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Research Article

SUSTAINABLE AND ADVANCED INTEGRATED APPROACH TO MITIGATE GROUNDWATER POLLUTION IN MINING AND MINERAL-PRODUCING REGIONS

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Abstract
The pollution of groundwater in producing mineral areas is one of the most important environmental issues because the activities of mineral production can affect the natural hydrogeology and geochemistry of mineral production areas. Heavy metals, metalloids, sulphates, acidity, dissolved solids and suspended matter can be introduced to aquifers through heavy metal, metalloid, sulphates, acidity, dissolved solids and suspended pollutant contamination that occurs during excavation, tailings disposal, overburden dumping, ore processing, mine-water discharge and weathering of waste rock. This article reviews the significant sources, processes, pathways, impacts, monitoring methods and remediation options for groundwater pollution in the mining industry. Acid mine drainage, tailing seepage, contaminant leaching, fracture-controlled migration, interaction with surface water, and legacy pollution are discussed as important mechanisms of groundwater degradation. It also addresses environmental, agricultural and human health concerns stemming from contaminated groundwater, including through drinking water, irrigation, soil incorporation, crop uptake, livestock exposure and food-chain transfer. An integrated approach of source prevention, monitoring during the season, hydrochemical studies, calculation of pollution indices, GIS mapping, evaluation of health risks and application of treatment at the site is needed to achieve effective control. Remedial measures discussed include: neutralization, chemical precipitation, adsorption, pump-and-treat systems, constructed wetlands, bioremediation, sulfate reducing bacteria, permeable reactive barriers, limestone-based passive systems, and managed aquifer restoration. Preventive mine planning, appropriate remediation, and regulatory enforcement, community awareness, and post-closure surveillance are all vital to sustainable groundwater protection.

Keywords: Groundwater pollution; Mineral production zone; Acid mine drainage; Heavy metals; Remediation

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1. Introduction

In mineral production areas, groundwater is an important source of freshwater supplies for domestic, industrial and livestock uses, irrigation, and drinking-water supplies. The zones are susceptible to contamination due to the disturbance of the natural hydrogeological and geochemical balance in the subsurface environment caused by excavation, ore beneficiation, discharge of mine water, tailing storage and waste rock dumping, as well as dewatering. Groundwater pollution is slow, hidden, variable in space and once contaminants enter groundwater, they are difficult to remove from the water. Thus, groundwater pollution control necessitates remedial actions that involve source identification, monitoring, risk assessment, treatment selection and management of the water from the mines.

There are several potential source areas and pathways for contaminants to migrate from mining operations. Acidic drainage, sulfate, dissolved metals, suspended solids and other contaminants are potential sources of pollution for soil and water systems from mine pits, tailing impoundments, waste-rock piles, ore-processing residues, settling ponds, and abandoned mine structures. The contaminants can be introduced into the aquifer through seepage, infiltration, recharge zones, fractured rocks and through pore water movement. The problem worsens with changes in drainage to mine or exposure of mineralized rocks to oxygen and water, lowering groundwater levels by dewatering and creating artificial flow paths through fractured strata. Groundwater pollution from mineral production is a response to the interplay of geology, mining approach, groundwater flow, contaminant chemistry and waste management practices.

Acid mine water is a continuous type of pollution from mining activities. Can be formed by the reaction of sulfide-containing minerals with air and water to form acidic drainage with high concentrations of sulfate, Fe, Mn and toxic metals. This drainage can leach metals from the mine waste and host rocks, making them more mobile and thus leading to poorer quality groundwater. It is highlighted that the prevention, treatment, reuse and resource recovery of acid mine drainage need to be emphasized, rather than disposal-oriented management (Chen et al., 2021). Comparing the different remediation strategies revealed that more recent ones involve the use of a mix between chemical and biological, passive and advanced treatment systems (Daraz et al., 2023). In the case of treatment technologies, It was pointed out that the type of contaminants, sludge production, long-term performance, complexity, and cost of the technology must be considered when choosing (Ighalo et al., 2022).

Another problem with groundwater contaminated from mineral production is the presence of heavy metals. Mines and tailing ponds can release metals and metalloids that, depending on the type, can remain in the groundwater system and affect its suitability for the following purposes: drinking, irrigation, livestock, and ecological functions. Groundwater-dependent communities can have chronic exposure to toxic elements like iron, manganese, lead, cadmium, chromium, arsenic, copper, zinc and others. This have highlighted that the assessment of shallow groundwater affected by mining should be done using distribution analysis, source identification, and probabilistic human-health risk assessment, in addition to concentration based (Jiang et al., 2021).

