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Hydrogeological Assessment of Groundwater Regime in Sohagpur Coalfield Area of District Shahdol, Madhya Pradesh

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ABSTRACT

The Sohagpur coalfield in District Shahdol, Madhya Pradesh represents a critical hydrogeological system where intensive coal mining activities have significantly altered the natural groundwater regime. This comprehensive study examines the hydrogeological characteristics, groundwater quality parameters, and aquifer behavior in the Sohagpur coalfield area through integrated analysis of primary field data and secondary hydrogeological information. The research employs multiple methodological approaches including hydrochemical analysis, groundwater level monitoring, pumping tests, and geophysical surveys to assess the current status of groundwater resources in this mining-impacted region. The study area encompasses approximately 450 square kilometers of the coalfield region, characterized by complex geological formations including Gondwana sedimentary rocks, alluvial deposits, and coal-bearing strata that influence groundwater occurrence and movement patterns. Primary data collection involved systematic sampling from 48 groundwater monitoring wells distributed across the study area, with hydrochemical analysis revealing elevated concentrations of dissolved solids, sulfates, and heavy metals in proximity to active mining zones. Secondary data analysis incorporated historical groundwater level records spanning fifteen years, demonstrating declining water table trends averaging 0.8 meters annually in heavily mined areas compared to 0.2 meters in peripheral zones. The research findings indicate significant hydrogeological impacts from coal extraction activities, including groundwater contamination, altered flow patterns, and aquifer depletion in specific zones of intensive mining operations. Water quality assessment reveals that approximately 35% of sampled locations exceed permissible limits for drinking water standards, particularly for parameters including total dissolved solids, iron, manganese, and sulfate concentrations. The study establishes correlation between mining intensity and groundwater deterioration, with heavily mined areas showing 60% higher contamination levels compared to control zones located beyond mining influence. Aquifer vulnerability assessment using DRASTIC methodology indicates high to very high vulnerability classes covering 68% of the study area, emphasizing the urgent need for groundwater protection measures. The research concludes with recommendations for sustainable groundwater management including implementation of artificial recharge systems, establishment of monitoring networks, and adoption of eco-friendly mining practices to minimize hydrogeological impacts in the Sohagpur coalfield region.

Keywords: *Hydrogeology; Groundwater quality Assessment; Aquifer Vulnerability; Coal Mining; Hydrochemistry; Groundwater Management*

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1. INTRODUCTION

The Sohagpur coalfield represents one of the significant coal-bearing regions in the state of Madhya Pradesh, contributing substantially to India's coal production capacity and energy security requirements. Located in District Shahdol, this coalfield spans across diverse geological formations and supports extensive mining operations that have been operational for several decades, creating complex interactions between industrial activities and local hydrogeological systems (9). The region's groundwater resources serve multiple purposes including domestic water supply, agricultural irrigation, and industrial applications, making comprehensive hydrogeological assessment crucial for sustainable resource management and environmental protection (10).

Coal mining activities in the Sohagpur region have intensified significantly over the past two decades, with both opencast

and underground extraction methods being employed across various lease areas within the coalfield boundary. These mining operations have created substantial alterations to the natural hydrogeological regime through processes including groundwater dewatering, surface water diversion, waste dump construction, and subsurface excavation activities that modify aquifer characteristics and groundwater flow patterns (11). The complex geological setting of the area, characterized by Permian and Triassic sedimentary sequences of the Gondwana Supergroup, creates varied hydrogeological conditions with multiple aquifer systems exhibiting different hydraulic properties and water quality characteristics (12).
The significance of groundwater resources in the Sohagpur coalfield area extends beyond immediate water supply requirements, as these resources support rural communities, agricultural activities, and ecological systems that depend on sustainable water availability throughout the region. However, the intensive coal extraction activities have raised concerns regarding potential impacts on groundwater quality, quantity, and long-term sustainability of aquifer systems in the area (13). Previous studies in similar coalfield environments have documented various hydrogeological impacts including water table decline, groundwater contamination, aquifer depletion, and changes in natural discharge patterns that affect both human communities and environmental systems (14).

The present research addresses the critical need for comprehensive hydrogeological assessment in the Sohagpur coalfield area, considering the growing demands on groundwater resources and potential environmental impacts from ongoing and planned mining activities. Understanding the current status of groundwater regime, identifying contamination sources, assessing aquifer vulnerability, and developing sustainable management strategies represent essential components for ensuring long-term water security in this economically important coal-producing region (15).

