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Comparative Analysis of Water Quality from Reclaimed, Abandoned, and Active Coal Mines

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Abstract

Coal mining is an important aspect of the global energy-generating process, especially in developing economies. Still, its environmental legacy, in terms of water quality deterioration, is a major burden in the long term. This narrative review will provide a detailed comparative study on the water quality as applied to active, abandoned, and reclaimed coal mines. The study examines the most significant physicochemical indicators, including pH, concentration of sulfates, and dissolved loads of metals, as well as the hydrogeochemical mechanisms of contaminant generation and their transport. It has been found that the worst and most intractable sources of water pollution are abandoned mines, which contain high levels of acidity and metals, as the geochemical reactions are not regulated. Whereas Active mines possess comparatively stable water quality that can be attributed to the developed treatment systems, yet they are to be run constantly, and they require considerable financial investment. Reclaimed mines show partial recovery of water quality, but stability in the long term is still not clear because not all reactive materials are completely isolated, and hydrological conditions are not constant. This study also identifies predictive modeling and integrated management methods as techniques for addressing the risks of long-term environmental risks. Climate variability is a new factor that has been outlined to influence contaminant dynamics, which may accelerate the production of acid and the mobilization of metals. In general, a multidisciplinary approach that includes hydrogeochemistry, engineering solutions, ecological rehabilitation, and the adequate application of policy should underlie sustainable mine water management to decrease the long-term impact of coal mining on water sources.

Keywords: Coal mining; Acid mine drainage; Water quality; Mine reclamation; Hydrogeochemistry; Heavy metals; Mine water management

1. Introduction

Coal mining is an important aspect of the world's energy production, especially in developing economies that are still relying on coal mining to aid in the generation of electricity and industrial production. Although there have been rises in switching to renewable energy, coal remains a significant source of power in terms of availability and infrastructure that has already been developed (Tiwary, 2001). Nevertheless, the environmental cost of coal mining is tremendous and permanent, and the problem of water quality deterioration is one of the most continuous.

Mining activities disrupt the natural geological structures and expose minerals that contain sulfide, especially pyrite (FeS_2), to the atmospheric oxygen and water. Oxidation reactions caused by this exposure create acid mine drainage (AMD), which is characterized by low pH, high levels of sulfates, and high concentrations of dissolved metals (iron (Fe), aluminum (Al), and manganese (Mn)) (Akcil and Koldas, 2006; Nordstrom, 2011). AMD, once begun, can last decades or centuries, and it is a long-term environmental issue (Younger, 2001).

The water quality effects are different at various mine lifecycle phases. Active mines can usually maintain the quality of water contained in the mines by engineered treatment systems, but such systems need constant operation and are costly (Johnson & Hallberg, 2005). Contrastingly, abandoned mines are uncontrolled systems in which continued oxidation of the sulfides results in the continued contamination and ecological degradation of the surrounding environment (Gray, 1997; Younger, 2001). Reclaimed mines have partial recovery, yet, in the long term, they are not stable because of the residual geochemical activity and hydrological variability (Skousen et al., 2017).

Recent studies have highlighted the significance of the use of hydrogeochemical modelling and combined management techniques in the prediction and countering of mine water contamination. The chemical processes and long-term contaminant behavior can be simulated by means of such tools as PHREEQC (Parkhurst and Appelo, 2013). Also, the variability of climatic conditions is becoming a well-known factor that is capable of affecting the production of contaminants, their transportation, and the effectiveness of their treatment (Palmer et al., 2010).

Although there is a lot of research, the majority of the studies concentrate on single parts of mine water systems, and therefore, there is minimal comparative knowledge of different types of mines. Co-ordinated analyses to put together the interaction of hydrogeochemical processes, environmental conditions, and management practices across the lifecycle of the mine are needed.

Thus, the purpose of this narrative review is to give a comparative evaluation of the water quality of active, abandoned, and reclaimed coal mines. The objectives are to:

1. Evaluate key physicochemical parameters and contamination patterns
2. Review hydrogeochemical processes governing the water quality.
3. Test the effectiveness of remediation and reclamation.
4. Identify the research gaps and future research on sustainable mine water management

2. Theoretical Framework

The conceptual framework that helps to develop the comparative analysis in this study is associated with the idea that mine status is correlated with hydrogeochemical processes and environmental results. The level of sulfide exposure, hydrological conditions and management intervention are determined by mine status, which can be active, abandoned or reclaimed. These parameters control the important processes on pyrite oxidation, acid production and mobilization of metals, which subsequently manage water quality parameters such as pH, sulfate level, and dissolved metals.