Good remediation is dependent upon monitoring and evidence-based assessment. There is a need for water-quality analysis, pollution indices, spatial mapping, and risk assessment to determine hotspots, rank polluted sites, select treatment options and to measure remediation performance. Measurable indicators like water-quality and pollution indices can be important in remediation planning, as demonstrated by the ranking of sequential passive treatment systems for acid mine drainage (Pocaan et al., 2026). These methods are crucial because the effectiveness of treatment depends on the acidity, the concentration of the metals, flow rate, residence time, type of metal, type of reactive material and hydrogeological conditions.

Recent research indicates that a combination of preventive, active, passive, biological, and in-situ approaches to remediation are needed. Preventive measures are the management of tailings, containment of wastes, controlled drainage, collection of leachate, and prevention of oxidation of sulfides. However, when contaminated water exists, active treatment methods like neutralization, chemical precipitation, adsorption, ion exchange, membrane filtration, and pump-and-treat systems can be used, but may be energy-intensive, use chemicals, and involve sludge disposal. Passive treatment systems such as limestone drains, constructed wetlands, settling ponds, and permeable reactive systems can be helpful for longer-term management, particularly in abandoned mining operations, or in low flow areas (Rambabu et al., 2020). Microbes involved in sulfate reduction, metal immobilization and contaminant transformation. It is necessary to consider the efficiency of treatment, cost, environmental impacts, and long-term applicability when designing sustainable acid mining drainage (AMD) control (Rezaie & Anderson, 2020). The need to assess remediation solutions within a structured framework, as opposed to through the selection of a specific technology (Thisani et al., 2021).

In-situ, permeable reactive barriers are significant tools for capturing contaminated groundwater plumes and rendering the metals, acidity or immobilizing the pollutants so that they can not migrate. Machine-learning simulation and optimization of several permeable reactive barriers (PRBs) for acid mine drainage (AMD) treatment, highlighting the importance of modelling and site-specific design (L. Zhou et al., 2026). Water protection needs to be coordinated with water management in extractive industries at a broader scale. The water use, pollution control, water treatment, water reuse, water governance, and water sustainability as parts of the mining-water management (Schneider & Wolkersdorfer, 2021). In conclusion, an integrated approach and a risk-based approach are needed to the problem of groundwater contamination caused by mineral production areas. The aims are to identify pollution sources and pathways, to review the acid mine drainage and heavy metal pollution, the monitoring and risk assessment methods, as well as the active, passive, biological and in-situ remediation methods and the sustainable strategies for aquifer protection and public-health risk reduction.

2. Hydrogeological and Environmental Characteristics of Mineral Production Zones

Mineral production zones are complex hydrogeological environments that are influenced by a combination of geologic, lithologic, aquifer type, topography, rainfall, soil permeability, drainage patterns, fracture density and disturbance by mining activity on the ground surface and within the subsurface. These areas typically contain open-pit mines, underground mines, ore processing facilities, overburden dumps, piles of waste rock, tailing storage facilities, haul roads, channels for mine water discharge and abandoned mine voids. Each can affect groundwater either by changing how groundwater flows in the natural environment or by adding potential groundwater pollutant source areas. It is therefore necessary to first determine the hydrogeological and environmental context before assessing the severity of the pollution and determining the remedial measures to be implemented.

The most significant control of groundwater quality in mineral production areas is the geological and lithological setting. When exposed to weathering, oxidation, and leaching, minerals found in the mineral-bearing formations may affect the chemistry of the groundwater, often as sulfides, oxides, carbonates, silicates, and traces of minerals containing metals. Contamination is different in each mineral deposit and host rock. Iron-mining areas can exhibit iron, manganese and other trace element concentration increases while coal-mining areas are often associated with increased sulfate, dissolved solids, acidity, and heavy metals. The distribution of metals in groundwater in an area affected by iron mining is influenced by both the mining pressure and seasonality (Giri et al., 2023). High concentration of heavy metals and health hazards around Singrauli coal mining region, which showed that the pollution of heavy metals in groundwater is due to the influence of mine drainage, overburden leachate, and interaction with aquifer (Srivastava et al., 2022).

The transport of contaminants by aquifers is determined by aquifer type, and is influenced by direction, rate, and extent of movement. The shallow unconfined aquifer is especially susceptible to contamination from tailings, mine spoil, waste dumps and polluted runoff by infiltration and recharge. Fractured hard-rock aquifers may have groundwater flow that is irregular and fast due to the presence of joints, faults, fractures, bedding planes, and blasting-induced cracks which form preferential flow paths. This can include pathways where acidic drainage and metals are able to pass through natural attenuation areas. With dissolution channels, cavities and conduits in karst aquifers, pollutants can be carried along with little filtration over long distances. In a karst lead–zinc mine the distribution of heavy metals in groundwater and surface water can be linked to health risk, and that the structure of the aquifer can be a significant factor in the migration of pollutants and the resulting health risk (J. Zhou et al., 2024) .