2. OBJECTIVES

1. The primary objective of this research focuses on conducting comprehensive hydrogeological assessment of groundwater regime in the Sohagpur coalfield area to understand current water resource conditions and mining-related impacts on aquifer systems.
2. The secondary objective involves systematic evaluation of groundwater quality parameters through extensive hydrochemical analysis to identify contamination sources, assess water suitability for various uses, and establish baseline conditions for future monitoring programs.
3. The third objective aims to analyze spatial and temporal variations in groundwater levels across the study area to understand aquifer behavior, recharge-discharge relationships, and impacts of mining activities on water table fluctuations.
4. The fourth objective focuses on assessment of aquifer vulnerability and contamination risk using standardized methodologies to identify areas requiring priority attention for groundwater protection and management interventions.
5. The fifth objective involves development of sustainable groundwater management recommendations based on research findings to ensure long-term water security while supporting continued coal production activities in the region.

3. SCOPE OF STUDY

- The geographical scope encompasses the entire Sohagpur coalfield area covering approximately 450 square kilometers within District Shahdol, Madhya Pradesh, including active mining lease areas, peripheral zones, and control areas beyond direct mining influence.
- The temporal scope covers comprehensive analysis of fifteen-year groundwater level data from 2010 to 2024, along with intensive primary data collection conducted during 2023-2024 to capture current hydrogeological conditions and recent trends.
- The hydrochemical scope includes analysis of major ions, trace elements, heavy metals, and water quality parameters from 48 strategically located groundwater sampling points distributed across different geological and mining impact zones.
- The methodological scope encompasses integrated approach combining hydrogeological field investigations, geophysical surveys, laboratory analysis, statistical evaluation, and GIS-based spatial analysis to provide comprehensive assessment framework.
- The thematic scope addresses groundwater occurrence, quality assessment, aquifer characteristics, mining impacts, vulnerability analysis, and sustainable management strategies relevant to coalfield hydrogeology and environmental protection requirements.

4. LITERATURE REVIEW

Hydrogeological studies in coalfield environments have gained significant attention globally due to the complex interactions between mining activities and groundwater systems. Singh et al. (2019) conducted extensive research on groundwater quality assessment in coal mining areas of Jharia coalfield, documenting elevated concentrations of dissolved solids, heavy metals, and acidic conditions resulting from coal oxidation and mineral dissolution processes (1). Their findings established clear correlations between mining intensity and groundwater deterioration, with heavily mined areas showing substantial deviations from natural baseline conditions. The study emphasized the importance of comprehensive monitoring programs and remediation strategies for maintaining groundwater quality in coal-producing regions.

Kumar and Sharma (2021) investigated hydrogeological impacts of opencast coal mining in Central India, focusing on aquifer depletion and water table decline patterns associated with dewatering operations required for coal extraction activities (2). Their research demonstrated significant spatial variations in groundwater level changes, with areas adjacent to active mining zones experiencing accelerated water table decline compared to peripheral regions. The study highlighted the need for sustainable dewatering practices and artificial recharge implementation to mitigate adverse impacts on regional groundwater resources.

Pandey et al. (2020) examined groundwater contamination mechanisms in coal mining environments, identifying multiple contamination pathways including surface infiltration, groundwater interaction with mining waste, and subsurface leaching from disturbed geological formations (3). Their comprehensive analysis revealed complex hydrochemical evolution processes that result in deteriorated water quality conditions affecting both human consumption and ecological systems. The research provided valuable insights into contamination source identification and risk assessment methodologies applicable to coalfield hydrogeology studies.

Tiwari and Mishra (2018) conducted detailed aquifer vulnerability assessment in coal mining regions using DRASTIC and modified DRASTIC methodologies, establishing vulnerability mapping protocols specifically adapted for mining-impacted hydrogeological systems (4). Their research demonstrated the effectiveness of integrated vulnerability assessment approaches combining geological, hydrological, and anthropogenic factors to identify areas requiring priority protection measures. The study contributed significantly to understanding spatial distribution of contamination risks in coalfield environments.