The resultant water quality states affect the ecological influences and determine the priorities of management. There are cross-cutting modifiers, such as climate variability, geological conditions, and governance structures, which influence every stage of the system. This framework offers a framework of comparative assessment between the types of mines and is depicted in Figure 1.

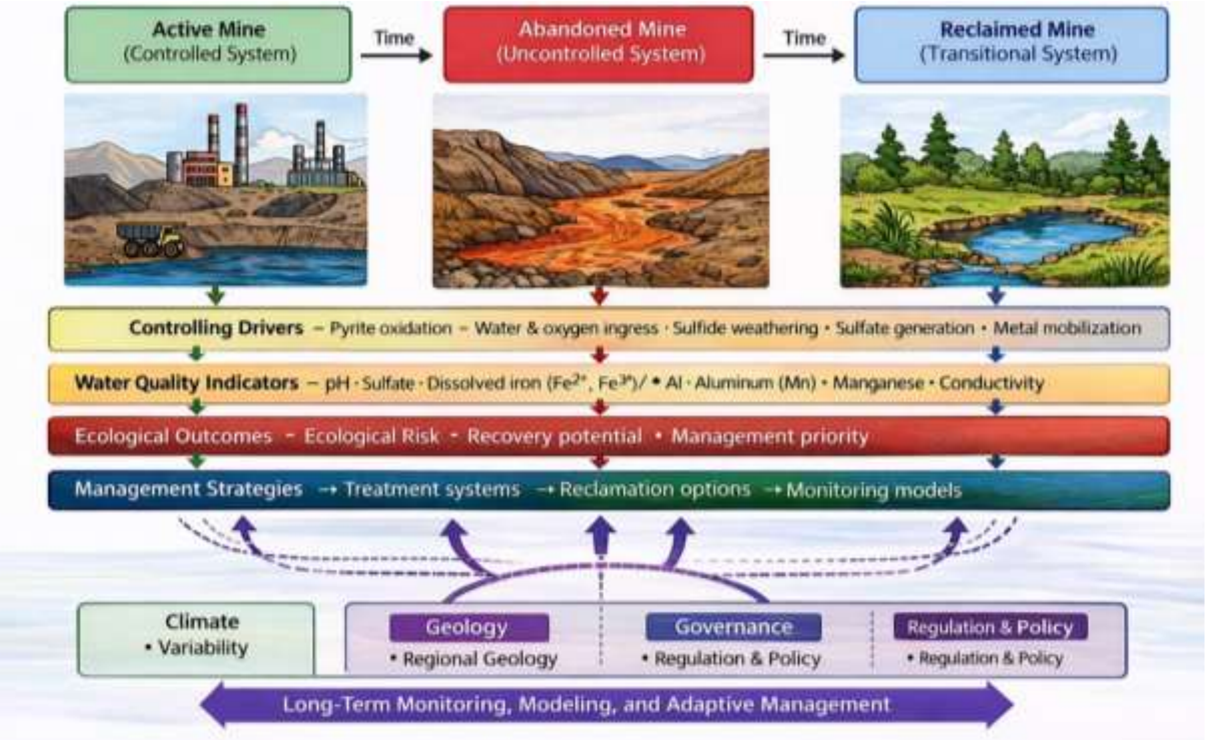

Figure 1. Theoretical framework for comparative mine water quality analysis

Comparative mine water quality analysis theoretical framework demonstrating how mine status affects the controlling drivers, water quality indicators, ecological outcomes, and management priorities, cross-cutting modifiers are climate, geology, and governance

3. Methodology

3.1 Study Design

This research will follow a narrative review approach in order to synthesize and critique existing scientific literature on the topic of water quality surrounding active, abandoned, and reclaimed coal mines. Narrative reviews are notably suitable to synthesize the multidisciplinary studies, define tendencies, and gain conceptual knowledge in a variety of environmental systems where quantitative meta-analysis cannot be conducted due to methodological heterogeneity (Kefeni et al., 2017; Simate & Ndlovu, 2014).

3.2 Literature Search Strategy

The extensive literature search was carried out on the largest scientific databases, including Scopus, Web of Science, Science Direct, and Google Scholar, in order to address as many peer-reviewed publications as possible. Search was restricted to the publications of the period 2000 to 2024, encompassing the fundamental and recent developments in the research of mine water. The search strategy involved a combination of keywords and Boolean operators, including:

1. "Acid mine drainage" AND "coal mining"
2. "Mine water quality" AND "heavy metals"
3. "Abandoned mine drainage" OR "AMD"
4. "Mine reclamation" AND "water quality"
5. "Hydrogeochemical modeling" AND "mining"

3.3 Inclusion and Exclusion Criteria

Scientific rigor and relevance were attained by strictly applying inclusion and exclusion criteria.

