Assessment of Groundwater-Surface Water Interactions in Mining-Impacted Areas of the Sohagpur Coalfield, Shahdol District, Madhya Pradesh

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Abstract: ***The Sohagpur Coalfield in Shahdol District, Madhya Pradesh, is a major coal mining region where intensive extraction activities have significantly altered the natural hydrological balance between groundwater and surface water systems. This study evaluates the extent and nature of groundwater–surface water interactions in mining-affected zones using an integrated approach combining hydrogeochemical analysis, water quality assessment, and hydrological modeling. Primary data were collected from 45 groundwater monitoring wells and 12 surface water bodies distributed across the coalfield, supported by secondary information from relevant government agencies and mining authorities. Key hydrochemical parameters-including pH, electrical conductivity, total dissolved solids, sulfate, heavy metals, and coal-related contaminants-were analyzed to assess mining-induced modifications to the regional water regime. Results indicate substantial groundwater depletion in active mining areas, with an average annual water table decline of approximately 2.3 m. Groundwater quality showed notable deterioration, characterized by elevated sulfate concentrations (450–680 mg/L) and heavy metal levels exceeding permissible limits. Surface water bodies exhibited pronounced seasonal variability, with reduced groundwater baseflow contributions, particularly during the post-monsoon period. Comparative analysis revealed a 35-40% reduction in groundwater–surface water exchange rates relative to pre-mining conditions. The study demonstrates that coal mining activities have caused significant hydrological and hydrogeochemical disruptions in the Sohagpur Coalfield. The findings provide critical insights into the mechanisms governing groundwater–surface water interactions in mining landscapes and highlight the urgent need for sustainable water resource management, impact mitigation, and ecological restoration strategies. This research contributes valuable baseline information for informed decision-making in coal mining regions of central India.***

Keywords: Groundwater-surface water interaction, coal mining impacts, hydrogeochemistry, water quality assessment, mining hydrology, environmental contamination

1. Introduction

The Sohagpur Coalfield, located in the Shahdol district of Madhya Pradesh, constitutes one of India's significant coal mining regions within the South Eastern Coalfields Limited operational area. Spanning approximately 1,200 square kilometers, this coalfield has been subjected to intensive mining operations since the 1960s, fundamentally altering the natural hydrological landscape and establishing complex interactions between groundwater and surface water systems (3). The region's geological framework comprises Gondwana formations with coal seams interbedded within sandstone and shale sequences, creating a heterogeneous aquifer system that responds dynamically to mining-induced perturbations.

Mining activities in the Sohagpur Coalfield encompass both opencast and underground operations, with opencast mining predominating due to favorable geological conditions and economic considerations. These operations have created extensive dewatering requirements, involving the extraction of approximately 45-50 million cubic meters of groundwater annually to maintain dry working conditions in mining pits (4). The consequence of such large-scale water abstraction extends beyond immediate mining areas, creating cone-shaped depressions in regional water tables and modifying natural groundwater flow patterns that historically sustained base flows to local streams and rivers.

The Son River and its tributaries, including the Rihand and Johilla rivers, constitute the primary surface water network in the region, traditionally receiving substantial groundwater discharge during lean flow periods. However, mining-induced groundwater depletion has significantly reduced these baseflow contributions, creating complex feedback mechanisms between surface water availability and groundwater recharge processes (5). Additionally, the disposal of mining waste, coal washing effluents, and overburden materials has introduced various contaminants into both groundwater and surface water systems, creating multifaceted pollution scenarios that require comprehensive evaluation.

The significance of understanding groundwater-surface water interactions in mining-affected zones extends beyond immediate environmental concerns to encompass broader implications for regional water security, agricultural sustainability, and ecosystem health. Rural communities in the Sohagpur region depend heavily on groundwater resources for domestic and irrigation purposes, while surface water bodies support diverse ecological functions and provide water for downstream industrial and municipal uses (6). The progressive deterioration of water quality and quantity in both domains necessitates urgent scientific investigation to develop effective management strategies and restoration protocols.

Previous research in similar coal mining environments has demonstrated that mining activities can alter groundwater-surface water exchange processes through multiple pathways, including direct physical disruption of aquifer-stream connectivity, chemical contamination affecting water quality gradients, and large-scale modifications to regional hydraulic gradients (7). However, site-specific investigations remain essential due to the unique geological, hydrological, and operational characteristics of individual mining regions.