Mining activities have a great impact on the natural groundwater-flow system. Excavation uncovers new mineral surfaces which can be exposed to oxygen, rain, and reactions with groundwater. Dewatering reduces groundwater levels and can change hydraulic gradients which sometimes result in contaminated water from mine pits, waste dumps, and contaminated surface-water bodies moving toward surrounding aquifers. Blasting and drilling create fractures and increased hydraulic connectivity, and underground workings and abandoned voids can be sources of artificial reservoirs or conduits for contaminated water. The alteration of surface permeability, runoff direction and recharge behaviour by overburden dumping or tailing storage also occur. As a result, zones of mineral production can be the source of disturbance from recharge and transfer of contaminants, either vertically to the aquifers or laterally to wells, springs, streams, agricultural fields and settlements. Table 1 lists the key controls that are responsible for groundwater contamination in the mineral production area.

Table 1. Controls on Mining-Related Groundwater Pollution

Factor	Role in Pollution	Groundwater Impact
Geology and lithology	Controls natural metal release and water chemistry	Fe, Mn, sulfate, acidity, and trace-metal enrichment
Aquifer type	Determines contaminant movement and vulnerability	Fast migration in shallow, fractured, and karst aquifers
Mining disturbance	Alters groundwater flow through excavation, blasting, and dewatering	New pathways for contaminant transport
Tailings and overburden dumps	Act as long-term leaching sources	Metals, dissolved solids, and acidic drainage
Rainfall and recharge	Increase leaching and seasonal variation	Seasonal rise or spread of contaminants
Surface-water interaction	Connects mine drainage with aquifers and streams	Combined groundwater and surface-water pollution
Source complexity	Pollution may come from mining, smelting, and natural weathering	Requires source-based remediation

Groundwater vulnerability is also affected by environmental conditions. The flow of contaminants from mining surfaces into the ground is affected by rainfall intensity, monsoonal recharge, slope gradient, drainage density, soil texture, loss of vegetation and land-use changes. Infiltration may also cause leaching of metals, sulfate and dissolved ions during periods of high rainfall through tailings, exposed rocks, and/or mine spoil. Low-lying areas can lead to ponding, infiltration and accumulation of contaminants while steep slopes can lead to increased movement of contaminated run-off and sediment. Some fine-grained soils can slow the movement of contaminants and some sandy, fractured, weathered or highly permeable soils can accelerate contaminant movement. This is due to the above mentioned factors, which often lead to significant spatial and seasonal variations in groundwater pollution in mining areas.

In numerous mineral production areas there are also close relationships between groundwater and surface water. Surface water may be polluted by the drainage of the mines and surface water may recharge shallow aquifers during wet seasons. This connectivity adds to the complexity of assessing the situation as both water systems could be considered as interconnected exposure pathways. The concentration of different metals in groundwater and surface water of a coal-mining region and found their implications in terms of toxicity and human health (Tiwari et al., 2025). Additionally, source identification is essential as contamination can be from the mining activities, smelting activities, natural weathering, tailings seepage, overburden leachate and mixed anthropogenic activities. The importance of source-oriented health-risk assessment around mining and smelting regions and demonstrated that remediation needs to be targeted, which requires the identification of the origins of pollutants (Shao et al., 2025) .

3. Sources, Processes, and Pathways of Groundwater Pollution

In mineral production areas, groundwater contamination occurs as a result of the action of present day pollution sources, diffuse leaching sources, polluted structures from abandoned mines and natural water–rock reactions. Whereas pollution from a single industrial outlet is generally limited to one or a few sources, pollutants associated with mining are typically increased by multiple connected sources, such as mine pits, tailing ponds, overburden dumps, waste-rock piles, ore-processing zones, mine-water discharge channels, haul roads, smelting-related zones, contaminated run-off, and abandoned mine voids. They can contribute dissolved metals, sulfate, acidity, suspended solids, mineral pollutants, salts, and microbial pollutants to the subsurface environment.

In the mineral production areas, one of the most visible sources of groundwater pollution are point sources. Pollutants can be discharged from tailing ponds, slurry ponds, settling ponds, ore washing sites, mine water outlets, chemical storage sites and waste areas associated with smelting into adjacent soil and ground water. Because fine mineral residues, sulfides, metals, metalloids, and processing chemicals are often found in tailings, they are particularly important. The unlined, broken or poorly maintained tailings ponds can leak contaminants into shallow aquifers. Polluted water can also collect in abandoned voids and mine pits, and flow into surrounding formations or through fractures. Both natural geochemical processes and mining disturbance are shown to influence groundwater evolution in a mining area, thus demonstrating that water–rock interaction and anthropogenic activities both play a role in groundwater contamination (Z. Liu et al., 2024). The groundwater contamination pathways, processes, and sources of major concern for mineral production locations are shown in Figure 1.

