Geochemical And Hydrological Assessment Of Water Quality In Copper Mine Of Khetri Nagar Rajasthan

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Abstract

This study presents a comprehensive geochemical and hydrological assessment of water quality in the Khetri Nagar copper mining region, focusing on the contamination levels and their implications for human health and the environment. Analysis revealed elevated concentrations of heavy metals, including copper (up to 2.5 mg/L), lead (up to 0.15 mg/L), and arsenic (up to 0.05 mg/L), exceeding safety limits established by the World Health Organization (WHO) and Bureau of Indian Standards (BIS). Hydrological parameters, including pH, electrical conductivity (EC), and total dissolved solids (TDS), indicated significant contamination effects. The study highlights severe health risks, such as gastrointestinal issues and neurological disorders, especially for vulnerable populations. Environmental impacts include potential toxicity to aquatic life, soil degradation, and adverse effects on groundwater recharge. Recommendations include the implementation of advanced water treatment technologies, improved waste management practices, and regular monitoring. Public health interventions and stricter regulatory enforcement are essential to address the contamination issues. Future research directions include longitudinal studies, impact assessments of mine waste on ecosystems, exploration of alternative treatment methods, and socioeconomic impact evaluations. This research underscores the urgent need for comprehensive measures to mitigate contamination and safeguard both environmental and public health in the Khetri Nagar region.

Keywords: Khetri Nagar, water quality, heavy metals, copper mining, contamination, environmental impact, public health, water treatment, geochemical assessment, hydrological analysis

1. Introduction

Overview of Khetri Nagar Copper Mines

Khetri Nagar, located in the Jhunjhunu district of Rajasthan, India, is renowned for its rich copper mineralization, making it one of the primary copper mining regions in the country. The copper deposits in Khetri are predominantly found in the form of chalcopyrite, which is the most common copper ore mineral. The mining activities in this region date back to the early 20th century, with significant development taking place in the 1960s and 1970s (Agarwal, 1974). The Khetri Copper Complex, operated by Hindustan Copper

Limited, comprises a fully integrated facility, including mining, beneficiation, smelting, and refining operations.

Importance of Water Quality Assessment

Mining activities, particularly those related to metal extraction, can significantly impact the surrounding environment, especially water resources. The release of heavy metals and other pollutants from mining operations can lead to the contamination of surface and groundwater, posing serious risks to human health and the environment. In the context of Khetri Nagar, it is crucial to monitor water quality to assess the extent of contamination and its potential impact. The area is characterized by a semi-arid climate with limited rainfall, making water a critical resource for local communities and agriculture (Sharma & Singh, 2010).

Objectives of the Study

This study aims to conduct a comprehensive geochemical and hydrological assessment of water quality in and around the Khetri Nagar copper mines. The specific objectives are to:

1. Analyse the concentration of major ions and trace elements in surface and groundwater samples.
2. Assess the hydrological characteristics, including pH, temperature, and flow rates.
3. Compare the observed concentrations with established water quality standards to evaluate potential health risks.
4. Investigate the spatial distribution and temporal trends in water quality parameters.

In previous studies, copper concentrations in water sources near mining areas were found to exceed 0.5 mg/L, significantly above the World Health Organization's (WHO) recommended limit of 0.05 mg/L for drinking water (WHO, 2011). Additionally, elevated levels of other heavy metals, such as lead and arsenic, have been detected, raising concerns about their long-term impacts on public health and agriculture (Reddy & Subbaiah, 2009). This study seeks to provide an updated and detailed assessment to inform local authorities and stakeholders about the current state of water quality in the region.

2. Study Area and Background

Geological and Hydrological Characteristics

Khetri Nagar, situated in the northeastern part of Rajasthan, lies within the Aravalli Mountain Range, known for its rich mineral deposits. The geology of the region is characterized by Proterozoic metasedimentary rocks, primarily consisting of quartzites, schists, and phyllites, with significant occurrences of copper sulphide minerals, particularly chalcopyrite (Banerjee, 1980). The area also features several geological structures, including folds, faults, and shear zones, which have facilitated the formation and localization of mineral deposits (Gupta & Iyengar, 1998).

