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.

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,

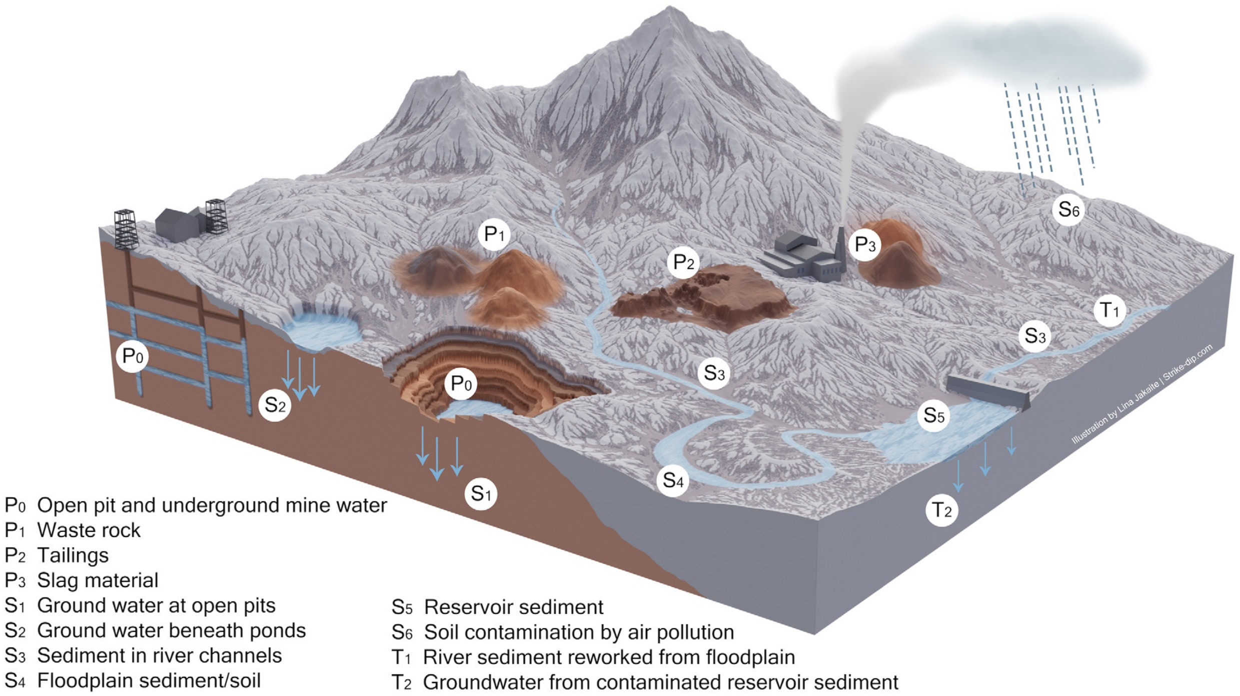

Fig. 1 Pollution pathways in the mining environment. P: primary contamination, S: secondary contamination, T: tertiary contamination. Modified after Moore JN and Luoma SN (1990) Hazardous wastes from large-scale metal extraction—A case study. *Environmental Science & Technology* 24(9): 1278–1285, https://doi.org/10.1021/es00079a001.

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.

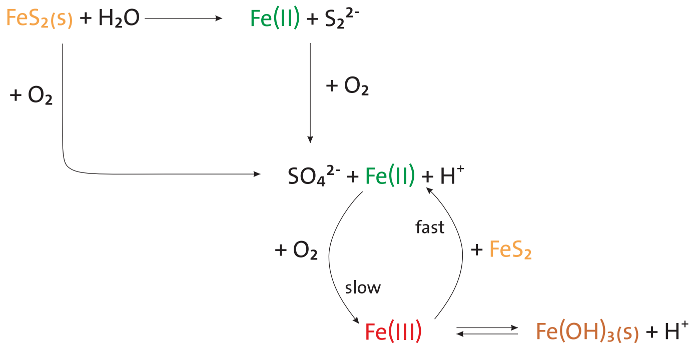

Fig. 2 Diagrammatic representation of the pathways during abiotic pyrite/marcasite oxidation. Based on information in Kester DR, Byrne RH and Liang Y-J (1975) Redox reactions and solution complexes of iron in marine systems. *ACS Symposium Series* 18: 56–79, https://doi.org/10.1021/bk-1975-0018.ch003; 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.

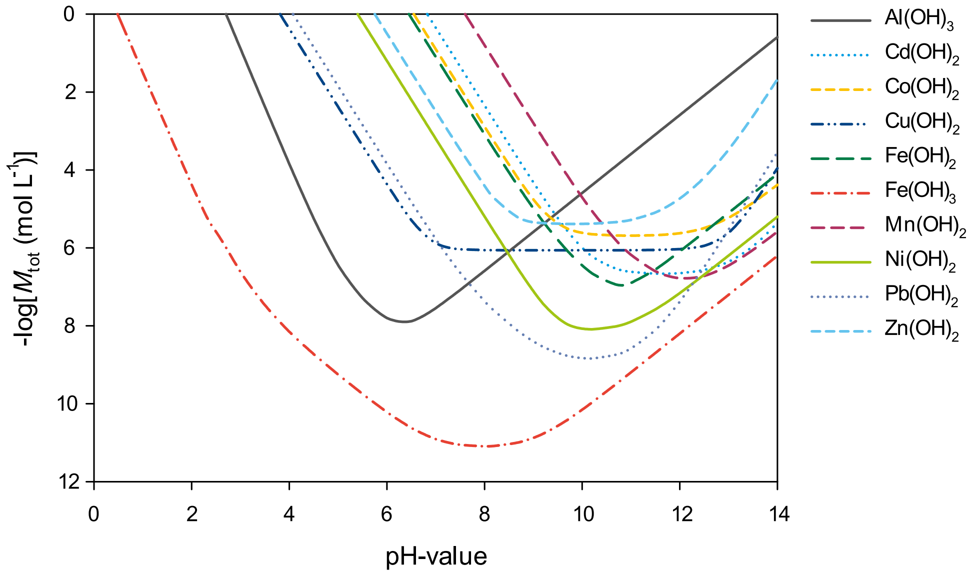

Fig. 3 Solubility of environmentally relevant metal hydroxides as a function of the pH value. Modified and supplemented according to Cravotta CA, III (2008) Dissolved metals and associated constituents in abandoned coal-mine discharges, Pennsylvania, USA. Part 2: Geochemical controls on constituent concentrations. *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). Common parameters of concern are low pH values, high copper, iron and sulfate concentrations in connection with elevated electrical conductivities.

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 (□□□ □□□□), 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.