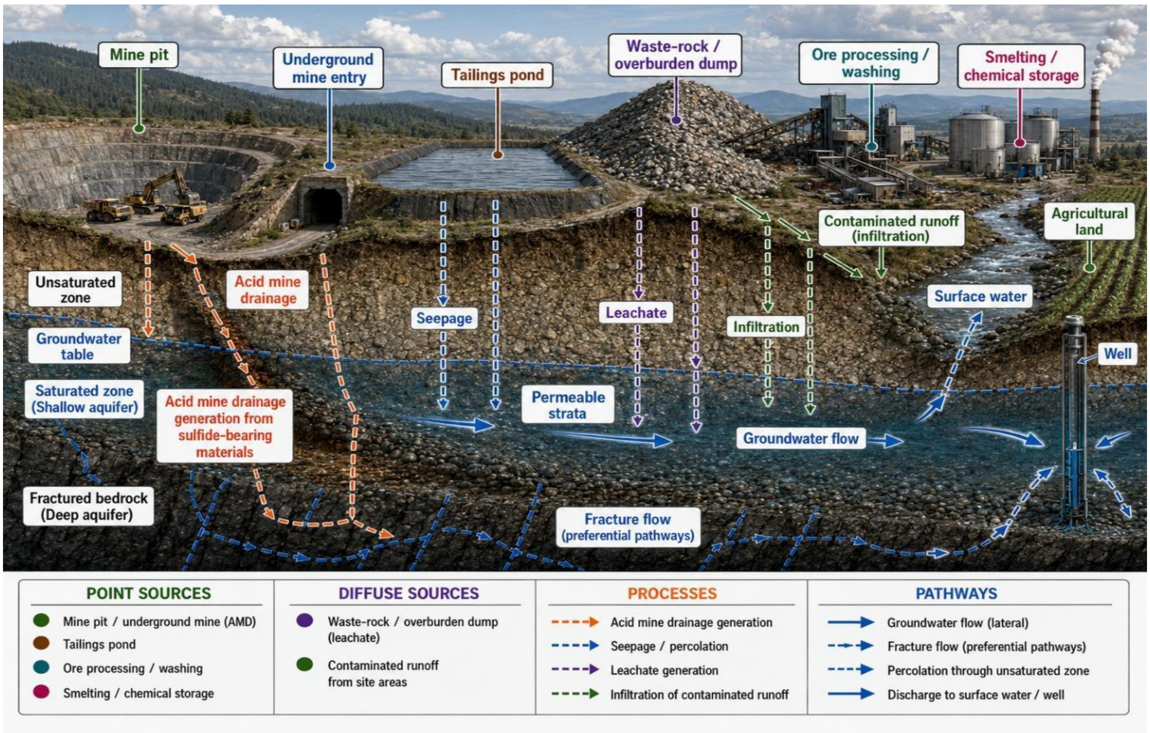


Figure 1. Sources, Processes, and Pathways of Groundwater Pollution in Mineral Production Zones

Diffuse sources also contribute significantly as they emit pollutants across a wide area and not from a single point of discharge. Rainfall may cause leachate to be produced from overburden dumps, waste rock piles, mineral surfaces, haul roads and contaminated soils. Rainwater that falls through the mine fill and weathered rock can get in contact with metals, sulfates, salts and other ions and dissolve them before reaching the unsaturated zone and shallow aquifers. It is not easy to control, as it is affected by rainfall intensity, the permeability of the soil, the slope, the waste composition and the recharge in the seasons in which it takes place. The groundwater quality in the Pingshuo mining area is also spatiotemporally variable, suggesting that the distribution of contaminants is significantly affected by the spatial and temporal sources and variations of hydrology (L. Sun et al., 2024).

One of the most significant processes causing groundwater degradation in the mineral production zones is acid mine drainage. It is created when sulfidic minerals come in contact with oxygen and water during the mining, blasting, dumping or weathering of post-mined areas. Acidic drainage from the sulfide oxidation enriches the concentrations and activity of potentially toxic elements (PTEs) such as iron, manganese, nickel, arsenic, lead, cadmium, chrome and others. This acid, metal-laden water can seep, percolate, recharge into groundwater in seepage, infiltration and recharge zones, fractured rocks and permeable strata. Although seasonal variations in groundwater levels can be quite significant, mining activities can have significant impacts on hydrogeochemical changes and human health risks for the mining community of Tarkwa in Ghana (Gwira et al., 2024).

Aquifer structure and subsurface pathways are important factors that affect the movement of contaminants. Pollutants may enter directly into groundwater from tailings, waste dumps and runoff in shallow unconfined aquifers. The fractured hard-rock aquifers have potential for rapid, irregular migration through the joints, faults, bedding planes and through cracks created by blasting. Where permeable, pollutants can flow along hydraulic gradients towards wells, springs, streams, ponds and farmland. The risk is further compounded by the process of groundwater to surface water connections, which can allow contaminated mine drainage to be introduced to streams, and polluted surface water into shallow aquifers during periods of higher flow.