The hydrogeology of Khetri Nagar is dominated by both surface and groundwater systems. The primary sources of surface water are seasonal streams and small reservoirs, while groundwater occurs in fractured rock aquifers. The region experiences a semi-arid climate, with an average annual rainfall of approximately 500 mm, predominantly occurring during the monsoon season (June to September) (Jain, 2005). Groundwater levels fluctuate significantly with the seasons, with deeper water tables typically observed during the pre-monsoon period.

Mining Activities and Their Environmental Impact

The Khetri Copper Complex, operated by Hindustan Copper Limited, is a major industrial establishment in the region, encompassing mining, beneficiation, smelting, and refining processes. The mining activities involve both open-pit and underground methods, with an annual production capacity of around 31,000 metric tons of copper (HCL Annual Report, 2010). The mining and associated metallurgical processes generate substantial quantities of waste materials, including tailings and slag, which are stored in tailing ponds and slag dumps, respectively.

The environmental impact of these activities is profound, particularly concerning the potential contamination of water resources. Acid mine drainage (AMD) is a significant issue, resulting from the oxidation of sulphide minerals exposed to air and water, leading to the formation of sulfuric acid. This process can mobilize heavy metals, such as copper, lead, zinc, and arsenic, from the ore and surrounding rocks into the water bodies (Rao, 1996). Previous studies have reported elevated concentrations of these metals in both surface and groundwater around Khetri Nagar, often exceeding permissible limits set by regulatory authorities (CPCB, 2008). For instance, copper concentrations in groundwater samples have been recorded as high as 2.5 mg/L, far above the Bureau of Indian Standards (BIS) acceptable limit of 0.05 mg/L for drinking water (BIS, 2012).

Climatic Conditions and Seasonal Variability

Khetri Nagar experiences a semi-arid climate characterized by hot summers and mild winters. The temperature varies from an average of 40°C in summer to around 10°C in winter (IMD, 2010). The region's rainfall is highly seasonal, with the majority occurring during the monsoon months. This seasonal variation plays a critical role in influencing the hydrological cycle, including groundwater recharge, surface runoff, and the concentration of pollutants in water bodies.

The monsoon season can lead to the leaching of contaminants from mine waste into water sources, exacerbating the pollution levels. Conversely, the dry season often results in reduced dilution of contaminants, potentially increasing the concentration of harmful substances in both surface and groundwater (Sharma & Khan, 2004). These seasonal dynamics underscore the importance of continuous monitoring to accurately assess the water quality and the associated environmental and health risks.

3. Methodology

Sample Collection and Preparation

To conduct a comprehensive assessment of water quality in the Khetri Nagar region, water samples were collected from multiple sources, including surface water bodies (such as streams and reservoirs) and groundwater (such as wells and boreholes). The sampling sites were strategically selected to cover areas both proximal and distal to the mining activities, ensuring a thorough spatial representation (Patra & Das, 2011). A total of 30 samples were collected during the pre-monsoon season of 2012 to capture the conditions when water tables are typically at their lowest, which can concentrate contaminants.

Surface water samples were collected using clean, pre-rinsed polyethylene bottles, submerged at a depth of approximately 30 cm below the water surface. Groundwater samples were obtained using submersible pumps, ensuring that stagnant water was flushed out before sample collection. All samples were immediately preserved by acidification with nitric acid to a pH of less than 2, as recommended by the American Public Health Association (APHA, 2005). The samples were then transported to the laboratory in an ice-cooled container and stored at 4°C until analysis.

Analytical Techniques

The collected water samples underwent a series of geochemical and hydrological analyses to determine the concentration of major ions, trace elements, and other relevant parameters. Major ions such as calcium (Ca^{2+}), magnesium (Mg^{2+}), sodium (Na^{+}), and potassium (K^{+}) were analysed using flame atomic absorption spectrophotometry (FAAS) (Manahan, 1994). Trace elements, including copper (Cu), lead (Pb), arsenic (As), and zinc (Zn), were quantified using inductively coupled plasma mass spectrometry (ICP-MS), which provides high sensitivity and accuracy (Skoog & Leary, 1992).

Hydrological parameters, including pH, electrical conductivity (EC), and total dissolved solids (TDS), were measured in situ using portable water quality meters. The pH values of the water samples ranged from 6.5 to 8.3, with an average of 7.4, indicating neutral to slightly alkaline conditions. The EC values varied between 500 to 2500 µS/cm, reflecting the presence of dissolved ionic species. TDS concentrations were found to be in the range of 300 to 1600 mg/L, suggesting moderate to high levels of dissolved solids (Trivedi & Goel, 1984).

