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Impact of Coal Mining on Groundwater Quality and Human Health: A Case Study

Swastik Choubay[1] and Ram Chandra Chaurasia[2]

[1] M.Tech Scholar, Department of Mining and Mineral Processing, Lakshmi Narain College of Technology, Jabalpur, Madhya Pradesh, 482053, India.

[2] Associate Professor, Department of Mining and Mineral Processing, Lakshmi Narain College of Technology, Jabalpur, Madhya Pradesh, 482053, India.

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Abstract

Groundwater resources in coal mining regions are increasingly threatened by intensive mining activities that alter natural hydrogeochemical conditions and facilitate the mobilization of heavy metals into aquifer systems. This study evaluates the groundwater quality and associated human health risks in the Sohagpur Coalfield, Shahdol District, Madhya Pradesh, India, a major coal-producing region of the Son Valley Basin. The assessment integrates hydrogeological perspectives with physicochemical and heavy metal analyses to investigate the influence of mining operations on groundwater quality. Human health risk assessment was performed following the United States Environmental Protection Agency (USEPA) methodology by estimating the Average Daily Dose (ADD), Hazard Quotient (HQ), Hazard Index (HI), and Carcinogenic Risk (CR) through the oral ingestion pathway. The findings reveal considerable spatial variability in groundwater chemistry, primarily controlled by geological formations, hydrogeochemical processes, mine water discharge, acid mine drainage, overburden leachates, and waste disposal practices. Elevated concentrations of selected heavy metals were observed in groundwater samples collected near mining activities, resulting in increased non-carcinogenic and carcinogenic risks at several locations. While many sampling sites exhibited HQ and HI values within acceptable limits, certain sites exceeded the recommended thresholds, indicating potential health risks associated with long-term consumption of untreated groundwater. Carcinogenic metals, particularly arsenic, chromium, cadmium, and nickel, contributed significantly to lifetime cancer risk where their concentrations surpassed guideline values. The study highlights the necessity for continuous groundwater quality monitoring, scientific mine waste management, periodic health risk assessment, and implementation of sustainable groundwater protection strategies in mining regions. The outcomes provide valuable information for environmental managers, policymakers, and mining authorities to support evidence-based groundwater management and safeguard public health in coal mining areas.

Keywords: Groundwater quality, Hydrogeochemistry, Human health risk assessment, Coal mining, Hazard Quotient, Hazard Index, Carcinogenic risk

1.0 Introduction

1.1 Mining and Gound Water Resources

India is solemnly dependent upon Coal as a major source of energy for economic activities and nation growth. To date, most of the Coal utilized each year is being excavated from the open or underground mines. South Eastern Coalfields Limited, which is the subsidiary of Coal India Limited is the primary producer of Non-Coking Coal in India. It operates in the Sohagpur coalfield, located in the Shahdol district of Madhya Pradesh, India. Mining in these areas affects the physicochemical quality of both ground and surface water. Mining-related activities like acid mine drainage, tailing ponds, mine water, and overburden place severe stress on freshwater resources in mining regions (Yadav & Chaurasia, 2025; Daharwal & Chaurasia, 2026; Chourasiya & Chaurasia, 2026). The environmental consequences of mining may persist during active operations and long after mine closure, emphasizing the importance of systematic closure planning, post-closure monitoring, and environmental risk management **(**Bisen et al., 2025; Bisen & Chaurasia, 2026). Sulfide minerals in the Coal can produce an acidic condition released to the aquifers during the mining operations. However, these conditions are solely mine-dependent, which is controlled by the hydro-geological and mining operations. The concentration of contaminants in the mine water varies in several ranges that sometimes also meet the drinking water standard. However, sometimes it also contains heavy metals that adversely affect the surface and the groundwater (Daharwal & Chaurasia, 2026; Chourasiya & Chaurasia, 2026). Besides the conventional contamination of mining operations. Insidious and toxic emissions from the Coal mine are a severe threat to the physical health and air quality of this region (Yadav & Chaurasia, 2025; Khan & Chaurasia, 2026). Furthermore, the product of incomplete combustion and the toxins released from the suspended aerosolized particles can also affect the nearby surface water source that may impact the groundwater. Similarly, the ash developed from the burnet Coal deposit over the surface water also can affect human health. Water is the basis of all fundamentals of human life, starting from food security and livelihood to sustainable development, considered a threatened natural resource. The intricate relationship between water consumption and availability describes the world's water scarcity. As several controlling factors influence the consumption and availability of water, the pattern of scarcity also varies depending upon the locality and region. Hence, a generalization of a global figure for water scarcity is complex. However, the agreed number is lesser than the 1000 m 3 /capita. Since the arrival of humankind in the world, they have exploited water resources. Uncontrolled urbanization has released an enormous number of adverse compounds into the water stream that severely affected the serenity of the natural water. Primarily, the use of river water in the industrial activities and sustaining the exploded population was majorly responsible for the degradation of surface and groundwater quality. The earth is a blue planet with 70% of its surface covered with water. However, 97% of them are saline in nature, only 3 % of it is fresh. Of this 3%, about 79 % is tied up in glaciers, polar icebergs, 20 % in groundwater, and 1 % in fresh water in rivers, lakes, and ponds suitable for human consumption which is considered an available resource used for various purposes. The global water distribution is presented in Figure 1. Earth's water movement dynamics are described through flowchart.