Inclusion Criteria

1. Peer-reviewed articles published in **Q1 and Q2 journals**
2. Studies focused on **coal mining environments**
3. Research reporting **quantitative water quality data** (e.g., pH, sulfate, metals)
4. Studies examining **hydrogeochemical processes**, remediation, or reclamation

Exclusion Criteria

1. Non-peer-reviewed sources (e.g., reports, conference abstracts)
2. Studies focused solely on non-coal mining systems unless directly comparable
3. Articles lacking sufficient methodological or analytical detail

This filtering ensured that only **high-quality, reliable scientific evidence** was included in the analysis (Lottermoser, 2010).

3.4 Data Extraction

Relevant data were retrieved systematically through the process of identifying the selected studies, which included:

1. **Physicochemical parameters**: pH, sulfate, total dissolved solids (TDS), Fe, Mn, Al and trace metals.
2. **Mine classification**: active, abandoned, or reclaimed.
3. **Geographical context**: area and weather conditions.
4. **Hydrogeochemical properties**: oxidation, interactions of minerals.
5. **Treatment procedures**: active and passive remediation systems.
6. **Key results**: environmental trends and effects.

3.5 Analytical Framework

The analysis was designed in three major dimensions:

Physicochemical Characteristics: Evaluation of the water quality parameter of acidity (pH), sulfate levels, and dissolved metal loads of water, which are the main indicators of mining-related contamination (Gray, 1997).

Hydrogeochemical Processes: Assessment of processes that control the formation of contaminants and their distribution, e.g., sulfide oxidation, metal mobilization, and secondary mineral formation (Nordstrom, 2011; Blowes et al., 2014).

Environmental and Management Outcomes*:* Comparison of the ecological effects, the effectiveness of the remediation, and long-term stability of the mine types with specific emphasis on the performance of the reclamation (Skousen et al., 2017).

This framework facilitated a comparative analysis of water quality in the mine lifecycle systematically and in an integrated manner.

3.6 Comparative Approach

A key feature of this review is its **comparative structure**, as it assesses the water quality in terms of the following:

1. **Active mines:** regulated systems, where treatment is in control.
2. **Abandoned mines**: permanent, chronic sources of contamination.
3. **Reclaimed mines:** reclaimed systems with different levels of success.

Comparing these categories, the research determines the trends in the severity of contamination, its effective management, and the long-term levels of environmental results (Johnson & Hallberg, 2005; Younger, 2001).

3.6 Limitations of the Study

Being a narrative review, the study lacks statistical meta-analysis, which could undermine the possibility of quantitative generalization. Moreover, the inconsistency in the methodologies used in the studies, e.g., sampling techniques, methods of analysis, and reporting standards, creates some uncertainty.

However, the emphasis on a high-quality and peer-reviewed literature and the application of a systematic analytical framework contribute to the strengthening and reliability of the results. Moreover, the narrative approach enables more profound conceptual understandings and critical analysis of complicated environmental processes that cannot be measured by the mere quantitative approaches (Simate & Ndlovu, 2014).

4. Results

4.1 Hydrogeochemical Processes Governing Mine Water Quality

The synthesis of the reviewed studies indicates that acid mine drainage (AMD) is the prevailing process that governs the quality of water in the coal mining environment. The formation of AMD occurs when the sulfide minerals are oxidized, particularly the pyrite (FeS_2), in the presence of oxygen and water. This results in the creation of sulfuric acid and dissolution of iron, leading to low PH and high levels of insoluble metal (Nordstrom, 2011; Akcil & Koldas, 2006).

Acidophilic microorganisms and particularly those that oxidize iron, including *Acidithiobacillus ferrooxidans*, catalyze the oxidation process of ferrous to ferric iron (Blowes et al., 2014). This mediation by microbes accelerates the reaction rates and also aids in the rapid acid formation of mine waters.

The metals, including Fe, Al, Mn, Zn, and Pb, are highly soluble under acidic conditions and dissolve into the water systems that are surrounding (Lottermoser, 2010; Cravotta, 2008). The mobility and speciation of these metals are controlled by PH, redox potential (Eh), and complexation reactions and determine their transport and ultimate deposition (Younger et al., 2002).

The formation of secondary minerals is also a major process. Ferrihydrite, goethite, and jarosite are some of the minerals that have the property of immobilizing the metals temporarily, i.e., serve as sinks. These stages, however, are not very stable and can give off the accumulated metals under varying environmental conditions, leading to delayed contamination (Nordstrom, 2011; Kirby & Cravotta, 2005). The key hydrogeochemical processes that govern the water quality and their effects are summarized in Table 1.