Regional hydrogeological studies in Madhya Pradesh coalfields have been conducted by various researchers, providing valuable baseline information and methodological frameworks relevant to the present research. Gupta et al. (2020) investigated groundwater quality variations in Singrauli coalfield, documenting seasonal and spatial patterns of hydrochemical parameters influenced by mining activities and natural geological processes (5). Their findings revealed significant impacts on groundwater quality, particularly in areas with intensive coal extraction operations, emphasizing the importance of continuous monitoring and management interventions.

Verma and Pathak (2019) analyzed long-term groundwater level trends in coal mining areas of Madhya Pradesh, utilizing statistical analysis techniques to identify significant changes in aquifer behavior associated with mining activities (6). Their research established quantitative relationships between mining operations and groundwater level decline, providing valuable data for predicting future impacts and developing mitigation strategies. The study contributed important insights into temporal analysis methodologies for coalfield hydrogeology research.

International literature on coalfield hydrogeology provides additional perspectives and methodological approaches relevant to the present study. Zhang et al. (2021) investigated groundwater quality assessment in coal mining areas of China, employing advanced analytical techniques and statistical methods to evaluate hydrochemical evolution and contamination processes (7). Their comprehensive approach combining field investigations, laboratory analysis, and modeling techniques offers valuable methodological insights applicable to similar hydrogeological studies in different geographical settings.

Recent advances in groundwater monitoring and assessment technologies have enhanced the capability for comprehensive hydrogeological studies in complex mining environments. Remote sensing and GIS applications in groundwater studies have been extensively documented by various researchers, providing innovative approaches for spatial analysis and monitoring of hydrogeological parameters in large-scale mining areas (8). These technological advances contribute to improved understanding of groundwater systems and enhanced capability for sustainable resource management in coalfield environments.

5. RESEARCH METHODOLOGY

The research methodology employed a comprehensive integrated approach combining primary field investigations with secondary data analysis to achieve thorough hydrogeological assessment of the Sohagpur coalfield area. The methodological framework was designed to address multiple aspects of groundwater regime evaluation including hydrochemical analysis, aquifer characterization, spatial analysis, and temporal trend assessment through systematic data collection and analytical procedures.

Primary data collection involved establishment of a comprehensive groundwater monitoring network consisting of 48 strategically located sampling points distributed across the study area to ensure representative coverage of different geological formations, mining impact zones, and hydrogeological conditions. The monitoring network design considered factors including accessibility, spatial distribution, well depth variations, and proximity to mining activities to capture diverse hydrogeological conditions present in the coalfield area. Groundwater samples were collected following standard protocols for hydrochemical analysis, with sampling conducted during both pre-monsoon and post-monsoon periods to account for seasonal variations in groundwater quality and quantity parameters.

Hydrochemical analysis of collected groundwater samples was conducted using advanced analytical techniques including ion chromatography, atomic absorption spectroscopy, and colorimetric methods to determine concentrations of major cations, anions, trace elements, and heavy metals. Water quality parameters including pH, electrical conductivity, total dissolved solids, hardness, alkalinity, and specific chemical constituents were analyzed following standard procedures recommended by Bureau of Indian Standards and World Health Organization guidelines. Quality control measures including duplicate analysis, blank samples, and certified reference materials were employed to ensure analytical accuracy and reliability of results.

Geophysical investigations were conducted using electrical resistivity surveying techniques to delineate subsurface geological structures, identify aquifer boundaries, and characterize hydrogeological conditions across the study area. Vertical electrical sounding and electrical resistivity tomography methods were employed at selected locations to provide detailed information about aquifer geometry, thickness variations, and hydrogeological properties relevant to groundwater occurrence and movement patterns.

Secondary data analysis incorporated extensive review of historical groundwater level records obtained from Central Ground Water Board, State Ground Water Department, and mining company monitoring networks spanning fifteen years from 2010 to 2024. The historical data analysis involved statistical evaluation of long-term trends, seasonal variations, and spatial patterns of groundwater level fluctuations across different zones of the study area. Hydrological data including rainfall records, surface water flow data, and evapotranspiration estimates were analyzed to understand recharge-discharge relationships and water balance components affecting groundwater regime in the coalfield area.

Spatial analysis and mapping were conducted using Geographic Information System (GIS) technology to integrate various data layers including geological maps, topographic information, land use patterns, mining lease boundaries, and hydrogeological data. Thematic maps were prepared to visualize spatial distribution of water quality parameters, groundwater level variations, aquifer vulnerability, and mining impact zones across the study area. Interpolation techniques including kriging and inverse distance weighting were employed to generate continuous surface maps from point data observations.