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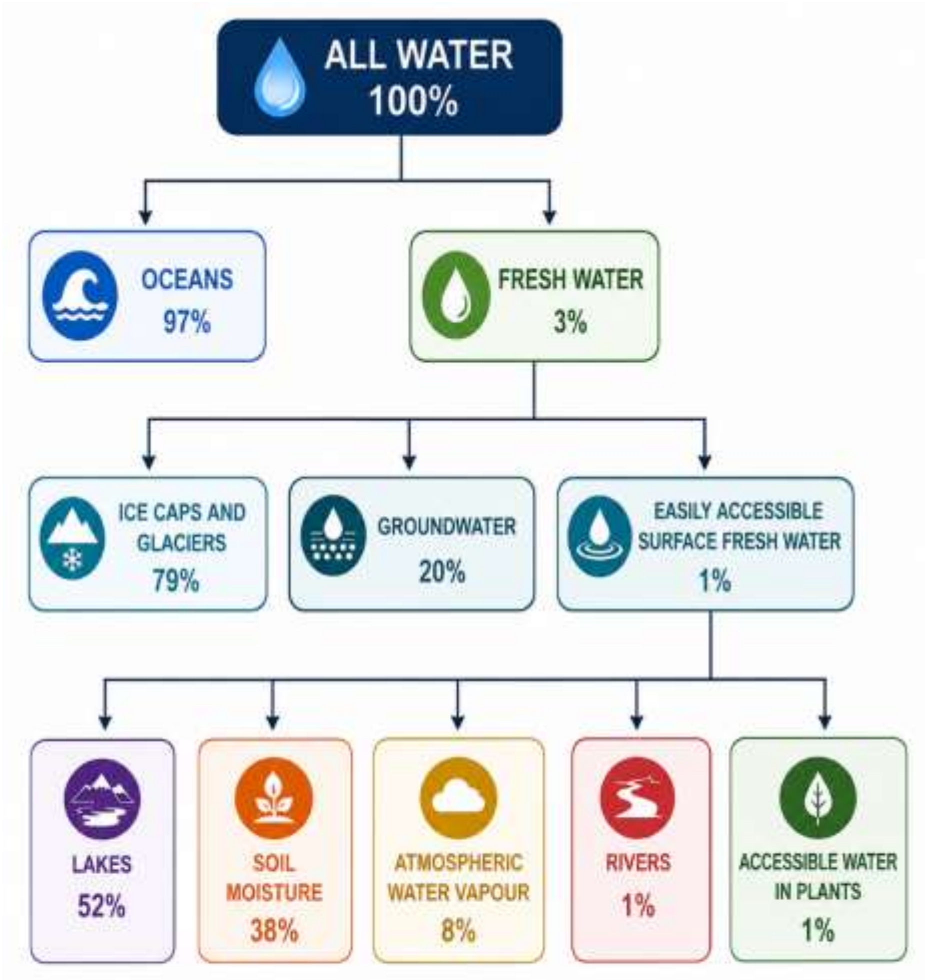

Figure 1 Estimate of Global Water Distribution

1.2 Groundwater

Ground water works as a supply system of surface streams like the river and wetlands and hence possesses a necessary ecological consequence. It is the sole source of drinking water and, hence, wildlife and agricultural and other anthropogenic activities. Various activities like climate change and human activities have had adverse effects on groundwater resources and the globe. Hence, pressure on the groundwater reduces the replenishment of the river stream, and hence the evapotranspiration increases, which hampers the water cycle. It also increases the salinity and reserved water in the water reservoir. So, preserving groundwater resources is very much necessary as the recharge rate is lower than the withdrawal. And it is economically unfeasible to restore the contaminated or modified groundwater. So, the reason for groundwater monitoring is Analyzing the baseline status of the groundwater to understand the current state to forecast the trend and comprehend the changes happening and the impact of anthropogenic activities on the physicochemical characters of the groundwater. Such monitoring is particularly important in coal-mining regions because environmental impacts can continue after cessation of mining activities and therefore require systematic post-closure assessment and monitoring (Bisen et al., 2025; Bisen & Chaurasia, 2026; Bisen et al., 2025b). Providing a solid platform for the scientific management and policy-making of groundwater resources.

Groundwater monitoring is carried out through a technically standardized continuous method involving in-situ approaches like laboratory analysis involving relevant variables and the ex-situ methods like airborne and satellite observation. Monitoring programs are normally composed of both the monitoring of quality and quantity monitoring. Monitoring on a local scale is scrutinized by analyzing the high number of bore well, hand pumps, and multi-level water sampling from different saturation of water zones. The number of sampling points and analysis of different physicochemical variables based upon available numerical models is most important for filling up the information gap between the temporal and spatial. However, the reliability of those data's subjected to the number of input points. If the input point is less, then the validity of those data will be uncertain. Nowadays, satellite-based observations play a pivotal role in revealing the status of ground water in terms of variation in changes and the comparison between the past and present states on a global scale. However, the resolutions are lower both spatially and temporally. Systematic analysis of this information can generate an overall groundwater picture globally, providing a stage to accurately predict the future of ground water availability and the possible variation.

1.3 Groundwater Scenario of the World

As discussed earlier, groundwater replenishes the surface stream, which in turn controls the stability of the land surface and supplies the potable water for humankind to consume and hence controls the water need of humankind (FAO 2004). For example, over 75 % of the water needs in Lithuania, the Russian Federation, Saudi Arabia, Jamaica, Swaziland, Georgia, Libya, Mongolia, Estonia, and Iceland. The following shows the countries that extract the highest amount of groundwater. And the presence of the subtropical countries in the list is because of the extensive agricultural activities in these countries. Agriculture is the groundwater water-intensive sector consuming almost 60% of it, whereas almost 20% is supplied for industrial activities. Both domestic and other purposes consume rest. Due to these countries' semi-arid or arid climatic conditions, the water-intensive crop requires more groundwater (IGRAC's, 2010).

On the other hand, the industry-intensive countries like the US, groundwater is used for industrial activities. According to a UNEP report, groundwater is the major source of drinking water in some countries, providing almost 40% of the global domestic water supplies (UNEP, 2003). Though most cities were previously dependent upon surface streams, mainly rivers, for water supply, nowadays, due to the population boom and unplanned urbanization, megacities are getting dependent upon groundwater. Suburban and small towns, those having inaccessibility to river water, remain fully dependent on groundwater for domestic and other uses. It is the bridge connecting the water supply gap during the dry season.

