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The potential threat of mine drainage to groundwater resources

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Abstract

Groundwater is an extremely valuable freshwater resource for drinking and agricultural use, and its value is increasing with global population growth. One of the potential threats to its water quality is mine drainage from abandoned mines. In recent years, progress has been made in investigating the impact of mine drainage on groundwater, as the use of various isotope analyses and improvements in numerical simulation techniques are applied constructing detailed conceptual models for evaluating contamination. This review examines the case studies to date from around the world and reports on the causes and characteristics of mine drainage, the potential for groundwater contamination, and some thoughts on the actions that should be taken.

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Keywords

Abandoned mines, Mine drainage, Metals contamination, Groundwater resources.

Introduction

Mine drainage is generally characterized by high concentrations of SO_4^{2-}, metals, and metalloids (hereinafter collectively referred to as metals) and is of serious environmental concern at many abandoned metal, native sulfur, and coal mines worldwide. Mine drainage is generated by oxidative dissolution of sulfides (exposed during and after mining) in contact with groundwater and the atmosphere and then released to surface and subsurface environments [1–4]. The pH values of mine drainage are often low due to these factors, known as acid mine drainage (AMD), but in some cases it is neutral due to the buffering effect of carbonate minerals [5,6]. Most currently operating mines have a zero-discharge policy for mine drainage, but for abandoned mines without legally responsible owner, mine drainage often escapes downstream with little or no treatment, except in cases where local governments or other organizations manage the mines [2,7]. Indeed, it is estimated that there are more than one million abandoned mines worldwide, there are 35,000 abandoned metal mines in the USA, 10,000 in Canada, and at least 1000 mines in Sweden [6,8,9]. However, not all abandoned mines produce mine drainage, for example, Japan has more than 5000 abandoned mines, and about 100 of these sites produce mine drainage [10,11]. This fact suggests that this generation of mine drainage reflects the different mining methods, topography, and geological conditions of each mine site. In addition, it reflects the effectiveness of measures implemented over several decades to reduce mine drainage.

Mine drainage originates from old mine workings at abandoned mines and from mine waste deposits. Mine wastes comprise unwanted and uneconomic materials (rocks, sediments, tailings, metallurgical wastes, dusts, ashes, and processing chemicals) that are dumped near mines. In the Río Tinto Mining District of Andalusia, Spain, where more than 5000 years of mining and natural weathering of sulfide ores have resulted in riverine input of As, Fe, Cu, Cd, Ni, Pb, and Zn, together with dust dispersion [12–15]. Similarly, in England and Wales, mine drainage from abandoned metal mines is a widespread form of water pollution [7,16]. The environmental impact of mine drainage resulting from mining waste has been reported to occur not only from abandoned mines but also from operating mines. The Zambian Copperbelt is famous for copper (Cu) and cobalt (Co) sulfide ore deposits in Central Africa, during the ore beneficiation and metal recovery processes, low pH sludge is generated and acid mine drainage discharges into the nearby surrounding environments [17]. In Cambodia, artisanal gold miners dump tailings and mine drainage from gold processing into rivers [18]. Coal-mine wastes can also be a major source of mine drainage and metal-sulfide waste rocks [1,2,19–28]. Demand for minerals continues to grow rapidly in emerging economies: in 2018, global coal consumption grew by 1.4%, double the 10-year average increase, while coal production increased by 162 million tonnes of oil equivalent (4.3%) [21]. Opencast mining has economic advantages over underground mining but affect the soil, vegetation, fauna, landforms, and surface water runoff, thus being potential threat to underground water storage [25,29–32].

A similar potential threat is from ores in the shallow alluvium deposits. Thailand has problems with tin residue. Most tin ores are found in alluvial deposits and the waste piles contain high As, and percolation from the tailing ponds can leak and, eventually, contaminate the groundwater [33]. Similar problems are of concern in Pakistan due to mine effluent generated by coal mining [22]. In the Philippines, artisanal and small-scale gold mining operations are major contributors to the Philippines' annual gold (Au) output, and these activities lack adequate tailings management strategies, so contamination of the environment is prevalent [34]. Carbonate aquifers hold substantial groundwater resources in many areas. In Europe, for example, water resources hosted in carbonate rocks satisfy ~50% of human consumption. Such aquifers are particularly vulnerable to contamination, especially in areas affected by mining activities [35]. With more than 3500 coal mines closed over the last 30 years, China is incurring environmental problems, particularly worsening contamination of carbonate aquifers [20,23,36].

