# Effects of Mining on Surface Water

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



## Glossary

**To date, a comprehensive English language mine water glossary does not exist. In most cases, the glossary in the GARD Guide (www.gardguide.com) or in McLemore (2008) might be a first stop.**

**Acid/Acidity** Acid/Acidity are two different concepts. "Acid" refers to the proton acidity and is measured with a pH-meter. Acidity is the sum of the proton acidity, metal acidity and other naturally occurring acids. It is determined by titration.

**Adit** Adit is a horizontal or close to horizontal tunnel or gallery that connects the surface with an underground mine.

**Barite** Barite is a sulfate mineral with the formula $BaSO_4$.

**Calcite** Calcite is a carbonate mineral with the formula $CaCO_3$.

**Dolomite** Dolomite is another carbonate mineral with the formula $CaMg[CO_3]_2$.

**Electrical conductivity** Electrical conductivity 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.

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**Feldspar** Feldspar is a collective name for a large group of silicate minerals with the formulae $KAlSi_3O_8$, $NaAlSi_3O_8$, and $CaAl_2Si_2O_8$.
**Heavy metal** Heavy metal is a music style. According to the International Union of Pure and Applied Chemistry (IUPAC), no other usage is recommended (Duffus, 2002), as there are more than 40 definitions, thus rendering the meaning vague.
**Marcasite** Marcasite is a sulfide mineral with the formula $FeS_2$. Though chemically identical to pyrite, it has another crystal structure.
**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.
**Ochre** Ochre is a collective term for yellow to dark orange iron oxides with a clayey to sandy composition.
**Orphaned** Orphaned mines are abandoned mines that are ownerless.
**pH** pH is a parameter that expresses the activity of protons (positively charged hydrogen ions) in liquids. There is nothing such as a "pH-scale" and it has no units as it results from the calculation of a logarithm. The lowest, that means most acid, ever measured pH in nature is −3.6 and the highest alkaline one 13. It is measured with a pH-probe.
**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.
**Pyrrhotite** Pyrrhotite is a sulfide mineral with the formula $Fe_{(1-x)}S$; $x = 0–0.2$. In contact with water and oxygen, this mineral also forms acid mine or rock drainage.
**Redox potential** This parameter indicates the sum of all oxidation and reduction reactions in a liquid and is an expression for the "free" electrons in a solution. It provides a measure of the oxidizing or reducing tendency of this solution. A redox potential below zero millivolt (mV) indicates reducing and a redox potential above zero millivolt an oxidizing environment. It is measured with a redox probe and must be corrected to the standard hydrogen electrode (www.Wolkersdorfer.info/orp).
**Semi-metals** Semi-metals (metalloids) are elements that show characteristics of both metals and non-metals or either of them. Commonly recognized semi-metals are arsenic, boron, germanium, antimony, silicon, and tellurium.
**Suspended Solids (SS)** Suspended Solids are all the smaller particles in a liquid that stay suspended. They may settle once the liquid's velocity slows down or when time passes.
**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.
**TDS (total dissolved solids)** TDS are indicative for the sum of all inorganic and organic ions dissolved in a liquid. The higher the TDS concentration, the more ions are dissolved, which means the water is more mineralized. In mining influenced water, it must be measured by gravimetry and not approximated by a simple calculation from the electrical conductivity (Hubert and Wolkersdorfer, 2015).
**Trans-drainage basin diversion** Trans-drainage basin diversion means that water from one river drainage basin is transferred into another drainage basin by way of pipes or channels.

## Introduction

Mining includes modern, small-scale, and artisanal surface mining, strip mining, placer mining, underground mining, solution mining, *in situ* mining, quarrying, or the extraction of groundwater. Approximately 240,000 km$^2$ of the Earth's surface are covered by abandoned, closed, or orphaned mines (Wolkersdorfer, 2008). There, pollution pathways include surface, groundwater as well as aerial deposition (Fig. 1), and potentially contaminated sediments might collect in the stream beds and lakes. Mining influenced water can develop acid (below pH 5.6), circumneutral (between pH 5.6 and 8), or basic pH values (above pH 8), and in terms of dissolved matter, it can be dilute, mineralized, or saline (Nordstrom et al., 2015). Once inland waters are contaminated by mine water, their remediation can take long and may involve large financial burdens (ERMITE Consortium et al., 2004).

Protecting the environment from pollution, both from tailings and from the mine workings is a complex problem (ERMITE Consortium et al., 2004), and its solution takes the combined efforts of many partners. Unquestionably, the best protection of the ecosphere would be to prevent mining entirely or, alternatively, recycle all used metals, rocks or aggregates (European Innovation Partnership on Raw Materials, 2016). Yet, both options are currently not feasible in face of the demand of a growing world population for raw materials. Therefore, responsible and sustainable mining uses a life cycle assessment including the "mining for closure" principle and the "cradle-to-grave" approach (Idowu et al., 2013; Northey et al., 2018; Peck et al., 2005; Wörlen et al., 2005).

Examples in this article are not chosen to single out individual mine sites or mining houses, but as relevant examples describing a particular mechanism or case. Many of the well documented mine sites are operated by responsible companies that openly discuss their problems, while many heavily polluting mine sites (Earthworks and Oxfam America, 2004) are inadequately documented,

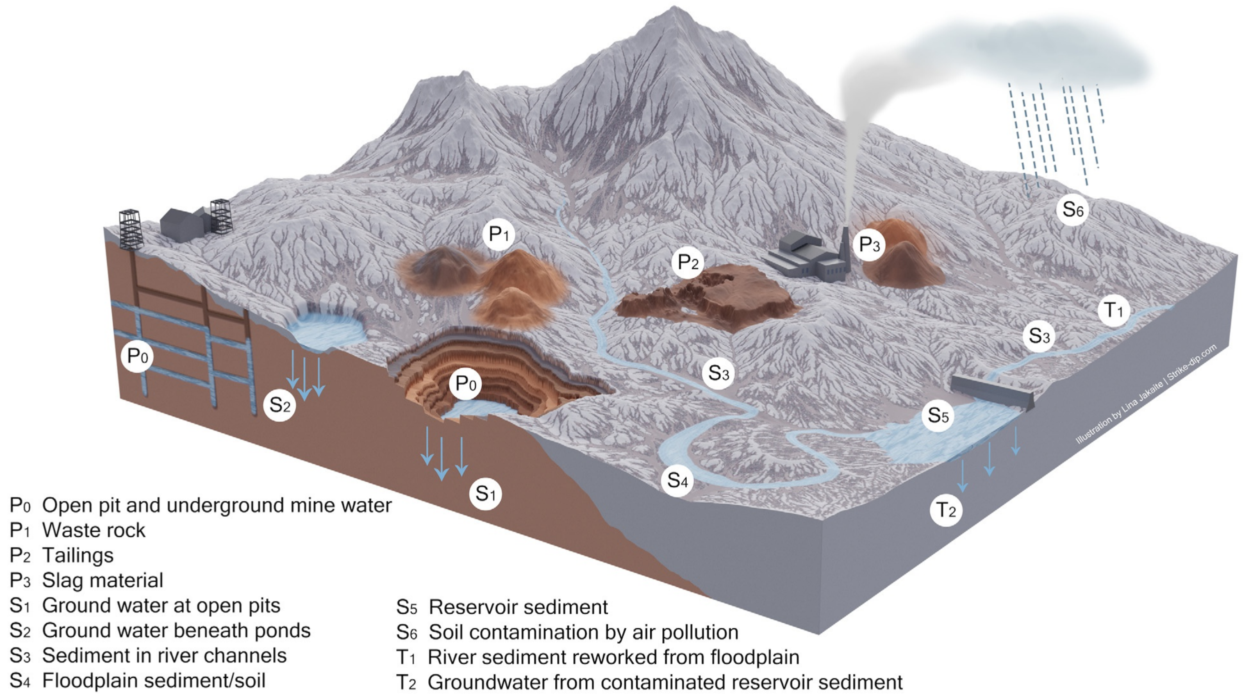


**Fig. 1** Pollution pathways in the mining environment. P: primary contamination, S: secondary contamination, T: tertiary contamination. Modified after Moore JN and Luoma SN (1990) Hazardous wastes from large-scale metal extraction—A case study. *Environmental Science & Technology* 24(9): 1278–1285, https://doi.org/10.1021/es00079a001.

because the owners restrict publication of unwanted results or access to these sites. In addition, it is noteworthy to state that responsible mining tries to avoid lasting environmental damages. Responsible mining ensures that the mining operation has its social license to operate and mining remnants are mitigated as well as remediated to near pre-mining conditions as best as possible (International Council on Mining and Metals, 2008).