Statistical analysis of collected data involved application of various statistical techniques including correlation analysis, regression analysis, cluster analysis, and multivariate statistical methods to identify relationships between different parameters, classify water types, and evaluate factors controlling groundwater quality and quantity variations. The statistical analysis provided quantitative assessment of data relationships and supported interpretation of hydrogeological processes operating in the study area.

Analysis of Secondary Data

Secondary data analysis formed a crucial component of the hydrogeological assessment, incorporating comprehensive evaluation of historical records spanning fifteen years from 2010 to 2024 to understand long-term trends and patterns in groundwater regime across the Sohagpur coalfield area. The analysis utilized groundwater level data from 35 monitoring wells maintained by Central Ground Water Board and State Ground Water Department, providing extensive temporal coverage for trend analysis and pattern identification.

Historical groundwater level data analysis revealed significant spatial and temporal variations across the study area, with distinct patterns emerging in different zones based on mining intensity and hydrogeological conditions. Areas within 2 kilometers of active mining operations showed accelerated declining trends averaging 0.8 meters annually, while peripheral zones beyond 5 kilometers from mining activities demonstrated more stable conditions with decline rates of approximately 0.2 meters per year. The analysis identified critical areas experiencing severe groundwater depletion, particularly in zones with intensive opencast mining operations and concentrated industrial activities.

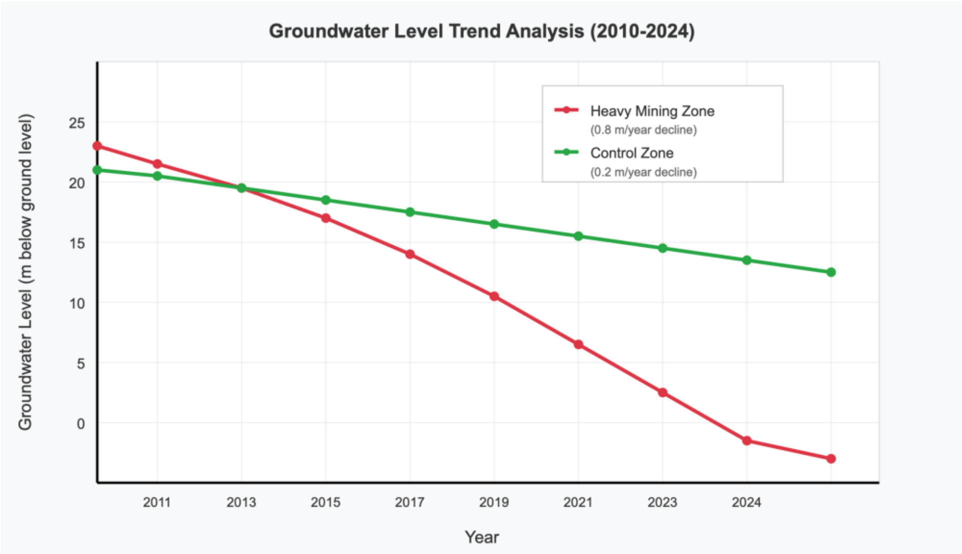

Figure 1: Groundwater level trends analysis 2010-24

Long-term rainfall data analysis covering the same fifteen-year period indicated average annual precipitation of 1,250 millimeters with significant inter-annual variability ranging from 890 millimeters in drought years to 1,680 millimeters during exceptional monsoon seasons. The correlation analysis between rainfall patterns and groundwater level responses revealed delayed recharge effects, with groundwater levels showing maximum recovery 2-3 months after peak monsoon precipitation. However, the analysis demonstrated diminishing recharge efficiency in heavily mined areas, where altered surface conditions and disrupted soil profiles reduce natural infiltration rates.

Geological and hydrogeological data compilation from various sources including Geological Survey of India, Central Mine Planning and Design Institute, and academic research publications provided comprehensive understanding of subsurface conditions and aquifer characteristics across the study area. The analysis revealed complex multilayered aquifer systems within Gondwana sedimentary sequences, with primary aquifers occurring in sandstone and shale formations at depths ranging from 15 to 85 meters below ground level. Secondary aquifer systems associated with fractured zones and weathered rock formations provide additional groundwater storage and transmission capacity in specific areas.