Table 1. Overview of Hydrogeochemical Processes and Their Impact on the Water Quality in the Coal Mining Environment

Process	**Mechanism**	**Impact on Water Quality**	**Key Parameters Affected**
Pyrite oxidation	FeS_2 reacts with O_2 and H_2O	Acid generation, pH decline	pH, sulfate
Microbial catalysis	Bacteria accelerate oxidation	Faster AMD formation	Fe^{2+}, Fe^{3+}
Metal mobilization	Low pH increases solubility	Elevated metal concentrations	Fe, Al, Mn, Zn
Secondary mineral formation	Precipitation of Fe compounds	Temporary metal storage	Fe, Al

Hydrological transport	Movement of contaminants	Spread to surface/groundwater	TDS, conductivity

The hydrogeochemical reactions that lead to the formation of acid mine drainage, such as oxidation and the formation of acids, as well as the mobilization of metals, are depicted in Figure 2.

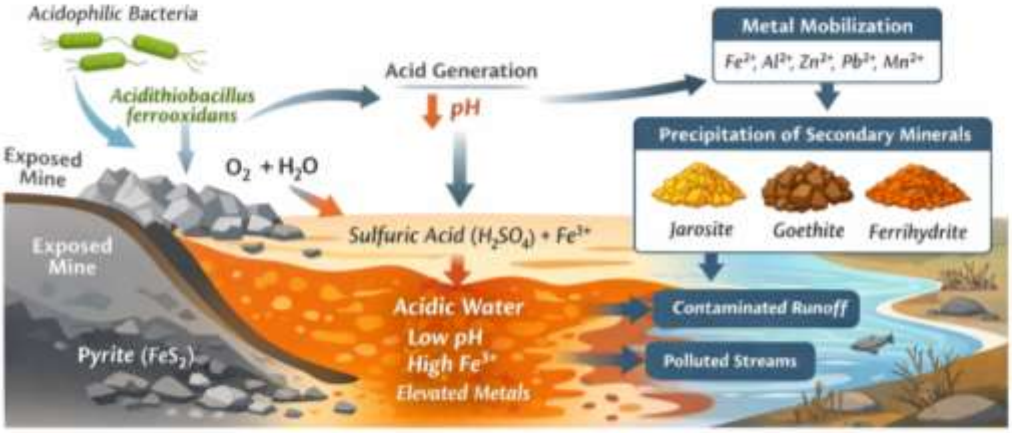

Figure 2. Conceptual model of acid mine drainage (AMD) formation

Diagrammatic representation shows how acid mine drainage (AMD) forms with the oxidation of pyrite, catalysis by microbes, the formation of acid, and the mobilization of metals.

4.2 Comparative Physicochemical Characteristics

A comparative evaluation of the water quality in the active, abandoned, and reclaimed coal mines indicates that the three mines have very clear variations in the main physicochemical parameters. As shown in Table 2, the findings indicate the worst water quality in abandoned mines, characterized by extremely low pH and high metal concentrations, due to the lack of control over AMD generation (Gray, 1997; Younger, 2001).

Table 2. Comparative Water Quality Parameters Across Mine Types

Parameter	Active Mines	Abandoned Mines	Reclaimed Mines
pH	6.0 – 7.5	2.0 – 4.0	5.5 – 7.5
Sulfate (mg/L)	500 – 2000	2000 – 10000	300 – 1500
Iron (mg/L)	< 5	50 – 500	< 10
Aluminum (mg/L)	< 2	10 – 100	< 5
Manganese (mg/L)	< 2	5 – 50	2 – 10

Conversely, active mines have a relatively constant water quality, which is attributed to the fact that the mines are treated in order to eliminate acidity and dissolved metals before discharge (Johnson & Hallberg, 2005; Kefeni et al., 2017). Such stability, however, relies on the maintenance and constant operation.

Reclaimed mines are intermediate in nature with better PH and lower levels of metals as compared to abandoned mines. However, the variability is high, which is the manifestation of the dissimilarity of the design of the reclamation and the geochemical stability in the long term (Skousen et al., 2017). Figure 3 further demonstrates the difference in pH, sulfate, and metal loading between the classes of mines.