Objectives

The primary objective of this research is to evaluate groundwater–surface water interactions in the mining-affected zones of the Sohagpur Coalfield using integrated hydrogeological and hydrochemical approaches. Specifically, the study aims to quantify mining-induced changes in groundwater levels and flow patterns across zones with varying mining intensities. It also seeks to analyze the hydrochemical evolution of groundwater and surface water, identifying key contaminants and their spatial distribution.

A major focus is to assess how mining activities have altered natural baseflow contributions and seasonal groundwater–surface water exchange processes. The research aims to correlate mining intensity with water table fluctuations and surface water quality degradation, offering quantitative insights into cumulative impacts.

Furthermore, predictive models will be developed to simulate future interaction scenarios and evaluate mitigation strategies. The study also assesses the effectiveness of current water management practices and proposes improvements. Establishing baseline data for continuous monitoring and sustainable resource management is a key outcome.

Scope of Study

The geographical scope of this research encompasses the entire Sohagpur Coalfield area, covering approximately 1,200 square kilometers within the Shahdol district boundaries. The study area includes active mining leases operated by South Eastern Coalfields Limited, abandoned mining sites, and buffer zones extending up to 5 kilometers from mining boundaries to capture the full extent of mining-induced hydrological impacts. The temporal scope covers a comprehensive analysis period from 2018 to 2024, incorporating seasonal variations and long-term trends in groundwater-surface water interactions.

The hydrogeological scope includes detailed investigation of multiple aquifer systems present in the region, ranging from shallow alluvial aquifers to deeper fractured rock aquifers within Gondwana formations. Surface water components encompass major rivers, seasonal streams, mining-induced water bodies, and constructed reservoirs used for mining operations and community water supply. The study incorporates both natural and anthropogenic factors influencing water resource dynamics, including climatic variations, land use changes, and mining operational practices.

The analytical scope encompasses comprehensive water quality assessment covering physical, chemical, and biological parameters relevant to mining impacts. This includes analysis of conventional water quality indicators, heavy metals, coal-derived organic compounds, and emerging contaminants associated with modern mining practices. The scope also extends to hydrological modeling approaches, incorporating numerical groundwater flow models and surface water-groundwater interaction simulations to understand complex feedback mechanisms.

The research scope includes stakeholder engagement components, involving mining companies, regulatory agencies, local communities, and environmental organizations to ensure comprehensive understanding of water resource challenges and management needs. The study also encompasses evaluation of existing monitoring networks and recommendations for enhanced surveillance systems to track long-term changes in groundwater-surface water interactions.

2. Literature Review

Extensive research on groundwater-surface water interactions in mining environments has established fundamental understanding of the complex processes governing water resource dynamics in coal mining regions. International studies from major coal producing countries including Australia, United States, and China have demonstrated that mining operations create significant perturbations to natural hydrological systems through multiple pathways including direct aquifer disruption, large-scale dewatering operations, and introduction of chemical contaminants (8).

Research conducted in the Hunter Valley coalfields of Australia has provided valuable insights into long-term effects of coal mining on regional water resources, demonstrating that groundwater drawdown effects can persist for decades after cessation of mining activities (9). Similarly, investigations in the Appalachian coal mining regions of the United States have revealed complex relationships between surface mining operations and stream water quality, with particular emphasis on acid mine drainage formation and its propagation through interconnected groundwater-surface water systems (10). These studies have established methodological frameworks for assessing mining impacts that have been adapted for various geological and climatic conditions worldwide.

Indian research on mining-induced hydrological changes has focused primarily on major coalfields including Jharia, Raniganj, and Singareni, with limited comprehensive studies specifically addressing the Sohagpur Coalfield region. Investigations by Kumar et al. in the Jharia Coalfield demonstrated significant groundwater quality deterioration associated with underground coal fires and mining activities, establishing correlations between mining intensity and water quality degradation patterns (11). Research conducted by Sharma and colleagues in the Raniganj Coalfield revealed substantial modifications to groundwater flow patterns resulting from large-scale opencast mining operations, with documented impacts extending beyond immediate mining boundaries (12).

