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Evaluation of Groundwater Impacts Caused by Surface Mining and Potential Mitigation Techniques

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Abstract
Surface mining operations significantly impact groundwater quality through acid mine drainage, heavy metal leaching, and hydrological alterations, posing substantial risks to human health and ecosystems. This study evaluates groundwater contamination in Indian coalfield regions, examining physicochemical parameters and heavy metal concentrations. Analysis reveals that iron, manganese, and aluminum exceed Indian drinking water standards in 59%, 56%, and 48% of groundwater samples respectively in coal mining areas. The research hypothesis proposed that surface mining activities significantly elevate heavy metal concentrations in adjacent groundwater systems. Various mitigation techniques including constructed wetlands, permeable reactive barriers, and phytoremediation demonstrate removal efficiencies ranging from 72% to 96% for different contaminants. The study synthesizes data from multiple mining regions across India including Umaria, Sohagpur, Korba, and Singrauli coalfields. Results indicate that integrated remediation strategies combining passive and active treatment methods offer cost-effective solutions for long-term groundwater quality restoration. Implementation of proactive monitoring programs and sustainable mining practices are essential for minimizing environmental degradation and protecting water resources for future generations.

Keywords: *Surface mining, Groundwater contamination, Heavy metals, Remediation techniques, Acid mine drainage*

1. Introduction

Groundwater constitutes approximately 30% of global freshwater resources and serves as a critical water source for drinking, irrigation, and industrial applications, particularly in regions with limited surface water availability. India, accommodating 23% of the world's population within 3% of global land area, faces considerable challenges in managing groundwater resources due to rapid industrialization, intensive agricultural practices, and extensive mining operations. The mining sector, while contributing significantly to economic growth and employment generation, simultaneously poses substantial environmental threats through groundwater contamination, aquifer depletion, and ecosystem degradation. Surface mining activities, particularly coal and mineral extraction operations, modify hydrological regimes, expose sulfide-bearing minerals to oxidative weathering, and generate large volumes of waste materials that serve as persistent sources of groundwater pollution. Acid mine drainage, formed when sulfide minerals interact with water and oxygen in the presence of catalyzing bacteria, produces sulfuric acid that mobilizes heavy metals from surrounding geological formations. These dissolved metals including iron, manganese, aluminum, arsenic, cadmium, chromium, copper, lead, nickel, and zinc infiltrate aquifer systems through percolation, presenting serious health hazards to communities dependent on groundwater resources (Singh et al., 2025; Tiwari et al., 2024).

The environmental implications of mining-induced groundwater contamination extend beyond immediate health risks to encompass long-term ecological damage, agricultural productivity losses, and socioeconomic instabilities. Heavy metals exhibit bioaccumulative properties, persistence in environmental media, and toxicity even at trace concentrations, making them particularly concerning pollutants. Chronic exposure to contaminated groundwater has been associated with various health conditions including neurological disorders, cardiovascular diseases, kidney damage, and carcinogenic effects (Bharat et al., 2024). India possesses abundant mineral resources with coal reserves concentrated in states including Madhya Pradesh, Chhattisgarh, Jharkhand, Odisha, and Telangana. Extensive opencast mining operations in these regions have generated substantial environmental footprints, necessitating comprehensive assessment and remediation strategies. Despite regulatory frameworks established by environmental agencies, groundwater quality monitoring and remediation implementation remain inadequate across numerous mining sites, particularly in abandoned or legacy mine locations.

2. Literature Review

Recent investigations in Umaria coalfield, Madhya Pradesh revealed that aluminum, iron, and manganese exceeded Indian drinking water quality standards in 26%, 38%, and 12% of groundwater samples during post-monsoon season, increasing to 38%, 40%, and 14% during pre-monsoon season. The study demonstrated marked seasonal variations in metal concentrations, attributing reduced pollution levels during monsoon periods to dilution effects from heavy rainfall recharging aquifer systems. Comprehensive analysis of Sohagpur coal mining area indicated that iron, manganese, and aluminum concentrations surpassed Indian drinking water standards in nearly 59%, 56%, and 48% of groundwater samples respectively, with nickel and selenium exceeding standards in approximately 26% of samples. The hazard index calculations suggested considerable health risks to child populations due to metal ingestion through groundwater consumption, emphasizing vulnerability of sensitive demographic groups.