1.4 Groundwater Scenario of the India

India, although small in terms of geographical size, harbours a disproportionately large proportion of the world's population. The country covers an area of around 3.29 million km², which is only 2.4% of the earth's land surface, but it accommodates nearly 15–18% of the world's population. On the other hand, India has access to only about 4% of the world's fresh water resources, which is equivalent to almost 1,086 km³ of usable water per year. The imbalance creates great pressure on water resources, and groundwater becomes an important part of national water security.

The distribution of groundwater in space and time is mainly controlled by the physiography, monsoonal climate and geology of the country. The northern mountain belt acts as a climatic barrier and increases monsoon precipitation over the northern plains, causing substantial groundwater recharge in the alluvial regions. The consolidated and structurally complex rocks of the mountainous belt generally have low groundwater storage potential but the foothill zones, especially the Terai and Bhabar belts, are conducive for substantial infiltration and subsurface recharge leading to development of confined and semi-confined aquifer systems.
The Indo-Gangetic alluvial tract is the most productive ground-water province of the country with thick, laterally extensive sedimentary deposits and multi-layered aquifer systems. These aquifers support intensive agriculture, domestic water supply and industrial demand. In contrast, the groundwater regime of peninsular India is dominated by hard-rock aquifers where groundwater occurs only in weathered and fractured zones and exhibits high spatial variability. The crystalline lithology limits the potential of groundwater in areas such as Chhattisgarh and Jharkhand while better groundwater conditions are observed in hilly regions such as Jammu and Kashmir in valley-fill and sedimentary zones.

Salinity ingress and seawater intrusion in island and coastal regions like Andaman and Nicobar Islands and Lakshadweep are increasing challenges, worsened by over-extraction, reduced recharge and rising sea levels. Recent national groundwater assessments show that a large number of the more than 5,700 administrative units assessed are classified as over-exploited, critical and semi-critical indicating increasing stress on groundwater reserves. Andhra Pradesh, Punjab, Haryana, Rajasthan and Tamil Nadu have been reporting high concentration of stressed groundwater units consistently.

In general, India's groundwater is characterized by uneven availability, declining water levels, quality degradation and increasing climate variability. A region-specific aquifer-based management framework is needed for addressing the challenges at the level of 2026 involving scientific assessment, controlled abstraction, artificial recharge measures, enforcement of policies and climate resilient water planning to ensure long-term sustainability.

2. Literature Review

The effect of mining on the water table's physicochemical characteristics and the environment, the hydrogeological investigation of mine water, contamination of soil through these activities, and the geoenvironmental studies around mining areas are very well studied. Herein we have tried to consolidate some of those studies to prepare the knowledge base. Groundwater is one of the most critical dynamic water sources controlled by the difference between the aquifer's optimum and minimum water level and principally recharged through the monsoon rainfall throughout the year. The delicate equilibrium between the recharge and discharge is distorted by the overexploitation of the groundwater resulting in the depletion of the groundwater table that adversely affects the surface and sub-surface environment. For an urban and sub-urban population where surface water availability is minimal, groundwater acts as a reliable source of pollution-free water for domestic use.

The groundwater recharge estimates are being analyzed using the water table fluctuation method. The change in the observed water level in the well is a boundary for adding or removing water in the water table. If the level increases, the water table is recharged, whereas the reduction in water level marks the removal of water. The lateral inflow or interlayer leakage may cause this recharge. This water level in the observation well represents a vast area; hence, it is considered the integrated approach. Several other methods employ a data-based observation system in the unsaturated zones, considered a point measurement approach. In order to sustain and maintain the ecological balance, groundwater plays a vital role. The rainfall mainly controls the replenishment of this groundwater. Because of the high temporal and remarkable variability of the rainwater in the Indian subcontinent, managing the groundwater is very tricky. Urbanization, industrialization, irrigation activities, and mining have posed severe stress, hampering the delicate dynamics of groundwater resources (Chatterjee et al., 2010). overburden, waste disposal, industrial effluents, acid mine drainage, and wet excavations in mine water in the Coal mining area polluted the water in this region.

A detailed hydrochemistry study was employed to understand. The intermixing of a range of groundwater in a limestone embedded aquifer is analyzed. It is being seen that the young water is mixed with the older connate water through an interface zone. This phenomenon is revealed by analyzing the distribution of ions in groundwater. Researchers have analyzed the quality of groundwater resources from different sources like Tube well, dug well, Bore well, etc. It has been reported that the exposure to high coliform content and nitrate and manganese make the well water in this study not suitable for the drinking water. It is being found that the chemical character of the groundwater in terms of TSS, BOD, COD, sodium, copper, electrical conductivity, and lead content in the water.

Lind et al., (1998) has reported the disturbance in pH balance in groundwater quality by mining activation. Similarly, Maticie, (1999) has studied the groundwater quality in Slovenia and analyzed the impact of agricultural activity on the water quality. An excess concentration of trace ions is reported in this region's ground water. Jain and Sharma are developing a regression equation (2000) to predict the groundwater quality of Sagar district, Madhya Pradesh. A significant correlation between water quality and electrical conductivity is revealed in this study.

The suitability of water quality for industrial, domestic, and irrigation purpose collected from 77 mine water samples was analyzed for water quality by Singh et al., (2010) in the mining region of Raniganj. It is being found that the mine water of this Coalfield region is mildly acidic to alkaline. Na-HCO3- and Ca–Mg-SO4 are dominant hydrochemical species and found in high concentrations in Raniganj and Barakar, respectively. The quality assessment shows a Considerably high amount of C, TDS, TH, SO42- , Fe, Mn, and Cr is found after groundwater quality assessment in several mine water samples.