Pollution from the past is also important. Some sites may still emit pollutants after mining has ceased, such as abandoned mines, old tailing dumps, unsealed pits, waste dumps and voids left after mining. The presence of mineral pollutants and the contamination of groundwater by coliform bacteria in an area affected by mining activities; thus, the risk may be chemical, microbial or both (Kazemi et al., 2024). The distribution of Ni across the groundwater sources of a mining-affected region is associated with spatial health hazards, highlighting the differences in exposure risks among communities due to different pathways of pollutants (Salehi et al., 2024).

4.Major Contaminants and Groundwater Quality Degradation

Contamination in the groundwater in a mineral production area can result from a variety of sources, including the release of contaminants from mineralized rocks, mine pits, tailings storage facilities, waste rock dumps, aquifer disturbance, and run-off from industrial activities and smelting facilities, as well as ore-processing residues. The type and intensity of contamination is dependent on the mineral being mined, the composition of the host rock, the type of mining, the geochemical conditions, the recharge pattern, the type of aquifer and the land use patterns.

Heavy metals are the most important contaminants in mining-affected groundwater due to their toxicity, persistence and tendency to bioaccumulate in soil, plants, water bodies and human tissues. Commonly reported metals are iron, manganese, lead, cadmium, chromium, copper, zinc, nickel and mercury. These can be added to the groundwater via oxidizing sulfide, acid mine drainage, seepage from tailings ponds, leaching from waste rock heaps, and discharge from ore processing sites. Natural weathering also can cause metal enrichment in mineralized areas but in these areas metal release is hastened by mining activities which expose fresh rock surfaces and enhance the water–rock interaction. Groundwater contamination as a result of mining operations in the Aravalli Hills near Delhi, indicating that mining operations in sensitive geological environments can have a broader regional impact on groundwater quality (Gani & Pathak, 2025).

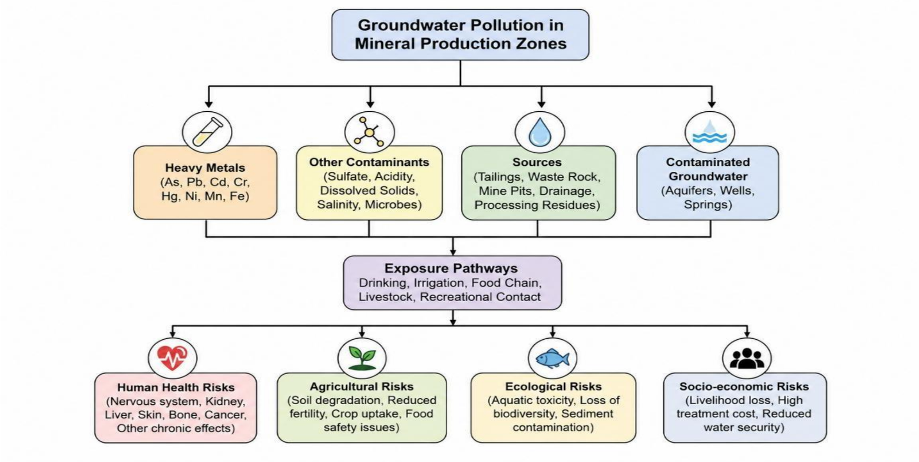
Metalloids and trace elements, especially the toxic components such as arsenic, are also major contributors to groundwater degradation. The mobility of these is strongly controlled by pH, redox potential, adsorption/desorption reactions, mineral dissolution, organic matter, and iron/manganese oxide phases. In acidic conditions, many metals become more soluble, and the oxidation–reduction reactions can cause the release of arsenic and other trace elements from mineral surfaces or sediment-associated forms. By applying hydrogeochemical analysis and self-organizing mapping, To trace the heavy-metal contamination of groundwater: advanced geochemical and data-driven methods can aid in distinguishing between natural water–rock interaction and mining-related pollution sources (Sun et al., 2025). Table 2 summarizes the major groups of contaminants that affect groundwater quality.