The environmental impact of abandoned mines is a global issue and, with the rise of public awareness and activism, in some cases, this has led to opposition to the development of new resources [4,37]. Previous reviews on select aspects of mine drainage are listed in Table 1. These reviews have considered the mechanisms of production of mine drainage, its treatment, and counter measures against controlling its generation, particularly mining wastes as a mine drainage source, but few have focused on the impact of mine drainage on groundwater resources [3,4,7,9,15,19,23,36–43]. This review surveys case studies of groundwater contamination affected by mine drainage, and reports from the aspect of research methodology.

Online journals with a scope of groundwater hydrology and environmental pollution associated with mining activities were searched for "acid mine drainage" and "mine drainage" keywords between January 2015 and August 2021. In addition, articles cited in relevant literature and published during the writing of this review were also included, resulting in a total of 380. All of these were scrutinized, and 88 articles were selected for review as they were considered to contain the relevant information (Figure 1). In order to select appropriate articles for this review, articles dealing with real mine drainage issues in the environment were screened based on their title, abstract and texts. The number of countries affected is 36, covering the regions of Africa, Americas, Asia, Europe and Oceania, suggesting that groundwater pollution, possibly caused by mine drainage, is a global issue (Table 2).

Mechanisms of mine drainage generation and migration

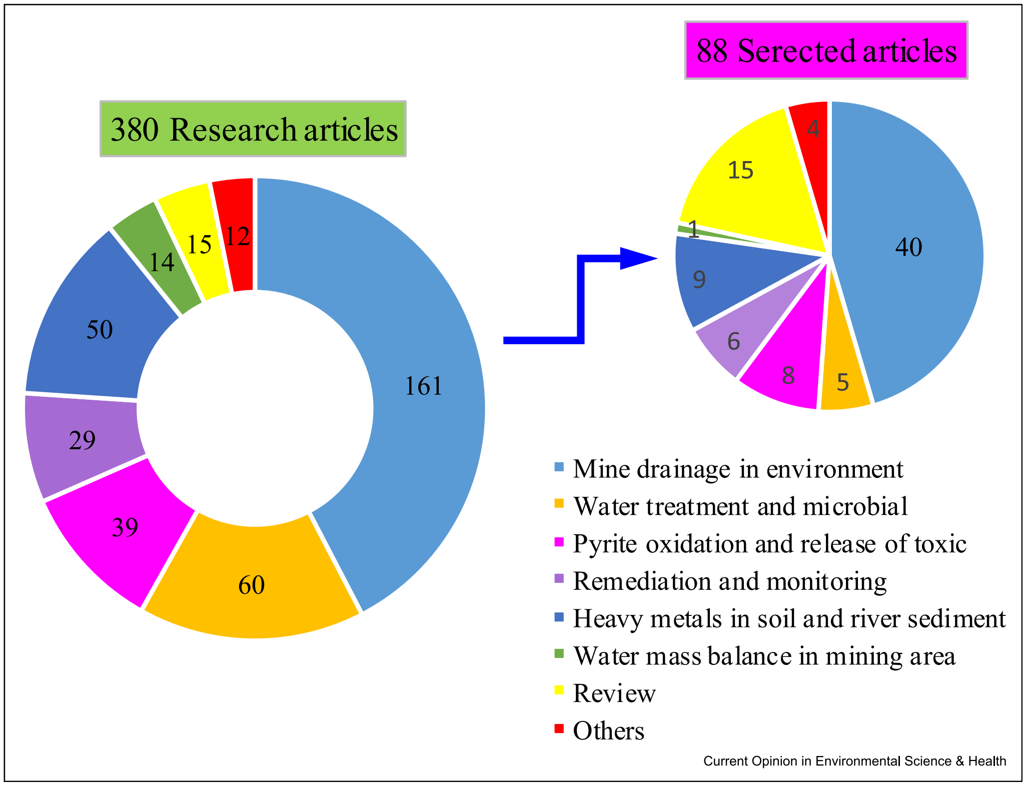
Mine drainage is generated by iron disulfide (FeS_2), commonly known as pyrite, exposed to water and

Table 1

Previous reviews on various aspects of mine drainage.