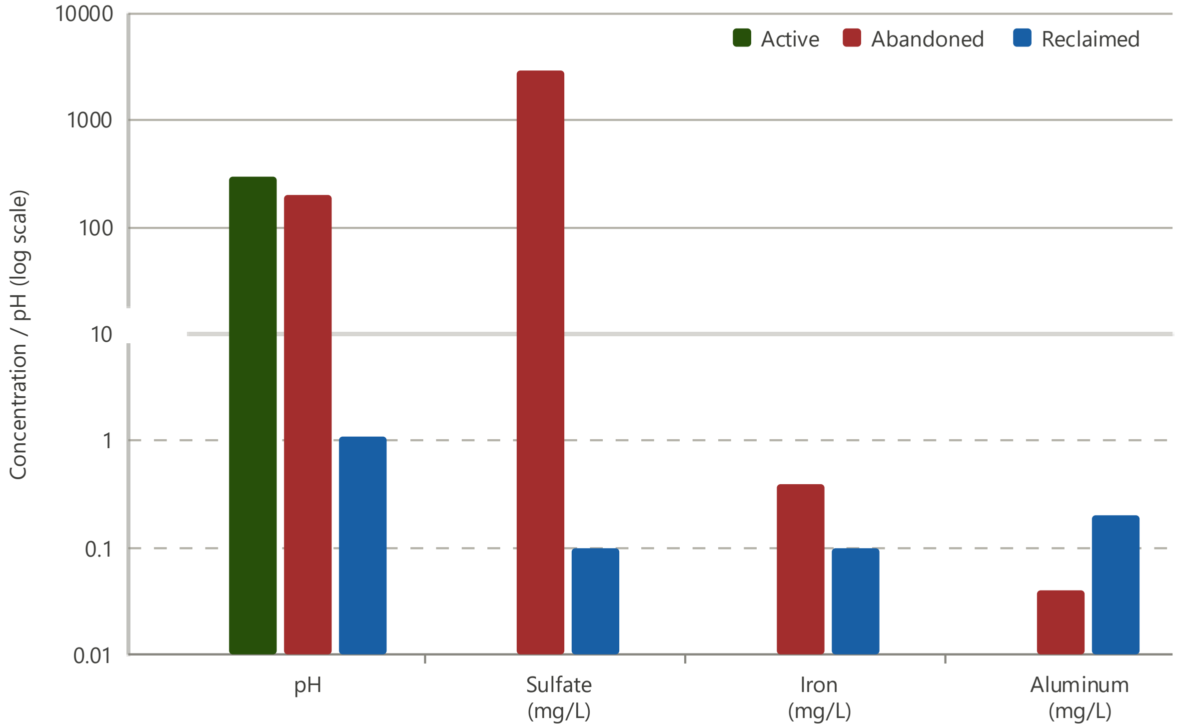

Figure 3. Comparative water quality characteristics of mines

Relative differences in acidity, content of sulfates, metal loading and management status of active, abandoned, and reclaimed coal mines through comparative water quality characteristics.

4.3 Water Quality in Active Coal Mines

Active coal mines are generally controlled by the environment and use artificial systems of treatment to handle the wastewater. These mechanisms are lime neutralization, aeration, sedimentation, and advanced filtration systems (Johnson & Hallberg, 2005; Kefeni et al., 2017).

Findings of various studies show that active mines usually keep:

1. Near-neutral pH conditions (6–7.5)
2. Decreased levels of dissolved metals.
3. Controlled sulfate levels

These are the results that prove the efficiency of the treatment systems to reduce pollution. Nonetheless, the findings also point to the fact that the quality of water in the active mines is not naturally stable but rather controlled artificially.

Operational challenges include:

1. High financial costs of treatment.
2. Sludge disposal requirements
3. Vulnerability to system failure.

In other instances, extreme weather or operational interference has been recorded to increase the levels of contaminants temporarily, and this means that water quality may decline very quickly without constant management (Kefeni et al., 2017).

4.4 Water Quality in Abandoned Coal Mines

Abandoned coal mines are the most significant source of water pollution in the long-run. The characteristics of such systems include:

1. Highly acidic conditions (pH < 4)
2. Extremely high concentrations of sulfates.
3. Higher concentration rates of dissolved metals.

The untreated nature of AMD processes leads to continuous contamination as the processes continue to progress without an end (Younger, 2001; Cravotta, 2008). Such locations are frequently the sources of constant pollution, which leads to the pollution of whole river systems.

Field investigations have always indicated that mine wastes are the most significant contributors to watershed-wide pollution, and even minor discharges have a huge proportion of the contaminant loads (Gray, 1997; Singh et al., 2010).

