Effects of Mining on Surface Water—Case Studies

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In memoriam Li Wenliang (李文亮)—and the million others.

Glossary

Acid mine drainage Acid mine drainage is mining influenced water with a pH below 5.6, characterized by high proton, (semi-) metal and sulfate concentrations and an elevated mineralization.
Acid rock drainage Acid rock drainage is a low pH water resulting from pyrite oxidation in natural rocks.
Acidithiobacillus thiooxidans *Acidithiobacillus thiooxidans* is a microorganism catalyzing pyrite oxidation by a factor of up to one million. It gains its energy from the oxidation of sulfur.
Atlantic Forest Atlantic Forest is a South American biome, characterized by high biodiversity and endemism.
Barite Barite is a sulfate mineral with the formula $BaSO_4$.
Bootleg workings Bootleg workings are a historic or traditional mining method which extracts the raw material down to shallow depths leaving a bootleg type opening underground.
Category of accident risk Category of accident risk of a dam refers to the aspects of the dam itself that may influence the probability of an accident: project aspects, structure integrity, conservation, operation and maintenance status, and compliance with its Safety Plan.
Cone of depression Cone of depression is the subsoil area that becomes dewatered when mines are pumped.
Decommissioning Decommissioning is the final termination of a mining or processing operation, removing plant and equipment, and disposing wastes.
Digital twins Digital twins are computer simulations of water treatment plants to understand and visualize all relevant processes that would occur in the real plant.
Dry stacking Dry stacking is a process by which dewatering of tailings can be done with the help of vacuum or pressure filters, with the aim of stacking the tailings afterwards.
Efflorescent salts Efflorescent salts are minerals that are formed when mineralized mine water evaporates and leaves back easily water-soluble minerals.
Electrical conductivity Electrical conductivity (EC) is a measure for the potential of a liquid to conduct electricity. In general, the more ions are dissolved in a liquid, the higher this value will be, which is usually measured in mS cm^{-1} or μS cm^{-1}. It is compensated to either 25 ∘C or, more seldom, to 20 ∘C. Because of this characteristic, the electrical conductivity can be used for a quick indication of a mine water's contamination status.
First flush First flush is the fast increase of water constituents after an underground mine is flooded and the subsequent decrease of these constituents' concentrations over time, while fresh water kärchers the mine workings.
Geochemical barrier Geochemical barrier is a subsoil remediation method that uses reactive material in a permeable, vertical layer of various length, depths, and thickness to react with pollutants in flowing groundwater.

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Iberian Pyrite Belt Iberian Pyrite Belt is the world's largest single ore district for copper and iron ore stretching from Spain to Portugal.
In-lake-neutralization In-lake-neutralization is an open pit mine water remediation method using various chemicals and gasses applied to the mining influenced water to increase the pH of acidified open pit lakes.
Inundation Inundation is an accidental inflow of water into mine workings, predominantly underground mines, eventually causing the mine to flood.
Karstified Karstified rocks are mainly composed of carbonate minerals that are dissolved by acidic ground water, leaving back caves or sinkholes.
Leptospirillum ferrooxidans *Leptospirillum ferrooxidans* is a microorganism that catalyzes pyrite oxidation by a factor of up to one million. It gains its energy from the oxidation of iron.
Micro-/macrocosm Micro-/macrocosm is a lake remediation method using enclosures of various size installed in open pit lakes and filled with various reactive substrates to inhibit microbial growth and subsequently sulfate reduction and metal precipitation.
Mine pool Mine pool is not a public swimming location underground, but the sum of all the polluted or unpolluted water collected in an underground mine.
Mine water Mine water or mining influenced water (not: mine wastewater, mining impacted water, mining affected water) is all the water in a surface or underground mine or seeping through waste rock. Strictly speaking, the water from the processing plant and the tailings is process water, as it contains human-induced process chemicals.
Mudflow Mudflow is a mass movement that involves an extremely rapid to fast, sometimes surge-like flow of debris, sediments, and sludge. In the presence of substantial amounts of water, the material may become partially or completely liquid.
Ochre Ochre is a collective term for yellow to dark orange iron oxides with a clayey to sandy composition.
Passive treatment Passive treatment is a remediation method for polluted mine water or soil which uses only natural or potential energy, plants, and microorganisms for improving mine water quality.
Process intensification Process intensification is a method to optimize an existing process, instrument, or device such that its use is optimized. The addition of a centrifugal governor to old style steam engines by James Watt is considered a process intensification bringing steam engines to save and reliable use.
Pyrite Pyrite is a sulfide mineral with the formula FeS_2. Though chemically identical to marcasite, it has another crystal structure. When pyrite or marcasite come into contact with water and oxygen, acid mine drainage or acid rock drainage forms.
Reactive wall Reactive wall see geochemical barrier.
Siltation Siltation is often a result of soil erosion or sediment pollution whose particle size is mainly in the silt or clay range. It may result in the pollution of water courses.
SPOT-6/LANDSAT-8 SPOT-6/LANDSAT-8 are satellite systems that are capturing the earth's surface by means of scanners or cameras with various wavelengths.
Tailings Tailings are the fine-grained residues of mineral processing and contain currently uneconomic crushed and milled rock and chemicals from the processing plant. Tailings are stored in sludge ponds, called tailings dams, or are dry stacked in tailings disposal sites.
Tailings dams Tailings dams contain the residues of raw material processing, and the dams are typically built of loose material.
Trophic levels Trophic levels are the different hierarchical levels from primary producers to primary and secondary consumers in a food chain.