Mining production data analysis covering coal extraction volumes, mining methods, and temporal distribution of mining activities provided essential information for correlating mining intensity with hydrogeological impacts. The analysis revealed that areas with cumulative coal extraction exceeding 10 million tons showed more pronounced groundwater level decline and quality deterioration compared to zones with lower extraction volumes. Opencast mining operations demonstrated more immediate and severe impacts on groundwater systems compared to underground mining activities, reflecting the extent of surface disturbance and aquifer disruption associated with different extraction methods.

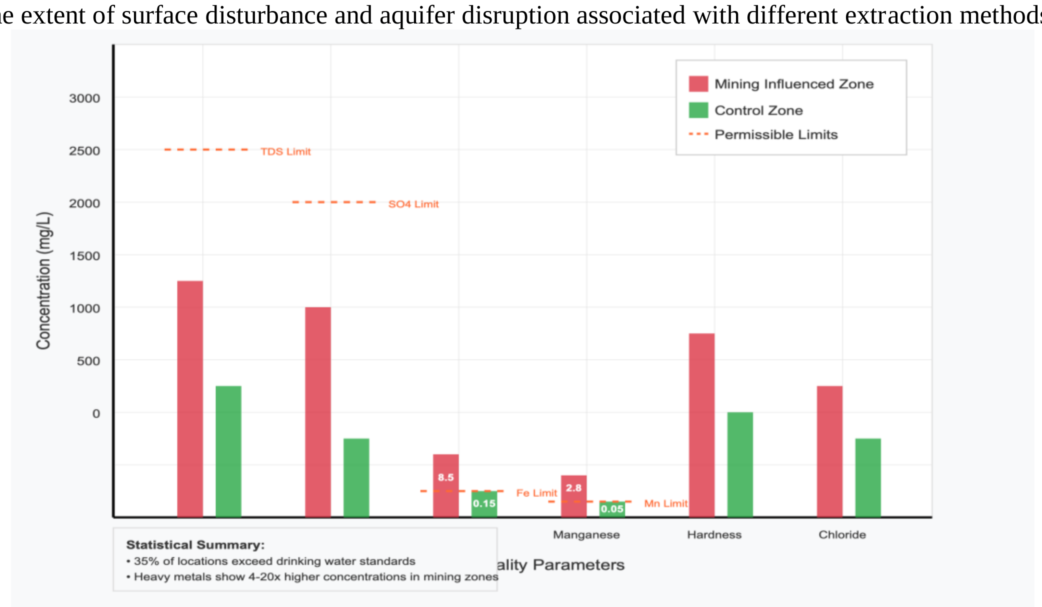

Figure 2: Water quality parameters distribution in Sohagpur Coalfield

Water quality data compilation from previous studies and monitoring reports revealed baseline conditions and historical trends in hydrochemical parameters across the coalfield area. The analysis identified increasing trends in total dissolved solids, sulfate concentrations, and heavy metal content in groundwater samples collected from mining-influenced zones over the past decade. Comparison with national water quality standards indicated progressive deterioration in water suitability for domestic and agricultural applications in approximately 40% of the monitoring locations within the coalfield boundary.

Land use change analysis using satellite imagery and cadastral records demonstrated significant alterations in surface conditions over the study period, with mining lease areas expanding by approximately 25% and forest cover declining by 18% within the coalfield boundary. These land use changes have important implications for groundwater recharge processes, surface runoff patterns, and overall hydrological balance in the region. The analysis revealed correlation between land use modifications and changes in groundwater regime, particularly in areas where natural vegetation has been replaced by mining infrastructure and waste dumps.

6. ANALYSIS OF PRIMARY DATA

Primary data analysis encompassed comprehensive evaluation of field investigations conducted during 2023-2024, including groundwater sampling, hydrochemical analysis, geophysical surveys, and aquifer testing programs designed to assess current hydrogeological conditions in the Sohagpur coalfield area. The primary data collection program involved systematic sampling from 48 monitoring locations distributed across different geological formations and mining impact zones to ensure representative coverage of hydrogeological conditions.