Title:	Year	Reference
Impact of climate change on acid mine drainage generation and contaminant transport in water ecosystems of semi-arid and arid mining areas	2013	[38]
Acid mine drainage: Challenges and opportunities	2014	[7]
Sustainable rehabilitation of mining waste and acid mine drainage using geochemistry, mine type, mineralogy, texture, ore extraction and climate knowledge	2015	[3]
Acid mine drainage: Prevention, treatment options, and resource recovery: A review	2017	[4]
Arsenic, selenium, boron, lead, cadmium, copper, and zinc in naturally contaminated rocks: A review of their sources, modes of enrichment, mechanisms of release, and mitigation strategies	2018	[39]
Review mine waste rock: Insights for sustainable hydrogeochemical management	2020	[19]
Occurrence and environmental impact of coal mine goaf water in karst areas in China	2020	[23]
Sustainable resolutions for environmental threat of the acid mine drainage	2020	[37]
A comprehensive review of environmental and operational issues of constructed wetland systems	2020	[40]
Metal(loid) release from sulfide-rich wastes to the environment: The case of the Iberian Pyrite Belt (SW Spain)	2021	[15]
The role of macrophytes in constructed surface-flow wetlands for mine water treatment: A review	2021	[41]
Characteristics of water hazards in China's coal mines: A Review	2021	[36]
Do old mining areas represent an environmental problem and health risk? A critical discussion through a particular case	2021	[9]
A critical review of prevention, treatment, reuse, and resource recovery from acid mine drainage	2021	[42]
Microbial sulfur metabolism and environmental implications	2021	[43]

Figure 1



Summary of bibliometric analysis.

oxygen, resulting in oxidation and hydrolysis that produce sulfuric acid (H_2SO_4), which in turn leaches other metals, as shown in Equation (1).

$$2FeS_2 + 7O_2 + 2H_2O = 2Fe^{2+} + 4SO_4^{2-} + 4H^+ \quad (1)$$

Pyrite oxidation is facilitated by Fe^{3+}, formed either directly through the oxidation of Fe^{2+} by dissolved oxygen (Equations (2) and (3)) (i.e. [2, 12, 18, 19, 29, 83]).

$$4Fe^{2+} + O_2 + 4H^+ = 4Fe^{3+} + 2H_2O \quad (2)$$

$$FeS_2 + 14Fe^{3+} + 8H_2O = 15Fe^{2+} + 2SO_4^{2-} + 16H^+ \quad (3)$$

Once conditions become more acidic, the dissolution/oxidation of other associated sulfide minerals (e.g., sphalerite (ZnS) and chalcopyrite ($CuFeS_2$)) is also accelerated as illustrated in Equations (4) and (5).

$$ZnS + 2O_2 \rightarrow Zn^{2+} + SO_4^{2-} \quad (4)$$

$$CuFeS_2 + 4O_2 \rightarrow Cu^{2+} + Fe^{2+} + 2SO_4^{2-} \quad (5)$$

The details of the process are complex, involved in sequential and parallel reactions, such as gas exchange, mineral precipitation, surface chemistry, redox reactions, and even catalyzed by bacteria, and how these reactions are related is still under debate. Of these, bacteria have attracted much attention in recent years as they can have a small to large impact on this process by facilitating the oxidation of sulfide minerals [23,52,86]. In addition, mine drainage can be generated from the oxidation of sulfidic minerals [19,43]. In the case of mine drainage from underground mining, pH, and metal concentrations are highly dependent on the flow rate of groundwater infiltrating from the surface and to what degree it is in contact with the atmosphere. As mining activity progresses, groundwater seepage in excavated areas lowers the groundwater table, allowing groundwater aerobic, enhancing mine drainage generation [68,84]. If an abandoned mine and its surrounding area are in a groundwater flow field (i.e., where there are clear flow pathways such as in carbonate aquifers or faults) the groundwater and generated mine drainage flow in the direction of lower hydraulic potential and discharge to a lower topographic elevation, such as rivers and lakes [56]. Pollution of groundwater occurs during these processes. Mine drainage in opencast mining involves the same principles.

Table 2

The various countries covered by the mine drainage research.