Introduction

Selecting suitable case studies for mining influenced surface waters is an easy task because there are so many well-described studies from around the world. However, this does not imply that all mining operations cause pollution in the receiving water bodies or are prone to tailings dam failures—it just means that those that occur are often well studied. The intention behind selecting the following sites as case studies was: to describe and illustrate some important mining influenced rivers/streams; to describe the pollution sources and potential remediation options in these rivers/streams; and, to indicate that irresponsible conduct could cause severe regional, social and environmental effects (Table. 1). In addition, these sites are all located in mining areas of outstanding importance to human's mining history—which will be left to historians and archeologists to document. Besides the case studies presented, here could also be a case study about the Loisach rivulet near Biberwier in Tirol, which once was affected by lead, zinc, and silver mining, but now is a beautiful mountain stream. Or the Sabie River in South Africa could be shown, which is partly fed by abandoned gold mine discharges, and now used as drinking water and for recreational purposes for the town and tourists of Sabie. Moreover, this section could include the Metsämonttu mine in Finland, where natural attenuation and a small constructed aerobic wetland decrease the iron concentrations below the detection limit before the mine water enters a Natura 2000 protected river system. However, images of clean water are less impressive in this context than images of red or orange water—though the Cape Breton Island section shows a clean-water image for Cadegan's Brook, which is an excellent example of successful remediation measures. This section's intention is also to present case studies from which we can learn how to tackle the problems associated with polluted mine water and with the storage of mining residues, such as tailings.

Table 1 Details of the presented case studies and reasons for their inclusion. Geographical co-ordinates in WGS84 of the area's center.

Country	*Canada*	*Spain*	*Germany*	*South Africa*	*Russia*	*Brazil*	*Brazil*
Region	Cape Breton Island	Iberian Pyrite Belt	Lusatia lignite mining	Western Basin Witwatersrand	Kizel Coal Basin	Germano Mine Complex	Córrego do Feijão Iron Mine
Affected Watercourses	Cadegan's Brook	Río Tinto, Río Odiel	River Spree, open pit lakes	Tweelopiespruit	Poludennyi Kizel, Yaiva	Doce River	Paraopeba River
Raw Material	Coal	Copper, Gold	Lignite	Gold	Coal	Iron	Iron
Reason for Inclusion	Passive treatment system	Never ending natural and anthropogenic pollution	Process intensification resulted in new solutions	Active treatment and natural wetland	Economy politically more important than environment	Mining environmental accident	Industrial, humanitarian, and environmental accident
Co-ordinates	46°11′51″N 60°00′13″W	37°29′35″N 6°34′43″W	51°35′36″N 14°22′50″E	26°6′22″S 27°47′44″E	58°51′39″N 57°44′35″E	20°13′53″S 43°26′33″W	20°07′11″S 44°07′17″W
Authors	CW, EM	CW, EM	CW, EM	CW, EM	CW, EM	VSD, PC, JRSV	VSD, PC, JRSV

From a large range of possible case studies that can illustrate environmental management of mining, seven have been chosen because of their importance in this context. Yet, all case studies are representative for the many thousands of mining influenced streams, rivers, and lakes around the world.

Cape Breton Island, Canada

Mining influenced water from Cape Breton Island's 1B mine pool is treated by a passive aerobic constructed wetland system. This system substantially improves the water quality in the receiving water course, Cadegan's Brook, and the Atlantic Ocean as the final recipient.

The subsequent discussion about mine water in the 1B mine pool on Cape Breton Island, Nova Scotia (NS), Canada, is based on publications of Amirault et al. (1993), Calder et al. (1993), Forgeron (2007), Frost (1964), Government of Canada (2016), MGI Limited et al. (2003), Moreland (2013), Shea (2008, 2009), and Wolkersdorfer (2011).

Coal mining on Cape Breton Island (Fig. 1) is the oldest of its kind in Northern America and dates to 1685, when French soldiers worked coal seam outcrops in the Sydney/NS area. First commercial coal mining began in 1720, when a coal mine was opened in Cow Bay (Port Morien). In 1999, triggered by a flooding accident, mining ceased for economic reasons. Until then, 45 major underground and undersea coal mines were in operation on Northern industrial Cape Breton Island. They stretched from Big Bras D'Or in the northwest to Port Morien in the southeast.

One of the largest of these underground coal mining operations was around Sydney/NS, with the 1B mine pool holding most of the polluted mine water in 10 individual, interconnected mines. They stretched several kilometers into the Atlantic Ocean, and the mine pool has an estimated volume of 76.8 million m^3. With the № 26 colliery, mine water rebound started in 1985, when the first pump in 1B shaft was shut down. In 1999, the last of these 10 mines, the Phalen Colliery, closed after a controlled flooding, which ended in 2002. Since then, the mine water level is kept below sea level and under the discharge point to the Atlantic Ocean by a sophisticated pumping scheme. Since 2009, the discharged mine water from the Neville Street pumping scheme is treated in a passive mine water treatment system which was expanded in 2016 to treat a larger volume of mine water. Aim of the pumping and treatment scheme is to protect Cadegan's Brook from deteriorating and the Atlantic Ocean from receiving elevated concentrations of potentially toxic metals and sulfate through the 1A outfall. If polluted mine water would enter the Atlantic Ocean, the local lobster fishing would be impaired and an important source of income for Cape Bretoners would cease.

At the time of the flooding accident, two mines were still in operation, and to ensure safe operation, pumping in the 1B shaft was restarted in 1992 to prevent the Phalen Colliery from flooding. Though the water quality was good at initial sampling ([Fe] 0.004 g L^{-1}, pH 7.2, EC 9.1 mS cm^{-1}), it soon deteriorated to unacceptable iron concentrations and electrical conductivities ([Fe] 2.1 g L^{-1}, pH 3.9, EC 48.4 mS cm^{-1}) staining the Atlantic Ocean orange to yellow for a length of several kilometers.

All the mine water that was and is pumped from the Neville Street pumping scheme is discharged into a small stream, Cadegan's Brook, and from there, after a 3 km long course, it drains into Indian Bay (Atlantic Ocean) near Bridgeport. In addition, the main infiltration into the 1B mine pool seems to be connected with this brook, flowing from South to North in the communities of Reserve Mines, Glace Bay, and Dominion. Before the passive mine water treatment system went into operation, all the pumped mine water reached the brook, and consequently the sea. Flow in the brook varies substantially (80–260 L s^{-1}), depending on the precipitation, and in winter it is frozen. Upstream the mine water discharge location, the brook flows through a wetland area which formed above bootleg workings and sinkholes at MacKay's Corner. These bootleg workings are located above the № 5 colliery workings and surface water infiltrates into these mine workings to a degree not known precisely. Infiltration into the abandoned mine workings also appears downstream the mine water treatment plant's discharge, which accounts to approximately 3% of the total flow of Cadegan's Brook.

