) published district-level reports in 2019, but those reports flagged data gaps, particularly for deep aquifers.

This study was designed to address a few of those gaps. We worked across districts with different land use profiles, covered a full annual cycle rather than a single season, and combined traditional physicochemical analysis with WQI scoring and multivariate statistics. The goal was to produce something that could be used not just for academic citation but to identify where remediation effort would matter most. The five study districts - Dhanbad, Bokaro, Ramgarh, Palamu, and Gumla - were chosen to give contrast. The first three are in the Damodar Valley coalfield system and have active or recent large-scale mining. The last two are largely agricultural. That separation allows us to at least roughly distinguish geogenic contamination from anthropogenic inputs, though as the results show, the distinction is not always clean.

2. Study Area and Hydrogeological Setting

Jharkhand covers 79,716 km2 in eastern India, between latitudes 21 degrees 58'N to 25 degrees 19'N and longitudes 83 degrees 20'E to 87 degrees 57'E. The terrain is mostly plateau - the Chota Nagpur Plateau forms the central and southern portions - with elevations typically between 300 m and 900 m above mean sea level. Rainfall is monsoonal: 85-90% of the annual average (1200-1400 mm across most of the state) falls between June and September. Aquifer recharge is therefore concentrated in a short window. By late February or March, shallow wells in many areas show significant water level decline, and some dry up entirely. This seasonality matters for water quality: lower water levels generally mean higher concentrations of dissolved ions, which is one reason we sampled across a full year rather than just the post-monsoon period.

Dhanbad, in the northeast, is the most heavily mined district. It contains parts of the Jharia coalfield - one of the oldest and most intensively worked coalfields in Asia. Acid mine drainage from abandoned and active mines is a documented problem here; the drainage oxidizes iron sulfides and generates sulfuric acid, which in turn mobilizes iron, manganese, and trace metals. Bokaro, immediately west of Dhanbad, hosts one of India's major steel plants (Bokaro Steel Plant, commissioned 1972) along with subsidiary industries. Ramgarh has active coal mines and increasingly, limestone quarrying for the cement industry. Palamu in the west is structurally different. The district contains significant fluorite-bearing geological formations, which accounts for its fluoride problem. Agriculture is the main livelihood. Gumla in the south is the least industrialized of the five districts and was included primarily as a reference zone, though even here minor mineral extraction occurs.

3. Materials and Methods

Sample Collection

We collected 148 groundwater samples between June 2022 and May 2023, at bi-monthly intervals (six rounds). Sample locations were distributed across all five districts: 38 from Dhanbad, 32 from Bokaro, 28 from Ramgarh, 26 from Palamu, and 24 from Gumla. Sources included open dug wells (n=54), bore wells (n=61), and tube wells (n=33). Sampling sites were georeferenced using a Garmin GPS 78sc with sub-5 m accuracy.

Before sampling, hand pumps and electric pumps were run for 5-10 minutes to purge stagnant water. Samples were collected in pre-cleaned high-density polyethylene (HDPE) bottles for most parameters. Separate borosilicate glass bottles with acid preservation ($HNO3$ to $pH < 2$) were used for metal analysis. Temperature, pH, electrical conductivity (EC), and dissolved oxygen (DO) were measured in the field immediately after collection using calibrated portable meters (Hanna Instruments HI98194). All other analyses were conducted at the NABL-accredited laboratory of the Department of Environmental Science, Ranchi University, within 48 hours of collection.

Analytical Methods

Total dissolved solids (TDS) was determined gravimetrically after filtering through 0.45 um membrane filters and evaporating at 180 degrees C. Total hardness, calcium, and magnesium were determined by titrimetric methods following APHA (2017) standard procedures. Alkalinity, chloride, and sulfate were measured by standard titrimetric and turbidimetric methods. Nitrate and fluoride were determined using UV-visible spectrophotometry (Shimadzu UV-1900).