Title:	Year	Country	Reference
Africa			
Evaluation of mine site reclamation performance using physical models: Case of Ity mine (Ivory coast)	2021	Côte d’Ivoire	[44]
Characterization and environmental impact assessment of gold mine tailings in arid regions: A case study of Barramiya gold mine area, Eastern Desert, Egypt	2019	Egypt	[45]
Impact of mine tailings on surrounding soils and ground water: Case of Kettara old mine, Morocco	2014	Morocco	[46]
Geochemistry and potential environmental impact of the mine tailings at Rosh Pinah, southern Namibia	2015	Namibia	[6]
Gold mine tailings: A potential source of silica sand for glass making	2020	South Africa	[47]
Trend evolution of physicochemical parameters and metals mobility in acidic and complex mine tailings long exposed to severe mediterranean climatic conditions: Sidi Driss tailings case (NW-Tunisia)	2019	Tunisia	[48]
Geochemical behaviour of heavy metals in sludge effluents and solid deposits on the Zambian Copperbelt: Implication for effluent treatment and sludge reuse	2021	Zambia	[17]
Americas			
Environmental impact on soil, water and plants from the abandoned Pan de Azúcar Mine	2013	Argentina	[49]
Synchrotron XAS study on the As transformations during the weathering of sulfide-rich mine wastes	2019	Argentina	[50]
Passive co-treatment of Zn-rich acid mine drainage and raw municipal wastewater	2013	Bolivia	[51]
Chitin as a substrate for the biostimulation of sulfate-reducing bacteria in the treatment of mine-impacted water (MIW)	2019	Brazil	[52]
Combining zinc desorption with EXAFS speciation analysis to understand Zn mobility in mining and smelting affected soils in Minas Gerais, Brazil	2021	Brazil	[53]
Electrokinetic remediation of manganese and zinc in copper mine tailings	2019	Chile	[54]
A methodology based on magnetic susceptibility to characterize copper mine tailings	2020	Chile	[55]
Modelling of sulfide oxidation with reactive transport at a mine drainage site	2000	Canada	[56]
The behavior of inclined covers used as oxygen barriers	2003	Canada	[57]
Numerical modelling of flow and capillary barrier effects in unsaturated waste rock piles	2005	Canada	[58]
Numerical simulations of pyrite oxidation and acid mine drainage in unsaturated waste rock piles	2005	Canada	[59]
Stable isotope geochemistry of ground and surface waters associated with undisturbed massive sulfide deposits; constraints on origin of waters and water−rock reactions	2006	Canada	[60]
Numerical prediction of the long-term evolution of acid mine drainage at a waste rock pile site remediated with an HDPE-lined cover system	2018	Canada	[61]
Three-dimensional hydrogeological modeling to assess the elevated-water-table technique for controlling acid generation from an abandoned tailings site in Quebec, Canada	2018	Canada	[62]
3D time-lapse geoelectrical monitoring of water infiltration in an experimental mine waste rock pile	2019	Canada	[63]
Scale dependence of effective geochemical rates in weathering mine waste rock	2020	Canada	[64]
Arsenic and mercury contamination and complex aquatic bioindicator responses to historical gold mining and modern watershed stressors in urban Nova Scotia, Canada	2021	Canada	[8]
Reactive transport modelling to investigate multi-scale waste rock weathering processes	2020	Peru	[65]
Pyrite flotation separation and encapsulation: A synchronized remediation system for tailings dams	2021	Peru	[66]
Predicting ground-water movement in large mine spoil areas in the Appalachian Plateau	1999	USA	[67]
Chemical evolution of coal mine drainage in a non-acid producing environment, Wasatch Plateau, Utah, USA	2000	USA	[27]
Characterisation of acid mine drainage using a combination of hydrometric, chemical and isotopic analyses, Mary Murphy Mine, Colorado	2002	USA	[68]

Table 2 (*continued*)