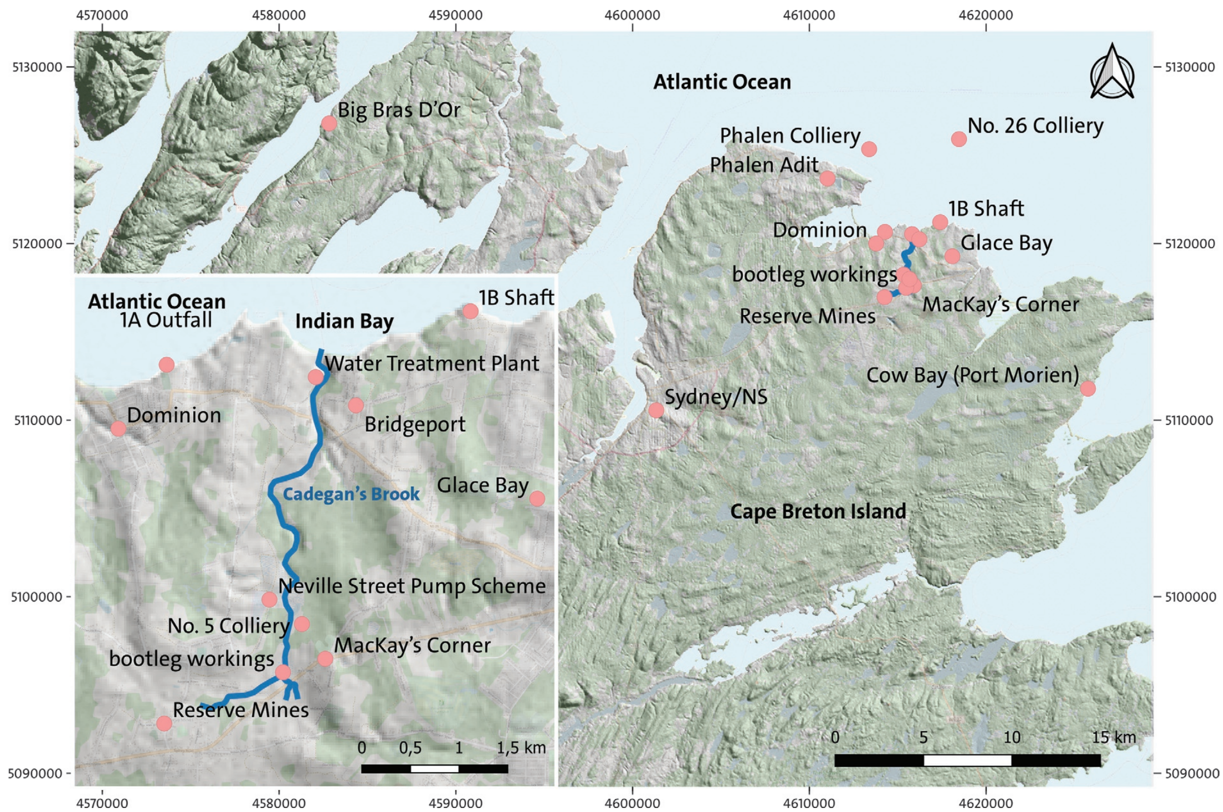

Fig. 1 Details of the Sydney/NS coal mining region. Sources: Open Street Maps community, Nova Scotia (NS) Department of Natural Resources.

In 2003, before the passive water treatment system went into operation, total dissolved solids upstream the discharge locations ranged between 72 and 364 mg L^{-1}, and downstream between 160 and 1400 mg L^{-1} (controlled by the sulfate concentration), while upstream iron concentrations were 0.1–2.5 mg L^{-1}, and downstream concentrations up to 1.7 mg L^{-1}. After the treatment system went into operation, upstream electrical conductivity was about 385 μS cm^{-1} and downstream about 1124 μS cm^{-1} but improved along the course of the brook to 100–200 μS cm^{-1} (2009 and 2011 data). Iron concentrations downstream of the discharge location were in the range of 0.4–0.8 mg L^{-1}. This shows that the brook's chemical water quality improved after the mine water treatment system became operational.

Before the passive treatment system came into operation in 2009, Cadegan's Brook was heavily stained with iron precipitates up to its mouth at Indian Bay. Even after the water quality improved, these precipitates still existed and made the stream bed muddy nearly everywhere. In 2013, four years after the passive mine water treatment system's construction, a benthic macroinvertebrates study was conducted. This study showed that the brook's water quality improved (Fig. 2) and reached acceptable water quality standards, indicating that the mine water remediation scheme was successful.

Río Tinto, Spain

This case study about the Río Tinto River exemplifies how thousands of years of mining results in a unique ecosystem with highly acid water. It also shows that some mining influenced inland waters became so highly polluted that they will very likely never be remediated.

The following discussion for the Spanish and Portuguese Río Tinto River is based on publications by Ariza (1998), Chacon-Baca et al. (2021), Grande et al. (2014), Leblanc et al. (2000), Nieto et al. (2007), Olías et al. (2020), Olías and Nieto (2015), Olías et al. (2004), Ruiz Cánovas et al. (2019), Sainz and Loredo (2005), Salkield (1987), and Torre et al. (2014).