Quality Control and Assurance

To ensure the reliability and accuracy of the analytical results, a rigorous quality control and assurance protocol was followed. This included the use of standard reference materials, procedural blanks, and duplicate samples. The accuracy of the analytical methods was verified by analysing certified reference materials, and the results were within 5% of the certified values. Procedural blanks were used to check for any contamination during sample processing, and duplicate samples were analysed to assess the precision of the measurements, with relative standard deviations generally below 10% (EPA, 1994).

The data obtained from the analyses were subjected to statistical evaluation to determine the mean, median, and standard deviation for each parameter. This statistical treatment provided a comprehensive understanding of the water quality in the study area, highlighting both spatial and temporal variations. The analytical procedures and quality control measures ensured that the data were robust and reliable, forming a solid foundation for subsequent interpretation and discussion.

4. Results and Discussion

Geochemical Characteristics of Water

The geochemical analysis of water samples from the Khetri Nagar region reveals a diverse composition of major ions and trace elements, influenced significantly by mining activities. Table 1 presents the concentrations of selected major ions and trace elements detected in surface and groundwater samples. The concentration of copper (Cu) ranged from 0.1 mg/L to 2.5 mg/L, with an average of 1.2 mg/L, exceeding the World Health Organization's (WHO) recommended limit of 0.05 mg/L for drinking water in several instances (WHO, 2011). Lead (Pb) levels were also concerning, with values ranging from 0.01 mg/L to 0.15 mg/L, surpassing the permissible limit of 0.01 mg/L set by the Bureau of Indian Standards (BIS) (BIS, 2012).

Table 1: Concentrations of Major Ions and Trace Elements in Water Samples from Khetri Nagar (2012).

Parameter	**WHO Limit**	**BIS Limit**	**Min Value**	**Max Value**	**Mean Value**	**Standard Deviation**
Copper (Cu)	0.05 mg/L	0.05 mg/L	0.1 mg/L	2.5 mg/L	1.2 mg/L	0.7 mg/L
Lead (Pb)	0.01 mg/L	0.01 mg/L	0.01 mg/L	0.15 mg/L	0.08 mg/L	0.04 mg/L
Arsenic (As)	0.01 mg/L	0.01 mg/L	0.002 mg/L	0.05 mg/L	0.02 mg/L	0.01 mg/L
Zinc (Zn)	3 mg/L	5 mg/L	0.1 mg/L	1.8 mg/L	0.9 mg/L	0.5 mg/L

Arsenic (As) concentrations varied from 0.002 mg/L to 0.05 mg/L, with a mean value of 0.02 mg/L, indicating potential health risks. Although zinc (Zn) levels were generally within acceptable limits, the presence of other toxic elements warrants careful monitoring and remediation efforts. The observed concentrations of these contaminants suggest a substantial input from mining waste, particularly through acid mine drainage (AMD), which can leach metals from the surrounding rock into the water bodies (Reddy & Subbaiah, 2009).

Hydrological Characteristics

The hydrological analysis revealed that the pH values of water samples ranged from 6.5 to 8.3, with a mean of 7.4, indicating neutral to slightly alkaline conditions. This pH range is typical of environments impacted by AMD, where the neutralization of acid by carbonate minerals can result in variable pH levels (Rao, 1996). The electrical conductivity (EC) values ranged from 500 to 2500 µS/cm, with an average of 1200 µS/cm, reflecting moderate to high levels of dissolved ions. The total dissolved solids (TDS) concentrations varied between 300 mg/L and 1600 mg/L, with an average of 850 mg/L, suggesting significant ionic content due to mineral dissolution.

The seasonal variability in these parameters was notable, with higher EC and TDS values recorded during the pre-monsoon season. This is likely due to the concentration of dissolved constituents because of lower water levels and reduced dilution capacity (Sharma & Khan, 2004). Additionally, the flow rates of surface water bodies varied considerably, with reduced flow during the dry season, further concentrating contaminants.

Spatial Distribution and Temporal Trends

The spatial analysis indicated that water samples collected closer to the mining operations exhibited significantly higher concentrations of heavy metals and other contaminants compared to those from more distant locations. For instance, copper levels were notably higher in samples collected within a 5 km radius of the mining site, highlighting the localized impact of mining activities (Banerjee, 1980). The spatial distribution pattern underscores the importance of monitoring and managing the areas immediately surrounding the mining complex to mitigate environmental and public health risks.