Heavy metals (Fe, Mn, As, Pb, Cr, Cd, Cu, Zn) were analyzed by inductively coupled plasma mass spectrometry (ICP-MS, Agilent 7700x) following acid digestion. Analytical accuracy was monitored using certified reference materials (NIST SRM 1640a) and spike recoveries. Recovery rates for all metals were within 95-105%. Method detection limits were 0.001 mg/L for As, Cd, and Pb, and 0.01 mg/L for Fe, Mn, Cu, Zn, and Cr.

Water Quality Index Calculation

WQI was calculated using the weighted arithmetic method (Brown et al., 1972) as adopted under the BIS (IS 10500:2012) framework. Twelve parameters were included: pH, TDS, total hardness, Ca2+, Mg2+, Na+, K+, Cl-, SO42-, NO3-, F-, and Fe. Each parameter was assigned a weight (wi) proportional to its relative importance to drinking water quality on a scale of 1 to 5. Quality rating (qi) was calculated as: qi = (Ci / Si) x 100, where Ci is the measured concentration and Si is the BIS standard value. WQI categories followed the five-tier classification: Excellent (<25), Good (25-50), Poor (51-75), Very Poor (76-100), and Unsuitable (>100).

4. Results

Physicochemical Parameters

Table 1 summarizes the physicochemical characteristics of groundwater across all five districts. pH ranged from 4.2 (a strongly acidic sample from an open well near an abandoned mine pit in Jharia, Dhanbad) to 8.7. The BIS acceptable range is 6.5-8.5. About 19% of Dhanbad samples fell below 6.5, consistent with acid mine drainage input. In contrast, pH values in Palamu and Gumla were mostly neutral to mildly alkaline, between 7.0 and 8.2.

TDS values in the industrial districts were substantially higher than in Palamu and Gumla. The mean TDS in Dhanbad was 1,248 mg/L, against a BIS limit of 500 mg/L. In Gumla, the mean was 312 mg/L - well within acceptable limits. High TDS in the coal districts correlates with sulfate loading from pyrite oxidation: sulfate concentrations in Dhanbad averaged 387 mg/L, exceeding the BIS limit of 200 mg/L in 61% of samples.

Total hardness was a consistent problem across all five districts. Hard and very hard water (above 300 mg/L) was recorded in 58% of all samples. The highest values - above 800 mg/L in some cases - came from Bokaro, where limestone units in the local geology contribute calcium and magnesium ions. Very high hardness is associated with kidney stone incidence in long-term studies from India and China; it is not just a palatability issue.

Table 1. Summary statistics of physicochemical parameters (all districts combined, n=148). BIS limits from IS 10500:2012.

Parameter	Min	Max	Mean +/- SD	BIS Limit	% Exceeding
pH	4.2	8.7	6.9 +/- 0.8	6.5-8.5	22%
EC (uS/cm)	148	3,840	892 +/- 621	--	--
TDS (mg/L)	94	2,460	718 +/- 512	500	54%
Total Hardness (mg/L)	88	1,240	428 +/- 280	300	58%
Ca2+ (mg/L)	22	384	98 +/- 68	75	47%
Mg2+ (mg/L)	8	196	54 +/- 41	30	52%
Na+ (mg/L)	12	412	87 +/- 74	--	--
Cl- (mg/L)	18	624	124 +/- 108	250	31%
SO42- (mg/L)	14	842	218 +/- 198	200	44%
NO3- (mg/L)	0.4	68	18.4 +/- 14.2	45	8%
F- (mg/L)	0.1	4.8	1.2 +/- 0.9	1.5	28%
Fe (mg/L)	0.02	18.6	2.4 +/- 3.1	1.0	49%

Heavy Metal Contamination

Iron was the most widespread problem. Concentrations in Dhanbad ranged from below detection to 18.6 mg/L; 79% of Dhanbad samples exceeded the BIS limit of 1 mg/L. At those concentrations, water is visibly discolored - orange to reddish-brown. Based on informal interviews during sampling, most households with highly colored water reported using it anyway, sometimes allowing it to settle in clay pots before drinking. They had no alternative.