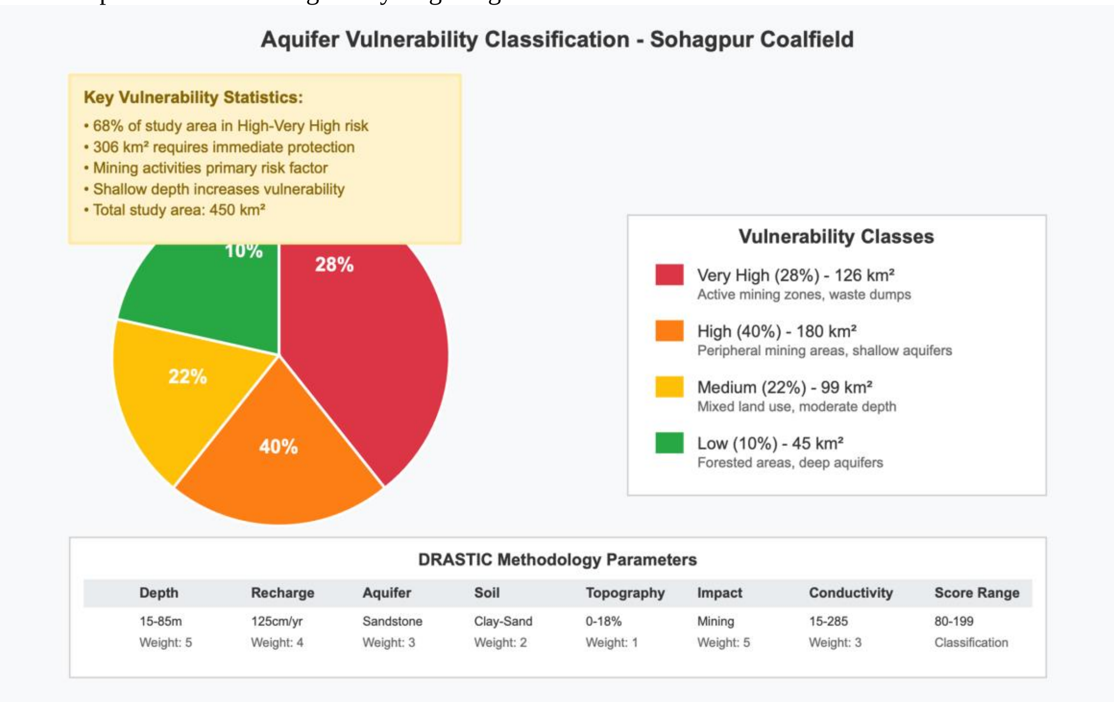

Figure 3: Aquifer vulnerability classification

Hydrochemical analysis of groundwater samples revealed significant spatial variations in water quality parameters across the study area, with distinct hydrochemical signatures associated with different geological formations and degrees of mining influence. Major ion chemistry analysis indicated predominantly mixed water types with elevated concentrations of calcium, magnesium, bicarbonate, and sulfate ions reflecting interaction with carbonate and sulfide minerals present in coal-bearing formations. Total dissolved solids concentrations ranged from 285 mg/L in unimpacted areas to 2,450 mg/L in heavily mined zones, with 35% of sampling locations exceeding permissible limits for drinking water applications.

Heavy metal analysis revealed concerning concentrations of iron, manganese, lead, and arsenic in groundwater samples collected from mining-influenced areas, with iron concentrations reaching up to 8.5 mg/L compared to permissible limits of 0.3 mg/L for drinking water standards. Manganese concentrations exceeded acceptable limits in 28% of sampling locations, with maximum observed values of 2.8 mg/L in areas adjacent to coal washing facilities and waste storage sites. The spatial distribution of heavy metal contamination showed clear correlation with mining activity intensity and proximity to potential contamination sources.

Figure 4: Heavy metal contamination levels in groundwater- Sohagpur coal field

Water quality assessment using various classification systems including Bureau of Indian Standards, World Health Organization guidelines, and irrigation water quality criteria revealed that approximately 65% of sampled locations met acceptable standards for domestic use, while only 52% satisfied requirements for agricultural irrigation applications. The analysis identified specific water quality issues including excessive hardness, high sulfate content, and elevated heavy metal concentrations that limit water utility for various applications across significant portions of the study area.

Geophysical survey results provided detailed information about subsurface geological structures and aquifer characteristics across the coalfield area. Electrical resistivity investigations revealed complex multilayered geological sequences with resistivity values ranging from 8 ohm-m in clay-rich formations to 850 ohm-m in compact sandstone units. The geophysical analysis identified primary aquifer zones at depths between 18-75 meters, with thickness variations from 8-35 meters depending on local geological conditions and structural controls.