4.5 Water Quality in Reclaimed Coal Mines

Reclaimed mines have different levels of water quality recovery, which are determined by the reclamation strategies. Reclaiming can be carried out through common reclamation, which includes:

1. Backfilling and grading
2. Topsoil replacement
3. Vegetation establishment
4. Hydrological reconstruction

She goals of these interventions include decreasing erosion, restricting oxygen contact, and stabilizing hydrological processes (Skousen et al., 2017).

Findings reveal that reclaimed mines usually exhibit:

1. Higher PH to the neutral conditions.
2. Reduced metal concentrations
3. Improved water clarity

However, various studies point out that reclaimed systems are unstable geochemically, especially where the sulfide materials are not isolated completely. Periodic variation in the water table and seasonal variations may cause recurring oxidation and delayed contamination (Lottermoser, 2010).

4.6 Regional Variations in Water Quality

Significant regional variations in water quality were witnessed in key coal mining areas.

China

The mining of coal in China has a high level of heavy metal contamination because of the vigorous mining and inconsistent application of the regulations (Li et al., 2014).

United States (Appalachia)

The Appalachian region exhibits widespread effects of abandoned mine drainage, though some of the regions have been enhanced by regulatory systems that have ensured that water quality is better (Younger, 2001).

South Africa

AMD has had a severe impact in South Africa, particularly in the Witwatersrand Basin on groundwater systems and urban water supply (McCarthy, 2011).

4.7 Synthesis of Results

The comparative analysis shows that there are three major patterns:

1. The **abandoned mines** produce the worst and most long-lasting contamination due to the uncontrolled geochemical processes.
2. **Active mines** are regulated in terms of water quality, which is obtained as a result of the continuous treatment and management.
3. **Reclaimed mines** depict a partial recovery, although the stability in the long term is unpredictable based on the underlying hydrogeochemical processes.

These discoveries underscore the need to incorporate the understanding of processes, management practices, and monitoring in the long-term to deal with mine water pollution.

5. Discussion

The result of this review demonstrates that the hydrogeochemical processes and the interventions that are made in the management of coal mining environments are the fundamental drivers of the water quality in these environments. The comparative study of the active, abandoned, and reclaimed mines gives an evident line of measurement of impact on the environment, with abandoned mines being the most adverse and enduring sources of contamination, whereas active and reclaimed systems demonstrate levels of control and reclaim.

5.1 Dominance of Acid Mine Drainage as a Controlling Process

A central finding of this study is that acid mine drainage (AMD) continues to be the major source of water quality deterioration in all forms of mines. When the sulfide minerals, especially the pyrite, undergo oxidation, a series of reactions takes place, leading to acid formation and release of metals into aqueous systems (Nordstrom, 2011; Akcil & Koldas, 2006). This process turns out to be self-sustaining once it is established, especially in abandoned systems where mitigation measures are not instituted.

The ability of AMD to persist shows one major problem: mine water pollution is not a short-term problem but a long-term geochemical process. In materials that are exposed, oxidation reactions will also occur even after mining activities are abandoned, with the resultant contamination that can be decades or centuries long (Younger, 2001). This is the reason why the worst water quality is always observed in the results of abandoned mines.

5.2 Management-Dependent Stability in Active Mines

One of the principal differences appears between managed and unmanaged systems. Active mines prove the fact that water quality can be successfully managed by using engineered treatment systems, but this is a conditional process that should be managed by constant operation (Johnson & Hallberg, 2005). Conversely, abandoned mines have been used as an example of systems in which hydrogeochemical processes are left unregulated, causing continuing contamination. This is in contrast to highlight the role played by the management intervention in altering the natural geochemical behavior.

5.3 Reclaimed Mines: Between Recovery and Uncertainty

The reclaimed mines are a good example of how the environment can be restored, yet they also expose great restrictions. Although the surface stabilization and vegetation cover can mitigate the erosion and enhance the water quality, the subsurface processes usually occur (Skousen et al., 2017; Lottermoser, 2010).

This shows that the degree to which sulfide materials are separated and the regulation of the hydrological conditions are very critical to the success of reclamation. This causes reclaimed systems to be contaminated, delayed, or intermittently.

5.4 Role of Hydrogeochemical Modeling

Hydrogeochemical modeling helps in making insightful contributions to the long-term behavior of mine water. The chemical reaction, metal speciation, and mineral equilibria can be simulated with the help of such tools as PHREEQC (Parkhurst and Appelo, 2013). These models have the capability of assisting in decision-making by forecasting the trends of contaminants and analyzing remediation strategies.

Although they have potential, modeling approaches do not have extensive integration into operational mine management, and there is a gap in research and practice.