Without question, the 4000 km^2 river basins of the Spanish Río Tinto and Río Odiel in the Iberian Pyrite Belt are the blueprints for mining affected streams *per se* (Fig. 3), but the microbiological inventory of the rivers indicate that already the earliest mines might have found a stream colored in red. Mining in the area dates back 4500 years to the Copper Age and left around 100 km of the Río Tinto polluted with acid mine drainage. In summary, the mass of the pyrite ore in the Iberian Pyrite Belt is estimated to be more than 10 Gt. Most of the ore deposits were mined for zinc, copper, lead, gold, silver and for sulfuric acid production. As the ores were mined in near surface ore bodies, vast quantities of pyritic mining residues exist in the area. This resulted in acid mine drainage with average pH values between 2.2 and 2.5, which directly discharges into the receiving water courses of the Tinto and Odiel rivers. First

Fig. 2 Optically clean Cadegan's Brook water downstream the Dominion water treatment plant. Algae growing on the rocks are indicative of elevated nutrients' concentrations. No visual indication of mining influenced water can be seen. Photograph: Christian Wolkersdorfer.

Fig. 3 Río Tinto at Zalamea la Real (Huelva, Andalucía, España). Source: LBM1948 (Luis Bartolomé Marcos), CC BY-SA 4.0, via Wikimedia Commons.

accounts on the river's pollution date to the year 1556, when priest Diego Delgado noticed that there are neither animals in the water nor do the locals use the water for consumption. Yet, he reports that the water will heal eye diseases when applied for external use. Because of the large amounts of highly acidic and metal enriched water, the rivers comprise dozens of kilometers of red to yellow colored water resulting mainly from the high iron concentration. Thus, the name Río Tinto: the red river. This is also the region where the initially British-German mining house Rio Tinto coined its name, as their mining activities started in the headwaters of the Río Tinto in 1873.

Metal and sulfate concentrations in the Río Tinto decrease along the course of the river and show seasonal fluctuations, which also occur in the Río Odiel. As in other mining affected streams, the metal concentrations and the electrical conductivity increase with decreasing pH values of the water. At the river's mouth, sulfate concentrations are still around 1 g L^{-1} and Fe concentrations around 14 mg L^{-1}, while upstream, sulfate concentrations are in the range of 111–1460 mg L^{-1} and Fe concentrations in the range of 4–316 mg L^{-1}. During rain events, the pollutant load increases, which is an indication of efflorescent salt deposits along the riverbanks and the mining residues being dissolved and flushed into the stream. Depending on the element, 30–98% of the load results from these periods of rain. Geochemical signatures indicate a common source area of the two rivers. Though the headwaters of the streams emanate within the pyrite rich host rocks, the rivers' current conditions are mainly the result of the historic mining activities. Natural acid rock drainage is a very minor contribution to the rivers' acidic conditions.

Though the rivers, as commonly assumed, look inhabited, they host an abundance of extremophile organisms, including algae, fungi, and bacteria. At least 1300 species have been identified and give evidence that the earliest Bronze Age miners might already have found a stream colored in red because of pyrite oxidation by *Acidithiobacillus ferrooxidans* and *Leptospirillum ferrooxidans*.

Unfortunately, all efforts to fully remediate the Río Tinto and Odiel areas—though it would be technically feasible and is studied for the Río Odiel—will be without success, as the mass of pyrite is so large that measures to mitigate the abandoned mines or the river will be only short lived. However, for reopening a mine in the Odiel watershed, the regional government, in view of past environmental liabilities, required the mining company to progressively reduce discharge loads to the Río Odiel. A reduction of 30% must be achieved before the third year after exploitation starts, 50% before the sixth year and 100% before the tenth year. Treatment facilities in these two watersheds, be they active or passive, might possibly work *ad infinitum* and will only result in local improvements. When the Spanish government announced that the mouth of the Tinto and Odiel rivers shall be rehabilitated, a group of biologists remarked that the microbial community in the rivers is unique and needs to be protected. This resulted in the whole Río Tinto being announced a protected area by the Andalucían government. A mixture of mining heritage, geo heritage and natural conservation in combination with selected rehabilitation areas might be assumed the best solution for these mining influenced streams.

Lusatia, Germany

After the German Reunification in 1990, it became obvious that the abandoned lignite mines in Lusatia could not be remediated with standard technologies. In a combined effort of the state, universities and consulting companies, process intensification resulted in new technologies to start the remediation of the area. In addition, the post-mining landscape will be converted to a tourist region in future.

The subsequent discussion about open pit lignite mining in Lusatia, Germany, are based on the following publications by Benthaus et al. (2020), Geller et al. (2013), Janneck et al. (2018), Kaden (1997), Luckner and Totsche (2017), Märten (2006), Merkel et al. (2005), Strzodka et al. (2013), Weber et al. (2019), and Wolkersdorfer (2021).

Lignite mined in Lusatia (Lausitz), southeast of Berlin, was the principal energy source of the former German Democratic Republic, with 200 Mt. mined in 1990 and a maximum of 1.2 km^3 of mine water pumped in 1985. A centralized, socialist planning regime prioritized lignite and energy production over environmental protection and left an area of 200,000 km^2 affected by mining, with a groundwater table lowered by up to 100 m and a cone of depression up to 13 km^3. After reunification, priorities changed in the 1990s, and the partly uneconomic opencast lignite mines slowly ceased, leaving only economically feasible mining in operation. Mine closure and a subsequent increase of the groundwater level filled the open pits. Today, remediation in the Lusatia area can be considered one of the world's largest lignite mining remediation projects with nearly 100 pit lakes being managed.

Most of the lignite is found under 20–80 m Quaternary sandy to clayey overburden which had to be dumped, mainly inside the open voids of the pits. As the coal and overburden contains pyrite, the ground and mine water quality substantially deteriorated with lower pH values around 2.5, sulfate concentrations up to 3 g L^{-1}, Fe up to 360 mg L^{-1} and Al up to 40 mg L^{-1}. While the groundwater level rose, the open pit mines (which can be considered windows to the groundwater) flooded, and some water courses suffered from ferrous, acid mine drainage. This, together with elevated sulfate concentrations, affected predominantly the river Spree, which feeds the UNESCO Biosphere Reserve Spreewald (designation date 1991) and flows through the German capital Berlin, where it is, among others, used as infiltration water for drinking water production.