Another extensive study for analyzing the effect of industrial activity on groundwater quality in the Angul district is performed by Reza and Singh, (2010). This region is home to several huge industries like Coal mines of MCL, the Aluminium Plant of NALCO and its CPP, Talcher Super Thermal Power Station and Talcher Thermal Power Station of NTPC, etc. along the river stretches. These industries collect water from the Brahmani River and its tributaries within study areas. Further, they release their effluents in the stream of the Brahmin river. Additionally, the industrial runoffs, untreated domestic sewage from nearby settlements, heavily practiced open defecation along the riverbank, and mine drainage contribute to enhancing the river's pollution. It is pronounced that this deterioration inthe river water quality exerts both direct and indirect adverse effects on the human and ecosystem health depending on this river.

Water samples from overburden dumping in the Coal mining area in the Dhanbad region were collected by Rai et al., (2010) to analyze Grain size distribution, Bulk density, Electrical conductivity, pH, and Organic carbon, Nitrogen, Available phosphorus, and Organic matter like physicochemical characteristics. These parameters in the geoenvironmental are analyzed in the Geoenvironment Division Lab, CIMFR Dhanbad. This study was designed to understand the effect of overburden material on the water quality and its potential for the plantation and revegetation of the overburden. This data was proved helpful during the reclamation of the previously exploited and degraded open cast mines of Raniganj Coalfield in Dhanbad and West Bengal. There is a positive correlation coefficient observed between maximum water holding capacity, Particle density and maximum water holding capacity, particle density and total porosity, particle density and bulk density, bulk density and total porosity and maximum water holding capacity, organic matter and pH, pH and conductivity, organic carbon and pH, total porosity and bulk density, organic matter and electric conductivity, organic carbon and conductivity, and organic carbon and organic matter. The one-way analysis of variance understood the lower significance of spatial variation on the concentration of chemical factors.

Singh et al., (2011) studied the geochemical characteristics of groundwater in the Jharia Coalfield area by collecting twenty mine water samples from different sampling sites. The upper catchment area of this Coalfield was subjected to water quality assessment for the parameters of pH, EC, TDS, Alkalinity, Acidity, major anions (F-, Cl-, SO42-, NO3- and HCO3-), and major cations (Ca2+, Mg2+, Na+, K+). This whole study was undertaken to analyze the potential of the groundwater to be used for domestic purposes by comparing the parameters against ISO: 10500 standards. The ion chemistry, groundwater quality, and hydrogeological processes in Dumka and Jamtara districts are being studied by Singh et al. (2011) through a hydrogeochemical study with thirty representative samples. The samples are analyzed for pH, electrical conductivity, total dissolved solids (TDS), total hardness, anions (F-, Cl-, SO42-, NO3- and HCO3-), and cations (Ca2+, Mg2+, Na+, K+). The results dictate the faintly alkaline nature of water.

A similar study was undertaken by Khan et al., (2012) in the Singrauli area of north India to understand the impact of mining activities on the water quality in the specific sites. They have analyzed the typical Physico-chemical parameters like pH, total dissolved solids (TDS), bicarbonate, hardness, calcium, magnesium, sodium, potassium, chloride, Sulphate, copper, iron, cobalt, manganese, zinc, and chromium in 27 water samples. This specific study aimed to understand the holistic impact of mining and industrial activities on the water quality of the singeauli district. Hence, the sampling location was selected following an extensive preliminary field survey. Survey of India topographic map 63 L/12 on 1:50000 scale and satellite data of IRS P6 LISS III 4th May 2010 was used to prepare the Base map, drainage map, and land use/land cover of the study area. Analysis revealed the presence of a total of 15 different land use patter, among which the significant categories are open forest covers, uncultivated land, cultivated land, dense forest, and other categories, which cover 20.3 %, 20.2 %, 12.6 %, 11.0 % 35.8 % of the area respectively.

Further, the obtained drinking water quality analysis results were compared with World Health Organization standards, and it shows the soft to moderately soft alkaline nature of water. In contrast, the value of total alkalinity and TDS was higher than the desirable limit. Though the contraction of major ions like calcium and magnesium in the water is within permissible limits, the concentration of sulfate and potassium ions and sodium and chloride is higher in some locations. Among the trace ions, the concentration of copper and zinc is within desirable limits, whereas iron, cobalt, and chromium show higher values than the desirable limits, which deteriorates water quality.

The adverse effect of the mining activities on the ground and surface water quality of the Pimpri area was analyzed by Warhate and Wankar, (2012), and a water quality index was developed to understand the impact of water consumption on the human health. The area of Pimpri falls under the influence of WCL Kolera Pimpari open cast Coal mines, so the effect of these mines on the water quality was calculated by considering eight parameters, viz. pH, total hardness, TDS, chloride, nitrite, nitrate, Sulphate, and sodium. Several surfaces and groundwater sampling point was designated as the sampling spots. Water was collected from nalha as a surface water source and three tubewells as a groundwater source from Dec. 2003 to April 2006. Both the nalha and the river in this region directly receive the runoff from the Coal mines and are subjected to detailed study. The water from the river was collected from two different locations to understand a point source's impact. It is revealed that the water quality at Nalha is poor and unfit for human consumption without treatment. In contrast, the water quality in rivers and groundwater is acceptable.

In an interesting statistical approach, Khan et al., (2012) designed a descriptive statistical measure. They applied a partial correlation analysis to groundwater quality data set monitored in pre and post-monsoon for three years to reveal the seasonal variations of water quality in the river Ganga under Central Ganga Plain in India. The variables were divided into two categories as physical and chemical properties. The physical property encompasses the parameters of electrical conductivity (EC), pH, and hardness, whereas the chemical property consists of HCO3, Cl, SO4, Na, K, Ca, and Mg. The obtained chemical and physical properties dictate that the ground water quality varies drastically based on the season. Significant players in controlling the seasonal groundwater quality are ion exchange, dissolution mechanism, and anthropogenic influences such as fertilizer, pesticides, agricultural activities, and effluent discharge from other industrial units. The expert should monitor these parameters meticulously, especially in the post-monsoon season, when there is a chance of increasing the concentration in the groundwater, as was seen during the year 2005. The partial correlation coefficient analysis understood the presence of alkali and sulfate in the groundwater during the post-monsoon season. Statistical analysis also revealed a positive correlation between HCO3 with Cl, SO42-, Na, Ca+, pH, and hardness in the post-monsoon (2005) samples. In contrast, a negative correlation was found among the major variables except HCO 3 with Na, Mg, and hardness during the pre-monsoon (2006) suggested from the partial correlation of groundwater samples.