## What is mining influenced water

### Evolution of mining influenced water

Mining interferes with the natural geological conditions and transforms an often reducing environment, in which the minerals were thermodynamically stable, into an oxidizing one. These changes to the environment bring the minerals in contact with water, oxygen and an abundance of microbes that immediately take advantage of the new thermodynamic conditions and possibilities (McLemore, 2008; Wildeman and Schmiermund, 2004).

Sulfate enriched mine water predominantly results from the microbially catalyzed oxidation of the iron-sulfides pyrite, marcasite and pyrrhotite to sulfate and acid (Fig. 2), whereby pyrite and marcasite are the most common of these minerals in coal, base metal and gold deposits (Blowes et al., 2014; Nordstrom, 2011). In total, the process involves four steps, which shall be described for pyrite (Stumm and Morgan, 1996). Firstly, pyrite reacts abiotically with water and oxygen (I) or is used biotically by microorganisms for their metabolism. This results in high concentrations of dissolved sulfate, ferrous iron ($Fe^{2+}$) and protons. In the next step (II), the ferrous iron is oxidized to dissolved ferric iron ($Fe^{3+}$) which either oxidizes the pyrite to form more ferrous iron (III) or it reacts with the water and oxygen to form iron-oxihydrate precipitates (IV). Microorganisms, such as *Acidithiobacillus thiooxidans*, accelerate these relatively slow abiotic reactions 1 million times (Wolkersdorfer et al., 2020).

When carbonate or silicate minerals are present, they partly counteract the above reactions, as they buffer the produced protons. This means that the protons react with minerals such as calcite, dolomite, or feldspars, resulting in their dissolution and releasing their elements into the water. As the pH of the receiving inland waters will buffer pH from these reactions, many metals or metalloids will precipitate (Fig. 3) or co-precipitate, subsequently improving the water quality (Stumm and Morgan, 1996).

In the case of saline mine waters, the evolution is completely different. It is normally a physical process, by which solid salts are dissolved until they reach a (semi)stable equilibrium with the mine water. In mines with soluble salts, the physical and chemical reactions involved can be complicated, as the various solubilities of salts substantially change with temperature, saturation of the salts and the brine's composition (Herbert and Sander, 1987).

When pyrite oxidation as well as saline waters combine, the results are saline mine waters with elevated (semi-)metal and sulfate concentrations. This is often seen in coal mine discharges regardless of where on Earth they occur.

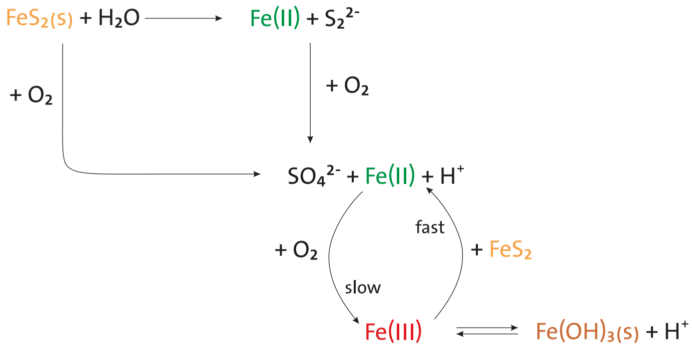


**Fig. 2** Diagrammatic representation of the pathways during abiotic pyrite/marcasite oxidation. Based on information in Kester DR, Byrne RH and Liang Y-J (1975) Redox reactions and solution complexes of iron in marine systems. *ACS Symposium Series* 18: 56–79, https://doi.org/10.1021/bk-1975-0018.ch003; Singer PC and Stumm W (1970) Acidic mine drainage—The rate-determining step. *Science* 167(3921): 1121–1123, https://doi.org/10.1126/science.167.3921.1121; Stumm W and Morgan JJ (1996) *Aquatic Chemistry—Chemical Equilibria and Rates in Natural Waters*. 3rd edn., New York: Wiley & Sons.

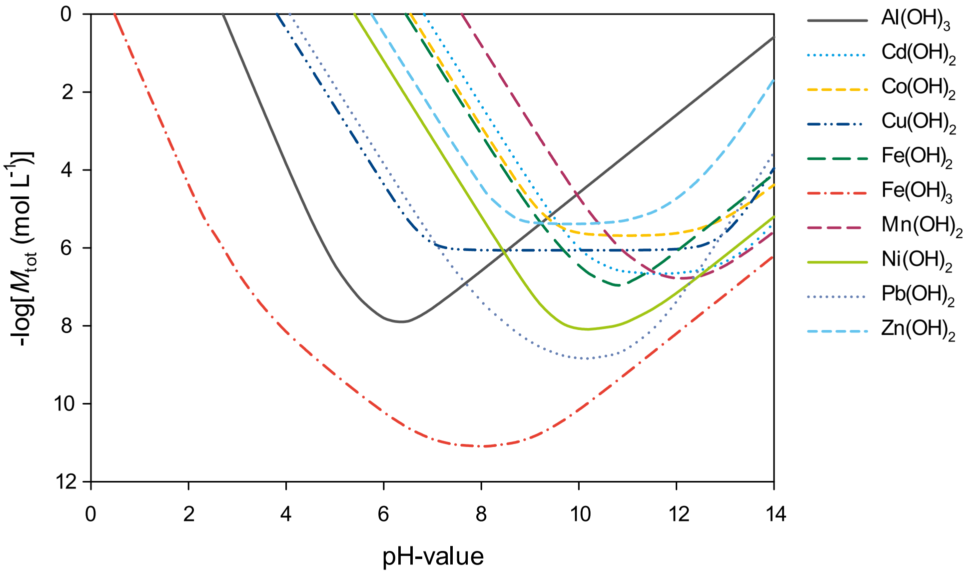


**Fig. 3** Solubility of environmentally relevant metal hydroxides as a function of the pH value. Modified and supplemented according to Cravotta CA, III (2008) Dissolved metals and associated constituents in abandoned coal-mine discharges, Pennsylvania, USA. Part 2: Geochemical controls on constituent concentrations. *Applied Geochemistry* 23(2): 203–226, https://doi.org/10.1016/j.apgeochem.2007.10.003, original data obtained from Charles A. Cravotta III, pers. comm. 2013.

## Mine water—Surface water linkages

To keep a mine operating, it needs a sustainable water management plan in place that accounts for pumping the water from the mine workings, supply of water for ore processing, dust suppression and human use. All these water streams in and around the mine need to be known to manage the water balance reliably (Punkkinen et al., 2016). Predominantly, the mine dewatering affects the groundwater, but in several cases also ecological affects might occur as surface water is diverted around a mine site, especially when trans-drainage basin diversion occurs (Marcus, 1997).

As long as a mine is operating, pumped water, as well as tailings dam and waste rock dump seepage water will come into contact with surface water, mostly following treatment—unless a mine operates in dry areas with a lack of groundwater. Once mining commences, the open voids will start to be filled with groundwater and the mine starts to flood, a process that usually takes years to decades. When the water level in the mine reaches the lowest discharge point, the mine water will start to discharge into the receiving water courses (Wolkersdorfer, 2008) or terminal pit lake sinks (McCullough et al., 2013). Those linkages between mine water and surface water can take many different forms: seepage from shallow underground workings, discharges from pit lakes, bore holes, adits, inclines, or shafts. Seepage can also occur through overburden and especially from collapsed hanging wall areas and may contribute notably to surface water contamination. For protecting the environment, shaft or adit discharge is preferable, as the water can be directed towards an active or passive mine water treatment plant.

Tailings are nearly always connected to inland waters, except when located in arid areas or they undergo submarine disposal (Dold, 2014). Tailings dam water sees various forms of linkage to surface water such as overflow, seepage water into surrounding water courses or indirectly though seepage into the groundwater, which might then emanate to the surface downstream of the tailings dam (Fortuna et al., 2021).