Temporal trends were assessed by comparing current data with historical records, revealing a gradual increase in contamination levels over the past two decades. This trend aligns with the expansion of mining operations and increased production activities (HCL Annual Report, 2010). The continuous monitoring of water quality is crucial to track these changes and implement timely interventions.

Discussion

The findings from the geochemical and hydrological analyses highlight the significant impact of copper mining on water quality in the Khetri Nagar region. The elevated levels of heavy metals, particularly copper, lead, and arsenic, pose potential health risks to local communities, especially those relying on groundwater for drinking and agricultural purposes. The presence of these contaminants, even at trace levels, can have long-term effects on human health and the environment, necessitating the implementation of stringent monitoring and remediation measures (Patra & Das, 2011).

The variability in hydrological characteristics, such as pH, EC, and TDS, underscores the dynamic nature of the water systems in the area, influenced by both natural processes and anthropogenic activities. The observed spatial and temporal trends provide valuable insights into the extent and evolution of water contamination, guiding future research and management strategies.

In conclusion, the study emphasizes the need for a comprehensive and ongoing assessment of water quality in mining-affected regions like Khetri Nagar. The integration of geochemical and hydrological data, along with regular monitoring, can provide a robust framework for mitigating the environmental impacts of mining and safeguarding public health.

5. Impact Assessment

5.1. Human Health Risk Assessment

The elevated concentrations of heavy metals detected in water samples from Khetri Nagar present significant health risks to local populations. The primary concerns involve copper, lead, and arsenic, which can have adverse effects on human health when present at elevated levels.

Copper: Prolonged exposure to high levels of copper can cause gastrointestinal distress, liver damage, and kidney damage (ATSDR, 2004). The concentrations observed in this study, reaching up to 2.5 mg/L, exceed the World Health Organization's (WHO) guideline value of 0.05 mg/L for drinking water (WHO, 2011). Continuous exposure to such levels could lead to chronic health issues, particularly in populations with pre-existing health conditions or those consuming large quantities of contaminated water.

Lead: Lead is a potent neurotoxin, especially harmful to children and pregnant women. Chronic exposure can result in developmental delays, cognitive deficits, and behavioural problems in children (CDC, 2012). The detected lead concentrations, which can reach up to 0.15 mg/L, are above the Bureau of Indian Standards (BIS) limit of 0.01 mg/L (BIS, 2012). Such levels in drinking water pose a severe risk to public health and necessitate immediate remedial measures.

Arsenic: Arsenic is associated with various health issues, including skin lesions, cancer, and cardiovascular diseases (NRC, 1999). The arsenic levels observed, up to 0.05 mg/L, approach the WHO guideline of 0.01 mg/L for drinking water (WHO, 2011). Long-term exposure to arsenic, even at lower concentrations, can lead to severe health complications and underscores the need for stringent water quality management.

5.2. Environmental Implications

The environmental impacts of the contamination detected in the Khetri Nagar water sources are significant and multifaceted. The presence of heavy metals can adversely affect local ecosystems, including aquatic life and soil quality.

Aquatic Life: Elevated levels of copper, lead, and arsenic can be toxic to aquatic organisms, affecting their growth, reproduction, and survival rates. Studies have shown that high concentrations of copper can cause gill damage and impaired respiration in fish, while lead can lead to reduced reproductive success and behavioural changes (Barton et al., 1997). The contamination of surface water sources can thus disrupt aquatic ecosystems and diminish biodiversity.

Soil Quality: Heavy metals can also impact soil health by altering its physical and chemical properties. Contaminants from mining activities can accumulate in the soil, affecting its fertility and plant growth. For instance, copper and lead can inhibit the uptake of essential nutrients by plants, leading to reduced agricultural productivity (Alloway, 1995). The potential accumulation of these metals in the soil can also pose risks to food security and agricultural sustainability in the region.

Groundwater Recharge: The contamination of groundwater by heavy metals can affect its quality and availability for agricultural and domestic use. High concentrations of dissolved metals can render groundwater unsafe for consumption and irrigation, impacting local livelihoods and exacerbating water scarcity issues (Sharma & Singh, 2010).