3.0 Materials and Methods

3.1 About Sohagpur Coalfield (SCF)

Sohagpur Coalfield is located in Shahdol district in the Indian state of Madhya Pradesh in the basin of the Son River. It is the biggest coalfield in the state of Madhya Pradesh. The Sohagpur Coalfield, spanning roughly 3,100 sq. km in Madhya Pradesh's Shahdol district, is a major Gondwana basin containing significant Permian-age coal deposits, particularly within the Barakar Formation. Latitude:23°12'31"N to 23°13'39"N and Longitude: 82°04'48"E to 82°06'23"E It consists of three sub-basins (Rungta-Amlai, Kotma, Bijuri) characterized by high-volatile bituminous coal, with extensive igneous intrusions affecting coal rank. Situated in the Son Valley, it is a Permian-Triassic extensional basin divided into North and South regions by the E-W trending Bahmani-Chilpa fault. The field is subdivided into three main areas: Rungta-Amlai, Kotma, and Bijuri, with variations in petrography and reflectance. Known for thick coal seams in the Barakar formation, the region is heavily explored for both coal and Coal Bed Methane (CBM) potential (Singh et al., 2025; Panwar et al., 2017; Panwar et al., 2019; Panwar et al., 2020; Panwar et al., 2021; Panwar et al., 2022).

Figure 2 Map of Study Area

Sohagpur Coalfield is a part of Central India Coalfields. The latter is spread over the districts of Surguja, Koriya (both in Chhattisgarh), Shahdol and Umaria (both in Madhya Pradesh). There are fourteen coalfields in this group, namely Korar, Umaria, Johilla, Sohagpur, Sonhat, Jhilimili, Chirimiri, Sendurgarh, Koreagarh, Damhamunda, Panchbahini, Hasdeo-Arand, Lakhanpur and Bishrampur. The group covers an area of about 5,345 square kilometres (2,064 sq mi) with estimated reserves of 15,613.98 million tonnes. The deposits are at a depth of 0–1200 meters. Therefore, extraction is mainly amenable to underground mining except a few blocks in eastern part of these coalfields which have opencast potential. Sohagpur Coalfield is spread over an area of about 3,100 square kilometres (1,200 sq mi) and has an estimated reserve of 4,064 million tonnes. There are four coal seams, about 1–4 m in thickness spread across three sub-basins: Burhar-Amlai sub-basin located in the western part of the coalfield, Kotma sub-basin, located on the Anuppur-Chirimiri branch line, 40 miles east of Burhar and the Jhagrakhand-Bijuri sub-basin in the easternmost part of the coalfield. In general the coal is of low rank, high moisture, high volatiles and non-coking type.

Sohagpur Coalfield is divided in two parts by the east-west running Barmni-Chilpa fault. Coal found on the north of this fault is characteristically different from the coal occurring south of the fault. Coking coal has been found in the north of the fault. Sharda Opencast Mine is being expanded from 0.50 million tonnes per annum to 0.85 million tonnes per annum and the mining area from 242.847 ha to 871.205 ha. Highwall mining has been introduced here. Normal open cast methods cannot be used as it is uneconomical to develop the coal seam by such methods in a small, confined area. By using this successful technology for the first time in India, the abandoned Sharda opencast mine has been a landmark in the Indian mining industry. Stratigraphic Sequence The general statigraphic succession of Sohagpur basin as per GSI is given in figure 3.

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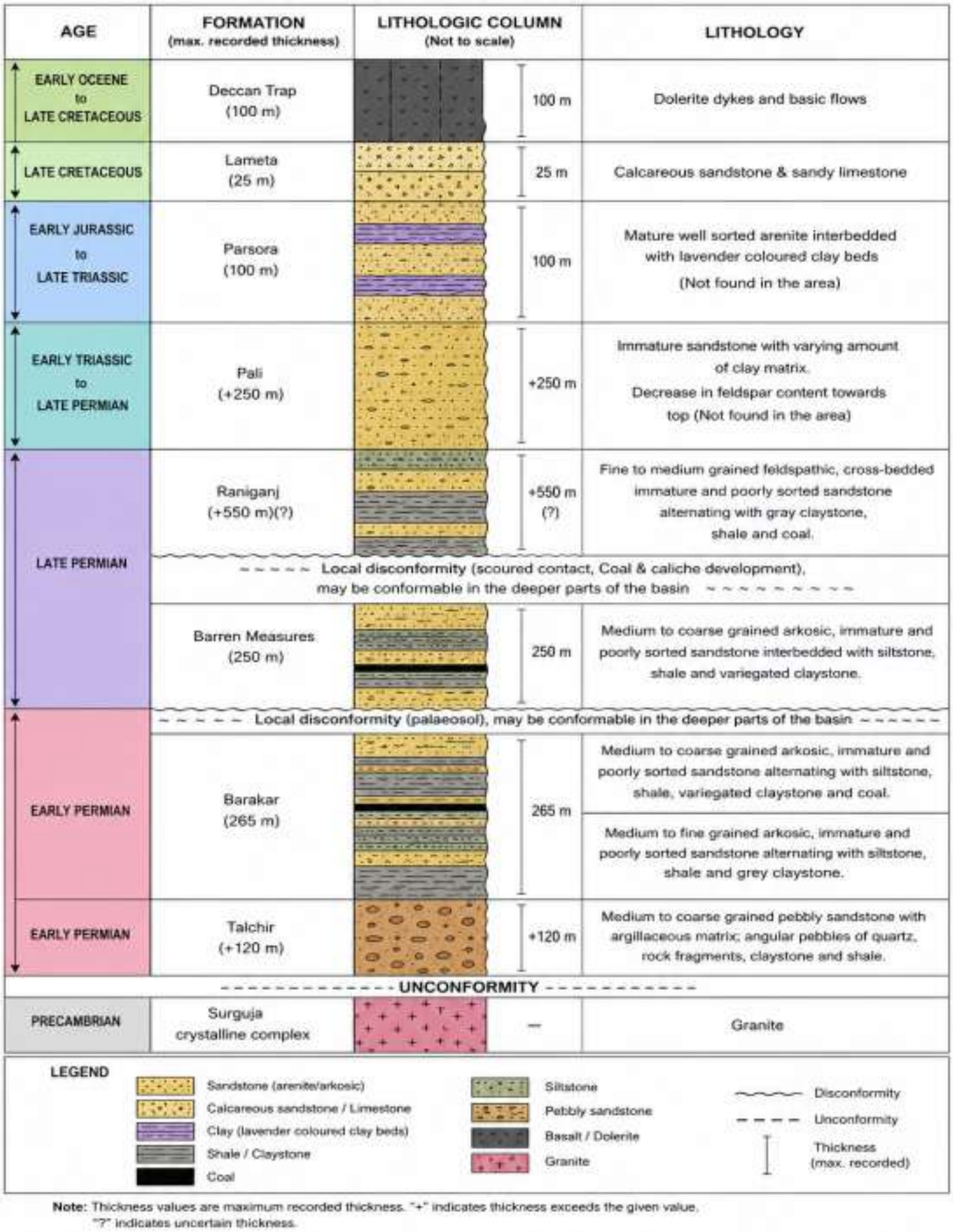