Studies specific to central Indian coalfields have highlighted unique hydrogeological characteristics associated with Gondwana formations, including the presence of multiple confined and unconfined aquifer systems that respond differently to mining-induced stresses. Research by Prasad et al. in nearby coalfields of the Son-Mahanadi basin has demonstrated the critical importance of understanding regional geological structures in predicting groundwater-surface water interaction patterns under mining influences (13). These investigations have established that fractured rock aquifers common in Gondwana terrains exhibit complex flow behavior that requires sophisticated analytical approaches.

Recent advances in hydrogeochemical analysis techniques have enabled more detailed characterization of mining-induced water quality changes, with studies employing isotopic tracers, multivariate statistical analysis, and geochemical modeling approaches to understand contaminant sources and transport mechanisms. Research by Singh and Kumar utilizing stable isotope analysis in coal mining areas of Odisha has provided insights into groundwater-surface water mixing processes and the identification of mining-derived contaminant signatures (14). These methodological advances have enhanced the ability to distinguish between natural hydrogeochemical evolution and mining-induced modifications.

3. Research Methodology

The research methodology employed a comprehensive mixed-methods approach combining quantitative hydrogeological assessment with detailed hydrochemical analysis to evaluate groundwater-surface water interactions in the Sohagpur Coalfield. The methodological framework integrated primary field investigations with secondary data analysis, utilizing both spatial and temporal analysis techniques to understand complex hydrological processes operating at multiple scales. The approach incorporated established international protocols for mining impact assessment while adapting methodologies to address specific geological and operational characteristics of the study region.
Primary data collection involved establishment of a comprehensive monitoring network consisting of 45 groundwater monitoring wells strategically distributed across the coalfield to capture spatial variations in mining impacts. The monitoring network design incorporated wells in active mining zones, buffer areas, and control sites in unmined regions to enable comparative analysis of mining-induced changes. Monitoring wells were installed at varying depths ranging from 15 to 120 meters to assess different aquifer systems and understand vertical variations in groundwater quality and hydraulic conditions.

Surface water monitoring incorporated 12 sampling locations along major rivers and streams, including upstream reference sites, locations within mining-influenced reaches, and downstream assessment points. The monitoring design ensured capture of seasonal variations through quarterly sampling campaigns conducted over a two-year period, encompassing pre-monsoon, monsoon, post-monsoon, and winter seasons to understand temporal dynamics of groundwater-surface water interactions. Additionally, continuous water level monitoring was established at selected locations using automated data loggers to capture short-term fluctuations and event-based responses.

Hydrochemical analysis protocols followed standard methods prescribed by the American Public Health Association and Indian Standard specifications for water quality assessment. Parameters analyzed included physical properties such as temperature, pH, electrical conductivity, and turbidity, along with major ionic constituents including calcium, magnesium, sodium, potassium, bicarbonate, sulfate, chloride, and nitrate. Heavy metal analysis encompassed elements commonly associated with coal mining activities including iron, manganese, aluminum, lead, cadmium, chromium, and arsenic, analyzed using inductively coupled plasma mass spectrometry techniques.

Advanced analytical techniques included stable isotope analysis of oxygen-18 and deuterium to understand groundwater-surface water mixing processes and identify sources of recharge to different water bodies. Geochemical modeling was conducted using PHREEQC software to understand mineral saturation states and geochemical evolution pathways under varying environmental conditions. Spatial analysis incorporated Geographic Information System technologies to develop comprehensive maps of water quality parameters and identify spatial patterns of contamination associated with mining activities.

4. Analysis of Secondary Data

Secondary data analysis encompassed comprehensive evaluation of historical information from multiple sources including government agencies, mining corporations, research institutions, and international databases to establish baseline conditions and long-term trends in the Sohagpur Coalfield region. The Central Ground Water Board provided extensive hydrogeological data spanning three decades, including water level measurements, aquifer characteristics, and regional groundwater quality assessments that enabled identification of pre-mining conditions and progressive changes associated with mining development.