5.5 Influence of Climate Change on Mine Water Systems

The variability of climate adds extra uncertainty to mine water systems. Precipitation and temperature changes may cause changes in the oxidation rates, contaminant transport, and the effectiveness of the treatment (Palmer et al., 2010).

For example:

1. Greater precipitation stimulates the movement of contaminants.
2. The presence of drought leads to the concentration of pollutants.
3. An increase in the temperature elevates the kinetics of the reaction.

These reasons underline the necessity of climate-adaptive management plans.

5.6 Regional Variability and Governance Factors

The comparative study of China, the United States, and South Africa shows that the quality of water is highly dependent on the regulation and institutional factors.

1. The processes of industrialization and active mining in **China** have caused extensive pollution, and the problems related to implementation and the cumulative impact (Li et al., 2014).
2. Legacy pollution continues to be a problem in the **United States**, particularly in the Appalachia region, although the regulatory systems and clean-ups have helped in the situation in most areas (Younger, 2001).
3. The environmental and socio-economic problems in **South Africa** have been experienced through the negative effects of acid mine drainage on groundwater and urban water supply (McCarthy, 2011).

Such differences demonstrate that technological solutions are not helpful. Managing mine water would also need good governance, enforcement of laws, and long-term investments.

5.7 Ecological and Environmental Implications

Besides the chemical parameters, mine water pollution has severe ecological impact. Low biodiversity, disruption of the food chain, and the structure of the ecosystem are caused by acidic conditions and high levels of metal (Gray, 1997).

The deposition of metal, especially iron hydroxides, has the ability to coat the streambeds and deteriorate habitats, further affecting aquatic organisms. Also, the accumulation of heavy metals in biota endangers the greater trophic levels and human population relying on the impacted water resources (Lottermoser, 2010).

5.8 Policy and Management Implications

The policy and practice implications of the findings of this review are as follows:

1. The abandoned mine remediation should be given priority because it has long-term effects on the environment.
2. Incorporate closure planning into mine design to avoid contamination in the future.
3. Enhance the standards of reclamation to provide stability in the long term.
4. Adopt watershed-wide management approaches to address cumulative impacts.

5. Integrate climate adaptation measures in the management of mine water.

These actions are fundamental towards changing reactive to proactive environmental management. Figure 4 illustrates a combined method of mine water governance in the long term.