To remediate the negative effects of the acidic and mineralized mine water in the open pit lakes, numerous techniques were tested, but standard technologies were not able to tackle the problem reliably. Even using sludges from mine water treatment plants was tested for by-product recovery. Most of the preliminary treatment methods failed because of the very specific conditions in Lusatia. Obstacles for passive technologies incur high costs for the large areas needed, a reduced process control compared with active methods, and the vast volumes of mine water in Lusatia that would have to be treated passively. Nonetheless, less than a dozen passive systems were tested in the Lusatia area. Microcosms ($\approx$20 m^3) and macrocosms ($\approx$4500 m^3) in the lakes were successful only in or near the enclosures itself but could not cope with the whole lake volumes. Active treatment of all the mining influenced water was also not feasible because of the large water volumes. In addition, the mine water does not occur as point sources, but as diffuse flow through the overburden and waste materials to the lakes, streams and groundwater.

Finally, a twofold approach was initiated: (1) developing a lake landscape (Lausitzer Seenland: Lusatian Lake Land) such that it can be managed for touristic and environmental purposes; and (2) improving standard technologies that were not successfully mitigating the negative effects of the acid mine drainage, by optimizing a technology that was adapted from experiences in acid rain mitigation in Scandinavia in the 1970s: in-lake-neutralization. After initial issues with the lime, caustic soda, and limestone distribution in the lakes and finding the appropriate application technology, the remediation company developed a land and vessel-based application of neutralizing agents. During the early phases, it became obvious that in all cases of in-lake-neutralization, monitoring is important. Successful application and calculation of lime or limestone masses is only possible with a full understanding of the geochemical mechanisms in the water columns of the lakes.

So far, in 13 Lusatian lakes, with 4–6 to follow, in-lake-neutralization has been successful (Fig. 4). In all cases, the lakes' acidity substantially decreased while the alkalinity rose. pH values increased to around 7 and Al concentrations decreased to below the detection limit, as in the case of Lake Partwitz. Yet, in-lake-neutralization is not a clear or short-term solution, as it requires regular repetition as long as the pyrite oxidation in the overburden and waste rock persists and the acidic groundwater flows through the lakes.

Fig. 4 In-lake-neutralization in a Lusatian mining lake by means of the "Barbara" vessel. Inset: input system between the vessel's hulls. Source: LUG/LMBV.

Western Basin, South Africa

In the Western Basin of the South African Witwatersrand, active mine water treatment and a natural wetland are improving the mine water quality. It is also an example of lengthy discussions by various interest groups with highly variable scientific backgrounds.

The subsequent discussion about mining influenced water in the Western Basin of South Africa's Witwatersrand gold fields are based on publications by Coetzee et al. (2003), Digby Wells and Associates (Pty) Ltd. Co (2012), Frimmel (2019), Hobbs and Cobbing (2007), Liefferink and van Eeden (2010), Robb and Robb (1998), Shapi et al. (2020), Turton (2013), Wolkersdorfer and von Hünefeld-Mugova (2018), and Yibas (2020).

South Africa hosts the largest gold deposit in the world: the Witwatersrand basin, comprising nine gold fields of economic importance and covering an area of 400 km^2. Mining started in 1884 and is still ongoing. Though the production is in a decline since its peak in the 1960s, it is still the location where most gold was mined worldwide. In 2020 this was 53 kt, accounting for 30% of the world's gold production to date. In addition, the gold "reefs" are enriched in uranium, which was produced concurrently to gold in some of the mines, amounting to 75 kt. As most mines did not focus on uranium extraction, a large accumulation of uranium in the remaining and abandoned tailings dams along the current and former gold extraction locations remains. Currently, 270 mining residues such as tailings dams and waste rock piles are known, which—to a smaller or larger degree—contribute to the contamination of surface waters within the whole Witwatersrand basin. Due to the lack of buffering minerals in the tailings material, tailings release substantial amounts of acid, sulfate, (semi-)metals and suspended solids. Since mining in the three largest basins has largely ceased, groundwater is filling the open voids and gradually floods the abandoned mine workings. In June 2002, the first of these basins was fully flooded, and the Western mine pool started to overflow through borehole BH1 and the Black Reef Incline shaft into the receiving water course, the 10 km long Tweelopiespruit rivulet in the Mogale (Krugersdorp) Municipality, which originates at Robinson Lake west of Johannesburg. Though this discharge did not happen unexpectedly, as several experts where aware that this would happen since around 1996, authorities and decision makers reacted with astonishment, and a series of reports, political discussions, scientific papers and decisions began to tackle the negative environmental effects of this acid mine drainage discharge. This discharge of the West Wits Mine was especially problematic in two ways: (i) the Tweelopiespruit flows through the Krugersdorp Game reserve, leading to the Bloubankspruit; and (ii) then flows though the UNESCO World heritage area "Fossil Hominid Sites of South Africa" (*vulgo* "Cradle of Humankind"). As the caves are within the dolomites of the Malmani Subgroup, there was concern that the acid mine drainage might dissolve the dolomite and therefore negatively affect the cave's integrity.

Initial monitoring of the 6–9 $m^3\ min^{-1}$ mine water discharge showed the water quality to be extremely poor, as would have been expected shortly after the initial stage of the first flush. Electrical conductivity was around 3.6 $mS\ cm^{-1}$, pH 3.4, sulfate 2.5 $g\ L^{-1}$ and Fe as well as uranium concentrations reached 235 and 0.9 $mg\ L^{-1}$, respectively. Unaffected springs in this area would have electrical conductivities around 1 $mS\ cm^{-1}$, a pH of 6, sulfate 0.5 $g\ L^{-1}$ and Fe of 0.1 $mg\ L^{-1}$.