Waste rock usually contains residues of the mining operation that are deemed currently economically unviable. If this material is chemically inert, the seepage water should pose no detrimental effects on the surface water other than modest increases of electrical conductivity or suspended solids content. Should the waste rock contain minerals (e.g., disulfides or efflorescent minerals) that produce acidity or elevated contaminant concentrations during weathering, the discharged seepage water may cause detrimental effects to the receiving water bodies.

### Physico-chemical characterization

Mining influenced water can be characterized by its physico-chemical parameters such as temperature, electrical conductivity, pH, redox potential, turbidity, color, and oxygen saturation. These are mainly interdependent from each other and normally there is no correlation between them, though temperature affects the solubility of oxygen, or pH the solubility of many metals. In addition, all these variables and parameters show high variability, ranging, for temperature, pH, and redox potential for example, from −2 °C to 58 °C, −3.6 to 13 and −500 to 900 mV, respectively.

High suspended solid loads and turbidity are common for many mining influenced waters. Turbulence keeps colloid-sized particles or flocculated oxyhydroxides in suspension and results in high concentrations of iron and aluminum in the water. Metal attenuation reactions can sometimes be recognized in the water by turbidity in certain places (Schmiermund and Drozd, 1997).

Mine water can discharge at elevated temperatures of up to 58 °C, resulting from either exothermic reactions or the geothermal gradient. For surface waters, the discharge of warm water can then provide habitats for non-native species, with sightings of released aquarium fish at mine water discharge points in Germany (personal observations), and a reduction of less heat tolerant species.

Very often, mining influenced water is colored, whereby the color depends on the water's constituents and colors the receiving inland waters. Iron rich water has usually colors that range between orange, brown and red, whilst copper rich effluents are greenish to blueish and nickel rich mine water has light blue to green colors. Aluminum and elevated alkalinity results in white colors. This coloring can either be due to dissolved metals (e.g., iron, copper, nickel) or to suspended precipitates, for example gibbsite.

### Chemical composition

The chemical composition of mine water shows a high degree of variability (Table 1). This is due to the large spectrum of geological settings (Smith and Huyck, 1999) and the biological, chemical and physical processes involved (Plumlee et al., 1999). In addition, the solubility of the metal hydroxides controls their concentrations in the mining influenced waters and the receiving water courses (Fig. 3).

Some of these elements in mining influenced water will appear in cationic species, such as calcium, others in anionic species like chloride—writing about an element as a constituent of mine water, therefore always implies it is in its ionic form. Extremely rarely, mine water will contain elements in their elemental form; exceptions might be the non-reactive and non-toxic noble gasses. Some of these elements are found more often in mine water, such as protons, iron, copper, aluminum, arsenic, chloride or manganese, others are less abundant, such as molybdenum, selenium, mercury, vanadium, or chromium. Yet, mine water contains water, $H_2O$, at a concentration of 55.5 mol $L^{-1}$. The next group of mine water constituents comprise the main ions of water: calcium, sodium, potassium, magnesium, hydrogen carbonate, sulfate, chloride, nitrate at an average concentration of around 0.5 mol $L^{-1}$ and the trace ions at an average concentration of 0.005 mol $L^{-1}$, which accounts to just 0.01% of the molar composition of water. These are average numbers, as in the case of the Iberian Pyrite Belt, the sulfate concentrations in the mine water account for approximately 2.9% of the water's ionic composition.

Not only does mining influenced water have a different chemical composition depending on the type of ore deposit, host and country rock, and the chemistry of the receiving water itself, but it also changes over time. When water discharges from underground mines, the first flush effect results in elevated concentrations of the most relevant components (Younger, 1997) for a longer time span. These elevated concentrations and the low pH values will impair and color inland waters for years to decades and will have negative effects on the ecological balance compared to pre-mining conditions. One of the reasons is that many elements usually show a higher solubility and often bioavailability at low pH values (Neil et al., 2009; Smith and Huyck, 1999).

## Mine types and characteristic effluents

### Introduction

Every ore body or mine type develops its characteristic effluent chemistry (Table 1). Reasons for this are the geochemical and hydrogeochemical reactions occurring during water–rock interaction. By knowing the geological, mineralogical, and climatic background of a mine site as well as the mining method applied, first estimates about the mine water chemistry and potential effects on surface water can be made (Plumlee et al., 1999). As described in the previous chapter, the final composition of the mine water is an interplay of various chemical and microbiological reactions and usually shows a high temporal and spatial variability. Their principles are identical at all mine sites around the world. Yet, the particulars are controlled by the site-specific conditions (Table 2).

**Table 1** Composition of different mine waters with the most predominant mine water constituents.

| *Locality* | *pH* | *$SO_4^{2-}$* | *$Fe_{tot}$* | *Al* | *Mn* | *Zn* | *Cu* |
|---|---|---|---|---|---|---|---|
| Iron Mountain California, USA (Cu)[N99] | 0.5 | 118,000 | 20,300 | 2210 | 17 | 2010 | 290 |
| Iberian Pyrite Belt, Portugal[a] | 1.4 | 157,229 | 52,767 | 7072 | 155 | 1885 | 2243 |
| Cae Coch, Wales (pyrite)[B97] | 2.5 | 5110 | 1460 | 84 | 3 | 1 | 0.2 |
| **Río Tinto, Spain (Cu, Au)**[O20,b] | 2.7 | 1123 | 145 | 65 | 5.3 | 16 | 15 |
| **Lappwald Lake, Lusatia, Germany (lignite)**[L20] | 2.9 | 1700 | 6.4 | | | | |
| **Kizel Coal Basin, Russia (coal)**[M18] | 3.0 | 3992 | 1608 | 79 | 13 | 0.4 | – |
| **Western Basin (8 shaft), S. Africa (Au)**[c] | 3.0 | 2410 | 54 | <0.1 | 15 | 0.06 | <0.01 |
| Fanie Nel Discharge, S. Africa (coal)[c] | 3.2 | 1217 | 265 | 31 | 20 | 2.3 | 0.072 |
| R. Hipper Discharge, UK (coal)[B97] | 3.6 | 1044 | 101 | 17 | 4 | 0.2 | 0.007 |
| Ynysarwed, Wales (coal)[B96] | 4.2 | 1554 | 180 | <0.5 | 6 | 0.06 | – |
| Oatlands waste rock dump, UK (coal)[B96] | 5.5 | 146 | 287 | 1 | 5 | 0.05 | <0.007 |
| Gernrode Harz Mts., Germany (fluorite)[H04] | 5.7 | 86 | 16 | – | – | 0.36 | 0.05 |
| Straßberg Harz Mts., Germany (fluorite)[R00] | 6.3 | 359 | 31 | – | 6 | 0.9 | 0.08 |
| Dunston Chesterfield, UK (coal)[B96] | 6.3 | 210 | 11 | <0.05 | 1.3 | <0.007 | |
| Duke's level Buxton, UK (coal)[B96] | 6.3 | 83 | 5 | 0.08 | 0.4 | 0.05 | 0.005 |
| Allen Hill Spaw, UK (metal)[B96] | 6.5 | 124 | 15 | 0.1 | 2 | 0.003 | – |
| Niederschlema, Germany (U)[W96] | 7.1 | 1138 | 3 | 0.4 | 3 | 0.1 | 0.03 |
| **1B Mine Pool (B-185), Canada (coal)**[c] | 7.1 | 1100 | 3.6 | 0.003 | 7.8 | 0.01 | 0.001 |
| **Cosbuden lake, Lusatia, Germany (lignite)**[L20] | 7.2 | 800 | 0.01 | | | | |
| Frazer's Grove Yorkshire, UK (fluorite)[J02] | 7.6 | 76 | 0.4 | | 0.8 | 0.2 | – |
| Mine № 3, Svalbard (coal)[B04] | 8.2 | 7 | <0.01 | <0.02 | 0.004 | 0.055 | <0.005 |
| Schwaz, Austria (dolomite, fahlore)[c] | 8.4 | 13 | < 0.01 | – | 0.002 | 0.022 | 0.04 |

Bold lines refer to the five case studies and superscript indices to the references.
[a]T. Valente.
[b]Median values 2017/2018; concentrations in mg $L^{-1}$. The Iberian Pyrite Belt stretches from Portugal to Spain, and the Río Tinto is one of the prominent rivers in the district.
[c]Unpublished data from Ch. Wolkersdorfer.