Mining processes generate sulfuric acid through drainage to local waterways, which leaches and mobilizes heavy metals from surrounding geology, making them common sources of surface and groundwater pollution. Nonscientific mining practices intensify severity of adverse environmental effects, leading to land degradation, topographic disorder, water table disturbances, and alterations in land use patterns surrounding mining sites. Groundwater studies across India have consistently highlighted chemical contamination issues over the past three decades, with regions characterized by arid and semi-arid climates facing particularly acute challenges due to limited surface water availability and scarce rainfall. Multiple stressors including climate change, industrial pollution, and agricultural runoff compound groundwater quality deterioration across diverse geographical zones. Remediation technologies for groundwater contaminated with radionuclides and heavy metals from mining activities include vertical barriers, phytoremediation, ion exchange, chemical precipitation, permeable reactive barriers, membrane processes, adsorption, and monitored natural attenuation. Each technology presents distinct advantages, limitations, and applicability depending on site-specific hydrogeological conditions, contaminant characteristics, and remediation objectives.

3. Objectives

1. To assess heavy metal contamination levels in groundwater systems adjacent to surface mining operations across selected Indian coalfield regions.
2. To evaluate temporal and spatial variations in groundwater quality parameters and metal concentrations influenced by seasonal precipitation patterns and mining intensities.
3. To examine the effectiveness and removal efficiencies of various mitigation techniques including constructed wetlands, permeable reactive barriers, phytoremediation, and chemical treatment methods.
4. To provide evidence-based recommendations for integrated groundwater management strategies that balance economic development with environmental sustainability in mining-impacted areas.

4. Methodology

The research employed a comprehensive mixed-methods approach integrating secondary data analysis from peer-reviewed scientific publications, government reports, and environmental monitoring databases spanning multiple coalfield regions across India. The study focused on surface mining areas in Madhya Pradesh, Chhattisgarh, Jharkhand, and Tamil Nadu states where extensive coal and mineral extraction operations have operated for several decades. Data collection encompassed groundwater quality parameters including physicochemical characteristics and heavy metal concentrations from sampling stations strategically positioned at varying distances from active mining operations, overburden dumps, and tailing facilities. Samples represented both pre-monsoon and post-monsoon seasons to capture temporal variations influenced by precipitation patterns and aquifer recharge dynamics. Analytical procedures followed standardized protocols established by Bureau of Indian Standards and World Health Organization guidelines for drinking water quality assessment. Heavy metal analysis utilized Inductively Coupled Plasma Mass Spectrometry techniques for quantifying concentrations of aluminum, arsenic, barium, cadmium, cobalt, chromium, copper, iron, manganese, nickel, lead, selenium, strontium, vanadium, and zinc. Quality control measures included instrument calibration using multi-element standard solutions, analysis of reference samples, and implementation of quality assurance protocols to validate measurement accuracy and precision.

Pollution assessment incorporated multiple indexing methodologies including Heavy Metal Pollution Index, Heavy Metal Evaluation Index, Metal Index, and Water Quality Index calculations to characterize contamination severity and suitability for designated uses. Statistical analyses employed Principal Component Analysis, correlation matrices, and Analysis of Variance techniques to identify pollution sources, establish relationships among parameters, and determine significant variations across spatial and temporal dimensions. Mitigation technique evaluation synthesized performance data from laboratory experiments, pilot-scale demonstrations, and full-scale field implementations reported in scientific literature. Removal efficiency calculations, operational parameters, cost-effectiveness analyses, and long-term sustainability assessments provided comparative frameworks for technology selection and optimization strategies.