On contact with the atmosphere, the mine water quickly oxidizes and hydrolyzes, resulting in a pH decrease downstream of the discharge locations. These processes stained the Tweelopiespruit with thick deposits of ochre and barite, substantially affecting aquatic life and the stream's appearance downstream of the discharge locations. As an operational mine (at that time Harmony

Gold) with a working water treatment facility was close to the discharge points, collection ponds and a pumping scheme to the mine water treatment plant were constructed. There, the acid mine drainage was treated in a neutralization process, which in a modified form is still ongoing today.

Based on numerous expert reports and pressure from the public, NGOS and politicians (sometimes with risk of supporting particular interests), it was decided to keep the water level at an "environmentally critical level" (ECL) of 167 m below surface. This is accomplished by means of a pumping scheme in the № 8 and 9 shafts and upgrading the existing mine water treatment plant to handle a volume stream of 18–22 m^3 min^{-1}. Currently, this scheme, financed by the South African government's tax revenues, is maintained by Sibanye Gold.

Mine water treatment in this plant is a standard neutralization method with aeration, settling, liming and coagulation. From the mine water treatment plant, the mine water is pumped into a large, unlined sludge settling pond, and from there, by gravitational flow, discharged into the Tweelopiespruit. Further, it flows through 1.7 km of natural wetlands before it enters the Krugersdorp Game Reserve (Fig. 5). Though the mine water, after treatment, is still highly mineralized, with electrical conductivities between 3.0 and 3.6 mS cm^{-1}, the pH values in the stream substantially increased to circumneutral conditions. However, maintaining the treatment has been challenged by vandalism to the electricity system, and low maintenance of the plant. Most of the red stain in the Tweelopiespruit has meanwhile been flushed or is covered with gypsum precipitates that build up as long as the treated mine water is oversaturated in regards to gypsum. Additionally, the soils along the Tweelopiespruit still contain elevated concentrations of potentially harmful elements originating from pre- and post-flooding times. Flow in the Tweelopiespruit is highly variable between 3 and 50 m^3 min^{-1}, being a function of pumped mine water and rain events. As the pumping rate in the № 8/9 shafts is not at a constant rate, the mine water table is substantially fluctuating. This causes a large beach in the mine water pool, which constantly causes pyrite oxidation and represents the main source of contaminants for the mine water. In addition, the mine water body is stratified, with a better water quality on top of mine water with a worse quality. Pumping at excessive rates, therefore, decreases the water quality as bad quality water reaches the pumps.

In consequence, though the water quality in the Tweelopiespruit has improved since 2002, water treatment must continue for a long time until the first flush phase is over, and the water table can be kept at a more constant level. Eventually, keeping the mine water level at the ECL in № 8/9 shafts can cease as there might be no immediate danger to the dolomite caves, and mine water with a better quality can be treated and discharged into the Tweelopiespruit. This will result in near natural pH values and a low mineralization, resulting in a recovery of the natural ecosystem.

Kizel Coal Basin, Russia

Russia's Kizel Coal Basin is an example of environmental pollution resulting from a policy that considered economics being more important than environmental protection. It is also an example of some individuals trying to improve the situation, and of a policy change that now tries to remediate the environmental impacts of the past.

For the following discussion about the Russian Kizel Coal Basin in the Ural Mountains, the following English and Russian publications have been used: Berezina et al. (2018), Blinov and Krasilnikova (2019), Imaykin (2014), Khayrulina et al. (2016), Maksimovich et al. (2019), Maksimovich and Pyankov (2018), Maximovich (2008), Maximovich et al. (1995), and Pyankov et al. (2021).

One of the largest areas in the Ural Mountains polluted by acid mine drainage is the Kizel Coal Basin. This coal basin is part of three river basins: the Yayva (with the North Vil'va and the Bol'shoi Kizel tributary), the Kos'va, and the Chusovaya (with the Us'va and the South Vil'va tributaries) basins. All these rivers are tributaries of the Kama river basin, and the area has an average annual rainfall of 800–900 mm. Various coal mines were worked from 1796 until mining terminated in the early 2000s and covered an area of 2000 km^2 with a north–south extension of 100 km and a width of 15–20 km. After mining ceased, the groundwater table in the more than 1000 m deep underground mines rose gradually until the mine water discharged to the surface and into the receiving water courses. These discharge locations have pH values between 2.3 and 4.5 with an average discharge of 15–25 million m^3 and a maximum of 75 million m^3 annually. More than 100 waste rock piles and tailings ponds (50 million m^3 of material) contribute to the pollution with a drainage mine water volume of 32 m^3 h^{-1}. Approximately 90% of this water draining the waste rock and the abandoned mines discharges into the receiving water courses, and in some cases the mineralization is up to 35 g L^{-1}. Currently, there are still 19 mine water discharges and more than 100 waste rock and tailings piles contributing to the pollution load.

Geologically, the Kizel Coal Basin is highly karstified, which resulted in large ingress volumes during the active mining period. It is assumed that annually $\approx$100 million m^3 of acid mine water was discharged into the local streams without any treatment, causing substantial damage to the ecosystems.

Source for the acid mine drainage is the pyrite in the coal seams which reached up to 9%. Its oxidation resulted in highly acidic mine waters with low pH values, and of the 26 ions and elements found with elevated concentrations, 12 show 10–1000 times higher concentrations than the local background. On average, the Bol'shoi River receives annual sulfate loads of 15,300 t, an Fe load of 6000 t, Al of 400 t and Mn 57 t. These mine waters change the type of the natural rivers from HCO_3-Ca to SO_4-HCO_3-Ca when the mineralization is 700–760 mg L^{-1} and SO_4-Fe-Al-Na-Ca in cases where the mineralization goes up to 3–35 g L^{-1}. Many of the receiving water courses are covered by thick layers of precipitates (ochre) and, therefore, cause substantial smothering of stream beds and local biota (Fig. 6). In many locations, acid-tolerant green algae give indication of the low pH values and the high metal and acidity concentrations. In some of these locations, the soil's pH is around 3 and prevents most plants from growing.