Sources: B96: Banks D (1996) The hydrochemistry of selected coal mine drainage and spoil-tip run-off water, Longyearbyen, Svalbard. *NGU-rapport* 96(141): 1–22; B04: Banks D (2004) Geochemical processes controlling minewater pollution. In: Prokop, G. et al. (eds.) *Conference Papers*, pp. 17–44. Wien: Umweltbundesamt; B97: Banks D, Younger PL, Arnesen RT, Iversen ER and Banks SB (1997) Mine-water chemistry: The good, the bad and the ugly. *Environmental Geology* 32(3): 157–174, https://doi.org/10.1007/s002540050204; H04: Hasche A and Wolkersdorfer C (2004) Mine water treatment with a pilot scale RAPS-system. *Wissenschaftliche Mitteilungen* 25: 93–99; J02: Johnson KL and Younger PL (2002) Hydrogeological and geochemical consequences of the abandonment of Frazer's grove carbonate hosted Pb/Zn fluorspar mine, North Pennines, UK. Special Publication. *Geological Society of London* 198: 347–363, https://doi.org/10.1144/GSL.SP.2002.198.01.24; L20: Lausitzer und Mitteldeutsche Bergbau-Verwaltungsgesellschaft mbH (2020) *Wasserwirtschaftlicher Jahresbericht der LMBV mbH—Zeitraum 01. January—31. Dezember 2019 [Water Management Annual Report of LMBV mbH—Period of 01 January—31 December 2019] (Report).* Senftenberg: Lausitzer und Mitteldeutsche Bergbau-Verwaltungsgesellschaft mbH. Available: https://www.LMBV.de/files/LMBV/Dokumente/Wassermanagement/Wasserjahresberichte/20200421%20Wawi_JB_2019_mit_Anlagen.pdf; M18: Maksimovich NG and Pyankov SV (2018) Кизеловский угольный бассейн—экологические проблемы и пути решения *[The Kizel Coal Basin—Ecological Problems and Solutions]. Perm, Raritet-Perm Publishing House; N99*: Nordstrom DK and Alpers CN (1999b) Negative pH, efflorescent mineralogy, and consequences for environmental restoration at the Iron Mountain Superfund site, California. *Proceedings. National Academy of Sciences. United States of America* 96(7): 3455–3462, https://doi.org/10.1073/pnas.96.7.3455; O20: Olías M, Cánovas CR, Macías F, Basallote MD and Nieto JM (2020) The evolution of pollutant concentrations in a river severely affected by acid mine drainage: Río Tinto (SW Spain). *Minerals* 10(7): 598, https://doi.org/10.3390/min10070598; R00: Rüterkamp P and Meßer J (2000) *Untersuchungen zur hydraulischen und hydrochemischen Situation in den drei Teilrevieren der gefluteten Flussspatgrube Straßberg [Investigations on the hydraulic and hydrochemical situation in the three sub-areas of the flooded Straßberg fluorspar pit] (Report № 1710–99-285).* Essen: Deutsche Montan Technologie GmbH; W96: Wolkersdorfer C (1996) *Hydrogeochemische Verhältnisse im Flutungswasser eines Uranbergwerks—Die Lagerstätte Niederschlema/Alberoda [Hydrogeochemical conditions in the mine water of a uranium mine—The Niederschlema/Alberoda deposit].* Clausthaler Geowiss. Diss., vol. 50, 1–216.

**Table 2** Commodities and typical parameters impairing inland waters. EC: electrical conductivity; SS: suspended solids.

| *Commodity* | *pH* | *EC* | *$SO_4^{2-}$* | *Fe* | *Al* | *Cu* | *Zn* | *U* | *Ra* | *Cl* | *Hg* | *As* | *N* | *SS* |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Coal and Lignite | ◆ | ◆ | ◆ | ◆ | ◆ | | | | | ◆ | | | | |
| Gold | ◆ | ◆ | ◆ | ◆ | | | | ◆ | | | ◆ | ◆ | | ◆ |
| Salt | | ◆ | | | | | | | | ◆ | | | | |
| Iron | ◆ | | ◆ | ◆ | | | | | | | | | | |
| Copper | ◆ | ◆ | ◆ | | ◆ | ◆ | | | | | | | | |
| Lead/Zinc | ◆ | ◆ | ◆ | | | | ◆ | | | | | | | |
| Uranium | ◆ | ◆ | ◆ | | | | | ◆ | ◆ | | | ◆ | | |
| Diamonds | | ◆ | | | | | | | | | | | ◆ | ◆ |
| Aggregates, Building Stones, Quarries | | | | | | | | | | | | | ◆ | ◆ |
| Others | ◆ | ◆ | ◆ | ◆ | | | | | | | | | ◆ | ◆ |

In the absence of disulfides or pyrrhotite in the host rock, (di-)sulfide weathering will not occur, and the mine water will not be acid. Yet, this does not guarantee that the mine water will be of good quality, as some elements are mobile under circumneutral or alkaline conditions. Such examples are elevated antimony concentrations in carbonate rocks (Wolkersdorfer and Wackwitz, 2004) or zinc-enriched mine waters in carbonate-hosted lead/zinc deposits (Johnson and Younger, 2002). When neither disulfides nor (semi-)metals that are mobile under elevated pH values nor water-soluble salts exist, the mine water quality will be within regulatory limits. In these cases, the mine water might even be used as drinking water without treatment (Wolkersdorfer, 2008).

Because the number of working and abandoned mines is large, mining influenced water can become a burden to humans and the environment when this water is polluted. Plumlee et al. (1999) compiled which type of ore body will very likely develop what type of mine drainage. Though their compendium is quite U.S.-based, it is of uniform relevance, as the geological, physical, biological, and chemical processes of mine water geochemistry are identical all around the world.

## Coal and lignite

Coal and lignite often contain varying proportions of disulfides because the depositional conditions favored the precipitation of these minerals (Pohl, 2020). Occasionally, the sulfur content of coal can reach up to 6%, which can produce substantial amounts of acid when not buffered by carbonate rocks. A general rule is that the higher the sulfur content, the higher the concentrations of the potential pollutants sulfate and iron (Younger, 2002). Common potential pollutants of concern from coal or lignite mines are acid, iron, sulfate, sodium and chloride.

Nearly all coal or lignite mining operations develop acid mine drainage if no precautions are taken, such as mixing the overburden with lime or co-depositing disulfide-rich material with buffering material. Mining methods substantially influence the final mine water quality after mining stops (Mentz et al., 1975). When the coal mine can be flooded, the water quality may gradually improve due to the first flush effects. Many long abandoned coal mines discharge water of good quality (Wolkersdorfer and Bantele, 2013). Yet, when large portions of the mines are open to the atmosphere, pyrite oxidation will continue in perpetuity and the discharge water quality may not substantially improve over time. pH values can be below pH 4 and sulfate as well as iron concentrations can be in the upper milligram to lower gram per liter range (McCullough et al., 2008; Prediction Workgroup of the Acid Drainage Technology Initiative, 2000). A contaminant that only received attention in recent years are PCBs (polychlorinated biphenyl) from hydraulic fluids discharged from German hard coal mines. Although most of the PCBs are below the detection limit in the water phase, they can be detected at some selected sites and concentrate in the sediments (Landesamt für Natur Umwelt und Verbraucherschutz NRW et al., 2018). Underground coal mines often have mine water with an elevated mineralization resulting from brines with high chloride and sodium concentrations. In some coal mine waters, barium concentrations cause barite precipitation when this mine water comes into contact with sulfate rich waters (Gombert et al., 2019).

## Gold

One of the largest environmental impact areas of a historic mining operation is the Spanish UNESCO World heritage site Las Médulas. Using a special type of hydraulic mining, called *ruina montium*, the Romans removed substantial amounts of overburden to access alluvial gold, making the site their largest gold operation (Revuelta, 2018). During the operation, about $84 \cdot 10^6$ $m^3$ of gravel, sand and silt were moved (Sanchez-Palencia et al., 2000) and sedimented into the receiving water courses and lakes. Similar situations can still be found in other parts of the world, where gold is mined by hydraulic mining. Yet, the most common mining method for gold in modern times is surface and underground mining combined with cyanide leaching. As gold co-occurs with disulfides, and sometimes uranium, gold mining usually results in highly acidic water with low pH values and elevated sulfate and iron concentrations. Because gold is not only mined in large scale operations, but in small-scale as well as illegal operations, often referred to as artisanal mining, environmental pollution from gold mining sees various forms (Riaz et al., 2019). They include mercury and suspended solids pollution and river course modifications from small or illegal mining operations as well as acid mine drainage and sulfate pollution from abandoned large scale operations. During large-scale active operations, mine and runoff water treatment ensures compliance to regulatory requirements, but cyanide or sulfate pollution is a common problem in these operations when not handled properly (Acheampong et al., 2010). Large areas in the Colorado's Rocky Mountains are polluted by acid mine drainage from abandoned gold mines. Waste rock piles, tailings and unremediated mine galleries discharge large amounts of metals into the receiving water courses, such as the Animas River Watershed (U. S. Department of the Interior—Bureau of Reclamation, 2015). Common parameters of concern from gold mines are acid, iron, sulfate, mercury, cyanide, suspended solids and arsenic.