Figure 3 Stratigraphic Column of Sohagpur Coalfield provided by the Indian Ministry of Mines on the National Mineral Exploration Trust

3.2 Method of working

The human health risk assessment (HHRA) was performed to evaluate the potential health risks associated with the consumption of groundwater contaminated by heavy metals in the study area. The assessment was conducted following the methodology recommended by the United States Environmental Protection Agency (USEPA) and focused exclusively on the oral ingestion pathway, which is considered the predominant route of human exposure to groundwater contaminants in mining regions. The study considered the adult population irrespective of gender, assuming long-term consumption of groundwater under normal residential conditions.

The methodology comprised four sequential steps: (i) determination of heavy metal concentrations in groundwater samples, (ii) estimation of the Average Daily Dose (ADD) through groundwater ingestion, (iii) assessment of non-carcinogenic risk using Hazard Quotient (HQ) and Hazard Index (HI), and (iv) estimation of carcinogenic risk (CR) for carcinogenic heavy metals.

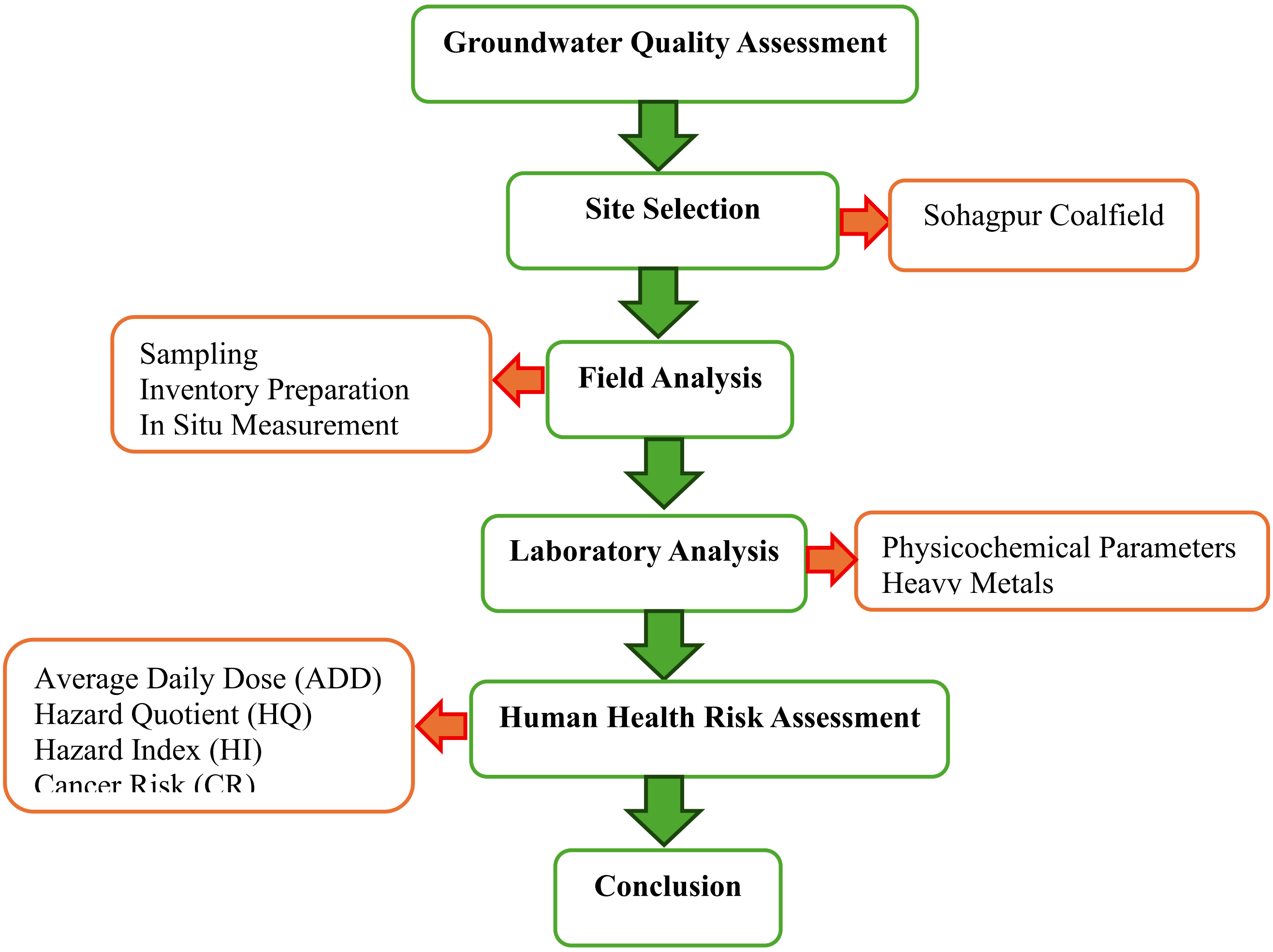

Figure 4 Flowchart showing process for method of working

Initially, groundwater samples were collected from selected locations across the study area following standard sampling protocols. The concentrations of heavy metals were determined using appropriate analytical techniques, and the measured concentrations (C) served as the basis for exposure assessment.

The Average Daily Dose (ADD), representing the daily intake of each heavy metal through drinking water, was calculated using the following equation:

$$\text{ADD} = \frac{C \times IR \times EF \times ED}{BW \times AT}$$

where C is the concentration of the heavy metal in groundwater (mg L^{-1}), IR is the daily ingestion rate (L day^{-1}), EF is the exposure frequency (days $year^{-1}$), ED is the exposure duration (years), BW is the average body weight (kg), and AT is the averaging time (days). Standard exposure parameters recommended by USEPA were adopted to ensure consistency and comparability with previous health risk assessment studies.

The non-carcinogenic health risk associated with each heavy metal was evaluated by calculating the Hazard Quotient (HQ), which compares the estimated daily exposure with the corresponding oral Reference Dose (RfD):

$$HQ = \frac{ADD}{RfD}$$

An HQ value less than one indicates that adverse non-carcinogenic health effects are unlikely, whereas an HQ value greater than one suggests the possibility of chronic health effects due to prolonged exposure.

Since individuals are exposed simultaneously to multiple heavy metals, the cumulative non-carcinogenic risk was estimated using the Hazard Index (HI), calculated as the sum of individual HQ values:

$$HI = \sum HQ$$

The Hazard Index provides an overall estimate of combined toxic effects from multiple contaminants. An HI value below one indicates acceptable health risk, while values exceeding one signify increasing concern regarding potential adverse health impacts.

For heavy metals classified as carcinogenic, the lifetime carcinogenic risk (CR) was estimated using the following equation:

$$CR = ADD \times SF$$