Table 2. Major Contaminants in Mining-Affected Groundwater

Contaminant Group	Examples	Key Effect
Heavy metals	Fe, Mn, Pb, Cd, Cr, Cu, Zn, Ni, Hg	Toxicity, persistence, bioaccumulation
Metalloids	Arsenic and trace elements	Long-term health risk
Major ions	Sulfate, chloride, nitrate, fluoride	Changes groundwater chemistry
Salinity indicators	TDS, EC, hardness	Reduces drinking and irrigation suitability
Acidity indicators	Low pH, acidity, sulfate	Increases metal mobility
Suspended/colloidal pollutants	Fine tailings, sediments	Carries adsorbed metals and increases turbidity

5.Environmental, Agricultural, and Human Health Risks

Groundwater pollution in mineral production zones produces multidimensional risks that extend beyond the deterioration of water chemistry. Contaminated aquifers can affect ecosystem stability, agricultural productivity, food safety, livelihood security, and public health, particularly in regions where local communities depend directly on wells, borewells, springs, and shallow aquifers. Mining-derived pollutants such as heavy metals, metalloids, sulfate, acidity, dissolved solids, and microbial contaminants may move from groundwater into soils, crops, livestock, surface-water bodies, and human exposure pathways. Hence, groundwater degradation in mineral production areas must be viewed as an environmental-health problem with long-term ecological and socio-economic consequences. The main exposure pathways and associated human health, agricultural, ecological, and socio-economic risks of groundwater pollution in mineral production zones are summarized in Figure 2.



Salinity indicators and major ions are good indicators of groundwater-quality degradation. High levels of sulfate are usually caused by sulfide oxidation and acid mine drainage while high levels of chloride, nitrate, fluoride, sodium, calcium, magnesium, bicarbonate, and hardness are more likely to result from mine-water discharge, mineral dissolution, industrial inputs, evaporation, and contaminated recharge. The measurement of electrical conductivity and total dissolved solids are especially good indicators of dissolved-ion enrichment. High salinity and hardness can make groundwater unfit for human consumption and irrigation, adversely impact soil structure, impact crop productivity, and result in long-term soil constraints in mining affected landscapes.

Parameters associated with acidity are of particular significance in areas impacted by acid mine drainage. Active oxidation, leaching and geochemical instability is signified by low pH, high acidity, high levels of sulfate and elevated levels of metals. Over time acidic groundwater can also leach other metals from rocks and sediments in the surrounding area, and worsen the pollution. Neutral or alkaline conditions, however, could favor precipitation, adsorption or immobilization of certain metals while several contaminants can be mobile as a function of redox state, complexation and competing ions. Source-apportionment and human-health-risk models used to assess heavy-metal contamination, and emphasized the need to connect the contaminant chemistry with source identification and exposure assessment (Liu et al., 2025).

The quality of groundwater and surface water around the mineral production areas is further complicated by the presence of suspended and colloidal pollutants. Fine particles in tailings, eroded mine spoil, processing residues and contaminated sediments have the potential to adsorb metals and transport them via groundwater recharge and/or shallow aquifers, or via surface runoff. These particles can be remobilized (increased turbidity, dissolved solids and metal concentrations) during monsoon or during the wet season. To evaluate the risks of industries on groundwater along with soil contamination and land use exposure, reported the high content of heavy metals in the soils and groundwater around industrial activities (Sharafi & Salehi, 2025).

They are mobile and persistent and are regulated by pH, redox conditions, mineralization, aquifer structure, organic matter, rainfall and anthropogenic inputs. Groundwater aquifers might be contaminated with heavy metals, which could pose human and ecological health risks (Ehsan et al., 2025).

6.Monitoring, Assessment, and Risk-Based Evaluation

Monitoring, assessment and risk based evaluation are used to guide the selection of remedial measures in mineral production areas. Planning for groundwater remediation should not be determined by identifiable signs of pollution or the common knowledge of the impact of mining. It necessitates a diagnostic approach that can identify the sources of pollutants, the pathways, the seasonal changes, the vulnerability of the aquifer, the receptors and the specific risks associated with the site. Sourced from natural water–rock interaction, contaminants can also come from ore-processing residues, acid mine drainage, overburden dumps, tailings and waste-rock piles in mining-affected areas.

Monitoring wells (dug, borewell, piezometers, springs, mine-pit water, points of tailing seepage, drainage channels and surface-water bodies nearby) should be included in a reliable monitoring network. Samples should be taken nearby tailing storage facilities, overburden dumps, waste-rock areas, abandoned mining voids, ore-processing centres, farming areas, and communities where groundwater is likely to flow and/or transport contaminants. It is also important to take background samples away from the mining influence zone in order to differentiate between geogenic enrichment and mining induced pollution. This network assists in the delineation of contamination gradients, sensitive receptors and remediation priority area. Table 3 shows the integrated framework of monitoring, assessment and risk based evaluation.