## Salt

Common salt and potash mining for NaCl, KCl and some Mg-salts, results in large residues of unwanted salt bearing material that is open to the atmosphere and is prone to weathering (Fig. 4). This causes elevated total dissolved solids concentrations as well as chloride, sodium and potassium-concentrations in the receiving water courses. An additional source of contamination is water pumped from the underground workings or the accidentally collapsed salt domes (Kolesnikov and Laskina, 2019). In France, for example, salt is mined by dissolving large salt domes until they purposely collapse and form surface depressions that will fill with water. This mining technology will alter surface water courses in addition to the groundwater regime. Parameters of concern are

**Fig. 4** Salt waste rock piles of the Unterbreizbach and Hattorf mines in Germany. In the foreground the receiving water course Werra. Photograph: Christian Wolkersdorfer.

elevated electrical conductivity and the before mentioned ions. These types of lakes can develop pH values of up to 9 and electrical conductivities of 134 mS $cm^{-1}$ (Żurek et al., 2018). Some of these collapse lakes are used for balneological applications in Romania (Mara et al., 2008), and the Wieliczka salt mine in Poland is a UNESCO world heritage site. During the course of time, salt mines will commonly stratify with a less mineralized water body overlaying highly mineralized mine water (Wolkersdorfer, 2008). Common parameters of concern are elevated electrical conductivity, sodium-, chloride- and potassium-concentrations.

### Iron

From a pollution point of view, iron or pyrite mines can be classified into two types: carbonate/oxide (hematite)- and sulfide-based ores. While iron oxides, such as these in Australia's Pilbara or Brasilia's Iron Triangle seldom pose a chemical threat to water courses, the opposite is true for iron disulfide mines such as California's Iron Mountain or Finland's Pyhäsalmi mines. Most of the banded iron formation mines in Brazil discharge mine water with electrical conductivities between 100 and 300 μS $cm^{-1}$, as low as rainwater (Quadros Amorím et al., 1999). If pollution into water courses occurs, it is mainly related to processing plants or to adjacent gold mining operations. Similar situations occur for iron carbonate mines, such as those in the German Siegerland area, where the pH values are circumneutral and metal concentrations are low (Heyl, 1954). Yet, the weathering products of iron (di-) sulfide minerals such as pyrite, marcasite and pyrrhotite pose a substantial threat to surface water courses. While pyrite and marcasite in mining wastes tend to oxidize to sulfuric acid, pyrrhotite oxidation seems to produce elemental sulfur with a lower acidity in the resulting mine drainage (Schumann et al., 2015). In the vicinity of sulfidic iron mines, pH values of 2–3, iron concentrations of several grams and high sulfate concentrations in the several hundred grams concentration range are common (Adams et al., 2007). The lowest natural pH value ever measured is from the Californian Iron Mountain pyrite mine and was as low as –3.6 (Nordstrom et al., 2000). Common parameters of concern are low pH values, high iron and sulfate concentrations.

### Copper

In nearly all copper mines in the world (di-)sulfide minerals are present (Pohl, 2020) and therefore, there is a high likelihood that the mines will discharge acid mine drainage or highly mineralized mine water. Besides copper and iron, these deposits contain a large set of other potentially toxic, chalcophile metals (Arndt et al., 2015), which comes as no surprise as the term chalcophile derives from the Greek word *χαλκός* for copper. Copper is mined in surface, underground and solution mines, and there is no substantial difference in the list of elements that can be found in the effluent. One exception is the effluent of solution or heap mining, which is usually extremely acid, but normally not discharged without treatment (but might leak into the subsurface). Main contaminants or parameters of concern from copper mines, independent of type, are low pH values, elevated electrical conductivities, and sulfate as well as iron concentrations that are the higher the lower the pH value is (Šerbula et al., 2016). At Parys Mountain in Wales, pH values of 2.5–3.7 and sulfate concentrations of 0.4–3 g $L^{-1}$ were reported with Fe showing 67–708 mg $L^{-1}$ and Cu 7–44 mg $L^{-1}$ (Rees, 2005). Similar conditions occur at other copper mines in the area (Mullinger, 2004), but the Welsh Parys mountain site has the fate of the highest pollution rank. Very similar conditions occurred at the Mount Lyell copper-gold mine in Tasmania, Australia, with pH values around 3, concentrations of sulfate 0.2–14, Fe 53–2200, and Cu 9–180 mg $L^{-1}$ (John and Partners Pty. Ltd., 1996).

### Lead/Zinc/Silver

Potential effects of lead and zinc mining on water courses highly depend on the geological setting of the deposit. Some European lead/zinc mines pose only small or negligible effects, while geologically similar lead/zinc mines in the U.S. cause detrimental environmental effects from secondary minerals and efflorescent salts (Alpers et al., 2000) around mine waste piles and processing plants (Besser et al., 2009). In these carbonate-hosted deposits, as long as the buffer capacity of the carbonates is not consumed, the pH values will be in the upper circumneutral range. Lead and to a lesser extent zinc are less mobile at these pH values (Fig. 3), and therefore the effects on the water courses are normally small, with exceptions such as the Swedish Lovisagruvan mine (Fahlqvist et al., 2012), where lead and zinc concentrations are ecologically relevant and pose a threat to the aquatic environment.

There might be some immediate increases of electrical conductivity after a mine is flooded, which results from the dissolution of secondary minerals in the open mine voids. Contamination also occurs when the pyrite- and marcasite-rich zones of these deposits are exposed to oxygen and humidity for a longer time. In these cases, the buffer capacity of the carbonate host rocks might become exhausted and acid or metal enriched mining influenced water develops, such as in the case of the Polish Chrzanów or the Picher, Oklahoma Mining Districts (Czop et al., 2007; DeHay et al., 2004). When conditions such as in the Alaskan Red Dog mine (Knapp, 2004) or the Picher Mining District (Tar Creek Superfund) occur, which can be considered one of the most polluted mining areas in the world, then the effects on the water courses will be detrimental. Reason for this pollution is the co-occurrence of lead and zinc with large deposits of disulfides. At the Red Dog mine, pH values of 3–5 with Zn concentrations between 0.3 and 3.3 g $L^{-1}$ and TDS of up to 15.4 g $L^{-1}$ have been reported. In Germany's long-abandoned central Harz Mountains silver/lead/zinc mining area, pH values are relatively high and elevated metal or semimetal concentrations can only be found in selected hot spots (Bozau et al., 2017). Common parameters of concern are lead, zinc, electrical conductivity, and a low pH value.

### Uranium

Uranium mining operations can be underground or in open pit mines. The mining technologies involved are either conventional mining or solution mining (Woods, 2018). Due to the high mobility of uranium in oxidizing environments and the co-occurrence with (di-)sulfides, uranium mining sites can often be considered problematic for the aquatic environment. Besides suspended solids from tailings sites and waste rock repositories, sulfate, uranium, radium, and low pH values are commonly found around working or abandoned uranium mine sites (Metschies et al., 2016; Vaupotič and Kobal, 1999; Woods, 2018). Immediately around the mine, tailings or waste rock sites, macrozoobenthos can be impaired when the metal concentrations in the receiving water courses exceed toxic concentrations (Humphrey et al., 2012; Trontelj and Ponikvar-Zorko, 1998). These effects of surface water contamination can last for a substantially long time when the groundwater is infiltrating surface water (Baacke et al., 2015). As iron is also mobile in low pH-environments, elevated iron concentrations are common in uranium mining areas. When the pH values increase over the course of the stream, ironoxides and the sorbed (semi-)metals can precipitate or co-precipitate. This can cause elevated (semi-)metal concentrations in the stream sediments (Neiva et al., 2014). Common potential pollutants are uranium, radium, arsenic, sulfate and low pH-values.