Title:	Year	Country	Reference
Geochemistry and stable isotope investigation of acid mine drainage associated with abandoned coal mines in central Montana, USA	2010	USA	[2]
Tackling mine wastes-Global collaboration is needed to mitigate the environmental impacts of mine wastes-	2016	USA	[14]
Acid mine drainage risks – A modeling approach to siting mine facilities in Northern Minnesota USA	2016	USA	[69]
Predicted post-closure aqueous geochemistry at the Cortez Hills underground mine, Nevada, USA	2021	USA	[70]
Asia			
Seasonal effects of natural attenuation on drainage contamination from artisanal gold mining, Cambodia: Implication for passive treatment	2022	Cambodia	[18]
Coupled S and Sr isotope evidences for elevated arsenic concentrations in groundwater from the world's largest antimony mine, Central China	2018	China	[71]
Origins and mixing contributions of deep warm groundwater in a carbonatehosted ore deposit, Sichuan-Yunnan-Guizhou Pb–Zn triangle, southwestern China	2020	China	[72]
Effects of Fe-rich acid mine drainage on percolation features and pore structure in carbonate rocks	2020	China	[73]
Public health risk of toxic metal (loid) pollution to the population living near an abandoned small-scale polymetallic mine	2020	China	[74]
Effects of groundwater table decline on vegetation transpiration in an arid mining area: A case study of the Yushen mining area, Shaanxi Province, China	2020	China	[75]
Varying effects of mining development on ecological conditions and groundwater storage in dry region in Inner Mongolia of China	2021	China	[21]
Impacts of acid mine drainage on karst aquifers: Evidence from hydrogeochemistry, stable sulfur and oxygen isotopes	2021	China	[20]
Solid-phase partitioning and release-retention mechanisms of copper, lead, zinc and arsenic in soils impacted by artisanal and small-scale gold mining (ASGM) activities	2020	Philippine	[34]
Acid mine drainage in an Indian high-sulfur coal mining area: Cytotoxicity assay and remediation study	2020	India	[31]
Application of artificial neural network coupled with genetic algorithm and simulated annealing to solve groundwater inflow problem to an advancing open pit mine	2016	Iran	[32]
Forecast of AMD quantity by a series tank model in three stages: Case studies in two closed Japanese mines	2020	Japan	[10]
Projecting future changes in element concentrations of approximately 100 untreated discharges from legacy mines in Japan by a hierarchical log-linear model	2021	Japan	[11]
Acid mine drainage sources and impact on groundwater at the Osarizawa Mine, Japan	2021	Japan	[76]
Does a sum of toxic units exceeding 1 imply adverse impacts on macroinvertebrate assemblages? A field study in a northern Japanese river receiving treated mine discharge	2020	Japan	[77]
Phialocephala fortinii increases aluminum tolerance in *Miscanthus sinensis* growing in acidic mine soil	2021	Japan	[78]
Metal accumulation and tolerance in *Artemisia indica* var. *maximowiczii* (Nakai) H. Hara. and *Fallopia sachalinensis* (F.Schmidt) Ronse Decr., a naturally growing plant species at mine site	2021	Japan	[79]
Improvement in pH and total iron concentration of acid mine drainage after backfilling: A case study of an underground abandoned mine in Japan	2021	Japan	[80]
Potential of coal mine waste rock for generating acid mine drainage	2016	Pakistan	[22]
Heavy metal contamination and health risk assessment in the vicinity of the abandoned Songcheon Au–Ag mine in Korea	2008	South Korea	[81]
Risk assessment of arsenic from contaminated soils to shallow groundwater in Ong Phra Sub-District, Suphan Buri Province, Thailand	2018	Thailand	[33]
Europe			
Prediction of diffuse sulfate emissions from a former mining district and associated groundwater discharges to surface waters	2014	Germany	[82]
The role of mineral assemblages in the environmental impact of Cu-Sulfide deposits: A case study from Norway	2021	Norway	[83]

(*continued on next page*)

Table 2 (*continued*)

Title:	Year	Country	Reference
Arsenic in the Wiśniówka acid mine drainage area (south-central Poland) –Mineralogy, hydrogeochemistry, remediation	2018	Poland	[29]
Changes of groundwater chemistry caused by the flooding of iron mines (Czestochowa Region, Southern Poland)	2001	Poland	[84]
A national strategy for identification, prioritisation and management of pollution from abandoned non-coal mine sites in England and Wales. I. Methodology development and initial results	2009	UK	[1]
Effect of an extreme flood event on solute transport and resilience of a mine water treatment system in a mineralised catchment	2021	UK	[16]
Mineralogy and geochemistry of the copper-dominated neutral mine drainage at the Cu deposit Ľubietová-Podlipa (Slovakia)	2018	Slovakia	[5]
Aqueous geochemistry and oxygen isotope compositions of acid mine drainage from the Río Tinto, SW Spain, highlight inconsistencies in current models	2009	Spain	[12]
Hydrological investigation of a multi-stratified pit lake using radioactive and stable isotopes combined with hydrometric monitoring	2014	Spain	[13]
Monitoring opencast mine restorations using Unmanned Aerial System (UAS) imagery	2019	Spain	[30]
Conceptualization and finite element groundwater flow modeling of a flooded underground mine reservoir in the Asturian Coal Basin, Spain	2019	Spain	[24]
Assessing vegetation recovery in reclaimed opencast mines of the Teruel coalfield (Spain) using Landsat time series and boosted regression trees	2020	Spain	[25]
Acid mine drainage (AMD) treatment: Neutralization and toxic elements removal with unmodified and modified limestone	2015	Finland	[85]
Complete removal of arsenic and zinc from a heavily contaminated acid mine drainage via an indigenous SRB consortium Pierre	2017	France	[86]
Chemical treatment of highly toxic acid mine drainage at a gold mining site in Southwestern Siberia, Russia	2020	Russia	[87]
Carbonate aquifers threatened by legacy mining: hydrodynamics, hydrochemistry, and water isotopes integrated approach for spring water management	2021	Italy	[35]
Oceania			
Impacts of coal mining and coal seam gas extraction on groundwater and surface water	2020	Australia	[26]
Economic performance of active and passive AMD treatment systems under uncertainty: Case studies from the Brunner Coal Measures in New Zealand	2020	New Zealand	[28]
Mining in Papua New Guinea: A complex story of trends, impacts and governance	2020	Papua New Guinea	[88]