Table 3. Monitoring and Risk-Based Evaluation Framework

Component	**Core Parameters / Methods**	**Function in Groundwater Assessment**
Monitoring network	Wells, borewells, piezometers, springs, mine-pit water, seepage points, surface water	Detects contamination sources, movement patterns, and vulnerable receptors
Sampling strategy	Tailings areas, waste dumps, mine voids, processing zones, settlements, background sites	Separates mining-induced pollution from natural geogenic inputs
Seasonal assessment	Pre-monsoon, monsoon, and post-monsoon sampling	Captures leaching, dilution, recharge effects, and plume migration
Hydrochemical analysis	pH, EC, TDS, hardness, sulfate, nitrate, fluoride, major ions	Defines groundwater chemistry and suitability for use
Metal assessment	Fe, Mn, Pb, Cd, Cr, As, Ni, Cu, Zn, Hg	Identifies toxic contamination and long-term exposure concern

Pollution indices	WQI, HPI, Metal Index, contamination factor, ecological risk index	Converts complex chemical data into comparable pollution classes
Spatial and source tools	GIS, Piper/Gibbs plots, PCA, source apportionment, transport modelling	Maps hotspots, identifies sources, and predicts contaminant pathways
Risk evaluation	Hazard quotient, hazard index, carcinogenic risk, exposure pathways	Estimates human and ecological risk for decision-making
Treatment feasibility	Microbial conditions, reactive media, low-cost materials, site constraints	Guides selection of suitable remedial technologies

Groundwater quality in the area of mineral production is often found to vary from pre-monsoon to monsoon to post-monsoon seasons and hence a seasonal monitoring is essential. During drier times, the less recharge and the more evaporation will result in higher total dissolved solids, hardness, salinity and electrical conductivity. Infiltration of rainwater during the rainfall event can cause leaching of metals, sulfate, acidity, and dissolved ions from tailing, from rocks that have been exposed and mineralized by the presence of the mining operations and from mine waste or tailings. Post-monsoon monitoring is used to assess dilution and delayed recharge effects, and contaminant plume movement. The need for a systematic spatial and temporal assessment of heavy-metal contamination in groundwater from a typical mining area, as they proved its importance (Hao et al., 2024).

General water-quality parameters and toxic elements should be analyzed for in the lab. Some basic parameters like pH, EC, TDS, DO, Turbidity, Hardness, Alkalinity, Acidity, Sulphate, Chloride, Nitrate, Fluoride, Calcium, Magnesium, Sodium, Potassium give an idea about the hydrochemical evolution and suitability of water. Heavy metals and trace elements include those like iron, manganese, lead, cadmium, chromium, arsenic, nickel, copper, zinc and mercury, which are persistent, toxic and are important for human health, and should be analysed. These results should be compared with the standards for drinking-water and/or irrigation-water to determine the level of contamination.

Pollution indices can be used to simplify and interpret the data from complex chemicals. The Water Quality Index, Heavy Metal Pollution Index, Metal Index, contamination factor, pollution load index, ecological risk index, hazard quotient, hazard index and carcinogenic risk can be used to order the polluted sites and convey the risk to the regulators and communities. These indices are meant to be used in conjunction with hydrogeochemical interpretation, however. The need to understand the processes of acid mine drainage formation, the environmental effects, and treatment in order to create AMDR mitigation strategies, thus demonstrating the need to link assessment of AMDR with its treatment planning (Wibowo et al., 2023).

Risk based assessment is reinforced with hydrogeochemical and spatial tools. Piper diagrams, Gibbs plots, ion ratios, saturation indices, correlation analysis, principal component analysis, cluster analysis, source apportionment models, GIS mapping, contaminant transport modelling can be used to help pinpoint pollution sources, direction of pollution, speed of pollution, and vulnerable areas. They are useful in determining the location of recharge-control structures, permeable reactive barriers, and monitoring wells to be installed. Real exposure pathways, such as drinking water, irrigation, soil accumulation, crop uptake, exposure of livestock and interaction with surface water should also be taken into account when evaluating risks.

The feasibility of treatment should also be assessed. Sulfate reducing bacteria as a bacterium species which may be used for anaerobic bioremediation of AMD, so it is recommended to assess the microbial and geochemical conditions prior to biological treatment (Mafane et al., 2025). Agro-industrial and urban wastes can be evaluated for their remediation ability toward acid mine drainage using local materials which can be used for low-cost treatment (Aguilar-Garrido et al., 2023).

7.Remedial Measures and Integrated Groundwater Pollution Control Strategies

There must be a combination of prevention, containment, treatment and long term monitoring of development in mineral production areas to ensure remedial measures are effective in dealing with water pollution. Not all technologies are appropriate for all sites because some of the contamination associated with mining operations may include acid mine drainage, heavy metals, sulfate, salinity, dissolved solids, and microbial hazards. The selection of a scientifically sound strategy should be dependent on the type of pollutant, aquifer conditions, intensity of contamination, direction of groundwater flow, land availability, treatment efficiency, costs, maintenance requirements, and the sustainability of treatment.