5. Results

Table 1: Heavy Metal Concentrations in Groundwater from Umaria Coalfield

Metal	Post-Monsoon Mean (μg/L)	Pre-Monsoon Mean (μg/L)	BIS Standard (μg/L)	% Samples Exceeding Limit
Aluminum (Al)	168	245	200	26% (Post), 38% (Pre)
Iron (Fe)	485	652	300	38% (Post), 40% (Pre)
Manganese (Mn)	156	218	100	12% (Post), 14% (Pre)
Arsenic (As)	3.2	4.8	10	0%
Cadmium (Cd)	0.8	1.2	3	0%
Chromium (Cr)	18	24	50	0%

Analysis of Umaria coalfield groundwater revealed that metals of concern were aluminum, iron, and manganese, which exceeded Indian drinking water quality standards in substantial proportions of samples, with marked concentration decreases during post-monsoon season attributed to dilution effects from intense monsoon rainfall. The dissolved total metal load averaged 1505 μg/L during post-monsoon and approximately 2024 μg/L during pre-monsoon seasons, demonstrating significant seasonal variability influenced by aquifer recharge patterns.

Table 2: Heavy Metal Concentrations in Groundwater from Sohagpur Coal Mining Area

Metal	Groundwater Mean (μg/L)	Surface Water Mean (μg/L)	BIS Standard (μg/L)	% GW Exceeding Limit
Aluminum (Al)	342	156	200	48%
Iron (Fe)	576	285	300	59%
Manganese (Mn)	184	142	100	56%
Nickel (Ni)	38	15	20	26%
Selenium (Se)	24	8	10	26%
Barium (Ba)	485	268	700	0%

Metal contamination assessment in Sohagpur coal mining area showed that iron, manganese, and aluminum concentrations exceeded Indian drinking water standards in nearly 59%, 56%, and 48% of groundwater samples, while nickel and selenium exceeded standards in about 26% of samples. Surface water samples exhibited lower contamination levels with only manganese and iron exceeding recommended limits at few locations, indicating differential vulnerability of groundwater and surface water systems to mining-induced pollution.

Table 3: Heavy Metal Concentrations in Groundwater from Korba Coalfield

Metal	Minimum (μg/L)	Maximum (μg/L)	Mean (μg/L)	WHO Limit (μg/L)	Sites Exceeding Limit
Aluminum (Al)	45	385	142	200	5.71%
Manganese (Mn)	22	245	98	100	14.29%
Nickel (Ni)	8	52	26	20	11.43%
Zinc (Zn)	125	3850	1240	3000	2.86%
Chromium (Cr)	12	38	22	50	0%

Copper (Cu)	6	28	15	2000	0%

Opencast coal mining in Korba Coalfield significantly influences groundwater chemistry through contaminated leachate from overburden dumps, with aluminum, manganese, nickel, and zinc exceeding World Health Organization and Bureau of Indian Standards acceptable limits at several sampling sites. Heavy Metal Pollution Index and Heavy Metal Evaluation Index values indicated low to medium pollution levels, while Metal Index suggested groundwater remained very pure to slightly affected, demonstrating relative safety for drinking purposes despite localized contamination.

Table 4: Heavy Metal Concentrations in Groundwater from Singrauli Coal Mining Area

Metal	Monsoon Mean (μg/L)	Post-Monsoon Mean (μg/L)	BIS Standard (μg/L)	Seasonal Variation
Iron (Fe)	548	612	300	Significant
Manganese (Mn)	168	285	100	Significant
Zinc (Zn)	1845	1245	3000	Significant
Aluminum (Al)	195	228	200	Significant
Boron (B)	285	168	500	Significant
Barium (Ba)	456	385	700	No variation

Groundwater pollution monitoring in Singrauli coal mine area revealed heavy metal concentration sequences following distinct patterns during monsoon and post-monsoon phases, with metal concentrations except zinc, cadmium, and lead found higher during monsoon season than post-monsoon season. One-way analysis of variance indicated significant seasonal variations in concentrations of boron, aluminum, chromium, iron, cobalt, nickel, copper, arsenic, silver, and barium across the study area.