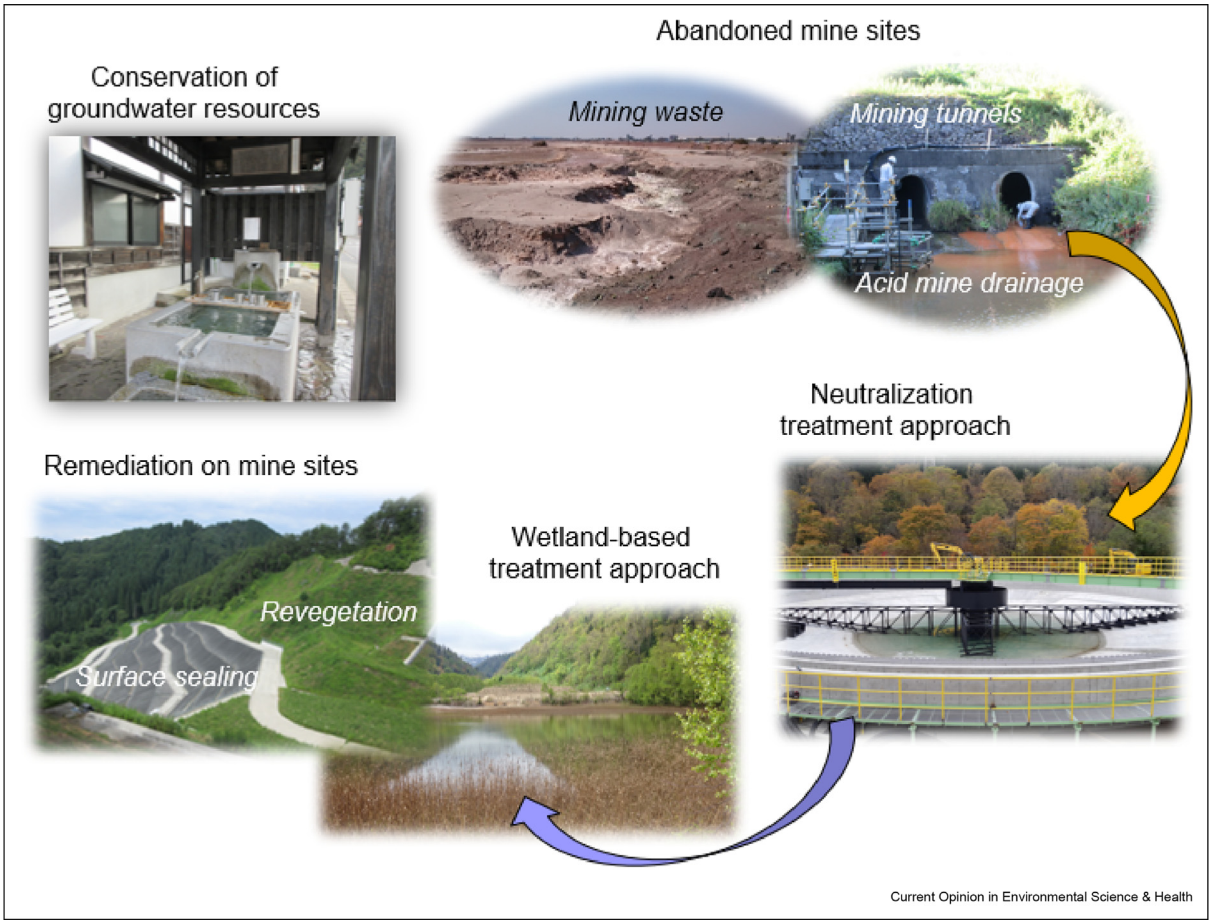
With waste rock piles by mining, mine drainage is produced when rainwater and snowmelt water infiltrate into the top surface of pikes and percolate in unsaturated conditions. This process is controlled by gravitational and capillary forces and may form preferential pathways depending on the particle size distribution and internal structures of the layers [44,56–59,61–63,66]. The generated mine drainage is eventually discharged into the subsurface or, if the base rock is relatively impermeable, it is discharged from the pile toe and impacts surface water [14,22,33,34,44–48,50,53–55,58,63,87].