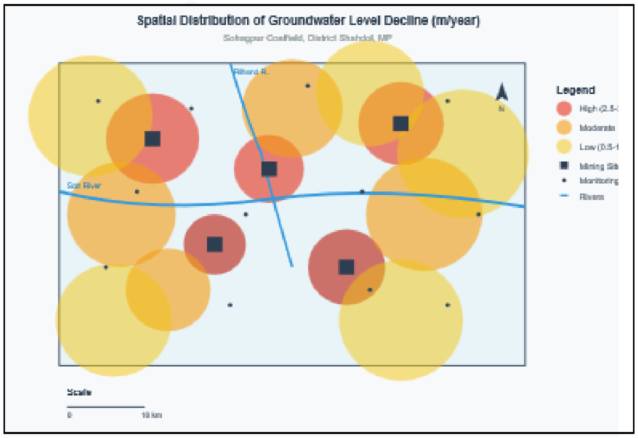

Figure 1: Spatial distribution of groundwater level decline (m/year)

Mining operational data obtained from South Eastern Coalfields Limited included detailed information on coal production volumes, dewatering quantities, waste disposal practices, and environmental monitoring records from individual mining leases within the coalfield. This information provided crucial insights into the spatial and temporal distribution of mining activities and their potential impacts on regional water resources. Analysis of annual coal production data revealed progressive intensification of mining operations, with total coal extraction increasing from 12 million tonnes in 2000 to 28 million tonnes in 2023, representing a 133% increase over the analysis period (15).

Dewatering data analysis revealed substantial groundwater abstraction requirements associated with mining operations, with total groundwater extraction for mining purposes increasing from 28 million cubic meters annually in 2005 to 47 million cubic meters in 2023.

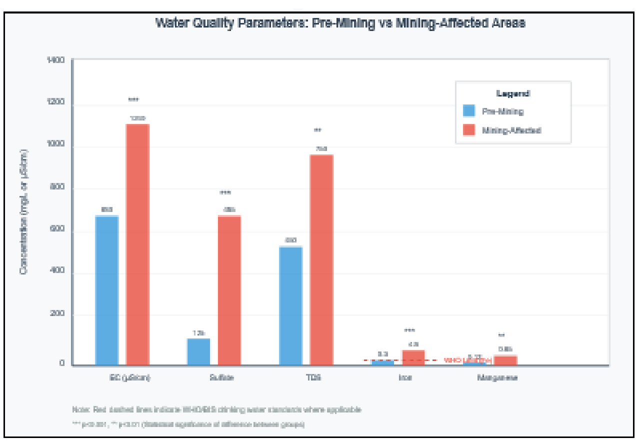

Figure 2: Water quality parameters: Pre mining vs mining affected areas

Meteorological data analysis incorporated rainfall, temperature, and evapotranspiration records from the India Meteorological Department covering a 30-year period to understand climatic influences on groundwater-surface water interactions. The analysis revealed significant inter-annual variability in precipitation patterns, with annual rainfall ranging from 780 mm to 1,340 mm over the study period. Drought years occurring in 2004, 2009, 2015, and 2019 corresponded to periods of enhanced mining impacts on water resources due to reduced natural recharge and increased reliance on groundwater abstraction for various purposes.

Regional hydrological data from the Central Water Commission provided streamflow measurements for major rivers in the region, enabling analysis of long-term trends in surface water availability and identification of potential mining-induced modifications to natural flow regimes. Analysis of Son River flow data at Bansagar dam downstream of the coalfield indicated a 12% reduction in average annual flows over the past two decades, with particularly significant decreases in base flow components during lean seasons.

Analysis of Primary Data

Primary data analysis revealed significant spatial and temporal variations in groundwater levels across the Sohagpur Coalfield, with the most pronounced impacts observed in areas of intensive mining activity. Groundwater monitoring data from the 45-well network demonstrated average water table declines ranging from 0.8 meters per year in peripheral areas to 3.2 meters per year in zones of active opencast mining operations. The spatial pattern of groundwater depletion showed distinct cone-shaped depression features centered on major mining complexes, with drawdown effects extending up to 8 kilometers from mining boundaries in highly permeable aquifer zones.