where SF represents the oral cancer slope factor ((mg kg^{-1} day^{-1})$^{-1}$). The calculated carcinogenic risk values were interpreted according to USEPA guidelines, where values less than 10^{-6} represent negligible risk, values between 10^{-6} and 10^{-4} indicate an acceptable or tolerable risk range, and values greater than 10^{-4} indicate an unacceptable lifetime cancer risk.

3.3 Health Risk Assessment Framework

The human health risk assessment (HHRA) was conducted to evaluate the potential adverse health effects associated with the consumption of groundwater contaminated by heavy metals in the study area. The assessment followed the risk assessment methodology recommended by the United States Environmental Protection Agency (USEPA) and focused on the oral ingestion pathway, which represents the primary route of exposure to groundwater contaminants in mining-affected regions. Since groundwater is extensively used for drinking and domestic purposes, prolonged exposure to dissolved toxic metals may result in chronic non-carcinogenic and carcinogenic health effects.

The assessment considered the adult population irrespective of gender, assuming long-term exposure under normal residential conditions. Heavy metals such as Fe, Mn, Pb, Cr, Cd, Ni, As, and other detected trace elements were evaluated based on their measured concentrations in groundwater samples. The health risk assessment comprised three major components: (i) estimation of Average Daily Dose (ADD), (ii) evaluation of non-carcinogenic risk using Hazard Quotient (HQ) and Hazard Index (HI), and (iii) estimation of carcinogenic risk (CR) for metals classified as carcinogenic.

The Average Daily Dose (ADD) through groundwater ingestion was estimated using the following equation:

$$ADD = \frac{C \times IR \times EF \times ED}{BW \times AT}$$

where:

Parameter	Description	Unit
C	Concentration of heavy metal in groundwater	mg L^{-1}
IR	Ingestion rate	L day^{-1}
EF	Exposure frequency	days $year^{-1}$
ED	Exposure duration	years
BW	Body weight	kg
AT	Averaging time	days

The exposure parameters adopted in this study were based on USEPA exposure assumptions for adults.

3.4 Non-Carcinogenic Risk Assessment

The potential non-carcinogenic health effects were evaluated using the Hazard Quotient (HQ), which compares the estimated daily exposure with the corresponding oral reference dose (RfD).

$$HQ = \frac{ADD}{RfD}$$

where: HQ < 1 indicates no significant non-carcinogenic health risk. HQ > 1 indicates potential adverse health effects due to chronic exposure.

Because residents are simultaneously exposed to multiple heavy metals, the cumulative non-carcinogenic risk was assessed using the Hazard Index (HI).

$$HI = \sum HQ$$

The interpretation of HI is as follows:

- HI < 1: Acceptable health risk
- HI = 1–4: Moderate health concern
- HI > 4: High probability of adverse health effects

The HI provides an integrated measure of the combined toxic effects of all detected heavy metals.

3.5 Carcinogenic Risk Assessment

The lifetime carcinogenic risk associated with exposure to carcinogenic metals (e.g., As, Cd, Cr(VI), Ni, and Pb where applicable) was estimated using:

$$CR = ADD \times SF$$

where: SF is the oral cancer slope factor (mg kg^{-1} day^{-1})$^{-1}$.

The total carcinogenic risk (TCR) was obtained by summing the individual carcinogenic risks of all carcinogenic metals.