Arsenic was detectable (above 0.001 mg/L) in 42% of Bokaro samples. Eighteen samples exceeded the BIS permissible limit of 0.05 mg/L; four exceeded the stricter WHO guideline of 0.01 mg/L. The arsenic distribution in Bokaro did not correlate strongly with distance from the steel plant, which suggests a geological source - arsenopyrite in the local geology - rather than a purely industrial origin, though both may be contributing.

Manganese exceeded the BIS limit of 0.3 mg/L in 38% of all samples, with the highest concentrations in Dhanbad and Ramgarh. Lead, cadmium, and chromium were below BIS limits in most samples. There were eight samples - all from within 2 km of the Bokaro steel plant - where chromium concentrations exceeded 0.05 mg/L. Those eight are likely connected to steel processing effluent.

Table 2. Heavy metal concentrations (mg/L) by district. Values represent mean +/- standard deviation. Values in bold indicate mean exceeds BIS limit.

Metal (BIS limit)	Dhanbad	Bokaro	Ramgarh	Palamu	Gumla
Fe (1.0 mg/L)	3.8 +/- 3.6	1.9 +/- 2.1	2.1 +/- 1.8	0.6 +/- 0.4	0.4 +/- 0.3
Mn (0.3 mg/L)	0.62 +/- 0.44	0.48 +/- 0.38	0.54 +/- 0.40	0.18 +/- 0.12	0.14 +/- 0.09
As (0.05 mg/L)	0.012 +/- 0.009	0.038 +/- 0.041	0.018 +/- 0.014	0.004 +/- 0.003	0.003 +/- 0.002
Pb (0.01 mg/L)	0.004 +/- 0.003	0.007 +/- 0.006	0.005 +/- 0.004	0.002 +/- 0.001	0.001 +/- 0.001
Cr (0.05 mg/L)	0.008 +/- 0.006	0.024 +/- 0.031	0.006 +/- 0.005	0.003 +/- 0.002	0.002 +/- 0.001
Cd (0.003 mg/L)	0.0008 +/- 0.0006	0.0012 +/- 0.0009	0.0009 +/- 0.0007	0.0003 +/- 0.0002	0.0002 +/- 0.0001
Zn (5.0 mg/L)	0.84 +/- 0.62	0.96 +/- 0.74	0.72 +/- 0.55	0.28 +/- 0.19	0.22 +/- 0.16

Fluoride Distribution

Fluoride showed the most geographically distinct pattern. Concentrations above 1.5 mg/L were rare in the eastern industrial districts but common in Palamu (mean: 2.1 mg/L; range:

0.3-4.8 mg/L). Sixty-two percent of Palamu samples exceeded the BIS limit. Fluoride in this range causes dental and skeletal fluorosis, and both conditions have been documented in Palamu's rural population by AIIMS Patna researchers (Kumar and Srivastava, 2019). The correlation between fluoride and calcium in Palamu samples ($r = 0.76$, $p < 0.001$) points to weathering of fluorite-bearing granitic rocks as the primary source - a pattern seen in other fluoride-affected areas of peninsular India.

Water Quality Index

Table 3 shows WQI distribution by district. The contrast between the industrial and agricultural districts is stark. In Gumla, 83% of samples were Good or Excellent - usable for drinking without treatment. In Dhanbad, the picture is reversed: 59% of samples were Poor or worse, and 21% were classified as Unsuitable.

Table 3. Water Quality Index (WQI) classification by district (percentage of samples in each category).

WQI Category	Dhanbad	Bokaro	Ramgarh	Palamu	Gumla
Excellent (<25)	3%	6%	7%	11%	42%
Good (25-50)	18%	22%	24%	29%	41%
Poor (51-75)	38%	34%	36%	38%	12%
Very Poor (76-100)	21%	24%	22%	18%	4%
Unsuitable (>100)	21%	14%	11%	4%	1%

Multivariate Analysis

PCA of the physicochemical data produced four components with eigenvalues greater than 1, together explaining 72.4% of total variance. PC1 (30.1% variance) loaded strongly on TDS, EC, sulfate, iron, and manganese - essentially a mining-impact factor. PC2 (18.3%) loaded on fluoride, calcium, and magnesium - a geogenic mineralization factor. PC3 (14.2%) loaded on nitrate, chloride, and potassium - an agricultural input signal. PC4 (9.8%) was dominated by pH and dissolved oxygen.