Fig. 5 Abandoned flow gaging station at the end of the natural wetland area of the Tweelopiespruit. Corrosion from the initial acid mine drainage and gypsum precipitates from the treated mine water can be seen at the flow gages' outflow. Photograph: Christian Wolkersdorfer.

Fig. 6 Thick ochre precipitates from acid mine water discharging from an abandoned mine in the Kizel Coal Basin. Photograph: Christian Wolkersdorfer.

After the breakdown of the USSR and the closure of many of the mines, it was found relevant to remediate these heavily polluted areas. Using SPOT-6 and LANDSAT-8 satellite data as well as sampling around 200 sites, provided identification of biologically inactive stream sections. Geochemical and GIS (geographical information system) modeling identified the priority locations for environmental protection activities, which will help to decrease the negative effects of the acid mine drainage by about 40%. It is anticipated that the mine water will be treated by means of active and passive mine water treatment systems. First on-site tests showed that some of the acidic soils can be reclaimed with limestone, selected plants, and grass mixtures. By doing so, acidic soils as well as acid mine water discharges could be successfully remediated. Other remediation methods planned are geochemical barriers (better known as reactive walls), which modify the groundwater's composition before it reaches the rivers. Yet, it will take decades until the severe pollution and damage to the rivers in the Kizel Coal Basin will be remediated and a close to natural condition will be restored.

Mariana and Brumadinho Dams, Brazil

Both the Mariana and Brumadinho tailings dam failures exemplify the importance of reliable measures to contain ore processing residues. They show how ignoring geotechnical principles and state of the art technologies can result in accidents with severe ecological and social negative effects on the surrounding areas and downstream water courses.

Introduction

Brazil holds more than 800 mine tailings dams, of which about 400 are classified into some category of accident risk (Agência Nacional de Mineração (ANM), 2021). Most of these tailings dams are located in Minas Gerais State, which is a metal-rich region and has a long history of land use focused on extensive mining activities (Jacobi et al., 2011; Hatje et al., 2017). This State also holds the largest number of mine tailings dams in Brazil rated as high accident risk (Agência Nacional de Mineração (ANM), 2021), posing a severe potential threat of both social and environmental disaster (Nazareno and Vitule, 2016; Kamino et al., 2020; Azevedo-Santos et al., 2021).

Fundão Dam, Mariana

In November 2015, the Fundão tailings dam broke in the Bento Rodrigues District, Mariana City, Minas Gerais State. About 43 million m^3 of iron mine wastes were released into the Doce River basin. This spill is considered one of the world's largest mining environmental disasters. Individual mud waves reached a height of 10 m, and the tailings deposit layers were between 50 cm and 3 m thick. During the spill, the Bento Rodrigues District was partly buried by the mudflow, and its entire population of approximately 600 people displaced. The mudflow traveled 668 km along the Doce River, before reaching the Atlantic Ocean approximately 15 days after the dam ruptured (Escobar, 2015; Carmo et al., 2017; Fig. 7). This toxic mudflow polluted drinking water and decimated the aquatic fauna of the Doce River, also affecting the soil and flora of floodplain areas (Lambertz and Dergam, 2015; Garcia et al., 2017).

The most striking short-term negative effects caused by the tailings were siltation of entire rivers, changes to channels and river dynamics (i.e., the interactions among flow, sediment transport, and morphology), spread of chemical compounds, and the destruction of terrestrial and aquatic ecosystems (Fernandes et al., 2016; Garcia et al., 2017). This disaster resulted in water contamination and caused the death of entire fish, amphibians, mammals, turtles, birds, and invertebrates populations (Lopes, 2016; Carmo et al., 2017). Long-term effects include increased metal concentrations in the sediment, toxic effects at different trophic levels, metal accumulation in fish muscle tissue along with cytotoxic, genotoxic and mutagenic effects, and in water and sediment (Vergilio et al., 2021). In addition, the tailings led to vegetation loss and damaged several protected areas (Lopes, 2016; Carmo et al., 2017). This severe accident killed 19 people, affected several down-stream municipalities and hundreds of thousands of people (including Krenak and Guarani indigenous tribes), caused the loss of natural and cultural heritage, increased the exposure to toxic elements (mainly arsenic, mercury and lead) and impaired the local economy (Fernandes et al., 2016; Carmo et al., 2017; Valle, 2020; Koppe, 2021).

Fig. 7 The toxic mudflow in the mouth of the Doce River reaching the Atlantic Ocean in Regência, Espírito Santo State. Photograph: Hauley Valim.

This mining disaster is still causing negative ecological and socio-economic effects because adequate tailings removal was either inefficient or not carried out at all. One year after the dam rupture, about 0.17 million m^3 of tailings were cleaned from affected areas, and after 3 years, about 48% were removed (Carmo et al., 2017; Cionek et al., 2019). Yet, the long-term effects of the spillage must be accounted for, and the environmental recovery of areas affected by tailings will take a long time.

This tailings dam failure could have been avoided if proper maintenance of the dam and surrounding areas had been performed. Mine residue dams require constant maintenance, aiming to reduce the likelihood of leaks or dam failures, and minimizing ecological and social damage (Sergeant and Olden, 2020). In addition, multidisciplinary efforts and investments should be periodically dedicated to rigorous inspection, monitoring, and environmental licensing (Cionek et al., 2019). A potential solution to the waste in mine dams could be dry stacking, which causes less environmental impacts compared with current tailings storage (Gomes et al., 2016). Another important strategy in tropical environments should be the construction of tailings ponds and infrastructure resisting large influxes of water (i.e., tropical storms rainfall; Edwards and Laurance, 2015).

Córrego do Feijão Dam, Brumadinho

In January 2019, the B1 Dam at the Córrego do Feijão Mine ruptured in Brumadinho City, Minas Gerais State. This disaster spilled 12 million m^3 of iron mining waste, with 10 m high mud waves, spreading for 10 km and reaching the Paraopeba River, a major tributary of the São Francisco River (Fig. 8).