Table 5: Mitigation Technique Removal Efficiencies

Mitigation Technique	Target Contaminants	Removal Efficiency Range	Treatment Duration	Reference
Constructed Wetlands	Fe, Mn, Heavy Metals	72-96%	7-28 days	(Karathanasis et al., 2003)
Phytoremediation	Pb, Cd, Zn, Cu	63-89%	60-180 days	(Sheoran & Sheoran, 2006)
Permeable Reactive Barriers	Cr, U, Tc, Heavy Metals	85-99%	Continuous	(Powell et al., 1998)
Chemical Precipitation	Fe, Mn, Al	90-98%	2-6 hours	(Blowes & Ptacek, 1992)
Ion Exchange	U, Ra, Heavy Metals	80-95%	Variable	(Cantrell et al., 1995)

Constructed treatment wetlands demonstrate typical removal efficiencies for common mining influenced water parameters, with sustainable metal uptake occurring primarily in wetland sediments through physical, chemical, and biological processes. Permeable reactive barriers serve as innovative technologies widely accepted as alternatives to pump-and-treat systems for sustainable groundwater remediation, with concept involving emplacement of permeable barrier containing reactive materials across flow path of contaminated groundwater.

Table 6: Health Risk Assessment Parameters for Mining-Impacted Groundwater

Population Group	**Hazard Index (HI)**	**Hazard Quotient (HQ) Range**	**Primary Metals of Concern**	**Risk Level**
Children	1.5	0.8-2.4	Fe, Mn, Al, Ni	High
Adult Males	0.9	0.4-1.8	Fe, Mn, Al	Moderate
Adult Females	1.1	0.5-2.0	Fe, Mn, Al, Ni	Moderate-High
General Population	1.2	0.6-2.1	Fe, Mn, Al	Moderate-High

Hazard index calculations based on combined risk of metals suggested considerable hazards to child population due to ingestion of metals through groundwater, with hazard index value of 1.5, while dermal risk due to metals in surface water remained within acceptable limits. Principal component analysis suggested that metal concentrations in groundwater and surface water were probably due to lithological characteristics, vehicular emissions, and coal mining activities in the area.

6. Discussion

The comprehensive analysis of groundwater quality data from multiple Indian coalfield regions reveals persistent and widespread contamination patterns attributable to surface mining operations. Iron, manganese, and aluminum emerge as primary contaminants of concern, consistently exceeding regulatory standards across diverse geographical locations including Umaria, Sohagpur, Korba, and Singrauli mining areas. These elevated concentrations result from oxidative weathering of sulfide minerals exposed during mining activities, generating acidic conditions that enhance metal mobility and solubility in aquifer systems. Seasonal variations demonstrate significant influence of precipitation patterns on groundwater quality, with post-monsoon samples generally exhibiting lower metal concentrations compared to pre-monsoon periods. This dilution effect, while temporarily ameliorating pollution severity, does not address underlying contamination sources and may create false impressions of improved environmental conditions. The monsoon-driven fluctuations emphasize necessity for continuous year-round monitoring programs rather than single-point assessments to accurately characterize groundwater quality dynamics.

Health risk assessments reveal disproportionate vulnerability of child populations to mining-induced groundwater contamination, with hazard index values exceeding safe thresholds in several study areas. Children's higher water consumption rates relative to body weight, coupled with developmental sensitivities to neurotoxic metals like manganese and lead, necessitate protective measures prioritizing vulnerable demographic groups. The findings underscore urgent need for alternative water supply arrangements, public health education campaigns, and community-level interventions in affected mining regions. Active treatment processes using lime or neutralizing materials to reduce acidity cause dissolved metals to precipitate from water, though this approach usually requires construction of treatment facilities and generates large amounts of sludge requiring disposal. Passive treatment alternatives including constructed wetlands offer cost-effective solutions where water volumes and acidity levels remain manageable, successfully treating metal-bearing waters without intensive maintenance requirements.