Risk interpretation was based on USEPA guidelines:

CR Value	Risk Interpretation
$<10^{-6}$	Negligible risk
10^{-6}–10^{-4}	Acceptable/tolerable risk
$>10^{-4}$	Unacceptable carcinogenic risk

4. Result and Discussion

The human health risk assessment revealed that the estimated Average Daily Dose (ADD) varied considerably among the analyzed heavy metals due to differences in their groundwater concentrations. Metals detected at relatively higher concentrations contributed substantially to the overall exposure dose. Although essential trace elements such as iron and manganese exhibited comparatively higher ADD values because of their greater occurrence in groundwater, their toxicological significance depended on their respective reference doses.

The Hazard Quotient (HQ) values demonstrated that most groundwater samples presented HQ values below the acceptable threshold (HQ $<$ 1) for several metals, indicating negligible individual non-carcinogenic health risks. However, elevated HQ values were observed for selected toxic metals in locations influenced by mining activities, suggesting potential health concerns for populations consuming untreated groundwater over prolonged periods.

The cumulative Hazard Index (HI) indicated that multiple heavy metals collectively contributed to the overall health risk. Sampling locations situated close to mining operations, waste dumps, overburden deposits, and coal handling facilities generally exhibited higher HI values than those located farther from mining activities. This finding highlights the importance of considering combined exposure rather than evaluating each contaminant independently.

The carcinogenic risk assessment revealed that carcinogenic metals contributed differently to the lifetime cancer risk. Chromium, arsenic, cadmium, and nickel were identified as the principal contributors wherever their concentrations exceeded recommended guideline values. In several sampling locations, the calculated carcinogenic risk remained within the acceptable USEPA risk range (10^{-6}–10^{-4}), whereas a few locations exceeded the permissible limit, indicating the possibility of long-term cancer risk associated with continuous groundwater consumption.

Overall, the results indicate spatial variability in groundwater quality and corresponding health risks, reflecting the influence of geological formations, mining activities, waste disposal practices, and hydrogeochemical processes operating within the study area.

The human health risk assessment demonstrates that chronic exposure to heavy metal-contaminated groundwater may pose significant health concerns for communities residing in coal mining regions. Mining operations alter natural hydrogeochemical conditions by exposing mineralized strata, generating acid mine drainage, and enhancing the mobilization of trace metals into groundwater systems. Consequently, groundwater quality deteriorates, increasing the likelihood of human exposure through drinking water.

The predominance of elevated Hazard Quotient values for certain metals indicates that these contaminants represent the primary drivers of non-carcinogenic health risk. Although individual HQ values for some metals remained below unity, the cumulative Hazard Index highlights the additive effects of simultaneous exposure to multiple contaminants. Such cumulative exposure is particularly important because chronic ingestion of low concentrations of different metals may produce synergistic or additive toxic effects that are not apparent when individual contaminants are evaluated separately.

The elevated carcinogenic risk observed at several sampling sites suggests that long-term consumption of untreated groundwater may increase the probability of developing cancer over a lifetime. Metals such as arsenic and hexavalent chromium are well-established human carcinogens, while prolonged exposure to cadmium and nickel has also been associated with increased cancer incidence. Therefore, groundwater from locations exhibiting carcinogenic risk values above the acceptable threshold should not be considered suitable for direct human consumption without appropriate treatment.

Spatial variations in health risk indicate that groundwater quality is strongly influenced by proximity to mining infrastructure, waste rock dumps, coal stockyards, abandoned mine workings, and natural lithological characteristics. Hydrogeochemical processes including mineral dissolution, oxidation of sulfide minerals, adsorption-desorption reactions, and groundwater flow dynamics further control the mobility and bioavailability of heavy metals.

The findings underscore the need for continuous groundwater quality monitoring, periodic human health risk assessments, and the implementation of effective mitigation measures in mining regions. Appropriate interventions may include installation of community water treatment systems, protection of groundwater recharge zones, scientific management of mine waste, regular environmental surveillance, and public awareness programs regarding safe drinking water practices. Such integrated management strategies are essential for reducing long-term human health risks while ensuring sustainable groundwater resource management in coal mining areas.

5. Conclusion

The human health risk assessment conducted in this study provides a comprehensive evaluation of the potential health risks associated with the consumption of heavy metal-contaminated groundwater in the study area. By applying the USEPA risk assessment framework, the study quantified both non-carcinogenic and carcinogenic risks through the estimation of Average Daily Dose (ADD), Hazard Quotient (HQ), Hazard Index (HI), and Carcinogenic Risk (CR). These indicators collectively provide a reliable basis for understanding the potential impacts of long-term groundwater consumption on human health.

The results indicate that the health risks vary spatially depending on the concentration and distribution of heavy metals in groundwater. While several sampling locations exhibited HQ and HI values within acceptable limits, elevated risk values at certain locations suggest that prolonged consumption of untreated groundwater may pose significant non-carcinogenic health concerns. The cumulative Hazard Index further demonstrates that simultaneous exposure to multiple heavy metals can increase the overall toxic burden, emphasizing the importance of evaluating combined rather than individual contaminant effects.

The carcinogenic risk assessment revealed that carcinogenic metals such as arsenic, chromium, cadmium, and nickel may contribute to an increased lifetime cancer risk where their concentrations exceed recommended guideline values. These findings underscore the need for continuous monitoring of groundwater quality, particularly in mining-influenced areas where geogenic processes and anthropogenic activities enhance the mobilization of toxic metals into aquifers.

Overall, the study highlights the importance of integrating groundwater quality monitoring with human health risk assessment to support evidence-based environmental management and public health protection. Regular surveillance of groundwater resources, implementation of appropriate water treatment technologies, scientific management of mining wastes, and strict enforcement of environmental regulations are essential to minimize human exposure to hazardous contaminants. In addition, community awareness programs promoting the use of safe drinking water and periodic health screening of residents in mining regions should be encouraged. Such integrated measures will contribute to sustainable groundwater resource management and reduce the long-term health risks associated with heavy metal contamination in mining-affected environments.

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