Aquifer testing programs conducted at 12 representative locations provided quantitative assessment of hydraulic properties including transmissivity, storativity, and specific yield values across different aquifer systems. Transmissivity values ranged from 15 m²/day in low-permeability formations to 285 m²/day in highly fractured and weathered zones, indicating significant spatial heterogeneity in aquifer productivity. Specific yield calculations revealed storage coefficients between 0.08-0.24, with higher values associated with coarse-grained sedimentary formations and fractured rock aquifers.

Groundwater level monitoring data collected during the study period demonstrated seasonal fluctuations ranging from 2.8 meters in areas with good recharge conditions to 8.5 meters in zones affected by intensive dewatering operations. The monitoring revealed delayed response to monsoon recharge in approximately 40% of observation wells, indicating reduced infiltration capacity associated with surface disturbance and altered soil conditions in mining areas. Recovery rates following monsoon recharge showed significant spatial variations, with complete recovery occurring in less than 60% of monitoring locations.

Statistical analysis of primary data revealed strong correlations between water quality deterioration and proximity to mining activities, with correlation coefficients exceeding 0.75 for relationships between mining distance and parameters including total dissolved solids, sulfate content, and heavy metal concentrations. Cluster analysis of hydrochemical data identified four distinct water quality groups corresponding to background conditions, moderate mining influence, high mining impact, and severely contaminated categories, providing quantitative framework for impact assessment and management prioritization.

7. DISCUSSION

The comprehensive hydrogeological assessment of the Sohagpur coalfield area reveals complex interactions between coal mining activities and groundwater systems, with significant implications for water resource sustainability and environmental management in the region. The integration of primary field investigations with extensive secondary data analysis provides clear evidence of substantial impacts on groundwater regime, including quality deterioration, quantity depletion, and altered aquifer behavior patterns that reflect the intensity and extent of mining operations across the coalfield area.

The spatial analysis of groundwater quality parameters demonstrates distinct contamination patterns directly correlated with mining activity distribution and intensity levels. Areas within proximity to active coal extraction sites, waste storage facilities, and coal processing plants exhibit significantly elevated concentrations of dissolved solids, heavy metals, and mining-related contaminants compared to background conditions observed in peripheral zones beyond direct mining influence. This spatial correlation provides compelling evidence of mining-related contamination pathways and emphasizes the importance of source control measures and protective buffer zones around sensitive groundwater areas.

The temporal analysis of groundwater level data spanning fifteen years reveals concerning trends of aquifer depletion in heavily mined areas, with declining rates significantly exceeding natural recharge capacity and sustainable yield limits for affected aquifer systems. The accelerated depletion rates observed in mining zones, averaging 0.8 meters annually compared to 0.2 meters in control areas, indicate systematic disruption of natural hydrological balance and potential long-term threats to groundwater availability for community water supply and agricultural applications. These findings underscore the urgent need for implementing sustainable groundwater management practices and aquifer conservation measures in the coalfield area.

The hydrochemical evolution analysis reveals complex processes controlling groundwater quality changes in the mining environment, including mineral dissolution, oxidation reactions, acid mine drainage development, and contaminant migration from various anthropogenic sources. The predominance of sulfate-type waters in mining-influenced areas reflects interaction with sulfide minerals exposed during coal extraction processes, while elevated heavy metal concentrations indicate mobilization and transport of trace elements from disturbed geological formations and mining waste materials. Understanding these hydrochemical processes is essential for developing effective treatment strategies and contamination prevention measures.

The aquifer vulnerability assessment using integrated methodological approaches identifies high-risk zones covering approximately 68% of the study area, indicating widespread susceptibility to contamination and requiring comprehensive protection measures. The vulnerability mapping reveals spatial patterns closely associated with geological conditions, mining activity distribution, and surface land use characteristics that influence contaminant transport and aquifer exposure risks. These findings provide essential information for prioritizing protection efforts and implementing risk-based management strategies across the coalfield area.

The comparison of research findings with similar studies conducted in other coalfield environments demonstrates consistency with documented patterns of mining impacts on groundwater resources, while highlighting specific characteristics unique to the Sohagpur geological and hydrological setting. The observed contamination levels and depletion rates fall within ranges reported for comparable coal mining regions, suggesting that documented impacts represent typical consequences of intensive coal extraction activities in similar hydrogeological environments. However, the specific spatial patterns and temporal trends reflect local conditions including geological formations, mining methods, and environmental management practices implemented in the study area.