Mine drainage has severe environmental impacts, particularly on soil and water resources [4,37], with the combination of low pH and high metal concentrations having serious toxicological effects on aquatic ecosystems, such as rivers, which often have high metal loadings around abandoned mines [77]. Exposure of organisms to high metal concentrations may kill them directly, while long-term exposure with lower concentrations may cause increased mortality or other effects such as retarded growth, lower reproduction rates, deformities, and lesions [68]. Exposure to metal-bearing particles through inhalation and ingestion of contaminated food crops and drinking water are the most important pathways of risks to human health [74,81].

Evaluation of mine drainage by inductive reasoning

The understanding of groundwater flow systems and the impact of mine drainage on groundwater resources is based on both inductive and deductive reasoning. Inductive reasoning involves the interpretation of data such as isotopic compositions and water quality in an integrated manner and the development of a hydrogeological conceptual model to explain each dataset without contradiction [2,13,67,68,76]. Inductive reasoning typically involves the use of stable O–H

Figure 2



Remediation and wetland-based treatment approaches for the protection of groundwater resources.

isotopes (^{18}O and ^{2}H) in H_2O as tracers, because these isotopes are naturally occurring and in most cases are conservative in reactions in groundwater aquifers [2,13,23,67,68,72,73,76]. Lighter isotopes are preferentially involved in melting and evaporation, and heavier isotopes in condensation and freezing, allowing the possibility of identifying the origins of groundwater and mine drainage, or evaluating their mixing ratio [68]. A case study on the origin of mine drainage reported that there is a clear negative correlation between the average catchment elevation of a river, and stable O—H isotopes, showing that mine drainage originates at 400—500 m a.s.l., which corresponds to the elevation of the mountain body where the ore veins are distribute [76]. In the Apuan Alps (NW Tuscany, Italy), carbonate aquifers are contaminated by thallium (Tl) and an isotopic water study estimated the mean elevation of groundwater recharge and examined its relation to the location of abandoned mines as a source of Tl [35].

O—H isotopes have been widely applied as groundwater tracers, and they are also applicable in areas affected by mine drainage. Mine drainage usually contains high SO_4^{2-} concentrations, and many studies have reported the use of $\delta^{34}S$ values in identifying its origin [2,13, 20,23,27,60,71]. Carbon isotopic ratios ($\delta^{13}C$) have also been used [60]. Comprehensive interpretations have been undertaken in conjunction with measured water quality such as pH, electric conductivity, and cations, anions, and metal concentrations in groundwater and mine drainage. Some studies have attempted to validate conceptual models of groundwater flow and contamination by ^{3}H dating [53]. In research applying the aforementioned approach to coal mines in China, conceptual models have proposed through which pathways mine drainage percolated, such as faults and fractures in limestone, Karst conduits, and abandoned wells [20,23,71—73]. The results of these studies include that the stable isotopic compositions of carbon and sulfur were valid for distinguishing inorganic vs. organic carbon sources and pyrite vs. gypsum sulfur sources in mine drainage [27]. Research on the impact of mine drainage on groundwater in central Montana, USA, have suggested that the groundwater contains isotopically light sulfate, possibly due to mixing with mine drainage from the nearby coal mine [2].

A recent unique study [72] reported on groundwater from mining tunnels excavated at a depth of 1500 m, with Sr concentrations and $^{87}Sr/^{86}Sr$ ratios being determined as well as O−H isotopic ratios. A mixing model of shallow groundwater infiltration from the surface and deep groundwater formed during the last glacial period was thus developed. Another study [73] of the effects of mine drainage on pore structural changes in carbonate aquifers confirmed channel formation by mine drainage and blockage by precipitation of Fe hydroxides. These studies are noteworthy for their new insights into the potential impact of deep underground mining on groundwater resources.

Evaluation of mine drainage by deductive reasoning

Deductive reasoning draws conclusions based on universal principles, typically by numerical simulation. During mine operation, groundwater is discharged during excavation, and it is necessary to consider both the quantity of groundwater discharged and vertical fluctuations in the water table. Groundwater flow simulation, estimating groundwater flow based on Darcy's law and the conservation of mass, has been widely applied in studies of mine drainage environmental impact [24,26,57,58]. A study of a coal mine in Kentucky, USA, involved numerical simulations in elucidating the mechanisms of groundwater storage and flow [67]. Simulation results were consistent with the hydrogeological conceptual model through which mine drainage flowed along old valley topography beneath the residual sediments and out onto the ground surface, and with water-head observations at monitoring wells; the simulation was able to reproduce the actual underground flow field.