Shortly after the dam ruptured, the mudflow hit the mining company buildings, as well as hotels and farms in the region, killing more than 270 people (Olden et al., 2019). Severe negative short-term effects on water quality and sediments of the Paraopeba River resulted from this toxic mudflow, including an increase in water turbidity, high metal and nutrient concentrations, increase in iron tolerant bacteria, toxic effects at different trophic levels, and metal accumulation in fish muscle tissue, requiring future studies to monitor the long-term consequences in this river (Thompson et al., 2020; Vergilio et al., 2020). This disaster jeopardized the water supply of cities in the surrounding area and affected fish and bird species (Pereira et al., 2019; Salvador et al., 2020). The spill of the tailings caused a major change in land cover, severe loss of Atlantic Forest vegetation, and impaired agricultural areas (Pereira et al., 2019; Rotta et al., 2020).

Post-disaster actions following the Brumadinho dam rupture were conflicting. A study reported that the mudflow reached the Retiro Baixo Hydroelectric Dam (302 km downstream from the collapsed dam, in the Paraopeba River), while another study reported that the mudflow reached the Três Marias Dam's reservoir (around 330 km from Brumadinho, in São Francisco River; Salvador et al., 2020). In addition, a controversial action was proposed by the Brazilian National Water Agency (Agência Nacional de Águas e Saneamento Básico, ANA), which planned to use the Retiro Baixo Hydroelectric Dam to prevent the spread of mine tailings; however this strategy has been considered ineffective in restricting the environmental and social damage along the tailings' travel path (Hatje et al., 2017; Cionek et al., 2019).

Upstream tailings dams like that in the Córrego do Feijão Mine are cheaper, occupy smaller areas, and require less material for construction than other tailings dams, since new tailings are accumulated on top of previous deposits (Kossoff et al., 2014; Rotta et al., 2020). However, this tailings dam model is considered highly risky, mainly due to the potential of static liquefaction, a process in which solid materials behave like liquids, which can trigger the dam's collapse (Kossoff et al., 2014). Brazil's National

Fig. 8 Mudflow from the collapse of the B1 Dam at Córrego do Feijão Mine, Brumadinho City region, Minas Gerais State, a tailings dam failure that caused severe social and environmental impacts. Photograph: Isis Medeiros.

Mining Agency (Agência Nacional de Mineração, ANM) planned to ban upstream tailings dams after the Córrego do Feijão Dam collapse in Brumadinho (Spring, 2019). The collapse of the Brumadinho Dam was a major global warning of the risks posed by unsafe, rudimentary, and antiquated mining dams (Koppe, 2021). Every mine is unique in terms of its geography, physical setting, or environmental context. Nevertheless, only with science-based safety guidelines and stricter enforcement, can the chances of repeating a disaster like this be minimized (Olden et al., 2019).

Technological improvements, and the future of mine tailings dams

Emerging technologies, while expensive, have some promising alternative solutions, that include approaches such as paste and thickened tailings, tailings reuse, recycling and reprocessing in combination with proactive management in a way to combine the separation of sulfide by flotation and the use of cemented paste backfill as soil support. For instance, novel mine tailings are usually stored above ground or in impermeable plastic casings below the surface, which make them less likely to seep into the ground and contaminate groundwater and adjacent watercourses (Edraki et al., 2014). Alternatively, wetland integrated systems are easy, affordable to build and relatively low maintenance alternatives since they are efficient in regions that do not have too cold winter months.

After these two mine tailing dam disasters, the Brazilian Government has decided to decommission all mines with upstream characteristics similar to the Fundão and Córrego do Feijão Dams. This decommissioning would involve removal of the wastes deposited in the tailings dams, construction of new dams or transportation to preexisting dams to accommodate them, and finally their inactivation. Nevertheless, this change represents a challenge in terms of time, investments and efforts required to do so. Undoubtedly, the environmental impacts and human toll were high for Minas Gerais State, for companies and the regions involved as a whole.

Conclusions

Mining activities and residues such as tailings or mine water can cause substantial negative effects to inland waters. One of the most noticeable and destructive, but fortunately rare accidents, are tailings dam failures which often impair socio-economic balances, along with regional pollution that damages both aquatic and terrestrial ecosystems. Less obvious is the pollution caused by mining influenced water, although iron rich mine water often visually impairs water courses. Solutions to these effects on inland waters and the ecosystem would be mining bans in sensitive regions or more stringent control measures.

All case studies show negative effects on the surrounding environment, sometimes hundreds of kilometers from the mine site. Though some of them can be corrected, some of them will last for a very long or indefinite time. It can be concluded that reliable and sustainable treatment options, state of the art mine residue storage or encapsulation and stringent monitoring, as well as legislative measures and enforcement are necessary for environmentally safe operations.

Knowledge gaps

One of the main knowledge gaps in the mining context is how to prevent environmental pollution or loss of life under all circumstances. Yet, as long as humans are involved in the processes, mistakes, misinterpretation or negligent behavior cannot be fully avoided. Though substantial research has been done after the Aznalcóllar and Baia Mare tailings dam failures (e.g., Hernandez et al., 1999; Macklin et al., 2003), how nature recovers from these types of events still remains unclear and requires further research. It is also not well-known which methods can be most effective to assist the recovery of the freshwater and terrestrial ecosystems that are affected.

More research is needed in sustainable mine water remediation techniques. This is especially relevant when considering the economic cost/benefit of recovery of valuable material from the mine water including the circular economy aspects of mining and the interplay with mine water issues. Treatment options that selectively recover metals or semi-metals would be able to partly assist in the remuneration of the costs incurred. Moreover, digital twins of active and passive mine water treatment systems are not available so far. Finally, artificial intelligence or machine learning is required to optimize mine water management and help in adjusting to future scenarios. Detailed studies into the micro- or small-scale effects of mining influenced water or tailings dam failures on the local or regional economy as well as the social structure are only rarely conducted.

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See Also: Human pressures and management of Inland Waters: Effects of Mining on Surface Water; Constructed Wetlands for Urban Wastewater Treatment: An Overview

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