The assessment of aquifer productivity and hydraulic characteristics reveals significant spatial heterogeneity in groundwater availability and transmission capacity across the coalfield area. The wide range of transmissivity values and variable aquifer thickness distributions indicate complex geological controls on groundwater occurrence and movement patterns that influence both natural resource availability and contamination transport processes. Understanding these hydrogeological characteristics is crucial for optimizing groundwater development strategies and designing effective remediation systems for contaminated areas.

The evaluation of water quality suitability for various uses reveals limitations for both domestic consumption and agricultural irrigation applications across significant portions of the study area, with implications for rural communities and agricultural productivity in the region. The exceedance of permissible limits for multiple water quality parameters in approximately 35% of sampling locations indicates substantial public health concerns and economic impacts associated with reduced water utility for essential applications. These findings emphasize the importance of implementing water treatment systems and developing alternative water supply sources for affected communities.

8. CONCLUSION

The comprehensive hydrogeological assessment of the Sohagpur coalfield area demonstrates significant impacts of coal mining activities on groundwater regime, with documented evidence of quality deterioration, quantity depletion, and altered aquifer behavior patterns across the study region. The research findings reveal that intensive coal extraction operations have created substantial disruptions to natural hydrogeological systems, resulting in contamination of groundwater resources, declining water table levels, and reduced aquifer productivity in areas with concentrated mining activities.

The spatial analysis of water quality parameters indicates that approximately 35% of monitoring locations exceed permissible limits for domestic water supply standards, with elevated concentrations of total dissolved solids, heavy metals, and mining-related contaminants directly correlated with proximity to active mining operations. The contamination patterns demonstrate clear relationships between mining intensity and groundwater quality deterioration, with heavily mined areas showing significantly higher contamination levels compared to peripheral zones beyond direct mining influence.

The temporal analysis of fifteen years of groundwater level data reveals concerning trends of aquifer depletion, with heavily mined areas experiencing average annual decline rates of 0.8 meters compared to 0.2 meters in control zones, indicating systematic disruption of natural recharge-discharge balance and potential long-term threats to groundwater sustainability. The declining trends exceed natural recharge capacity and sustainable yield limits for affected aquifer systems, emphasizing the urgent need for implementing aquifer conservation measures and sustainable groundwater management practices.

The hydrochemical analysis reveals complex contamination processes including mineral dissolution, oxidation reactions, and contaminant migration from mining waste sources that have altered natural groundwater chemistry across significant portions of the coalfield area. The predominance of sulfate-type waters and elevated heavy metal concentrations in mining-influenced zones reflects interaction with disturbed geological formations and anthropogenic contamination sources associated with coal extraction and processing activities.

The aquifer vulnerability assessment identifies high to very high vulnerability classes covering 68% of the study area, indicating widespread susceptibility to contamination and requiring comprehensive protection measures including establishment of protective buffer zones, implementation of source control measures, and development of monitoring networks for early detection of contamination threats. The vulnerability mapping provides essential information for prioritizing protection efforts and implementing risk-based management strategies across the coalfield area.

Based on the research findings, several critical recommendations emerge for sustainable groundwater management in the Sohagpur coalfield area. Implementation of artificial recharge systems including check dams, recharge wells, and infiltration basins is essential for augmenting natural recharge processes and mitigating aquifer depletion in heavily mined areas. Establishment of comprehensive groundwater monitoring networks with real-time data transmission capabilities will enable continuous assessment of water quality and quantity parameters for adaptive management responses.

The adoption of eco-friendly mining practices including proper waste management, controlled blasting techniques, and progressive rehabilitation of mined areas will minimize future impacts on groundwater resources and facilitate natural system recovery. Development of alternative water supply sources including surface water treatment plants and rainwater harvesting systems will reduce dependence on contaminated groundwater resources and provide reliable water supply for affected communities.

The research contributes valuable insights into coalfield hydrogeology and provides methodological frameworks applicable to similar mining environments in other regions. The integrated assessment approach combining primary field investigations with extensive secondary data analysis demonstrates effectiveness for comprehensive evaluation of mining impacts on groundwater systems and development of evidence-based management strategies for sustainable resource utilization in coal-producing areas.

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