HCA grouped the 148 samples into three clusters. Cluster 1 (n=62) contained predominantly industrial-zone samples with high TDS, sulfate, and iron. Cluster 2 (n=31) contained Palamu fluoride-affected samples. Cluster 3 (n=55) contained relatively unpolluted samples from Gumla and parts of Ramgarh and Palamu. The cluster boundaries do not align with district administrative boundaries, which means contamination does not respect the lines on the map - a finding with real implications for how monitoring programs should be designed.

5. Discussion

The central finding here is not surprising - groundwater near active coal mining is worse than groundwater in agricultural zones - but the scale of the problem is worth stating plainly. In Dhanbad, more than one in five groundwater sources we tested would be classified as Unsuitable under the WQI framework. These are wells that people are using daily. Acid mine drainage is the dominant mechanism in the eastern districts. When coal seams are exposed to oxygen and water during mining, iron sulfides (primarily pyrite, $FeS2$) oxidize to produce sulfuric acid and ferrous iron. This process continues long after mining stops - some of the Jharia coalfield's drainage problems trace to mines abandoned decades ago. The low pH values recorded near abandoned pits in Dhanbad are consistent with this chemistry, and the iron-sulfate correlation in those samples ($r = 0.88$) is exactly what pyrite oxidation predicts.

The arsenic situation in Bokaro is harder to characterize. Arsenic can originate from arsenopyrite weathering (geological) or from steel manufacturing wastes (anthropogenic). The spatial distribution of high-arsenic samples in our data does not point unambiguously to either source. Some high-arsenic wells were near the steel plant boundary; others were 8-12 km away in areas without obvious industrial activity. A more detailed isotopic or geochemical tracing study would be needed to resolve this - the kind of study requiring resources not typically available in state university contexts.Fluoride in Palamu is a separate problem with a different character. The 2019 AIIMS study found dental fluorosis in 34% of children under 12 in three Palamu blocks. These are not abstract exceedances - they are affecting teeth and bones. The geological source means household-level treatment (defluoridation candles or bone char filters) is the only practical near-term option. No policy change will alter what the rock dissolves into the aquifer.

A few limitations are worth acknowledging. We sampled from accessible wells and pumps, which are not a random draw of all groundwater sources - remote areas with difficult road access are underrepresented. Our heavy metal analysis covered eight elements; there are others (barium, selenium, uranium) that could be present at concerning levels, particularly near uranium deposits in Singhbhum, which we did not include in this study. And WQI involves subjective weighting decisions; different weight assignments would shift category boundaries, though the broad pattern of industrial-zone degradation would persist.

6. Conclusions

Groundwater quality in Jharkhand's industrial belt is poor enough to be a public health problem now, not a potential future concern. More than half of all samples from Dhanbad, Bokaro, and Ramgarh exceeded BIS standards for at least one parameter. For iron and TDS, exceedances were the rule, not the exception. The specific contamination issues differ by district. Dhanbad's problem is primarily acid mine drainage - sulfate, iron, and low pH from pyrite oxidation. Bokaro has a more mixed picture that includes arsenic, probably from a combination of geological and industrial sources. Palamu's fluoride problem is geological, not industrial, which means it exists independently of mining and requires different interventions. From a practical standpoint, the most urgent need is a denser and more frequent monitoring network in Dhanbad and Bokaro. The current CGWB monitoring infrastructure is insufficient to track plume migration in a region with this density of active and abandoned mines. Household-level treatment options - iron removal units for the coal belt, defluoridation filters for Palamu - deserve more serious attention. These are not high-technology solutions, but they can be deployed without waiting for the regulatory changes that would address upstream pollution sources.

The hydrogeochemical cluster boundaries in our data cross district lines. Any monitoring or remediation program organized strictly by administrative district will miss contaminated areas in neighboring zones. A basin-level or plume-based approach to monitoring design is more logical, even if administrative reporting continues at the district level.

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