Many groundwater simulations coupled with water−mineral reactions have been reported during the 2000s with the increase in computational speed and capacity of computer systems [56,58,61,62,65,82]. For example, in the Sydney Coalfield, Canada, long-term predictions were attempted [61] concerning the effect of a cover system installed over waste rock to limit H_2O and O_2 ingress and to attenuate the environmental impact of mine drainage. Results indicate that groundwater quality will reach background levels within the next 40 years. Covers with capillary barrier effects has been proposed as a viable option for gas migration barriers for waste rock piles. Comprehensive research have been carried out on this subject, through laboratory tests, field measurements and simulations, then in addition to the predicted effects, the insight that capillary layers must be designed using relatively non-reactive or sulfur-free material to limit mine drainage [57−59]. As shown in the above case studies, groundwater simulations supported by sufficient high-quality data are thus an effective tool in designing mine drainage control measures. Hydrogeochemical models used in simulations are often parameterized by short-term, small-scale laboratory or field experimental data. However, model parameters and sulfide oxidation processes may vary temporospatially, and the upscaling of models are challenging, then it is an issue [64,65].

Management and future perspectives

Despite these studies, prevention of mine drainage is difficult, and abandoned mines worldwide still pose significant threats to the environment. Remediation usually involves input of lime to raise the mine drainage pH and to precipitate metals, although such treatment is expensive [28,37,51,52,68,85,86]. Furthermore, the time required for flow rates and metal concentrations of mine drainage to decrease naturally exacerbates the problem [7,42]. There are more than 5000 abandoned and closed mines in Japan, and mine drainage treatment is undertaken for ∼100 mines of them, taken under obligation to national and local governments over the past 50 years. A study of future predictions based on mine drainage water-quality data for these mines has indicated that it is over-optimistic to expect metal concentrations in most mine drainage to decrease to below nationwide drainage standard levels in the near future [11]. Furthermore, at mines with large mine drainage releases, the treatment may come complicated by climate change [10].

Based on the current understanding of mine drainage generation, the most effective countermeasure may be to use mining and construction wastes as materials to be backfilled into excavated areas created by mining activities, thereby raising the lowered groundwater table and submerging the mining wastes. However, the limitation of this method would be the impact on the surrounding environment if groundwater in contact with backfilled material with pyrite flowed off site [37,39]. Due to this issue, it is important to determine if the tunnel water would adversely affect the adjacent groundwater once hydraulic conditions stabilize and ambient groundwater flow is reestablished, as several cases of this have been reported in recent years [70,80]. The next-best solution may be to prevent rainwater and groundwater infiltration to reduce the production of mine drainage, or to improve the current drainage treatment methods to reduce cost [13,29,63]. For mine drainage treatment, cost reductions can be achieved with a wetland-based treatment approach. The wetland-based treatment approach have developed rapidly over the last 3 decades being established worldwide as an alternative to conventional and more technically equipped treatment systems. It has recently gained significant acceptability, with special regard to emerging economies, mainly because of their versatility, economic and environmental benefits [4,6,40,41]. These approaches are described in Figure 2.

Varying degrees of success were achieved through understanding the characteristics of mine sites and mine drainage. Sustainable solutions to the mine drainage problem are thus best attained through a business-like approach considering the integration of existing and developing technologies to devise a solution that addresses the problem in a holistic and sustainable manner [7]. It is necessary to prioritize abandoned mine sites and to create a database that consolidates the relevant data for review. In England, Wales, and Ireland, the effectiveness of this approach is indicated by pollution mapping and future predictions based on the Geographic Information System (GIS), its associated database, and various analysis tools [1,14,69]. Case studies involving GIS have indicated the close relationship between groundwater storage and vegetation at abandoned mine sites [21,75]. Since vegetation has been mentioned in mine drainage studies, mine-site remediation, and water treatment by constructed wetlands [3,15,25,30,40], there are new insights into the metal tolerance of plants [49,78,79]. To take advantage of this wide range of possibilities, a comprehensive engineering approach is necessary including collaboration straddling among different specialized fields.

Addressing the environmental impact of mine drainage is an urgent issue, not only for decommissioned mines but also for newly developed mines [88]. Frameworks transcending disciplines, organizations, and national boundaries should be established as soon as possible.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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