5.3. Recommendations for Mitigation and Monitoring

Based on the findings of this study, several recommendations can be made to address the identified environmental and health risks:

1. **Enhanced Monitoring**: Regular monitoring of water quality should be implemented to track changes in contaminant levels and assess the effectiveness of remediation efforts. This should include both surface and groundwater sources, with a focus on areas with high contamination levels.
2. **Water Treatment**: Implementing effective water treatment solutions, such as advanced filtration systems and chemical treatments, can help reduce the concentrations of heavy metals in drinking water. Techniques such as reverse osmosis and activated carbon filtration have been shown to be effective in removing contaminants (Madhavan et al., 2010).
3. **Pollution Control Measures**: To mitigate the impact of mining activities, pollution control measures should be enforced. This includes proper management of mine waste, the use of tailing ponds with adequate lining to prevent leaching, and the treatment of mine drainage before discharge (Reddy & Subbaiah, 2009).
4. **Public Awareness and Health Interventions**: Educating the local population about the risks associated with contaminated water and providing access to alternative safe water sources can help reduce health risks. Health interventions, including regular health screenings and treatment for affected individuals, are essential to address the impacts of contamination.
5. **Regulatory Framework**: Strengthening regulatory frameworks and enforcement mechanisms to ensure compliance with water quality standards and environmental regulations is crucial. This includes regular inspections and penalties for non-compliance to promote better environmental practices in mining operations.

By implementing these recommendations, it is possible to mitigate the adverse effects of mining-related contamination on both human health and the environment, contributing to a more sustainable and healthier future for the Khetri Nagar region.

6. Numerical Analysis and Statistical Data

Descriptive Statistics

To provide a comprehensive understanding of the water quality in the Khetri Nagar region, descriptive statistics were calculated for key parameters including copper, lead, arsenic, zinc, pH, electrical conductivity (EC), and total dissolved solids (TDS). The data was analysed to determine the central tendencies and dispersion of these parameters across different sampling locations.

Table 2 Table 2: Descriptive Statistics for Water Quality Parameters (2012).

Parameter	**Min Value**	**Max Value**	**Mean Value**	**Median Value**	**Standard Deviation**
Copper (Cu)	0.1 mg/L	2.5 mg/L	1.2 mg/L	1.0 mg/L	0.7 mg/L
Lead (Pb)	0.01 mg/L	0.15 mg/L	0.08 mg/L	0.07 mg/L	0.04 mg/L
Arsenic (As)	0.002 mg/L	0.05 mg/L	0.02 mg/L	0.02 mg/L	0.01 mg/L
Zinc (Zn)	0.1 mg/L	1.8 mg/L	0.9 mg/L	0.8 mg/L	0.5 mg/L
pH	6.5	8.3	7.4	7.3	0.5
Electrical Conductivity (EC)	500 µS/cm	2500 µS/cm	1200 µS/cm	1100 µS/cm	500 µS/cm
Total Dissolved Solids (TDS)	300 mg/L	1600 mg/L	850 mg/L	800 mg/L	450 mg/L

The mean values of copper and lead are notably high compared to their respective safety limits, indicating significant contamination. The standard deviation for copper and lead is also high, reflecting considerable variability in contamination levels across sampling sites.

Correlation and Regression Analysis

To explore the relationships between different water quality parameters, correlation and regression analyses were conducted.

Table 3: Pearson Correlation Coefficients for Water Quality Parameters.

Parameter Pair	Correlation Coefficient (r)
Copper and Lead	0.65
Copper and Arsenic	0.55
Lead and Arsenic	0.60
EC and TDS	0.85
pH and TDS	-0.40

The positive correlation between copper and lead ($r = 0.65$) suggests that sites with higher copper concentrations tend to also have elevated lead levels. Similarly, copper and arsenic show a moderate positive correlation ($r = 0.55$), indicating a potential link between these contaminants. The strong correlation between electrical conductivity (EC) and total dissolved solids (TDS) ($r = 0.85$) confirms that higher EC values are associated with increased TDS concentrations, which is expected due to the high ionic content in contaminated water.

Multiple regression analysis was performed to determine the influence of key parameters on copper concentration. The regression model is given by:

$$Copper=\beta0+\beta1(Lead)+\beta2(Arsenic)+\beta3(EC)+\epsilon$$

where $\beta0$ is the intercept, $\beta1$, $\beta2$, and $\beta3$ are the coefficients for lead, arsenic, and EC respectively, and ϵ is the error term.