### Diamonds

Reports about environmental pollution of river courses resulting from diamond mining are comparably rare—contrary to the connected social issues known under the term "blood diamonds" (Bieri, 2010). Yet, the large tailings dams and open pits as well as placer mines impair the local water courses with suspended solids and minor chemicals from the extraction process (Yelpaala and Ali, 2005). The reason for the relatively low effects on water courses is the host rock (kimberlite, lamproite, or lamprophyre), which is not prone to acid production (Ochieng et al., 2009). Some of the largest diamond mines in the western world are in areas that need to be protected because of their pristine character and the interests of indigenous peoples (van Luijk et al., 2020) and therefore discharges from these mines are strictly regulated. Yet, some diamond mines might develop an elevated mineralization and metal toxicity (McCullough and Sturgess, 2020).

In northern Canada, diamond mine water might have elevated electrical conductivities due to an increasing mineralization trend with depth (Herrell et al., 2018), and in some cases elevated nitrate or ammonia concentrations evolved as a result of explosives being abundant in the tailings and waste rocks (Bailey et al., 2013). In addition to that, high phosphate and chloride-concentrations exist.

A rare source of pollution to surface waters in the Russian Yakutia (Sakha, Якутия) diamond mining district is worth mentioning: radioactive nuclides from 12 "peaceful" underground nuclear explosions. Nuclides from the "backfired" nuclear explosions polluted the nearby environment. In addition, surface waters are contaminated with potentially toxic elements which also impair the people's health (Yakovleva et al., 2000). Common pollutants of concern are mineralization, nitrate, ammonia.

### Aggregate mining, building stones, quarries

Gravel and building stones comprise the world's largest amount of mined raw materials (Langer and Arbogast, 1998). Chemically, these types of mines seldom pose a risk for inland waters, but the suspended solids can cause a substantial change to water courses and aquatic life (Fig. 5). When aggregates are mined in alluvial deposits and the number of mines along a stream is large, they disturb fish and other wildlife (Marcus, 1997). Because of the high transport costs of aggregates and building stones, quarries are usually built in the vicinity of built-up areas (Langer and Arbogast, 1998). There, they often pose a visual threat in the landscape, and locals might complain about noise, vibration, or dust pollution (Schneider and Wolkersdorfer, 2021; Vandana et al., 2020), even though they can be advantageous as they provide recreational areas and new habitats for aquatic ecosystems.

A case of acid mine drainage formation was the greywacke quarries Großthiemig and Brößnitz, Germany, where pH values of 2.9 and iron concentrations of up to 80 mg $L^{-1}$ were measured (Gerstenberg, 2005) and a pilot passive treatment system was installed (Hubrig et al., 2014). Highly alkaline conditions developed in the Górka limestone quarry, Poland, with average pH values between 12 and 13, resulting from industrial waste deposited into the quarry during its operation (Czop et al., 2008). Pollutants that can be seen more often in water courses around quarries are nitrogen compounds, originating from unused explosives (Karlsson and Kauppila, 2015).

Some of the negative effects of aggregate mining or quarries is the modification of water sheds as the rocks or sediments are removed. This can result in changes of water courses as the water is flowing into different directions compared to pre-mining conditions (Langer and Arbogast, 1998). In addition, instead of diffuse flow of water into receiving steams, point sources with sometimes elevated flow might develop. Because groundwater levels might fall during mining, water courses could also fall dry during the duration of the quarrying. Even after quarrying ceases, and when the quarry is large, a cone of depression might persist and impair surface water courses. Common parameters of concern are elevated concentrations of suspended solids and modification of water courses and arsenic in limestone quarries.

### Others

Platinum mining usually results in contaminated effluents from the tailings areas, but seldom from the mine drainage *per se*. These effluents contain elevated concentrations of nitrogen oxide and TDS (Skinner, 2018). Around vanadium processing plants, ground and surface water has been reported to contain elevated vanadium concentrations (Kamika and Momba, 2014). Apatite and Iron-Apatite mines sometimes develop elevated phosphate concentrations in mine and tailings waters (Makarov et al., 2019; Reta et al., 2019). In recent years, selenium has been a matter of environmental concern in a range of mines, with Sudbury/Canada possibly leading this list (Warren, 2013). Elevated concentrations of the semi-metal Sb regularly occur in carbonate-hosted mines (Ilavský and Barloková, 2019; Wolkersdorfer and Wackwitz, 2004).

Potential contaminants that are seldom discussed within the mining context are organic compounds. They might be PAH, PCB, or oil from the mine workings itself or organic chemicals used in mineral processing.

Listing common pollution indicators for "other" mines is not useful, as they are highly variable and depend on the deposit type and the respective mine site. Yet, experience suggests, these are low pH, high sulfate, and TDS as well as suspended solids.

**Fig. 5** Aggregate mining in the Nakkhu Khola River valley (नखखु खोला), Katmandu, Nepal. Photograph: Christian Wolkersdorfer.

## Chemical and physical effects on surface waters

### Lakes

Acidity, mineralization, metal toxicity, and suspended solids are the main pollutants influencing lakes by mining influenced water. In most cases, these have negative effects on the ecosystems and to variable extent individual species (Tuovinen et al., 2012), especially where the mining influenced water directly enters the lake (Hartwig et al., 2005). Acid mine drainage increases the acidity in lakes, and as a result of the low pH values the metal concentrations increase (Castendyk and Eary, 2009; Gray, 1997). Pit lakes strongly differ from natural lakes and their shape and size influence their chemical and physical parameters, as their relative depths are markedly higher (Geller et al., 2013). Lake stratification is a function of the lake's wind fetch and solar irradiation as well as forces such as surface and groundwater density and heat (Hipsey et al., 2019). Due to their great depth, pit lake stratification occurs with an increase of total dissolved solids and electrical conductivity with depth (Castro and Moore, 2000). Influenced by high concentrations of dissolved substances, the color in mine lakes can vary between red (due to ferric iron with pH below 3) and blue/turquoise (aluminum buffer reactions at pH around 5). Besides the chemical changes of the natural lake's composition (Borvinskaya et al., 2017), suspended solids impair the lakes' ecosystem and physical conditions, though the low energy environment of lakes supports a fast settling. These sediments can even be used as geochemical markers and allow to reconstruct the mining history (Callender, 2000). Because lake sediments are large repositories of potentially toxic elements, changes in the pH or redox conditions can remobilize these elements (Azcue and Nriagu, 1993).

### Streams

In flowing waters there is a constant exchange of water with various physico-chemical parameters, and, consequently, the effects of mine water on the streams are characterized by dilution and buffering. Well-buffered streams are less affected by acidification compared to sedimentation or elevated metal concentrations (Bell and Donnelly, 2006; ERMITE Consortium et al., 2004). Once the buffer capacity is consumed, and depending on the pH, mineralization, hardness and dissolved organic matter, streams can develop eco-toxic concentrations of metals and metalloids and the ecosystem will be under pressure (van Dam et al., 2019) as described in the section "Biological and ecosystem effects".

Depending on the chemical composition of the discharged water, adsorption of metals onto sedimentary particles and plants can occur. If oxidizing conditions and neutral pH values dominate, metals can adsorb on clays, organic matter as well as on Mn-, Al- and Iron-oxides (Dong et al., 2007; Miller et al., 1996). Dissolved iron, which occurs most commonly in mine water influenced streams typically precipitates as oxides and hydroxides in the streambed close to the discharge point and is often visible (Mestre, 2009). These suspended iron oxyhydrate solids and the reddish color of dissolved iron in low pH-conditions cause many mining influenced streams and rivers to appear in reddish to orange colors (Fig. 6). In addition, the mining influenced water sometimes reduces the surface tension in the stream, which results in the formation of foam (Lottermoser, 2010).

When streams or rivers are used as raw water for drinking water production, discharges of mining influenced water can substantially impair the fresh water supply chain (McCarthy and Humphries, 2013). Remediating these surface water courses, especially in rural areas, can be challenging as well as time and cost consuming (ERMITE Consortium et al., 2004; Sumi and Gestring, 2013).