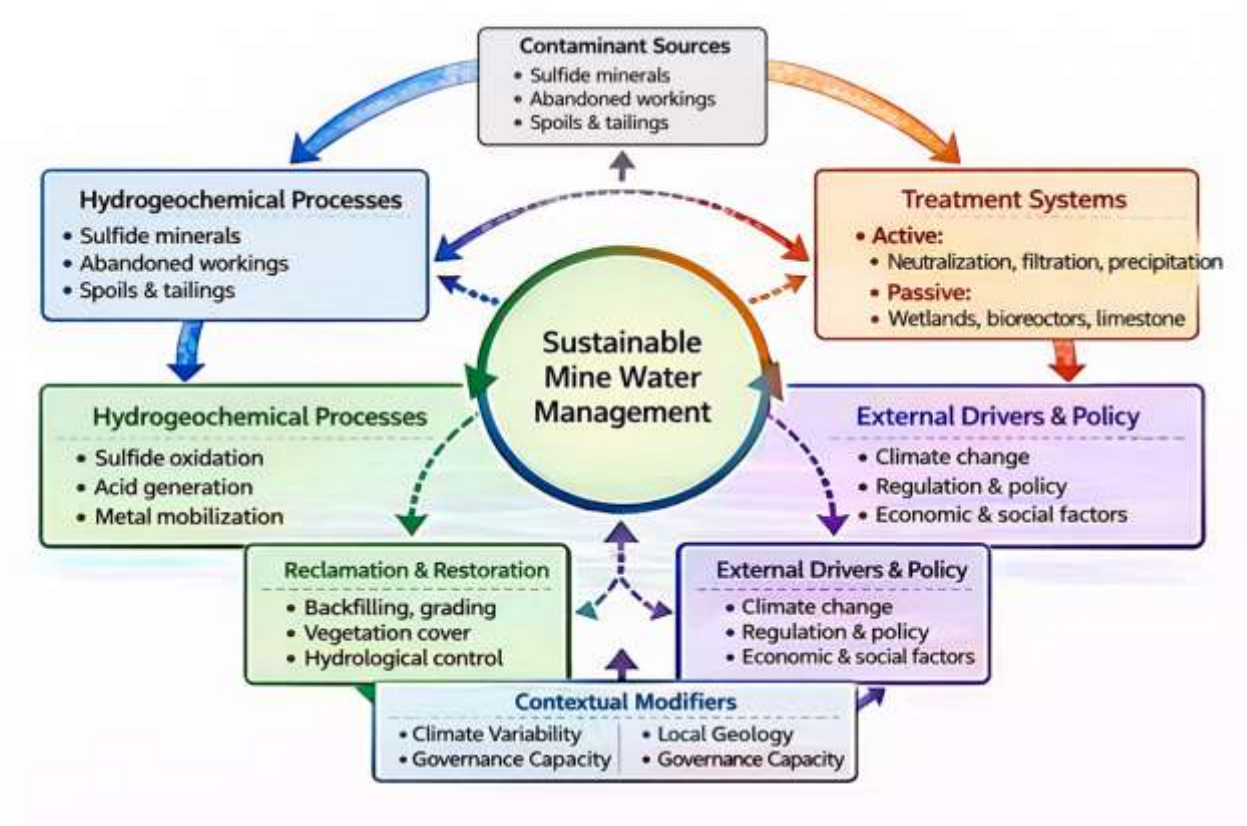

Figure 4. Conceptual framework on sustainable mine water management

Conceptual framework of sustainable mine water management, which demonstrates the interplay between hydrogeochemical processes, treatment systems, climate, and policy intervention.

Using this conceptual framework, management strategies may be considered in terms of their effectiveness, applicability, and sustainability in the long run under various mining conditions. A similar comparison of the management approaches of active, abandoned and reclaimed coal mines is as shown in Table 3.

Table 3. Comparative analysis of management strategies, mechanisms, effectiveness, and constraints of active, abandoned and reclaimed coal mines.

Mine Type	Management Strategy	Mechanism	Effectiveness	Limitations
Active	Chemical treatment (lime neutralization, filtration)	Neutralizes acidity and removes metals	High (short-term control)	High cost, requires continuous operation
Active	Advanced treatment (membrane, ion exchange)	Removes dissolved contaminants	Very high	Expensive, energy-intensive

Abandoned	Passive systems (constructed wetlands, limestone drains)	Natural neutralization and metal removal	Moderate to high	Slow response, site-specific
Abandoned	Source control (capping, water diversion)	Limits oxygen and water ingress	Effective (long-term)	Difficult implementation
Reclaimed	Land restoration (vegetation, soil cover)	Reduces erosion and infiltration	Moderate	Does not fully stop AMD
Reclaimed	Hydrological control (drainage design)	Stabilizes water flow and reduces exposure	Moderate to high	Long-term uncertainty

5.9 Overall Synthesis

The discussion confirms that the water quality within the coal mining regions is defined by the interactions of the natural processes and human interventions. Abandoned mines are uncontrolled systems that are contaminated, active mines are controlled, but dependent systems, and reclaimed mines are in-between systems whose long-term outcomes are unknown. This reinforces a key conclusion that sustainable mine water management should be based on the elimination of the causes of contamination and not on only treatment solutions.

6. Conclusion

The narrative review is a thorough comparative analysis of the water quality in active, abandoned, and reclaimed coal mines, in more detail, the prevailing effects of hydrogeochemical processes, and the effects that the management practices have had on the environment. The findings show distinctly that the most insurmountable and intractable causes of water pollution are symbolized by the deserted mines, which are driven by the unregulated acid mine drainage (AMD) and the unremitting sulfide oxidation. These systems pollute the watersheds with long-term loads of pollutants, which can not only impact on the whole watershed, but also these systems are extremely hazardous to the ecological and human condition.

Conversely, the water quality in active mines stays rather stable due to the planned treatment systems and the control of the water quality. But this stability is conditional and is based on constant functioning, economic investment, and institutional capacity. These systems have a high possibility of rapid degradation unless they are managed sustainably because of the geochemical processes.

There are measurable improvements in the water quality of recycled mines, in particular, higher pH and lower levels of metals. The long-term viability of reclamation has, however, been questioned due to the fact that the majority of the sites remain geochemically unstable due to the absence of complete isolation of the reactive material and fluctuating hydrologic conditions. This brings out the necessity of long-term monitoring and better reclamation design that encompasses both surface and subsurface processes.

The important role of hydrogeochemical models as well as climate-resilient management approaches, is also highlighted in the review as an important tool in predicting and lessening future risks. Climate variability will probably enhance the dynamics of contaminants, which will make the management of mine water even harder.

Generally, the environmental issues need a proactive and systematic approach that integrates scientific knowledge, engineering creativity, environmental restoration, and robust regulatory frameworks. Attention should be paid to the fact that the abandoned mines must be remedied, and long-term and adaptive strategies should be developed to protect the water resources.

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