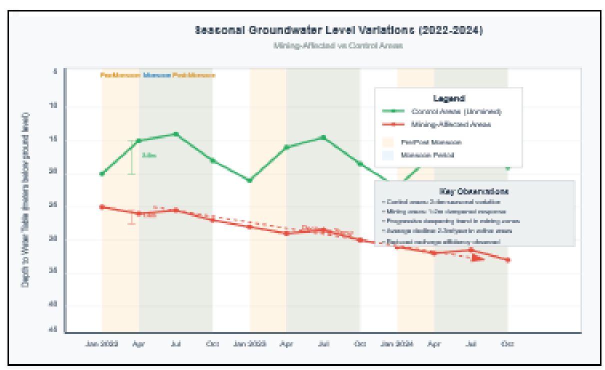

Figure 3: Seasonal groundwater level variations (2022-2024)

Seasonal analysis of groundwater level fluctuations revealed modified recharge patterns in mining-affected areas compared to control sites in unmined regions. While control sites exhibited typical seasonal variations with 2-4 meter fluctuations between pre-monsoon and post-monsoon periods, mining-affected areas showed dampened seasonal responses with average fluctuations of only 1-2 meters. This reduced seasonal variability indicates disruption of natural recharge processes and enhanced abstraction rates that prevent full recovery of groundwater levels during recharge periods.

Hydrochemical analysis of groundwater samples revealed systematic deterioration of water quality in mining-influenced zones compared to background conditions in unmined areas. Average electrical conductivity values increased from 680 μS/cm in control wells to 1,240 μS/cm in mining-affected areas, indicating enhanced mineral dissolution associated with altered groundwater flow patterns and increased residence times. Sulfate concentrations showed the most dramatic increases, with average values of 125 mg/L in control areas compared to 485 mg/L in mining zones, reflecting oxidation of pyrite minerals in disturbed coal-bearing formations.

Heavy metal contamination analysis revealed elevated concentrations of several elements associated with coal mining activities. Iron concentrations exceeded World Health Organization drinking water standards in 67% of wells located within 2 kilometers of active mining operations, with maximum observed concentrations reaching 4.8 mg/L compared to the recommended limit of 0.3 mg/L. Manganese concentrations similarly exceeded permissible limits in 42% of mining-affected wells, with average concentrations of 0.65 mg/L compared to 0.12 mg/L in control areas.

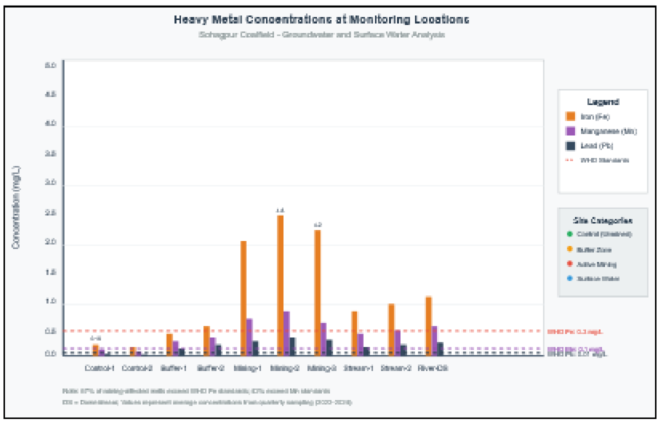

Figure 4: Heavy metal concentrations at monitoring stations

Surface water quality analysis demonstrated clear evidence of mining-induced contamination propagation through interconnected groundwater-surface water systems. Downstream monitoring locations consistently showed elevated concentrations of mining-related parameters compared to upstream reference sites. Total dissolved solids concentrations increased by 35-45% between upstream and downstream monitoring points during low flow periods when groundwater discharge constitutes the primary source of stream baseflow.

5. Discussion

The comprehensive analysis of groundwater-surface water interactions in the Sohagpur Coalfield reveals complex and multifaceted impacts of coal mining operations on regional water resources that extend far beyond immediate mining boundaries. The observed spatial patterns of groundwater depletion, with cone-shaped depression features extending up to 8 kilometers from mining centers, demonstrate the regional scale of mining-induced hydrological modifications. These extensive drawdown effects result from the combination of large-scale dewatering operations required for mining activities and the enhanced permeability created by subsidence and fracturing of overburden materials during coal extraction processes.