**Fig. 6** Mine Water discharge of the Heinrich colliery, Germany, into the river Ruhr. Suspended iron oxyhydrates flocculate as they get oxidized. On the left of the discharge, the precipitates stain the riverbanks, and, on the right, the fresh water of the Ruhr can be seen. Photograph: Marlene Julia Fromm.

### Precipitates in surface waters

Changing environmental conditions, such as aerating mixing processes when mining influenced water discharges into surface waters (Máša et al., 2012), initializes various physical and chemical processes which might result in precipitation. These processes are evaporation, oxidation of reduced species, changes in pH value and redox potential, flocculation, or coagulation. In mining influenced water, the most common precipitate is ochre ("yellow boy") which is a mixture of iron oxyhydrates and sulfate minerals, although the formation of ferrihydrite ($Fe_5HO_8 \cdot 4H_2O$), goethite (α-FeOOH) or schwertmannite [$Fe_8O_8(OH)_6SO_4$] differs based on the local conditions (Kairies et al., 2005; Schwertmann et al., 1995). Additionally, the visual appearance of ochre is quite different, ranging from gelatinous flocculants, suspended colloids, medium soft mud, foam on the water surface, coating on rocks to hard and thick encrustations. Most precipitates sorb or co-precipitate with trace elements like arsenic, cobalt, nickel, and zinc, as the ochre has a high specific surface area and is therefore responsible for mobility, fate and transport of trace elements in mining influenced waters (Kairies et al., 2005; Schemel et al., 2000). Other precipitates are aluminum oxyhydrates, which also sorb potentially toxic elements and contribute to the improvement of the waters conditions (Rothenhöfer et al., 2000). These characteristics of accumulating (semi-)metals are widely used as a means of geochemical exploration in natural waters (Förstner, 1981).

## Biological and ecosystem effects

Biological effects of mine drainage on the aquatic ecosystem range from severe effects that kill most macroinvertebrates and fish to improvements of the water quality when unpolluted mining influenced water drains into a polluted water course. These effects can result from large mining operations, mining accidents or by artisanal mining (Dabrowski et al., 2013; Hernandez et al., 1999; Macdonald et al., 2014, 2015). Effects on fish can vary depending on the animal's age: whilst juvenile fish might avoid mine water influenced streams, adults might be able to survive in the elevated pollutant concentrations. Ecosystem management programs need to be site specific, taking into consideration the high variability of geological and climatic conditions. When all the relevant factors are considered, potential negative effects of such a program can be avoided (Kruse Daniels et al., 2013).

A common pollutant is particulate matter like clay, silt, or sand from tailings dams, waste rock piles, or aggregate mining (Greig et al., 2005). Examples for this are the Ok Tedi mine in Papua New Guinea (Low and Gleeson, 1998) or the abandoned Mount Lyell Copper deposit in Australia (McPhail et al., 2001). Increased turbidity due to suspended solids also decreases light penetration into the water and therefore reduces photosynthesis (Wood and Armitage, 1997). Additionally, fish gills can become clogged, or fish eggs can suffocate due to settled suspended matter (Bilotta and Brazier, 2008; Butler and Ford, 2018). This inhibits the growth of algae or microorganisms and therefore prevents macroinvertebrates or fish from getting enough food, as the functioning of the food web for the biological survival of surface waters is interrupted. Additionally, biofilms might accumulate potentially toxic elements that concentrate in the higher organisms (Hobbs et al., 2019). Consequently, they move away or die, and the surface water becomes biologically dead. Yet, this does not necessarily imply that the water is *a priori* toxic. Another negative effect on livestock is the reduction of oxygen by processes that oxidize reduced constituents or organic matter (Weiner, 2010).

A positive biological effect on mine water quality is the filtering effect of sediments and the biota in natural wetlands. In many cases, it has been observed that the quality of mining influenced water substantially improves downstream of natural wetlands (Fyffe et al., 2015; Haarstad et al., 2012). This known effect has been used to construct the first artificial wetland for mine water treatment (Kleinmann et al., 1985). Yet, as the contaminants accumulate in the natural wetlands, unexpected incidents like flood events, droughts, or earthquakes might impair the pollutant deposits and could release them to downstream receptors.

## Management and mitigation of mining influenced water

### Principles of mine water management

Mitigation of the effects caused by mining influenced water is performed in one of five ways: avoidance, natural attenuation, active treatment, passive treatment, and *in situ* treatment. During a mining operation, negative effects on the environment cannot be completely avoided. However, because society relies on an input of raw materials, managing the risks from potential contaminants in mining influenced water to acceptable levels is a trade off against benefits acquired from operation. Ultimately, pollution arising from mining operations must be reduced by modifying the mining methods or averted by technical means (Skousen et al., 2019; Wolkersdorfer, 2021).

One of the key requirements to understand and optimize management and mitigation of mining influenced water and its effect on the surrounding inland water systems is monitoring (McLemore et al., 2014). This could also include participatory water quality monitoring (International Council on Mining and Metals, 2015), which assists in engaging local communities in developing remediation options.

### Avoidance

In principle, the best avoidance strategy would be to separate disulfides from water and oxygen to inhibit oxidation. In the context discussed herein avoidance includes all measures that prevent and slow down the evolution of mining influenced water or keep water away from the mines. The latter is achieved by installing cut-off walls, or surface water can be diverted around open pit mines (Steffen Robertson and Kirsten (B.C.) Inc and Norecol Environmental Consultants and Gormely Process Engineering, 1990). By reduction or segregation of acid-producing materials, the weathering processes are minimized, and (di-)sulfide oxidation is reduced. This requires sophisticated prediction and mine planning methods that allow a controlled flow of inert, acidic, and neutralizing rock material. In modern mining operations, exploration data, real time data, block models and artificial intelligence are used to direct the waste material to an appropriate location (More et al., 2020). In open pit mines, thorough mine planning including mixing of alkaline with acid producing material is recommended (Drebenstedt and Struzina, 2008; Wisotzky, 2004). Dams in underground mines separating disulfide rich areas from water and oxygen can prevent the formation of acid water or its discharge. Dry seals at mine entrances reduce oxygen contact with disulfide rich strata, while wet seals prevent oxygen contact and water discharge (Foreman, 1971). Tailings and waste rock can be managed with dry or wet covers, which can substantially reduce oxygen diffusion and slows down pyrite oxidation. Dry covers are layers of soil and gravel above mining waste repositories while wet covers could be ponded water on top of tailings (European Commission, 2009; Moncur et al., 2015).

### Natural attenuation

Natural or intrinsic attenuation is a process by which nature without human interaction mitigates the negative effects of mine effluents on receiving water courses, and this process has occurred since humans first mined. In general, attenuation is a slow process but an effective one, and in many cases, several decades of attenuation processes results in acceptable environmental conditions. Natural attenuation uses energy, such as solar energy and potential energy, and is assisted by microbes which oxidize or chemically reduce various contaminants in the mining influenced water. Very often, (semi-)metals are sorbed to suspended solids and by their removal in natural wetlands or when iron flocculants settle, the water quality continuously improves. Other mechanisms are simple settling of suspended solids while the water's velocity decreases, e.g., during flow into lakes. Natural attenuation also depends on dilution effects during rain events and on time, as several natural processes are a function of time. A commonly observed effect in flooded mines is the first flush, which lasts 3–5 times as long as it took the underground mine to be flooded (Younger et al., 2002). While the mine workings are flushed by relatively clean ground or rainwater, effluent salts and secondary minerals are washed out into the receiving water courses (Wolkersdorfer, 2021; Younger et al., 2002).

### Active treatment

Active treatment implies the use of chemical reactants, the supply of energy, and a continuous monitoring of the plant (Skousen et al., 1998; U. S. Environmental Protection Agency, 2014). This active process removes unwanted substances and ensures discharge criteria are met. Criteria for the selection of the various active treatment methods are the concentration, load, and chemical composition of the mining influenced water. Among the most common active processes are neutralization (especially Low Density Sludge and High Density Sludge treatment), and membrane processes (e.g., reverse osmosis). Although there are more than a dozen different active processes on the market, most of them are of marginal importance in the mining industry as they are unsuitable for high volumes of water or the cost of operation are high.