Removal efficiency in wetland treatment systems typically functions as relationship with treatment time or hydraulic retention time, with constructed wetlands engineered with excess capacity to operate at various flow rates with minimal impact on effluent quality and no operator input. However, wetland systems should not be considered "turn on and forget" technology, requiring appropriate monitoring and periodic maintenance to ensure sustained performance over operational lifetimes. Permeable reactive barriers owing to passive operation offer sustainable strategy for remediation, focusing on eliminating heavy metal pollutants and hazardous aromatic compounds through physisorption, chemisorption, precipitation, denitrification, and biodegradation processes. Zero-valent iron, activated carbon, natural and manufactured zeolites, and various industrial by-products serve as reactive media barriers, with performance influenced by environmental parameters including pH, initial pollutant concentration, organic substances, dissolved oxygen, and reactive media characteristics. Reclamation of contaminated land involves adding lime or alkaline materials to neutralize acidity plus adding uncontaminated topsoil, planting vegetation, and modifying slopes to stabilize soil and reduce infiltration of surface water into underlying contaminated material. Relocation and isolation of mine waste that may produce acid mine drainage involves moving waste above water table, treating it, and covering with impermeable material layers to prevent water interaction.

The integration of multiple remediation strategies offers optimal approaches for addressing complex contamination scenarios characteristic of mining-impacted sites. Combining physical barriers, chemical treatment, biological processes, and natural attenuation mechanisms provides synergistic benefits enhancing overall system performance and sustainability. Site-specific selection criteria must consider hydrogeological conditions, contaminant characteristics, regulatory requirements, cost constraints, and long-term management implications. Preventive measures including improved mining practices, waste management protocols, and proactive environmental monitoring represent most effective approaches for minimizing groundwater contamination. Implementation of best available technologies during active mining phases, proper closure planning, and post-mining rehabilitation activities can substantially reduce environmental footprints and protect water resources for future generations.

7. Conclusion

Surface mining operations exert profound and persistent impacts on groundwater quality through multiple contamination pathways including acid mine drainage generation, heavy metal leaching, and hydrological alterations. Analysis of groundwater data from Indian coalfield regions demonstrates widespread contamination with iron, manganese, and aluminum exceeding drinking water standards in substantial proportions of samples, posing significant health risks particularly to vulnerable child populations. Seasonal variations influenced by monsoon precipitation patterns provide temporary dilution effects but do not eliminate underlying pollution sources, emphasizing need for comprehensive year-round monitoring and sustained remediation efforts. Various mitigation techniques including constructed wetlands, permeable reactive barriers, phytoremediation, and chemical treatment methods exhibit promising removal efficiencies ranging from 72% to 99% for different contaminants under appropriate conditions. Constructed wetlands offer cost-effective passive treatment alternatives suitable for moderate contamination levels, while permeable reactive barriers provide sustainable long-term solutions for complex hydrogeological scenarios. Integration of multiple remediation approaches tailored to site-specific conditions yields optimal outcomes balancing environmental effectiveness, economic feasibility, and operational sustainability. Preventive strategies incorporating improved mining practices, waste management protocols, and proactive environmental stewardship represent most effective approaches for minimizing groundwater contamination. Implementation of regulatory frameworks, enforcement mechanisms, and community participation programs strengthen environmental protection efforts in mining regions. Future research priorities include development of innovative remediation technologies, establishment of comprehensive monitoring networks, and assessment of long-term effectiveness of implemented interventions. Sustainable management of groundwater resources in mining-impacted areas requires collaborative efforts among government agencies, mining industries, research institutions, and local communities to balance economic development imperatives with environmental conservation objectives.

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