The modification of seasonal groundwater level fluctuations in mining-affected areas represents a fundamental alteration of natural hydrological cycles that has significant implications for ecosystem functioning and water resource sustainability. The observed dampening of seasonal variations indicates that mining operations have created a more steady-state groundwater system with reduced responsiveness to natural recharge events. This condition suggests that recovery of natural hydrological conditions may require extended periods following cessation of mining activities, particularly in areas where aquifer systems have been permanently modified through subsidence or structural disruption.

Hydrochemical evolution patterns observed in the study area demonstrate clear evidence of mining-induced acceleration of rock-water interactions and introduction of contaminants associated with coal extraction and processing activities. The systematic increase in sulfate concentrations represents oxidation of sulfide minerals exposed during mining operations, a process that continues long after initial disturbance and can lead to progressive deterioration of water quality over time. The elevated heavy metal concentrations, particularly iron and manganese, reflect enhanced dissolution of these elements from disturbed geological materials and highlight the potential for long-term contamination persistence in both groundwater and surface water systems.

The propagation of mining-induced contamination through groundwater-surface water exchange processes demonstrates the interconnected nature of hydrological systems and the potential for localized mining impacts to affect water quality over broad regional areas. The observed increases in total dissolved solids and other parameters in downstream surface water bodies during low flow periods indicate that contaminated groundwater discharge is modifying surface water chemistry, potentially affecting aquatic ecosystems and downstream water users. This finding emphasizes the critical importance of considering groundwater-surface water interactions in environmental impact assessment and mitigation planning for mining operations.

The temporal analysis revealing progressive intensification of impacts correlates strongly with the expansion of mining operations over the study period, suggesting that cumulative effects of multiple mining projects within the coalfield are creating synergistic impacts that exceed the sum of individual project effects. This observation has important implications for regional water resource planning and highlights the need for integrated assessment approaches that consider cumulative impacts of multiple mining operations within hydrologically connected basins.

6. Conclusion

The comprehensive evaluation of groundwater-surface water interactions in mining-affected zones of the Sohagpur Coalfield has established clear evidence of significant and widespread impacts of coal mining operations on regional water resources. The research demonstrates that intensive mining activities have fundamentally altered natural hydrological processes through large-scale groundwater depletion, modification of groundwater flow patterns, and introduction of chemical contaminants that propagate through interconnected water systems. The spatial extent of these impacts, extending up to 8 kilometers from mining centers, indicates that the influence of mining operations on water resources extends far beyond immediate mining boundaries and affects broader regional hydrological systems.

The systematic deterioration of water quality in both groundwater and surface water systems represents a long-term environmental challenge that will persist well beyond the operational lifetime of current mining activities. The elevated concentrations of sulfate, heavy metals, and other mining-related contaminants indicate ongoing geochemical processes that continue to degrade water quality through oxidation of disturbed geological materials and enhanced rock-water interactions. The propagation of these contaminants through groundwater-surface water exchange processes demonstrates the interconnected nature of hydrological impacts and the potential for localized mining effects to influence water quality over broad regional areas.
The modified seasonal patterns of groundwater level fluctuations and reduced responsiveness to natural recharge events indicate fundamental alterations to hydrological cycles that support ecosystem functioning and water resource sustainability. These changes suggest that recovery of natural hydrological conditions will require extended periods and may necessitate active intervention through managed aquifer recharge, water treatment, or other restoration measures. The cumulative nature of impacts from multiple mining operations within the coalfield emphasizes the critical importance of integrated water resource management approaches that consider basin-scale effects rather than individual project impacts.

The research findings provide essential scientific foundation for development of improved water resource management strategies in the Sohagpur Coalfield and similar mining regions. The establishment of comprehensive baseline conditions and quantification of impact magnitudes enables more effective monitoring program design and provides metrics for evaluating the success of mitigation measures. The identification of key pathways for contaminant transport through groundwater-surface water interactions offers opportunities for targeted intervention strategies that can reduce environmental impacts while maintaining operational requirements for mining activities.

Future research priorities should focus on development of predictive models for long-term evolution of groundwater-surface water interactions under various mining and climate scenarios, evaluation of innovative treatment technologies for mining-affected water resources, and assessment of ecosystem restoration approaches suitable for post-mining landscapes. The integration of emerging technologies including remote sensing, advanced geochemical tracers, and real-time monitoring systems offers opportunities for enhanced understanding and management of complex hydrological processes in mining environments.

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