### Passive treatment

Passive mine water treatment is the improvement of water quality using only naturally available energy sources in gravity-flow treatment systems (such as wetlands or subsurface-flow bioreactors) which are designed to require only infrequent (albeit regular) maintenance to operate successfully over their design lives (literally from PIRAMID Consortium, 2003). Treatment is achieved entirely through potential (differences in altitude), solar or biological (bacteria) energy, and systems like that are operating from cold to warm climate zones. Passive systems include oxic or anoxic limestone drains, constructed aerobic or anaerobic wetlands, reducing alkalinity systems (RAPS, also called SAPS), settlement ponds, permeable reactive walls or vertical flow reactors (Brown et al., 2002; Wolkersdorfer, 2021). Passive systems, compared with active systems, usually cannot handle large volumes of mining influenced water or elevated pollutant concentrations.

### *In situ*-treatment

*In situ*-treatment is of particular importance for surface waters. One of the most common processes is in-lake treatment such as adding lime to pit lakes by boats or pipes (Benthaus et al., 2020). Water courses are sometimes treated by applying alkaline material directly into the flowing wave (Gusek and Figueroa, 2009; Uhlig et al., 2016). Especially for diffuse inflow of mining influenced waters, the construction of reactive walls (Bowden et al., 2005) can be used as an *in situ* option. Another avoidance or *in situ* method is stratification in flooded mines, which reduces the discharge of mine water with poor quality, as higher mineralized, thus more polluted mine water, remains in the deeper parts of the mine (Wolkersdorfer, 1996). A general recommendation which method to apply cannot be made before a detailed site investigation is first undertaken.

## Synthesis

Mining influenced water commonly evolves around underground and open pit mining operations through microbially catalyzed pyrite oxidation. For pH, these waters can be acid, circumneutral or basic, and from a mineralization point of view, dilute, mineralized or saline. Depending on the type of raw material, the pollution load of the mining influenced water and the pollutants of concern can vary substantially. This, consequently, has different effects on inland waters, which can be minimal in the best case and detrimental in the worst one. Potential effects are suspended solids, diversion of water courses, highly variable flows and a toxicity that impairs the ecosystems of the lakes, streams, and rivers. Many mining influenced waters have no effect on the receiving inland waters at all, some are even used as drinking water, because the first flush already passed. Yet, the most prominent effect on inland waters are red to orange stains from precipitates, a reddish to orangish color of the water, and a change of the aquatic ecosystem composition. Various mitigation options are available, ranging from doing nothing, commonly referred to as natural attenuation, to passive treatment and to active mine water treatment. *In situ*-treatment options are rarely used, but future developments will see these options more often.

To increase the public acceptance of mining operations, there is a need for improving communication and the availability of information. This ensures that the reasons for mining influenced water are understood and the measures of the mining houses to mitigate these effects are better known. Yet, the best solution would be if future developments and innovations would reduce the pollution emanating from mining operations such, that there are no effects on inland waters at all.

## Knowledge gaps

In relation to mining influenced inland waters, there are no knowledge gaps *per se*. Yet, there are many questions that need to be answered to increase the acceptance of mining in the public and to protect aquatic ecosystems. To a large degree, most of the solutions already exist, but economic pressures or irresponsible behavior often restrict their utilization. One of these solutions would be the valorization of mining residues, such as waste rock piles, tailings, or polluted mine water. Yet, much research will be needed to find applications for all the relevant water pollutants and mining residues. In addition, many treatment options for mine water are cost intensive, i.e., expensive, and financial restrictions or the competition on the market restrict their implementation. Therefore, there is a need for cheap and reliable treatment solutions, or, at least, treatment solutions which leave water, valuables and not much more than a footprint. Especially research on *in situ* remediation including the understanding of the mines' hydrodynamic conditions is needed. A knowledge gap is also the exact interplay between mining influenced water and the groundwater, the resilience of ecology to mining pollutants and how, precisely, contaminants affect humans and livestock too.

One gap is the site specific and temporal prediction of the water quality of working and abandoned mines and where diffuse mine water discharges will occur after mining ceases. Therefore, a world equation for mine water would be needed. This means, modeling and simulations should be able to predict exactly what mine water quality might be expected in each single stage of the mining operation, including the prediction of the mine water's potential toxicity on various aquatic species. Though first approaches for the chemical composition exist (Chetty et al., 2020; Van der Sloot and Van Zomeren, 2012), the mining community is still a large step away from a unifying solution.

On the monitoring and information side there is a need for new sensors where scaling would be inhibited, and no wipers or shutters are necessary to remove the fouling on the electrodes. As larger data sets are continuously collected during mining operations, big data operations and artificial intelligence are needed to optimize mining operations and reduce pollution. Additionally, an improved information policy and true information to the public is a key requirement to increase the acceptance of mining on one side and to reduce pollution by artisanal miners on the other side.

Modern civilization will need raw materials forever. Because a circular economy will not be able to supply a growing world demand while the population increases, mining operations will also be needed in the future. Therefore, it is essential that future mining operations and the mining houses will do everything that is needed to protect inland waters and groundwaters alike.

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mineclosure.gtk.fi—Geological Survey of Finland.
www.mend-nedem.org—MEND (Mine Environment Neutral Drainage) Canada.

# 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.

 https://doi.org/10.1016/B978-0-12-819166-8.00085-2 

**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.

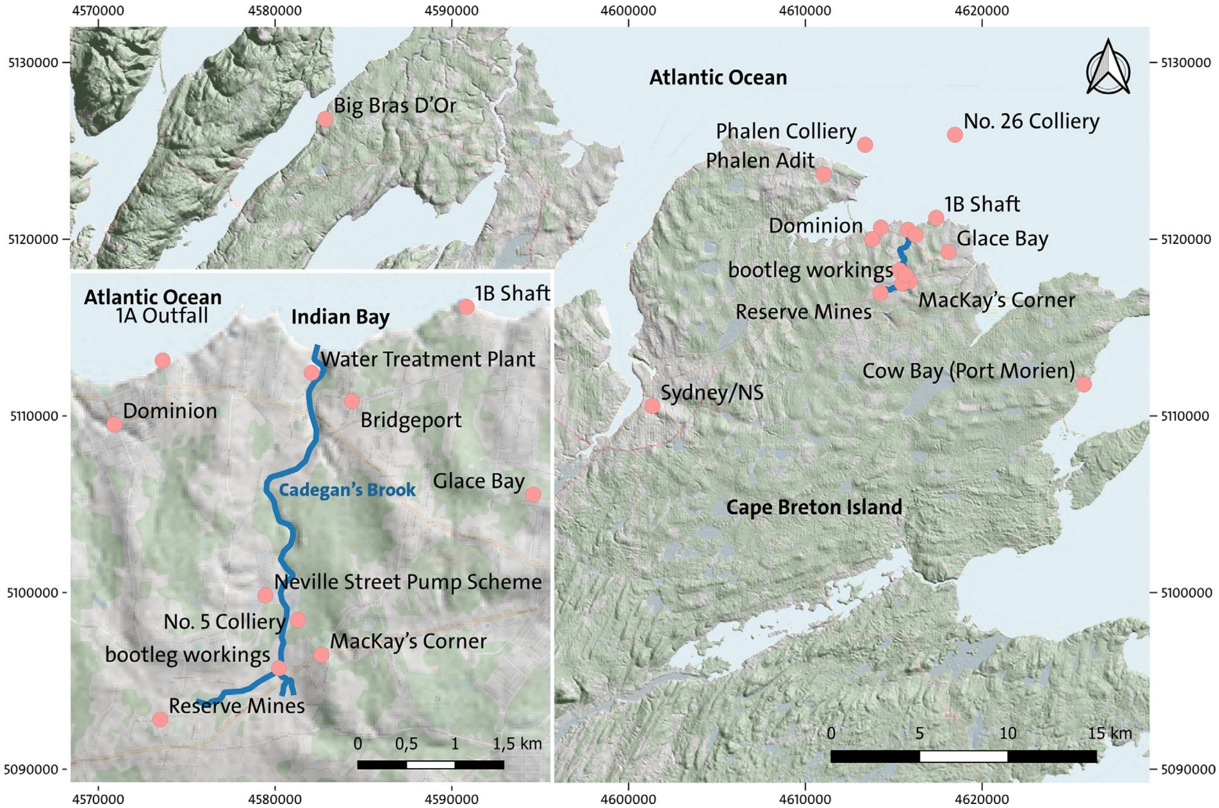


**Fig. 1** Details of the Sydney/NS coal mining region. Sources: Open Street Maps community, Nova Scotia (NS) Department of Natural Resources.

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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