Table 4: Multiple Regression Analysis for Copper Concentration.

Predictor	Coefficient (β)	Standard Error	t-Value	p-Value
Intercept (β_0)	0.10	0.05	2.00	0.05
Lead (β_1)	0.40	0.10	4.00	<0.01
Arsenic (β_2)	0.30	0.12	2.50	0.02
Electrical Conductivity (β_3)	0.02	0.01	2.00	0.05

The regression analysis indicates that lead and arsenic are significant predictors of copper concentration, with p-values less than 0.05. Electrical conductivity also shows a significant but weaker relationship with copper levels.

Trend Analysis

To evaluate temporal trends in water quality, historical data from previous studies were compared with current findings. The analysis revealed a gradual increase in copper and lead concentrations over the past two decades. For instance, copper levels have risen from an average of 0.8 mg/L in 1990 to 1.2 mg/L in 2012, and lead levels have increased from 0.05 mg/L to 0.08 mg/L during the same period (HCL Annual Report, 2010). This upward trend underscores the need for continuous monitoring and effective management practices to address growing contamination concerns.

In summary, the numerical analysis and statistical data provide a detailed understanding of the current water quality in Khetri Nagar, highlighting significant contamination levels and their implications. The correlations and regression analyses offer insights into the relationships between different water quality parameters, while the trend analysis underscores the importance of ongoing monitoring to manage and mitigate environmental and health risks.

7. Recommendations and Future Research

Recommendations

To mitigate the adverse effects identified in this study, several recommendations have been proposed:

1. **Implementation of advanced water treatment technologies** to reduce contaminant levels.
2. **Enhanced waste management practices** to prevent further contamination.
3. **Regular monitoring and surveillance** to track changes in water quality and assess remediation efforts.
4. **Public health interventions** to address health risks and educate local communities.
5. **Strengthening regulatory frameworks** and enforcing environmental standards.
6. **Promotion of sustainable mining practices** to minimize environmental impact.

These measures are crucial for improving water quality and ensuring the health and safety of the local population.

Future Research Directions

Future research should focus on:

1. **Longitudinal studies** to monitor changes in water quality and health outcomes over time.
2. **Impact assessment of mine waste** on ecosystems and soil health.
3. **Exploration of alternative water treatment methods** for more efficient and cost-effective solutions.
4. **Socioeconomic impact assessments** to understand the broader consequences of water contamination.
5. **Evaluation of remediation strategies** to identify effective approaches for reducing contamination and promoting environmental recovery.

8. Conclusion

The study on the geochemical and hydrological assessment of water quality in the Khetri Nagar copper mine region has provided a comprehensive overview of the current state of water resources in the area. The findings highlight significant concerns regarding contamination levels and their potential impacts on human health and the environment.

The geochemical analysis revealed elevated concentrations of heavy metals such as copper, lead, and arsenic, with copper levels reaching up to 2.5 mg/L, lead up to 0.15 mg/L, and arsenic up to 0.05 mg/L. These levels exceed both the World Health Organization (WHO) and Bureau of Indian Standards (BIS) guidelines for safe drinking water (WHO, 2011; BIS, 2012). The presence of these contaminants poses serious health risks, including gastrointestinal issues, neurological disorders, and carcinogenic effects.

Hydrological characteristics of the water in the region indicate variations in pH, electrical conductivity (EC), and total dissolved solids (TDS). The pH ranged from 6.5 to 8.3, suggesting neutral to slightly alkaline conditions, while EC and TDS values were relatively high, reflecting significant ionic content due to mining activities. These hydrological parameters underscore the influence of mining operations on water quality, with implications for both drinking water safety and environmental health.

The impact assessment demonstrated that elevated levels of heavy metals have considerable consequences for human health, particularly for vulnerable populations such as children and pregnant women. The environmental implications are also profound, affecting aquatic life, soil quality, and groundwater recharge. The findings highlight the urgent need for effective intervention measures to address contamination and protect public health.

The geochemical and hydrological assessment of water quality in the Khetri Nagar region underscores the need for comprehensive and sustained efforts to address the challenges posed by mining-related contamination. By implementing recommended interventions and pursuing further research, it is possible to mitigate health and environmental risks, improve water quality, and promote a more sustainable and resilient environment. The study serves as a critical step towards understanding and managing the impacts of mining on water resources, providing valuable insights for policymakers, researchers, and community stakeholders.

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