Prevention is the most important and first line of defence to protect groundwater. They consist of correct lining of tailing ponds, safe disposal of overburden and waste rock, collection of leachates, diversion of storm water, regulation of mine drainages, covering of potentially reactive wastes and prevention of sulfide oxidation. These help to minimize pollutant production prior to contamination of aquifers. Acidity and mobilization of metals can be mitigated in areas of acid mine drainage by the use of alkaline amendment, limestone drains, oxygen barrier covers, and separation of clean water from contaminated mine wastes. The importance of prevention is particularly highlighted as the groundwater remediation in fractured or deep aquifers can be slow and expensive.

For systems where long-term, low-maintenance control is desired passive treatment systems are applicable. Permeable reactive barriers and limestone based passive barriers can capture contaminated groundwater or acid mine drainage and decontaminate the water, neutralize the acidity and decrease pollutant transport. Review of passive acid mine drainage treatment systems that involve permeable reactive barriers and limestone-based systems, highlighting their significance in both design and testing, as well as their construction in the field (Wang et al., 2024). These systems are helpful because they are in-situ and do not need a continual energy input as with an active system. Their performance is however determined by the level of hydraulic residence time, by the content of reactive material, by the content of clogging potential, the flow rate, the content of contaminant and the long-term maintenance.

The efficiency of in-situ remediation can be enhanced by advanced design and optimization. Many sites have contaminant plumes with high chemical complexity, variable spatial extent, or large size, and multiple PRBs can be employed. Machine learning simulation and optimization can aid the design of multi-PRB systems to address acid mine drainage (Zhou et al., 2026). This is crucial when planning remediation in Q1, to connect field hydrogeology, contaminant migration, treatment placement, and modelling. Optimized barriers can enhance uncertainty reduction and performance of treatment in complex zones of mineral production.

Another key remediation method is using biological techniques, especially with sulfate-rich and metal-laden mine water. Sulfate-reducing bacteria will convert sulfates to sulfides, raise alkalinity and cause metal precipitation as metal sulfides. Sulfate reducing bacteria (SRB) as a treatment method for acid mine drainage (AMD) and found that it has the potential to be a sustainable treatment method. Biological systems can be used in an anaerobic bioreactor, constructed wetlands, organic substrate beds and passive treatment cells (Marques & Rodrigues, 2025). They are subject to pH, temperature, availability of organic carbon, metal toxicity and hydraulic conditions and site specific feasibility assessment is required prior to implementation.

For very high contamination of the groundwater or for the quick improvement of the groundwater of mine drainage, active treatment methods are still important. These methods include lime neutralization, chemical precipitation, coagulation, adsorption, ion exchange, membrane filtration and pump-and-treat. High removal efficiencies are possible using active methods, but these methods tend to require a continuous chemical input, energy input, trained operation and sludge management.

The remedy should be directed towards areas where contaminated groundwater is being used for drinking, irrigation or domestic purposes, in a health-risk-oriented manner. A study by Exposure reduction should be linked to remediation, as exposure of the human population to heavy-metal pollution in groundwater from a mining community can be a problem for health (Gwira et al., 2024). Alternative safe water supply, well protection, community awareness, routine monitoring and post treatment verification should therefore constitute a part of integrated control.

8.Conclusion

The problem of groundwater pollution in mineral production areas is long-term and is the result of disturbance of the ground and changes in the hydrogeology, acid mine drainage, seepage of the mine tailings, leaching of waste rocks and mobilization of heavy metals. This complexity comes from the interplay of various sources and pathways, such as infiltration, seepage, fracture flow, runoff, surface-water exchange, and aquifer transport. For this reason, degradation of groundwater impacts water quality, as well as the livelihoods of farmers, soil health and fertility, aquatics, livestock, and public health. A comprehensive and location-specific approach is needed to control effectively. Preventing pollution should be the first priority since remediation of polluted aquifers is more difficult and less sustainable than reducing pollution at the source. Such measures involve the building of lined tailings storage, stabilizing the overburden, collecting leachates, controlling the drainage of leachates, covering the waste rocks and preventing any sulfide oxidation. Remedial technologies can be considered when a site is already contaminated and include, but are not limited to, the following methods: neutralization, chemical precipitation, adsorption, pump-and-treat systems, constructed wetlands, bioremediation, sulfate-reducing bacteria, permeable reactive barriers, limestone-based passive systems, and managed aquifer restoration, depending on the type of contaminant, aquifer conditions, cost, effectiveness, and maintenance requirements. All actions for remediation should be based on monitoring and risk assessment. The implementation of seasonal sampling, hydrochemical analysis, pollution indices, GIS mapping, source apportionment, transport modelling and health-risk assessment are all critical in order to identify hotspots and prioritize action. The overall sustainable groundwater protection is based on scientific assessment, preventive planning of mining, appropriate remediation, regulation, awareness of the community and post closure surveillance.

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